

**Temperature, climate change, and human conception rates:
Evidence from Hungary**

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ABSTRACT

In this paper, we examine the relationship between temperature and human conception rates and project the impacts of climate change by the mid-twenty-first century. Using complete administrative data on 6.8 million pregnancies between 1980 and 2015 in Hungary, we show that exposure to hot temperatures reduces the conception rate in the first few weeks following the exposure, but a partial rebound is observed after that. Absent adaptation, climate change is projected to increase seasonal differences in conception rates, and a decline is expected in terms of annual conception rates. This latter decline is driven by a change in the number of induced abortions and spontaneous fetal losses. The overall number of live births is unaffected. However, some newborns may experience non-negligible consequences because of the altering in utero temperature exposure due to a shift in the timing of conception.

JEL codes: J13, Q54

Keywords: conception rate; fertility; temperature; weather; climate change

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Hőmérséklet, klímaváltozás és fogantatási ráta: Egy magyarországi elemzés eredményei

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Összefoglaló

Tanulmányunkban a hőmérséklet és a fogantatások közti kapcsolatot vizsgáljuk, valamint a klímaváltozás 21. század közepére várható hatását becsüljük. Elemzésünkben az 1980 és 2015 közötti 6,8 millió magyarországi terhesség adatainak segítségével megmutatjuk, hogy a magas hőmérsékletnek való kitettség csökkenti a fogantatási rátát az expozíciót követő néhány héten, majd egy részleges „korrekció” (növekedés) figyelhető meg a későbbi hetekben. A klímaváltozás hatására a fogantatási ráta szezonális különbségeinek erősödése és éves szintjének kismértékű csökkenése várható. Ez utóbbi csökkenést a terhességmegszakítások és spontán vetélések számának visszaesése okozza. A klímaváltozás az élveszületések számát érdemben nem befolyásolja. Ugyanakkor az újszülöttek egy részének fogantatási időpontja a klímaváltozás hatására megváltozik, így a különböző hőmérsékletű napoknak való terhesség alatti kitettségük is módosul, aminek további kedvezőtlen következményei lehetnek.

JEL: J13, Q54

Kulcsszavak: fogantatási ráta; fertilitás; hőmérséklet; időjárás; klímaváltozás

Temperature, climate change, and human conception rates: Evidence from Hungary

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Abstract

In this paper, we examine the relationship between temperature and human conception rates and project the impacts of climate change by the mid-twenty-first century. Using complete administrative data on 6.8 million pregnancies between 1980 and 2015 in Hungary, we show that exposure to hot temperatures reduces the conception rate in the first few weeks following the exposure, but a partial rebound is observed after that. Absent adaptation, climate change is projected to increase seasonal differences in conception rates, and a decline is expected in terms of annual conception rates. This latter decline is driven by a change in the number of induced abortions and spontaneous fetal losses. The overall number of live births is unaffected. However, some newborns may experience non-negligible consequences because of the altering in utero temperature exposure due to a shift in the timing of conception.

Keywords: conception rate; fertility; temperature; weather; climate change

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Data and code availability: All data and code necessary for replication of the results in this paper are available for download at <https://figshare.com/s/6a039f7a0bbfb8d5e3e1>. The original climate projections data can be downloaded from: <https://dataserver.nccs.nasa.gov/thredds/catalog/bypass/NEX-GDDP/catalog.html>. The original weather data can be downloaded from: <https://www.ecad.eu/download/ensembles/download.php>. Conception data has been produced using the individual-level de-identified live birth, induced abortion, and fetal loss records of the Hungarian Central Statistical Office (HCSO). The de-identified microdata sets are available only for research purposes in a secure data environment (HCSO-CERS research room).

1. Introduction

Scientists have been interested in the seasonality of human pregnancy and its associations with temperature for many decades now (Chang et al., 1963; Mills and Senior, 1930; Stoeckel and Choudhury, 1972; Takahashi, 1964). Despite this long-standing interest, the causal estimation on the relationship between temperature and overall conception rates is missing. Existing studies have only examined the effect of temperature on live birth rates, and they have found that exposure to hot temperature causes a decline in birth rates 9–10 months later (Barreca et al., 2018; Lam and Miron, 1996; Seiver, 1989). More importantly, the impacts of climate change on human conceptions remain unexplored, even though the projected warming of the climate has prompted numerous studies covering its effects on natural and human systems (Carleton and Hsiang, 2016; Dell et al., 2014; Scheffers et al., 2016).

While there is no causal evidence on the relationship between temperature and the human conception rate, the related literature points towards the existence of a negative impact. First, animal experiments suggest that males exposed to high temperatures are less fertile (Burfenig et al., 1970; Jannes et al., 1998; Paul et al., 2008; Wettemann et al., 1979; Yaeram et al., 2006), although the impact of heat stress on the conception capability of females is less clear (Hansen, 2009). Second, human studies have shown that exposure to heat suppresses spermatogenesis (Ahmad et al., 2012; Brown-Woodman et al., 1984; Carlsen et al., 2003; Garolla et al., 2013; Macleod and Hotchkiss, 1941; Robinson et al., 1968; Wang et al., 2007; Zhang et al., 2015).

In this paper, we analyze the impact of ambient temperature on the overall human conception rate in Hungary. We use administrative data with full coverage on pregnancies recorded by the country's health care system. Our data cover 6.8 million pregnancies with conceptions occurring between 1980 and 2015, including live births, spontaneous fetal losses, and induced abortions, incorporated into 37,440 county-year-week cells. To estimate the causal effect of temperature on the conception rate (defined by the number of conceptions per week in a given county per 100,000 women aged 16–44 years), we exploit the presumably random year-to-year variation in the calendar week-specific average temperature. We allow for a nonlinear temperature–conception rate relationship by using eight temperature categories that represent the number of days with different daily mean temperatures. We allow the weekly conception rate to be affected by lagged temperatures up to 25 weeks. This way we can identify the potential delayed impacts or shifts in conception rates. Our model controls for differences in county-specific seasonality and its change over time, as well as for county-specific shocks at the year level. Next, we combine our historical estimates with projections of 21 climate models to calculate the impact of climate change by the mid-twenty-first century (2040–2059). We project the impacts on (i) seasonal distribution and (ii) annual level of conception rate.

We find that exposure to hot temperatures (daily mean temperature $>25^{\circ}\text{C}$) has a deteriorating effect on conception rates in the short term (up to 5 weeks after the exposure), showing a U-shaped pattern with the strongest impact ranging from 2 to 4 weeks after the exposure. We find practically zero coefficients between weeks 6 and 10, and an increased conception rate from week 11 after the exposure, which suggests that exposure to hot temperatures changes the timing of some conceptions.

We also show that seasonal differences in conception rates are likely to be larger by the mid-twenty-first century because of climate change. Conception rates in the summer and early autumn months are projected to decrease, whereas conception rates during winter and late autumn are projected to increase. In addition, the annual conception rate is projected to decline. This decline is primarily driven by a change in the number of induced abortions and spontaneous fetal losses rather than by a change in the number of live births. Finally, we show that although the overall number of live births will not change significantly as a result of climate change, future warming will change the season of the conception of some newborns. This shift

could have important consequences on the affected newborns by altering their in utero temperature exposure.

Our study provides important contributions to the literature. To our knowledge, this is the first study that examines the impact of temperature on the human conception rate using data with full coverage on all pregnancies that are recorded by the health care system (live births, induced abortions, and spontaneous fetal losses). Furthermore, we project the impacts of climate change on the overall human conception rate and examine the impacts by pregnancy type. Thus, our paper offers important insights for climate change policy.

2. Data

2.1. Conceptions

To calculate conception rates, we use the administrative registers of the Hungarian Central Statistical Office. These individual-level registry data cover all clinically recognized pregnancies that end in a live birth, spontaneous fetal loss, or induced abortion between 1980 and 2016 in Hungary. In other words, they include all pregnancies that are reported to and documented by the national health care system (including public and private care as well). The de-identified microdata sets are available only for research purposes in a secure data environment of the Hungarian Central Statistical Office.

Because all these datasets contain information on the date of birth/abortion/fetal loss and pregnancy length, we can estimate the date of conception for all pregnancies. We do it in two steps. First, we estimate the first day of the last menses. Because gestation length is calculated from the first day of the last menses, and it is reported in completed weeks, we estimate the starting date of the menstrual cycle as follows:

$$M = LD - (GL \times 7 + 3) \quad (1)$$

where M is the first day of the last menses, LD is the last day of the pregnancy, GL is gestation length reported in completed weeks. Because the extra days beyond the completed weeks are dropped from the reported gestation length, the true gestational age is 0–6 days longer than the reported one. Therefore, we calculate the first day of the last menses adding 3 days (the average bias) to the reported pregnancy length.

In the second step, we estimate the date of conception based on the first day of the last menses. As conception occurs within hours after ovulation (Stirnemann et al., 2013; Wilcox et al., 1995), and the day of ovulation is most likely to be between the 11th and 19th day of the menstrual cycle (Baird et al., 1995; Cole et al., 2009; Ecochard and Gougeon, 2000; Fehring et al., 2006; Lenton et al., 1984; Stirnemann et al., 2013; Waller et al., 1998), we assume that conceptions occur on the 15th day. That is, we estimate the date of conception as follows:

$$FD = M + 14 \quad (2)$$

where FD is the first day of the pregnancy (conception day), and M is the first day of the last menses.

Based on the estimated conception dates, we calculate conception rates at the county-year-week level defined by the number of conceptions per week per 100,000 women aged 16–44. We divide each year into 52 weeks, which means that the last week is 8 days long (except leap years, when it lasts 9 days). The county of conception (pregnancy) is defined by the place of residence of the mother (at the end of pregnancy). Budapest, the capital city of Hungary, is a separate administrative unit, therefore, it is considered as an individual county. The number of women aged 16–44 (at the beginning of the year) for every year and county comes from the Hungarian Central Statistical Office. These population figures are assigned to the first week of

the year, and the unobserved county-week figures are estimated by linear interpolation between the years.

Pregnancies with missing information on gestational age or on the exact day of the end of the pregnancy are excluded, as well as pregnancies with non-Hungarian or unknown places of residence (less than 1% of all pregnancies in total). Our final sample covers 6,788,096 pregnancies (3,866,298 live births, 2,307,327 induced abortions, and 614,471 spontaneous fetal deaths) with conception days estimated to be between 1980 and 2015.

Finally, we note that the estimated conception dates are biased estimations of the actual conception dates. However, because conception rates are calculated at the year-by-calendar-week level, a small bias (a couple of days) in the estimated conception date does not change the week of conception in most cases. In addition, because the bias is very likely to be random, the calculated conception rates should not be greatly influenced.

2.2. Weather data

We use weather data from the E-OBS 19.0e dataset of the European Climate Assessment & Dataset project (Cornes et al., 2018), which provides daily weather measures for Europe at a spacing of $0.1^\circ \times 0.1^\circ$ in regular latitude/longitude coordinates from 1950 to 2018. The dataset includes information on maximum, minimum and average temperatures, and precipitation. We create eight binary temperature variables based on the average temperature (below -5°C , $-5-0^\circ\text{C}$, $0-5^\circ\text{C}$, $5-10^\circ\text{C}$, $10-15^\circ\text{C}$, $15-20^\circ\text{C}$, $20-25^\circ\text{C}$, over 25°C) and four precipitation variables indicating the amount of daily precipitation (0 mm, 0–1 mm, 1–5 mm, over 5 mm) to describe the daily weather conditions at the grid points within Hungary. Next, to preserve variation in temperature we average the new temperature and precipitation variables for each day over grid points within the 20 counties of Hungary.

Finally, we construct weekly level measures from the daily data by summing up the variables over the weeks for each county. Accordingly, eight temperature variables show the number of days in a given week and given county when the daily mean temperature falls in a certain temperature bin (below -5°C , $-5-0^\circ\text{C}$, $0-5^\circ\text{C}$, $5-10^\circ\text{C}$, $10-15^\circ\text{C}$, $15-20^\circ\text{C}$, $20-25^\circ\text{C}$, over 25°C), and four precipitation variables show the number of days when the amount of daily precipitation falls in a certain precipitation bin (0 mm, 0–1 mm, 1–5 mm, over 5 mm). The descriptive statistics are shown in Table 1.

The weather data are matched to the conceptions by the county of mother's residence (at the end of pregnancy).

Table 1. Descriptive statistics

	mean	SD	min	max	N
Conception rate	174.02	35.40	66.94	349.60	37,440
N of days per week with temperature					
≤−5°C	0.22	0.91	0	9	37,440
−5 to 0°C	0.68	1.50	0	8.14	37,440
0 to 5°C	1.16	1.87	0	9	37,440
5 to 10°C	1.11	1.77	0	7	37,440
10 to 15°C	1.19	1.85	0	7	37,440
15 to 20°C	1.44	2.02	0	7	37,440
20 to 25°C	1.01	1.83	0	7	37,440
>25°C	0.21	0.83	0	7	37,440

Notes: Units of observations: county-by-year-by-week. Weighted by the average female population (aged 16–44) of the counties between 1980 and 2015. Conception rate is defined as the number of conceptions per week per 100,000 women aged 16–44.

2.3. Climate projections

To quantify the impact of climate change by the mid-twenty-first century, we use the NASA Earth Exchange (NEX) Global Daily Downscaled Projections (GDDP) dataset, which provides daily maximum and minimum temperatures for the period from 2006 to 2100, and retrospectively simulated temperature variables between 1950 and 2005 (Thrasher et al., 2012). The NEX-GDDP data contain projections of 21 climate models for two representative concentration pathway scenarios (RCP 4.5 and RCP 8.5). The climate models are ACCESS1-0, BCC-CSM1-1, BNU-ESM, CanESM2, CCSM4, CESM1-BGC, CNRM-CM5, CSIRO-MK3-6-0, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, INMCM4, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM, MIROC-ESM-CHEM, MIROC5, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, and NorESM1-M. They were developed for the Fifth Assessment Report of the IPCC. 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). Each climate projection is downscaled at a spatial resolution of $0.25^\circ \times 0.25^\circ$.

We calculated daily average temperature as the mean of the maximum and minimum temperature. As for the historical weather data, we created eight temperature indicators to describe the daily weather conditions at the grid points located within the borders of Hungary (avg. daily temperature is below -5°C , $-5-0^\circ\text{C}$, $0-5^\circ\text{C}$, $5-10^\circ\text{C}$, $10-15^\circ\text{C}$, $15-20^\circ\text{C}$, $20-25^\circ\text{C}$, over 25°C). To obtain the projected temperature on a specific day in a given county, we simply averaged the eight temperature variables over the grid points located within the counties. Using these estimations, we calculate the distribution of temperature (i) in the period of 2040–2059 for the 42 climate projections (21 models, and two RCPs), and (ii) in the period of 1986–2005 for the 21 climate models by county and calendar week. Next, to make a projection for the whole country, we averaged the county-level temperature distributions using the female population aged 16–44 between 1980 and 2015 as weights. For the calculation of the projected impacts of climate change, we used these country-level (national) averages. The within-model changes were calculated as the difference between the periods of 2040–2059 and 1986–2005.

To investigate the impact of climate change on conception rates, we use the projected changes by calendar week.

3. Empirical strategy

3.1. Relationship between temperature and conception rates

We model the dynamics of the temperature–conception rate relationship at the county-week level. We estimate the following equation via ordinary least squares:

$$\ln(Y_{ct}) = \sum_k \sum_j \beta_k^j T_{c(t-k)}^j + \sum_k \sum_j \gamma_k^j P_{c(t-k)}^j + \tau X_t + \delta_{cw} + \eta_{cy} + \lambda_{cw}^a \times t + \lambda_{cw}^b \times t^2 + \varepsilon_{ct} \quad (3)$$

where Y is conception rate in county c at time t (year y , week w). T is a vector of variables indicating the distribution of daily mean temperature in county c at time t . The temperature variables represent the number of days when the daily mean temperatures are: below -5°C , $-5-0^\circ\text{C}$, $0-5^\circ\text{C}$, $5-10^\circ\text{C}$, $10-15^\circ\text{C}$, $15-20^\circ\text{C}$, $20-25^\circ\text{C}$, or above 25°C . In the analysis, T^{15-20} is the omitted category. That is, coefficient β^j shows the effect of one additional day when the daily mean temperature falls into temperature bin j on the log conception rate (relative to a day with a mean temperature of $15-20^\circ\text{C}$). P is a vector of precipitation controls, which shows the number of days where the amount of daily precipitation falls in a certain precipitation bin ($0-1$ mm, $1-5$ mm, over 5 mm). The omitted category is the number of days without precipitation. We allow the conception rate at time t to be affected by the temperature and precipitation variables up to 25 weeks prior ($k = 0, 1, \dots, 25$). In this specification, β_k coefficients are the effects of temperature at time t on log conception rate after k weeks (Stock and Watson, 2015). That is, the series of coefficients $\beta_0, \beta_1, \dots, \beta_{25}$ can be interpreted as the effect of temperature at time t on current and future conception rates (up to 25 weeks after the temperature exposure).

X is a variable controlling for the share of weekend days and holidays that fall on weekdays, at time t . County-by-calendar-week fixed effects (δ_{cw}) help account for time-invariant unobserved differences in seasonal conception rates across counties (e.g., owing to seasonal employment patterns). County-by-year fixed effects (η_{cy}) control for county-specific changes in the conception rate over time. These fixed effects adjust for, e.g., the county-specific effects of the 2008 economic crisis or the geographically diverse impacts of the transition to democracy. We also allow county-specific seasonality to change over time by adding county-by-week quadratic time trends (λ_{cw}). In sum, the effect of temperature on conception rates is identified from inter-annual variation in the calendar week-specific temperature after adjustment for differences in county-specific seasonality and its change over time, as well as for county-specific shocks to conception rate at the year level.

We weight by the counties' average female population size (aged 16–44) between 1980 and 2015. Standard errors are clustered by county and time (two-way clustering). For the estimations, we used STATA package `reghdfe`.

We test the sensitivity of the results by a wide range of additional model specifications. First, we exclude precipitation controls:

$$\ln(Y_{ct}) = \sum_k \sum_j \beta_k^j T_{c(t-k)}^j + \tau X_t + \delta_{cw} + \eta_{cy} + \lambda_{cw}^a \times t + \lambda_{cw}^b \times t^2 + \varepsilon_{ct} \quad (4)$$

Second, we exclude county-by-week quadratic time-trends:

$$\ln(Y_{ct}) = \sum_k \sum_j \beta_k^j T_{c(t-k)}^j + \sum_k \sum_j \gamma_k^j P_{c(t-k)}^j + \tau X_t + \delta_{cw} + \eta_{cy} + \varepsilon_{ct} \quad (5)$$

Third, we simply use county, year, and week fixed effects:

$$\ln(Y_{ct}) = \sum_k \sum_j \beta_k^j T_{c(t-k)}^j + \sum_k \sum_j \gamma_k^j P_{c(t-k)}^j + \tau X_t + \pi_c + \mu_y + \phi_w + \varepsilon_{ct} \quad (6)$$

Fourth, we include lagged conception rates (25 lags):

$$\begin{aligned} \ln(Y_{ct}) = & \sum_{h=1}^{25} \alpha_h \ln(Y_{c(t-h)}) + \sum_k \sum_j \beta_k^j T_{c(t-k)}^j + \sum_k \sum_j \gamma_k^j P_{c(t-k)}^j + \tau X_t + \delta_{cw} + \eta_{cy} \\ & + \lambda_{cw}^a \times t + \lambda_{cw}^b \times t^2 + \varepsilon_{ct} \end{aligned} \quad (7)$$

We also estimate specifications with 28 or 31 temperature and precipitation lags, and using 3°C wide temperature categories ($\leq -6^\circ\text{C}$, -6 to -3°C , -3 to 0°C , 0 to 3°C , 3 to 6°C , 6 to 9°C , 9 to 12°C , 12 to 15°C , 15 to 18°C , 18 to 21°C , 21 to 24°C , 24 to 27°C , $>27^\circ\text{C}$). Besides, as placebo checks, we use future weather data (measured exactly 1, 2 or 3 years later).

3.2. Projected impacts of climate change

To quantify the impacts of climate change, we combine the estimated temperature–conception rate relationship with the projected within-model changes in temperature distribution by calendar week between the periods of 1986–2005 and 2040–2059 for Hungary. We take the estimations on the temperature–conception relationship (β coefficients in Equation (3)) and multiply them by the projected temperature changes. We project the medium-term impacts on (i) seasonality and (ii) the annual conception rate.

To examine the impact on seasonality of conception rates, first, we calculate the projected impacts by calendar week in the following way:

$$V_{wmr} = \exp \left[\sum_k \sum_j \beta_k^j \left(T_{(w-k)mr}^{j,2040-2059} - T_{(w-k)m}^{j,1986-2005} \right) \right] - 1, \quad (8)$$

where V is the percentage change in conception rate for calendar week w , climate model m , and RCP r by the mid-twenty-first century. β_k^j is the estimated historical relationship between temperature bin j and conception rate for lag k ($k = 0, 1, \dots, 25$) (see Equation (3)). $T^{2040-2059}$ is a vector that shows the projected temperature distribution in the period of 2040–2059 for calendar week w , climate model m , and RCP r : N of days when the daily mean temperature falls into temperature bin j . Similarly, variables $T^{1986-2005}$ show the N of days when the retrospectively simulated daily mean temperature falls into temperature bin j in the period of 1986–2005 for calendar week w , climate model m .

Next, we calculate the projected conception rate for the period of 2040–2059:

$$Y_{wmr}^{2040-2059} = (1 + V_{wmr}) Y_w^{1986-2005}, \quad (9)$$

where we simply use the percentage change in conception rate for calendar week w , climate model m , and RCP r (V_{wmr}), and multiply it with the conception rate in the baseline period ($Y^{1986-2005}$).

Finally, we project the annual impact of climate change by averaging the projected weekly percentage changes using the total number of conceptions in the calendar weeks between 1980 and 2015 as weights:

$$Z_{mr} = \sum_w \frac{f_w V_{wmr}}{52}, \quad (10)$$

where Z is the projected annual percentage change in the conception rate for climate model m , and RCP r . V comes from Equation (8), and f is a weight variable (scaled to mean 1) based on the total number of conceptions between 1986 and 2005 in calendar week w .

To account not only for climate uncertainty but regression uncertainty as well (uncertainty in the relationship between temperature and conception), we re-estimate the regression coefficients of the baseline model specification (Equation (3)), applying bootstrap samples (500 times, sampling with replacement). Using the 500 coefficient estimations and the projections of the 21 climate models, we construct 10,500 possible projections (21*500) for each RCP scenario, by which we can incorporate both climate and regression uncertainty into the projected impacts of climate change (Burke et al., 2015).

We note that our calculations assume that the future relationship between temperature and the conception rate will be the same as in the past.

4. Results

4.1. Historical relationship between temperature and conception rates

Estimating the historical relationship between temperature and conception rates, we find that exposure to a hot ($>25^{\circ}\text{C}$) day slightly reduces conception rates in the week of the exposure (-0.18% , $p=0.068$) and the following week (-0.29% , $p=0.029$), compared with a day with a mean temperature of $15\text{--}20^{\circ}\text{C}$ (Fig. 1a). Two weeks after exposure, weekly conception rates are more strongly decreased, by 0.85% ($p=0.000$), whereas the coefficients on weeks 3 and 4 are both -0.80% ($p=0.000$). Five weeks after exposure, the impact is lower (-0.44% , $p=0.000$). Between weeks 6 and 10, the coefficients are practically zero, whereas from week 11, they begin to increase, and until week 22, they are consistently positive, indicating an increased conception rate over this period. However, most of the 95% confidence intervals include zero. These results suggest that exposure to hot temperatures changes the timing of some conceptions. Conceptions do not disappear because of the exposure, but are delayed by several weeks.

We investigate the possible displacement further by calculating the sum of the coefficients (total effect) over weeks (lags) 0–5 and 6–25. These calculations show the extent to which the initial change in conception rates over weeks 0–5 is compensated by a rebound in the later weeks. The total effect of exposure to hot temperature is -0.034 log points over weeks 0–5 and 0.017 log points over weeks 6–25 (Fig. 1b). This suggests that approximately half of the short-term decline is compensated by a rebound within 6 months following the exposure. Nevertheless, the total impact remains negative: exposure to a $>25^{\circ}\text{C}$ day reduces the overall conception rate over a 26-week period by 0.06% ($p=0.012$). The impacts of exposure to a $20\text{--}25^{\circ}\text{C}$ day are similar but lower in magnitude. The cumulative effects over weeks 0–5 and weeks 6–25 are -0.011 and 0.003 log points, respectively (see also Fig. A1 in the Appendix for the individual coefficients). Importantly, temperature exposure seems to have a monotonic, non-linear effect. Colder temperatures below the omitted category have small positive effects over weeks 0–5 and small negative effects over weeks 6–25, with no apparent differences between temperature categories.

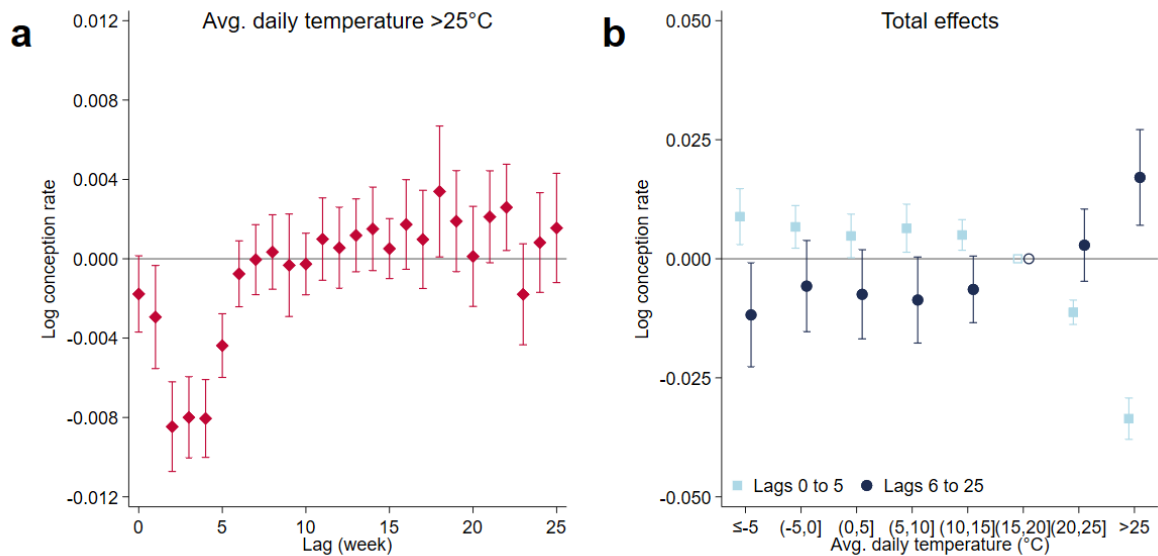


Fig. 1. Historical relationship between temperature and conception rates

Notes: (a) The effects of exposure to a day with an average temperature above 25°C on current and future conception rates up to 25 weeks (relative to a day with a mean temperature of 15–20°C). (b) The total effects (sum of the coefficients) over weeks (lags) 0–5 and 6–25 after exposure. All estimates are based on Equation (3). The error bars represent 95% confidence intervals. The outcome variable is the log conception rate. Conception rate is defined as the number of conceptions per week per 100,000 women aged 16–44, which has a mean of 174.02 in our sample. The model has county-by-year fixed effects, county-by-calendar-week fixed effects, and county-by-week quadratic time trends county by month-of-year specific linear time trends. We control for precipitation and the share of non-working days. We weight by the counties’ average female population size (aged 16–44) between 1980 and 2015. Standard errors are clustered by county and time.

We test the sensitivity of the results by a wide range of additional model specifications: controlling for lagged weekly conception rates (up to 25 weeks), excluding precipitation controls, using different fixed effects, excluding county-by-week quadratic time-trends (Fig. A2, Appendix), including more temperature lags (Fig. A3, Appendix), and using 3°C wide temperature categories (Fig. A4, Appendix). None of these changes alter the main conclusions, but the latter result suggests that the effects of temperature is increasing past 25°C.

In addition, as placebo tests, the temperature and precipitation variables are replaced with weather data that were measured exactly 1, 2 or 3 years later. Because conception rates could not have been affected by temperature in the distant future, zero or close to zero coefficients should be observed in the placebo regressions. These estimations further support the credibility of the baseline results (Fig. A5, Appendix). In general, as expected, the estimated individual coefficients are usually insignificant. The total impacts show fairly random pattern.

4.2. Projected impacts of climate change

To quantify the impacts of climate change, the estimated temperature–conception rate relationship is combined with the projected changes in temperature distribution between the periods of 1986–2005 and 2040–2059 by calendar week. First, we show the projections for the overall conception rate. Next, we replicate these projections by conception type (pregnancy outcome).

Seasonal differences in conception rates are likely to be larger by the mid-twenty-first century because of climate change (Fig. 2a and Fig. 2b). We project a substantial decline between the 23rd and 42nd calendar weeks as a result of the increase in the number of hot days.

The impacts are especially large for calendar weeks 30 to 38: the median projections in RCP 8.5 reflect a decline of between 5.5% and 7.5%. At the same time, conception rates are projected to increase in the first calendar weeks, and especially in the last 10 weeks of the year. Regarding the annual impact of climate change, practically all projections suggest a decline in annual conception rates (Fig. 2c). The interquartile ranges of the projections spread from -0.47% to -0.92% for RCP 4.5 and from -0.61% to -1.18% for RCP 8.5.

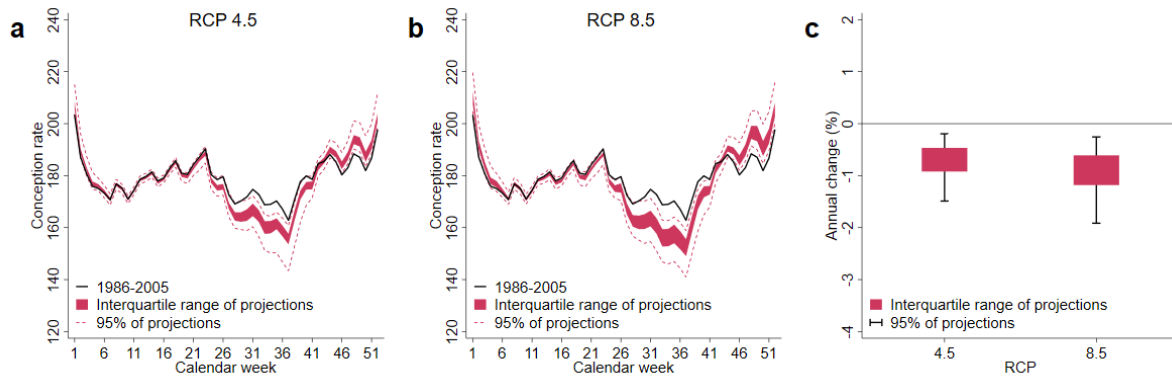


Fig. 2. Projected impact of climate change on conception rates

Notes: Impacts on the seasonal distribution (a,b) and annual volume (c) of conception rates by 2040–2059. The impacts are calculated using the projected within-model differences in temperature distribution between the periods of 1986–2005 and 2040–2059 by 21 climate models and the historical relationship between conception rates and temperature from Equation (3) (estimated by 500 bootstrap samples). For these graphs, conception rates in calendar week 52 are rescaled to 7 days. Conception rate is defined as the number of conceptions per week per 100,000 women aged 16–44.

Using alternative model specifications to estimate the historical temperature–conception rate relationship (see above), in most cases, does not considerably alter the projected impacts of climate change (Fig. A6, Appendix). However, if the seasonality of conception rates is not allowed to change over time, the projected impacts are more severe than in the baseline specification. This suggests that there is a spurious correlation between temperature and the change in seasonality of conception rates that has to be controlled for. In addition, using narrower (3°C wide) temperature categories results in a slightly stronger projected impact. This specification allows to account for the fact that the effect of temperature is increasing past 25°C (see Fig. A4, Appendix), and the average temperature within the $>25^{\circ}\text{C}$ category will increase in the future (Fig. A7, Appendix). Nevertheless, the qualitative results are the same in all these estimations: seasonal differences in conception rates will increase because of climate change and the annual rates will decrease by a few percent during the next decades.

Next, we calculate the impacts of climate change by conception type. We use historical estimates on the temperature–conception rate relationship from models where conception rates were calculated from pregnancies ending in (i) live births, (ii) induced abortions, or (iii) spontaneous fetal losses, and combine them with the projected temperature changes as was done before. Seasonal differences in conception rates will be larger for all kinds of conceptions (Fig. 3a,b,d,e,g,h). Conception rates in the summer and early autumn months are projected to decrease, whereas conception rates during winter and late autumn are projected to increase. A notable difference is that the winter/autumn increase is more significant for live births than for spontaneous fetal losses or induced abortions. As a result, the differences in terms of annual impacts are substantial (Fig. 3c,f,i). The overall conception rate based on live births seems to be unaffected by a climate change-induced shift in temperature distribution, whereas the annual conception rates based on induced abortions and spontaneous fetal losses are projected to

decline by a few percent. That is, the annual decline in overall conception rate (Fig. 2c) is primarily driven by a change in the number of induced abortions and spontaneous fetal losses rather than by a change in the number of live births.

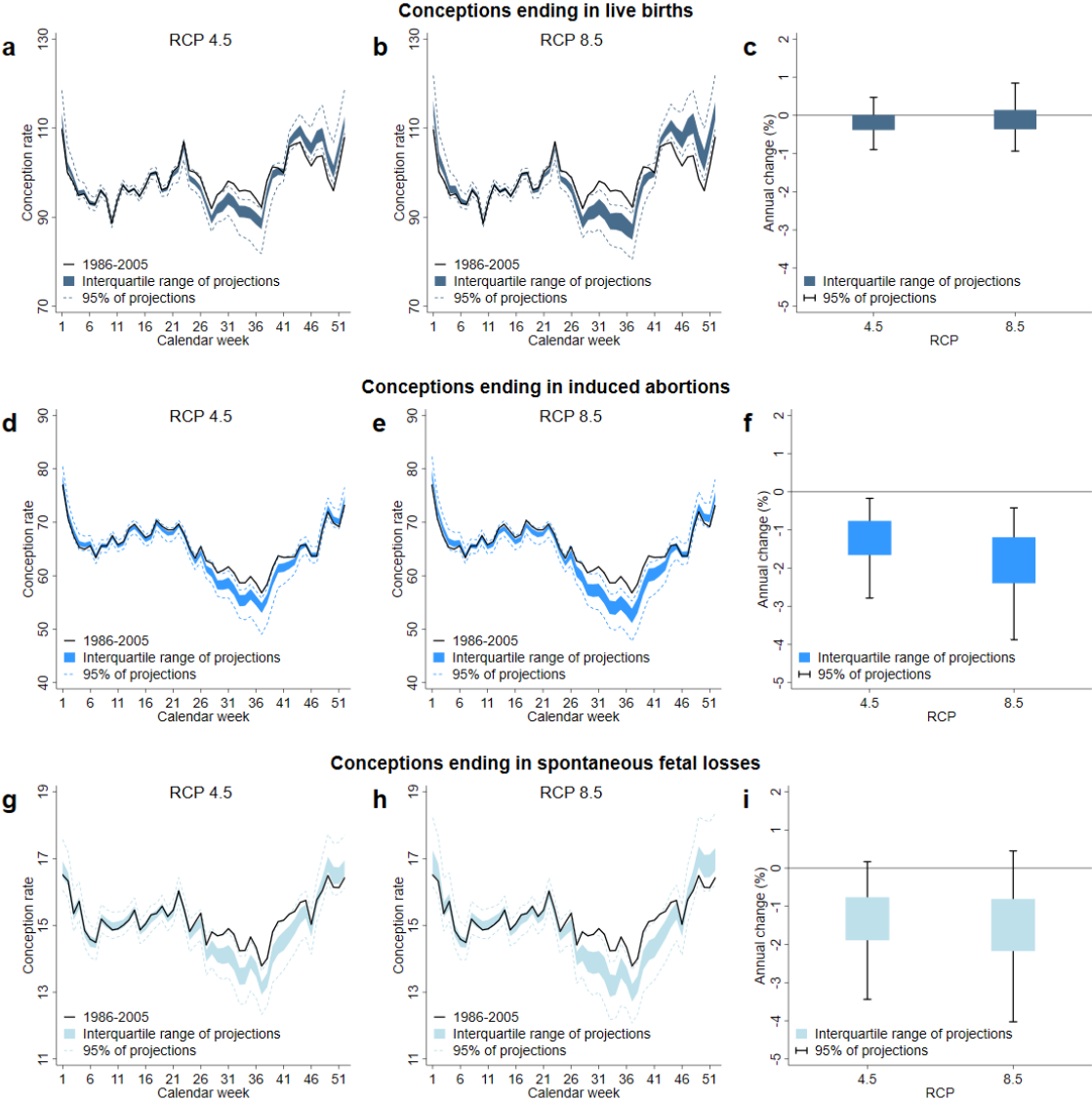


Fig. 3. Projected impact of climate change by conception type

Notes: The impacts on the seasonal distribution of conceptions ending in live births (a,b), induced abortions (d,e), and spontaneous fetal losses (g,h) by 2040–2059. The impacts on annual volume of conception rates in live births (c), induced abortions (f), and spontaneous fetal losses (i) by 2040–2059. The impacts are calculated using the projected within-model differences in temperature distribution between the periods of 1986–2005 and 2040–2059 by 21 climate models and the historical relationship between conception rates and temperature (estimated by 500 bootstrap samples). For these graphs, conception rates in calendar week 52 are rescaled to 7 days. Conception rate is defined as the number of conceptions (ending in live births/induced abortions/spontaneous fetal losses) per week per 100,000 women aged 16–44.

These results are likely to reflect that individuals who desire to have a baby are very likely to eventually have one, even if it is delayed because of exposure to hot weather. However, if heat exposure prevents an unintended pregnancy, then it is less likely that the “missing”

conception will be replaced by another pregnancy a couple of months later. Because most pregnancies ending in live births are planned/intended in Central and Eastern Europe (Bearak et al., 2018), it is not surprising that the overall impact of climate change is close to zero. In contrast, induced abortions are much more likely to be the result of unplanned pregnancies. Therefore, a sizeable rebound after the initial decline due to exposure to heat is not expected when analyzing conception rates calculated from pregnancies ending in induced abortions. That is, the overall impact of climate change should be negative. Regarding spontaneous fetal losses, numerous factors may contribute to the overall reduction in conceptions. First, unplanned pregnancies have higher odds of miscarriage (Maconochie et al., 2007). Second, some intended conceptions from the summer/early autumn months, which would have ended in a spontaneous fetal loss, are likely to occur a couple of months later as a result of climate change. This shift, however, influences in utero temperature exposures of the fetuses. Their first trimester exposure to hot days will decrease, whereas their exposure during the second and third trimesters will increase (Fig. A8, Appendix). Because animal studies suggest that heat exposure during early pregnancy increases embryo loss (Edwards et al., 2003; Romo-Barron et al., 2019; Ulberg and Burfening, 1967), this decreased first trimester exposure to hot days could lower the risk of miscarriage. Therefore, conceptions ending in a spontaneous fetal loss will increase to a lesser extent in the late autumn and winter months than a simple delay in the time of conception would predict.

We also note that although the annual conception rate based on live births (in other words, the number of births) will not change significantly as a result of climate change, the changing seasonal distribution of conceptions could have important consequences on the affected newborns. The warming climate will induce a shift in the timing of conception for a small fraction of live births. In general, conceptions will disappear from the summer months and will re-appear mostly in the winter and late autumn months (Fig. A9, Appendix).¹ Because of this shift, as highlighted before, the exposure of fetuses to hot days during the second and third trimesters of pregnancy will substantially increase, whereas the first trimester exposure will drop (Fig. A8, Appendix). A crude estimation suggests that the affected newborns will be exposed, on average, to around 16 additional hot days (>25°C) and 32 additional moderately hot days (20–25°C) during the second and third trimesters due to the change in the conception date (Table A1, Appendix). Considering the whole pregnancy, these figures are 9 and 16 days, respectively. At the same time, the exposure to cold days will substantially decrease. Because there is a negative relationship between in utero exposure to hot weather (especially in the second and third trimesters) and health at birth (Barreca and Schaller, 2020; Chen et al., 2020; Deschênes et al., 2009; Sun et al., 2019), the slight change in timing of conception could have a non-negligible impact. Further consequences are also possible, as temperature exposure during pregnancy influences adult outcomes too (Fishman et al., 2019; Hu and Li, 2019; Isen et al., 2017).

5. Discussion and Conclusion

Using complete administrative data from Hungary, we find that exposure to heat has a deteriorating effect on conception rates in the short term (up to 5 weeks after the exposure), showing a U-shaped pattern with the strongest impact ranging from 2 to 4 weeks after the exposure. In theory, three mechanisms can drive this relationship. First, heat might reduce sexual activity. Second, it could change conception chance. Third, it might influence the chance of a clinically unrecognized loss of an embryo. Unfortunately, the data we use do not allow us

¹ The definition and calculation of disappearing and re-appearing live births are provided in the notes of Fig. A9 in the Appendix.

to determine the exact importance of these channels. However, that we see a small effect in the week of the exposure and larger effects later suggests that hot weather has no sizable negative influence on sexual behavior. Indeed, previous studies report that heat does not decrease sexual activity (Hajdu and Hajdu, 2019), but interest in sex is rather driven by holidays and cultural/religious celebrations (Wood et al., 2017). The second channel might be an important one. As mentioned before, experiments with mammals suggest that the conception chance is diminished by heat exposure (Jannes et al., 1998; Paul et al., 2008; Wettemann et al., 1979; Yaeram et al., 2006). Human studies report that heat suppresses spermatogenesis (Ahmad et al., 2012; Brown-Woodman et al., 1984; Carlsen et al., 2003; Garolla et al., 2013; Macleod and Hotchkiss, 1941; Robinson et al., 1968; Wang et al., 2007; Zhang et al., 2015). Although the results of these papers are not directly comparable with our study, they are similar in that they usually report a prolonged and but reversible (U-shaped) impact on various sperm parameters. This suggests that exposure to heat decreases the conception rate by reducing human reproductive health. However, because a sizeable portion of human pregnancies end in a clinically unrecognized pregnancy loss (Wilcox et al., 1988; Zinaman et al., 1996) and therefore is not included in any administrative dataset, we cannot rule out that hot weather also diminishes the survival probability of the fetus after conception but before clinical recognition.

We find practically zero coefficients between weeks 6 and 10, and an increased conception rate from week 11 after the exposure, which suggests that exposure to hot temperatures changes the timing of some conceptions. However, we note that our results do not necessarily mean that hot temperature has a negative impact on the conception rate only up to 5 weeks following the exposure. Some pregnancies that fail to start due to exposure to hot weather (in the first weeks after the exposure) might experience a shift in conception date as little as one menstrual cycle and might occur 5-10 weeks after the exposure. This shift might veil the negative effects over this period.

Our calculations suggest that climate change-induced shift in temperature distribution will influence human conception. Seasonal differences in conception rates will be larger by the mid-twenty-first century, and the annual conception rate is projected to decline. We also find that the overall live birth rate, unlike the overall rate of induced abortions and spontaneous fetal losses, seems to be unaffected. However, future warming will change the season of the conception of some newborns, which will influence their in utero temperature exposure and thus might reduce their health at birth and affect later life outcomes.

Finally, we note that our findings are based on data from Hungary and cannot necessarily be generalized to other countries. However, climatic conditions are very similar in many European countries, thus, our results might be relevant for a larger geographic area. Nevertheless, further studies should assess how temperature and climate change might influence conceptions in other parts of the world.

References

- Ahmad, G., Moinard, N., Esquerré-Lamare, C., Mieuxset, R., Bujan, L., 2012. Mild induced testicular and epididymal hyperthermia alters sperm chromatin integrity in men. *Fertility and Sterility* 97, 546–553. <https://doi.org/10.1016/j.fertnstert.2011.12.025>
- Baird, D.D., McConaughy, D.R., Weinberg, C.R., Musey, P.I., Collins, D.C., Kesner, J.S., Knecht, E.A., Wilcox, A.J., 1995. Application of a Method for Estimating Day of Ovulation Using Urinary Estrogen and Progesterone Metabolites. *Epidemiology* 6, 547–550.
- 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. *Nature Climate Change* 10, 77–82. <https://doi.org/10.1038/s41558-019-0632-4>

- Bearak, J., Popinchalk, A., Alkema, L., Sedgh, G., 2018. Global, regional, and subregional trends in unintended pregnancy and its outcomes from 1990 to 2014: estimates from a Bayesian hierarchical model. *The Lancet Global Health* 6, e380–e389. [https://doi.org/10.1016/S2214-109X\(18\)30029-9](https://doi.org/10.1016/S2214-109X(18)30029-9)
- Brown-Woodman, P.D.C., Post, E.J., Gass, G.C., White, I.G., 1984. The Effect of a Single Sauna Exposure on Spermatozoa. *Archives of Andrology* 12, 9–15. <https://doi.org/10.3109/01485018409161141>
- Burfening, P.J., Elliott, D.S., Eisen, E.J., Ulberg, L.C., 1970. Survival of Embryos Resulting from Spermatozoa Produced by Mice Exposed to Elevated Ambient Temperature. *J Anim Sci* 30, 578–582. <https://doi.org/10.2527/jas1970.304578x>
- Burke, M., Dykema, J., Lobell, D.B., Miguel, E., Satyanath, S., 2015. Incorporating Climate Uncertainty into Estimates of Climate Change Impacts. *The Review of Economics and Statistics* 97, 461–471. https://doi.org/10.1162/REST_a_00478
- Carleton, T.A., Hsiang, S.M., 2016. Social and economic impacts of climate. *Science* 353, aad9837. <https://doi.org/10.1126/science.aad9837>
- Carlsen, E., Andersson, A.-M., Petersen, J.H., Skakkebaek, N.E., 2003. History of febrile illness and variation in semen quality. *Hum Reprod* 18, 2089–2092. <https://doi.org/10.1093/humrep/deg412>
- Chang, K.S.F., Chan, S.T., Low, W.D., Ng, C.K., 1963. Climate and conception rates in Hong Kong. *Human Biology* 35, 366–376.
- Chen, X., Tan, C.M., Zhang, Xiaobo, Zhang, Xin, 2020. The effects of prenatal exposure to temperature extremes on birth outcomes: the case of China. *J Popul Econ.* <https://doi.org/10.1007/s00148-020-00768-4>
- Cole, L.A., Ladner, D.G., Byrn, F.W., 2009. The normal variabilities of the menstrual cycle. *Fertility and Sterility* 91, 522–527. <https://doi.org/10.1016/j.fertnstert.2007.11.073>
- 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. *Journal of Geophysical Research: Atmospheres* 123, 9391–9409. <https://doi.org/10.1029/2017JD028200>
- Dell, M., Jones, B.F., Olken, B.A., 2014. What Do We Learn from the Weather? The New Climate-Economy Literature. *Journal of Economic Literature* 52, 740–798. <https://doi.org/10.1257/jel.52.3.740>
- Deschênes, O., Greenstone, M., Guryan, J., 2009. Climate Change and Birth Weight. *American Economic Review* 99, 211–17. <https://doi.org/10.1257/aer.99.2.211>
- Ecochard, R., Gougeon, A., 2000. Side of ovulation and cycle characteristics in normally fertile women. *Hum Reprod* 15, 752–755. <https://doi.org/10.1093/humrep/15.4.752>
- Edwards, M.J., Saunders, R.D., Shiota, K., 2003. Effects of heat on embryos and fetuses. *International Journal of Hyperthermia* 19, 295–324. <https://doi.org/10.1080/0265673021000039628>
- Fehring, R.J., Schneider, M., Raviele, K., 2006. Variability in the Phases of the Menstrual Cycle. *Journal of Obstetric, Gynecologic & Neonatal Nursing* 35, 376–384. <https://doi.org/10.1111/j.1552-6909.2006.00051.x>
- Fishman, R., Carrillo, P., Russ, J., 2019. Long-term impacts of exposure to high temperatures on human capital and economic productivity. *Journal of Environmental Economics and Management* 93, 221–238. <https://doi.org/10.1016/j.jeem.2018.10.001>
- Garolla, A., Torino, M., Sartini, B., Cosci, I., Patassini, C., Carraro, U., Foresta, C., 2013. Seminal and molecular evidence that sauna exposure affects human spermatogenesis. *Hum Reprod* 28, 877–885. <https://doi.org/10.1093/humrep/det020>
- Hajdu, T., Hajdu, G., 2019. Ambient temperature and sexual activity: Evidence from time use surveys. *Demographic Research* 40, 307–318. <https://doi.org/10.4054/DemRes.2019.40.12>
- Hansen, P.J., 2009. Effects of heat stress on mammalian reproduction. *Philosophical Transactions of the Royal Society B: Biological Sciences* 364, 3341–3350. <https://doi.org/10.1098/rstb.2009.0131>
- Hu, Z., Li, T., 2019. Too hot to handle: The effects of high temperatures during pregnancy on adult welfare outcomes. *Journal of Environmental Economics and Management* 94, 236–253. <https://doi.org/10.1016/j.jeem.2019.01.006>
- Isen, A., Rossin-Slater, M., Walker, R., 2017. Relationship between season of birth, temperature exposure, and later life wellbeing. *PNAS* 114, 13447–13452. <https://doi.org/10.1073/pnas.1702436114>
- Jannes, P., Spiessens, C., Van der Auwera, I., D’Hooghe, T., Verhoeven, G., Vanderschueren, D., 1998. Male subfertility induced by acute scrotal heating affects embryo quality in normal female mice. *Hum Reprod* 13, 372–375. <https://doi.org/10.1093/humrep/13.2.372>
- Lam, D.A., Miron, J.A., 1996. The effects of temperature on human fertility. *Demography* 33, 291–305. <https://doi.org/10.2307/2061762>
- Lenton, E.A., Landgren, B.-M., Sexton, L., 1984. Normal variation in the length of the luteal phase of the menstrual cycle: identification of the short luteal phase. *BJOG: An International Journal of Obstetrics & Gynaecology* 91, 685–689. <https://doi.org/10.1111/j.1471-0528.1984.tb04831.x>
- Macleod, J., Hotchkiss, R.S., 1941. The effect of hyperpyrexia upon spermatozoa counts in men. *Endocrinology* 28, 780–784. <https://doi.org/10.1210/endo-28-5-780>

- Maconochie, N., Doyle, P., Prior, S., Simmons, R., 2007. Risk factors for first trimester miscarriage—results from a UK-population-based case–control study. *BJOG: An International Journal of Obstetrics & Gynaecology* 114, 170–186. <https://doi.org/10.1111/j.1471-0528.2006.01193.x>
- Mills, C.A., Senior, F.A., 1930. Does Climate affect the Human Conception Rate? *Archives of Internal Medicine* 46, 921–929.
- Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. *Nature* 463, 747–756. <https://doi.org/10.1038/nature08823>
- Paul, C., Murray, A.A., Spears, N., Saunders, P.T.K., 2008. A single, mild, transient scrotal heat stress causes DNA damage, subfertility and impairs formation of blastocysts in mice. *Reproduction* 136, 73–84. <https://doi.org/10.1530/REP-08-0036>
- Robinson, D., Rock, J., Menkin, M.F., 1968. Control of Human Spermatogenesis Intrascrotal Temperature. *JAMA* 204, 290–297. <https://doi.org/10.1001/jama.1968.03140170006002>
- Romo-Barron, C.B., Diaz, D., Portillo-Loera, J.J., Romo-Rubio, J.A., Jimenez-Trejo, F., Montero-Pardo, A., 2019. Impact of heat stress on the reproductive performance and physiology of ewes: a systematic review and meta-analyses. *Int J Biometeorol* 63, 949–962. <https://doi.org/10.1007/s00484-019-01707-z>
- Scheffers, B.R., Meeester, L.D., Bridge, T.C.L., Hoffmann, A.A., Pandolfi, J.M., Corlett, R.T., Butchart, S.H.M., Pearce-Kelly, P., Kovacs, K.M., Dudgeon, D., Pacifici, M., Rondinini, C., Foden, W.B., Martin, T.G., Mora, C., Bickford, D., Watson, J.E.M., 2016. The broad footprint of climate change from genes to biomes to people. *Science* 354, aaf7671. <https://doi.org/10.1126/science.aaf7671>
- Seiver, D.A., 1989. Seasonality of fertility: New evidence. *Population and Environment* 10, 245–257. <https://doi.org/10.1007/BF01255839>
- Stirnemann, J.J., Samson, A., Bernard, J.-P., Thalabard, J.-C., 2013. Day-specific probabilities of conception in fertile cycles resulting in spontaneous pregnancies. *Hum Reprod* 28, 1110–1116. <https://doi.org/10.1093/humrep/des449>
- Stock, J.H., Watson, M.W., 2015. *Introduction to Econometrics*, 3rd edition. ed. Pearson Education.
- Stoeckel, J., Choudhury, A.K., 1972. Seasonal variation in births in rural East Pakistan. *J Biosoc Sci* 4, 107–116.
- 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. *Environmental Health Perspectives* 127, 067005. <https://doi.org/10.1289/EHP4648>
- Takahashi, E., 1964. Seasonal Variation of Conception and Suicide. *The Tohoku Journal of Experimental Medicine* 84, 215–227. <https://doi.org/10.1620/tjem.84.215>
- Thrasher, B., Maurer, E.P., McKellar, C., Duffy, P.B., 2012. Technical Note: Bias correcting climate model simulated daily temperature extremes with quantile mapping. *Hydrology and Earth System Sciences* 16, 3309–3314. <https://doi.org/10.5194/hess-16-3309-2012>
- Ulberg, L.C., Burfening, P.J., 1967. Embryo Death Resulting from Adverse Environment on Spermatozoa or Ova. *J Anim Sci* 26, 571–577. <https://doi.org/10.2527/jas1967.263571x>
- Waller, K., Swan, S.H., Windham, G.C., Fenster, L., Elkin, E.P., Lasley, B.L., 1998. Use of Urine Biomarkers to Evaluate Menstrual Function in Healthy Premenopausal Women. *Am J Epidemiol* 147, 1071–1080. <https://doi.org/10.1093/oxfordjournals.aje.a009401>
- Wang, C., Cui, Y.-G., Wang, X.-H., Jia, Y., Sinha Hikim, A., Lue, Y.-H., Tong, J.-S., Qian, L.-X., Sha, J.-H., Zhou, Z.-M., Hull, L., Leung, A., Swerdloff, R.S., 2007. Transient Scrotal Hyperthermia and Levonorgestrel Enhance Testosterone-Induced Spermatogenesis Suppression in Men through Increased Germ Cell Apoptosis. *J Clin Endocrinol Metab* 92, 3292–3304. <https://doi.org/10.1210/jc.2007-0367>
- Wettemann, R.P., Wells, M.E., Johnson, R.K., 1979. Reproductive Characteristics of Boars during and after Exposure to Increased Ambient Temperature. *J Anim Sci* 49, 1501–1505. <https://doi.org/10.2527/jas1979.4961501x>
- Wilcox, A.J., Weinberg, C.R., Baird, D.D., 1995. Timing of Sexual Intercourse in Relation to Ovulation — Effects on the Probability of Conception, Survival of the Pregnancy, and Sex of the Baby. *New England Journal of Medicine* 333, 1517–1521. <https://doi.org/10.1056/NEJM199512073332301>
- Wilcox, A.J., Weinberg, C.R., O'Connor, J.F., Baird, D.D., Schlatterer, J.P., Canfield, R.E., Armstrong, E.G., Nisula, B.C., 1988. Incidence of Early Loss of Pregnancy. *New England Journal of Medicine* 319, 189–194. <https://doi.org/10.1056/NEJM198807283190401>
- Wood, I.B., Varela, P.L., Bollen, J., Rocha, L.M., Gonçalves-Sá, J., 2017. Human Sexual Cycles are Driven by Culture and Match Collective Moods. *Scientific Reports* 7, 17973. <https://doi.org/10.1038/s41598-017-18262-5>
- Yaeram, J., Setchell, B.P., Maddocks, S., 2006. Effect of heat stress on the fertility of male mice in vivo and in vitro. *Reprod. Fertil. Dev.* 18, 647–653. <https://doi.org/10.1071/RD05022>

- Zhang, M.-H., Shi, Z.-D., Yu, J.-C., Zhang, Y.-P., Wang, L.-G., Qiu, Y., 2015. Scrotal heat stress causes sperm chromatin damage and cysteinyl aspartate-specific proteinases 3 changes in fertile men. *J Assist Reprod Genet* 32, 747–755. <https://doi.org/10.1007/s10815-015-0451-0>
- Zinaman, M.J., Clegg, E.D., Brown, C.C., O'Connor, J., Selevan, S.G., 1996. Estimates of human fertility and pregnancy loss. *Fertility and Sterility* 65, 503–509. [https://doi.org/10.1016/S0015-0282\(16\)58144-8](https://doi.org/10.1016/S0015-0282(16)58144-8)

Appendix

Figures

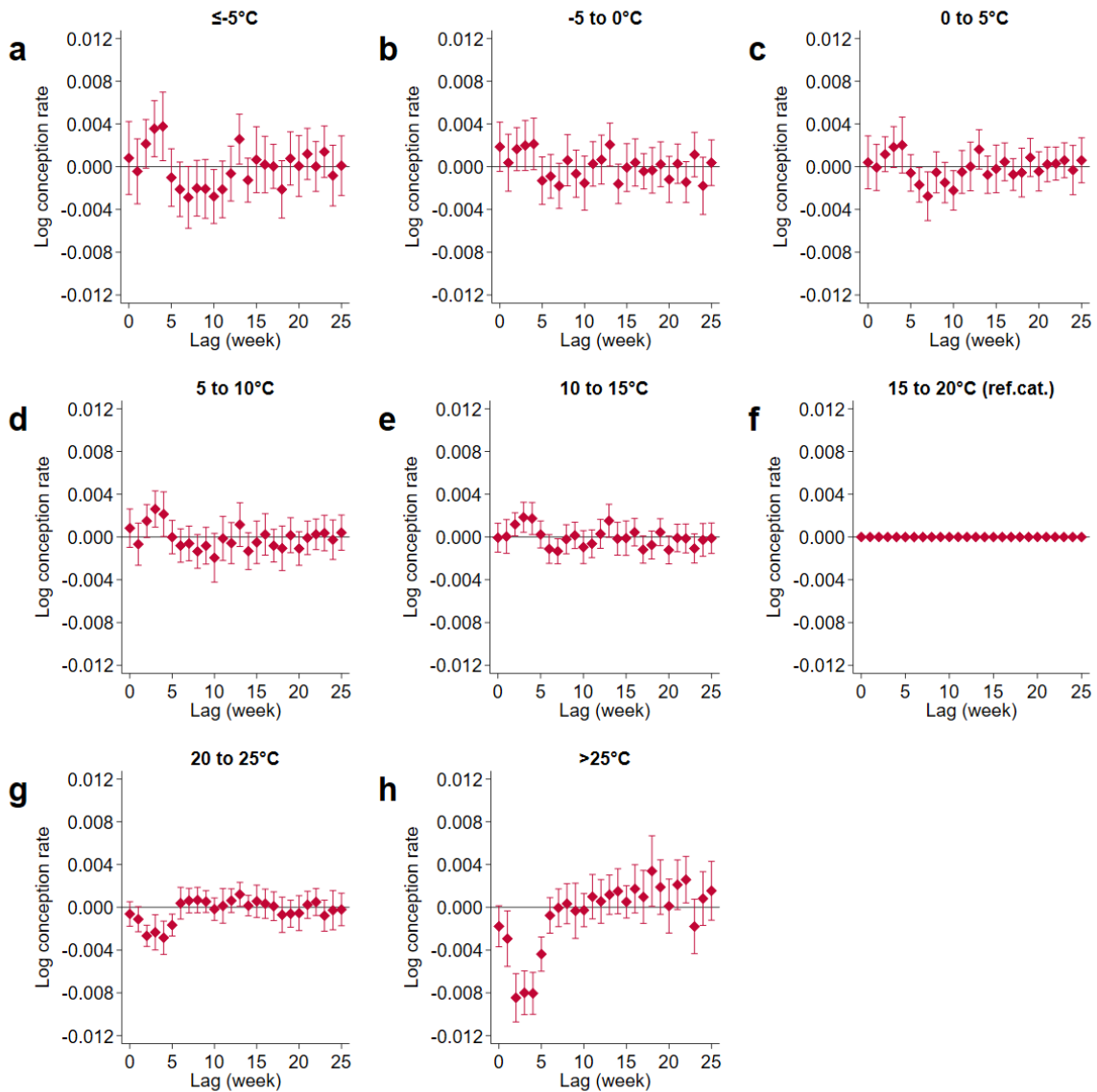


Fig. A1. Historical relationship between temperature and conception rates

Notes: The estimated coefficients for all temperature categories applying the baseline specification (Equation (3)). The squares show the effects of exposure to days with different average temperatures on current and future conception rates up to 25 weeks (relative to a day with a mean temperature of 15 – 20°C). The error bars represent 95% confidence intervals. The outcome variable is the log conception rate. Conception rate is defined as the number of conceptions per week per 100,000 women aged 16–44. The model has county-by-year fixed effects, county-by-calendar-week fixed effects, and county-by-week quadratic time trends county by month-of-year specific linear time trends. We control for precipitation and the share of non-working days. We weight by the counties' average female population size (aged 16–44) between 1980 and 2015. Standard errors are clustered by county and time.

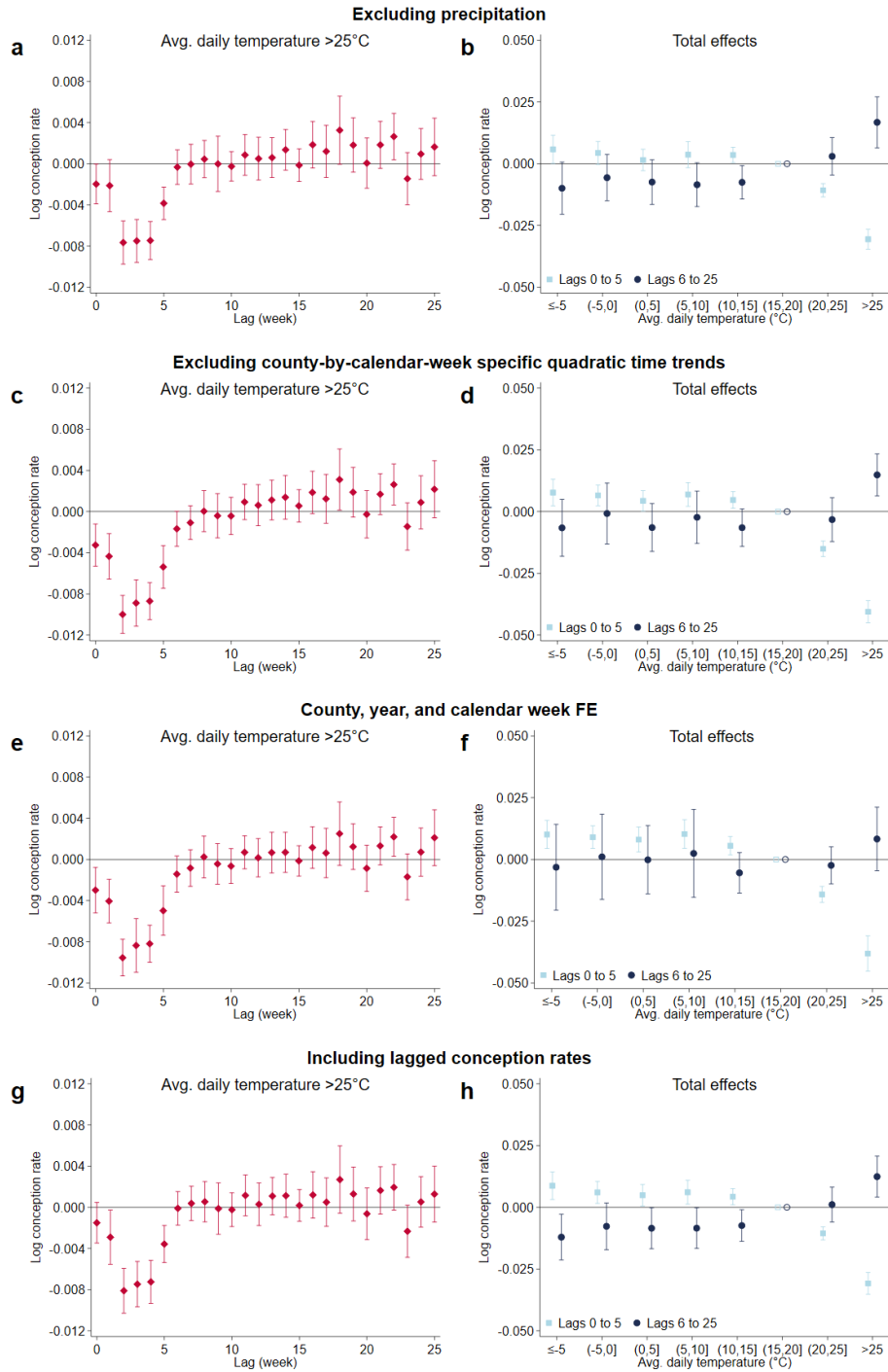


Fig. A2. Results of the sensitivity tests

Notes: (a,c,e,g) The effects of exposure to a day with an average temperature above 25°C on current and future conception rates up to 25 weeks (relative to a day with a mean temperature of 15–20°C). (b,d,f,h) The total effects (sum of the coefficients) over weeks (lags) 0–5 and 6–25 after exposure. Conception rate is defined as the number of conceptions per week per 100,000 women aged 16–44. The error bars represent 95% confidence intervals. (a,b) Precipitation controls are excluded. (c,d) County-by-calendar-week-specific quadratic time trends are excluded. (e,f) Time and location fixed effects are changed: only county, year, and week fixed effects are included. (g,h) Controlling for lagged conception rates. N of lags = 25. Year 1980 is excluded as lagged conception rates are missing.

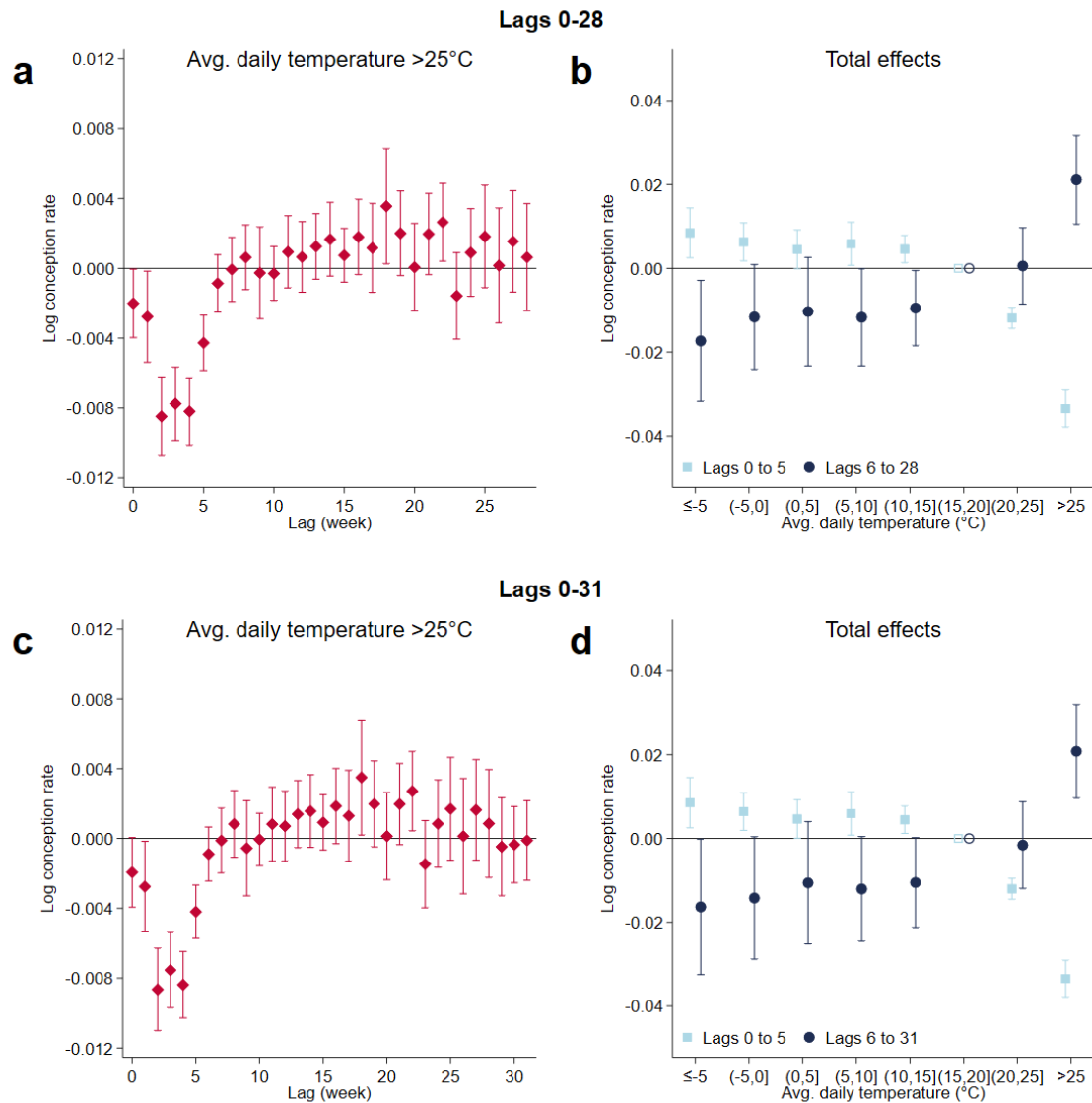


Fig. A3. Longer lag structures

Notes: The results of the estimations of the historical temperature–conception rate relationship including additional temperature and precipitation lags. **(a,c)** The effects of exposure to a day with an average temperature above 25°C on current and future conception rates up to 25 weeks (relative to a day with a mean temperature of 15–20°C). **(b,d)** The total effects (sum of the coefficients) over weeks (lags) 0–5 and 6–25 after exposure. The error bars represent 95% confidence intervals. The outcome variable is the log conception rate. Conception rate is defined as the number of conceptions per week per 100,000 women aged 16–44. The model has county-by-year fixed effects, county-by-calendar-week fixed effects, and county-by-week quadratic time trends county by month-of-year specific linear time trends. We control for precipitation and the share of non-working days. We weight by the counties’ average female population size (aged 16–44) between 1980 and 2015. Standard errors are clustered by county and time. **(a,b)** Including three additional temperature and precipitation lags (lags 26–28). **(c,d)** Including six additional temperature and precipitation lags (lags 26–31).

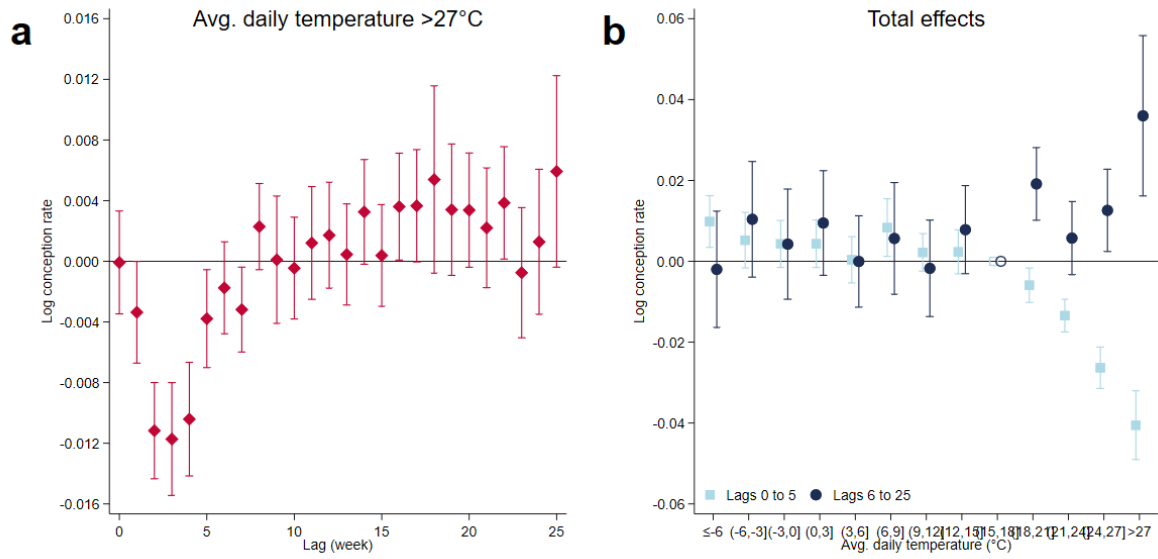


Fig. A4. Estimated impacts using 3°C-wide temperature categories

Notes: Estimations of the historical temperature–conception rate relationship using 3°C-wide temperature categories. The lowest category is $\leq -6^\circ\text{C}$, whereas the highest is $>27^\circ\text{C}$. In this analysis 15 to 18°C serves as the reference category. **(a)** The effects of exposure to a day with an average temperature above 27°C on current and future conception rates up to 25 weeks (relative to a day with a mean temperature of 15 – 18°C). **(b)** The total effects (sum of the coefficients) over weeks (lags) 0–5 and 6–25 after exposure. The error bars represent 95% confidence intervals. The outcome variable is the log conception rate. Conception rate is defined as the number of conceptions per week per 100,000 women aged 16–44. The model has county-by-year fixed effects, county-by-calendar-week fixed effects, and county-by-week quadratic time trends county by month-of-year specific linear time trends. We control for precipitation and the share of non-working days. We weight by the counties’ average female population size (aged 16–44) between 1980 and 2015. Standard errors are clustered by county and time.

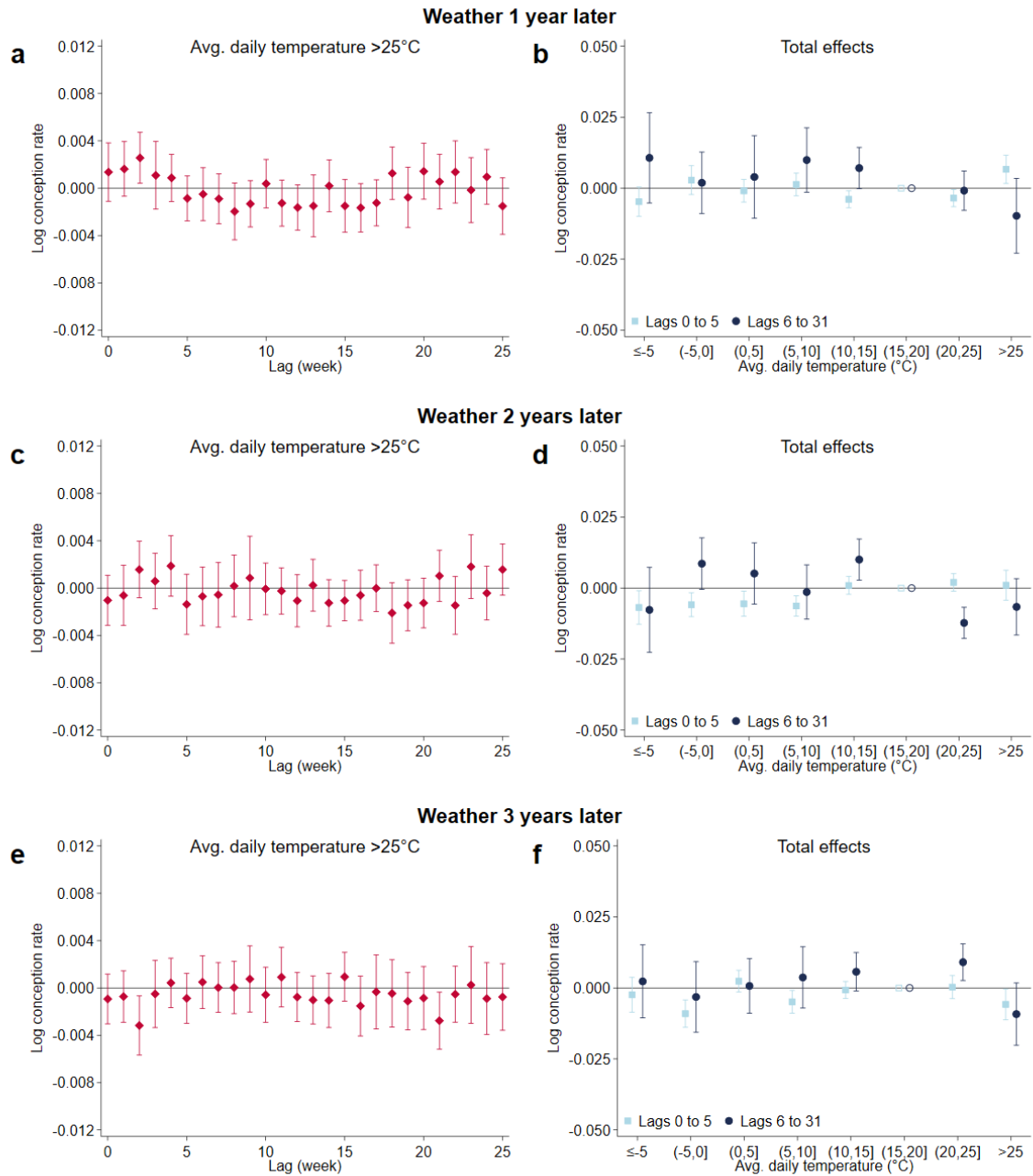


Fig. A5. Placebo tests with weather 1 year, 2 years, or 3 years later

Notes: Results of the placebo regressions where temperature and precipitation variables are replaced with weather data measured exactly one, two or three years later. Because conception rates could not have been affected by temperature in the distant future, zero or close to zero coefficients should be observed (a,c,e) The effects of exposure to a day with an average temperature above 25°C on current and future conception rates up to 25 weeks (relative to a day with a mean temperature of 15–20°C). (b,d,f) The total effects (sum of the coefficients) over weeks (lags) 0–5 and 6–25 after exposure. The error bars represent 95% confidence intervals. The outcome variable is the log conception rate. Conception rate is defined as the number of conceptions per week per 100,000 women aged 16–44. The model has county-by-year fixed effects, county-by-calendar-week fixed effects, and county-by-week quadratic time trends county by month-of-year specific linear time trends. We control for precipitation and the share of non-working days. We weight by the counties’ average female population size (aged 16–44) between 1980 and 2015. Standard errors are clustered by county and time.

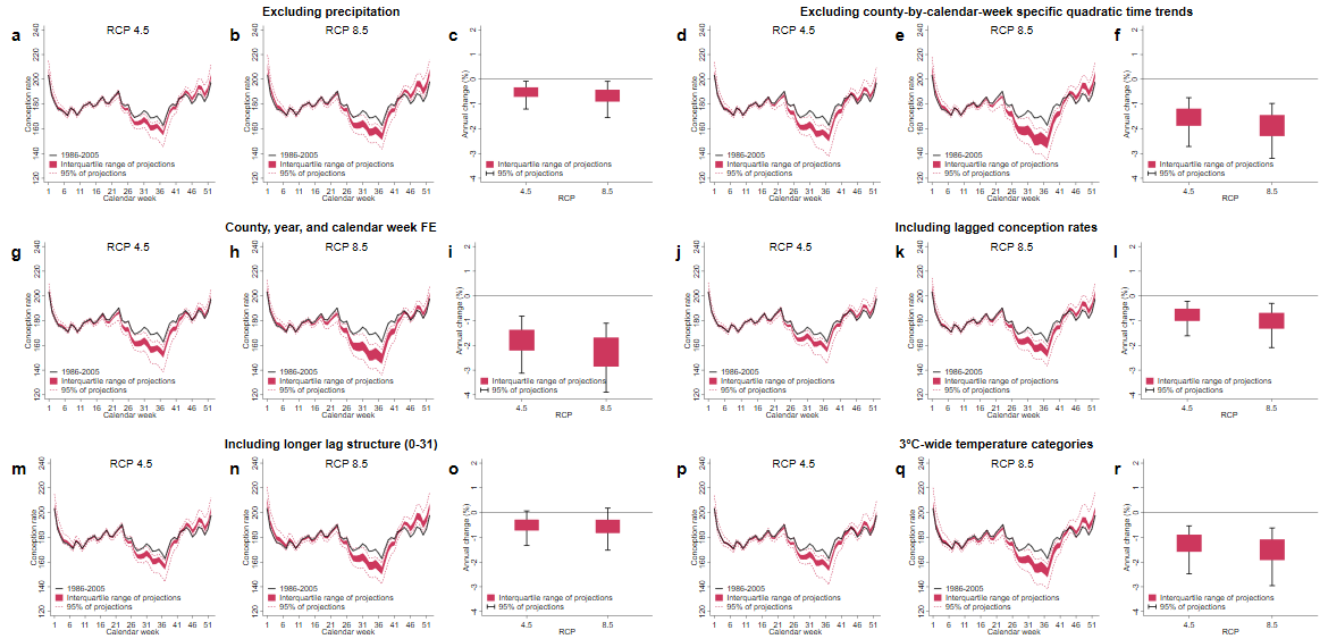


Fig. A6. Sensitivity of the projected impact of climate change

Notes: Impacts on the seasonal distribution (a,b,d,e,g,h,j,k,m,n,o,q) and annual volume (c,f,i,l,o,r) of conception rates by the mid-21st century (2040–2059) applying alternative model specifications for the estimation of the historical temperature–conception rate relationship. The impacts are calculated using the projected within-model differences in temperature distribution between the periods of 1986–2005 and 2040–2059 by 21 climate models and the historical relationship between conception rates and temperature (estimated by 500 bootstrap samples). For these graphs, conception rates in calendar week 52 are rescaled to 7 days. Conception rate is defined as the number of conceptions per week per 100,000 women aged 16–44. For further details on the different estimations of the historical temperature–conception rate relationship, see Fig. A2, Fig. A3 and Fig. A4.

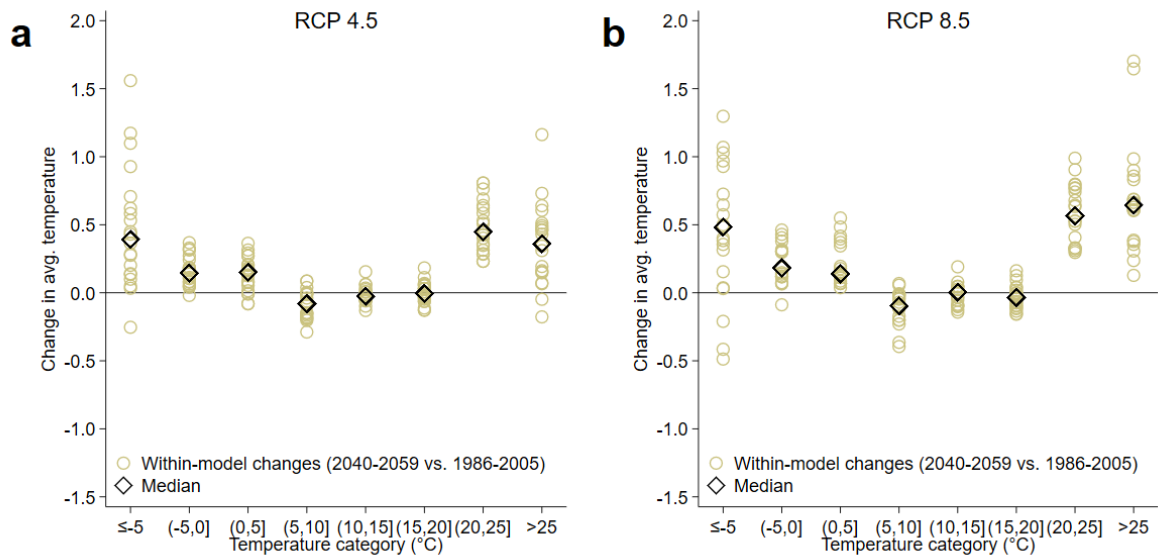


Fig. A7. Changes in average temperature within temperature categories (2040–2059 vs. 1986–2005)

Notes: Changes in average temperature within the temperature categories between the periods of 1986–2005 and 2040–2059 for RCP 4.5 (a) and RCP 8.5 (b). We calculated the mean temperatures within the eight temperature categories that are used in the baseline analysis. The within-model changes in mean temperatures are calculated as the difference between the periods of 2040–2059 and 1986–2005. The national averages of the mean temperatures are calculated as the unweighted average of the temperatures measured at the grid points within Hungary. The hollow circles are the projected changes from the 21 climate models, the black diamonds are the medians of these projections.

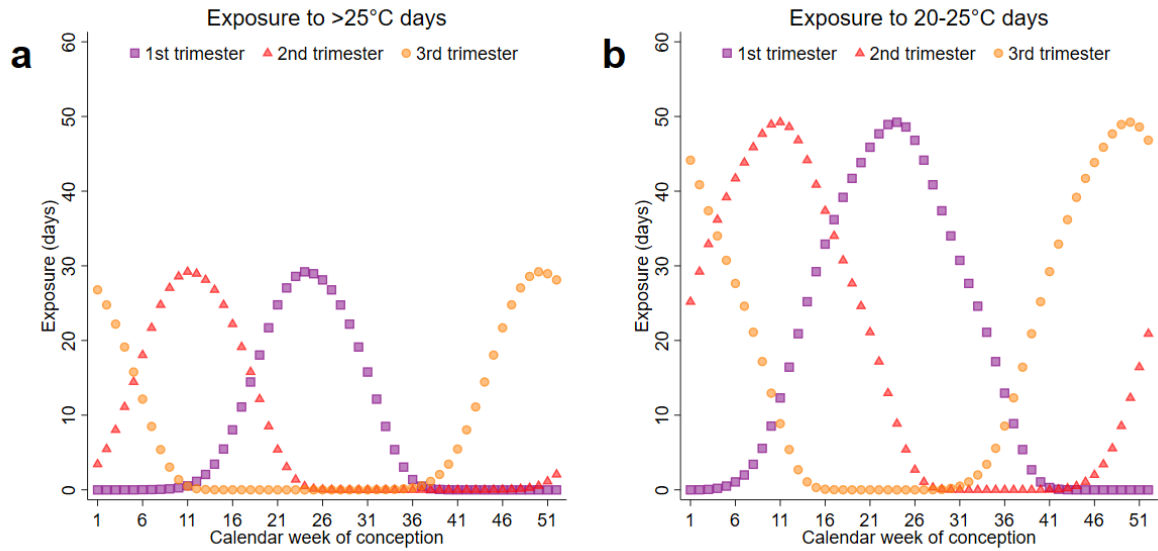


Fig. A8. Expected in utero exposure to hot days in 2040-2059 by the calendar week of the conception (RCP 8.5)

Notes: Expected in utero exposure to hot days (>25°C) (a) and moderately hot (20-25°C) days (b) during pregnancy by the calendar week of the conception in the period of 2040–2059. Pregnancies are assumed to be 39-week-long. The exposure figures are calculated using the average projections of the calendar week-level temperature distributions of 21 climate models (for RCP 8.5).

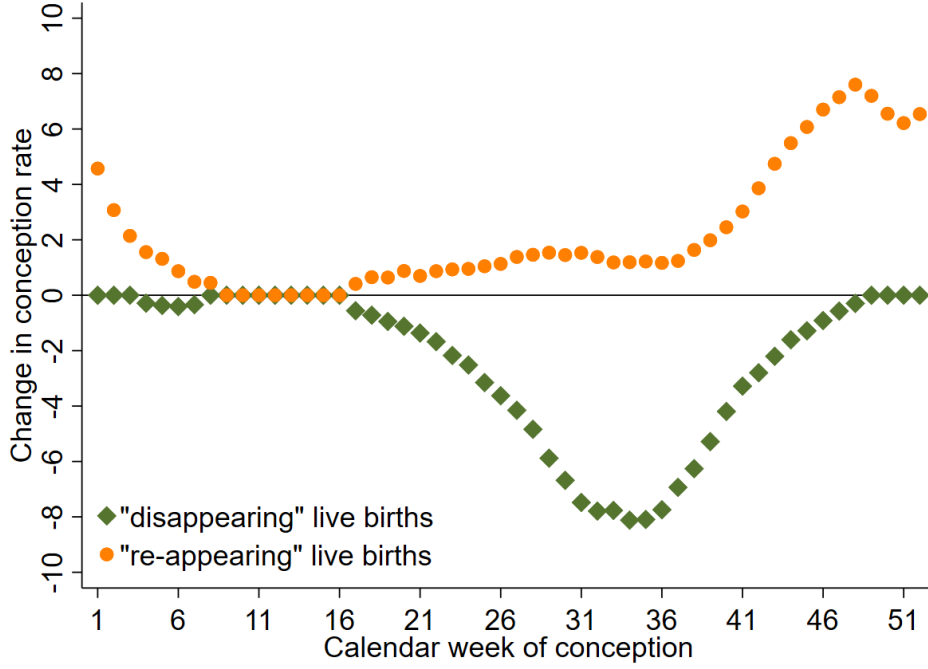


Fig. A9. Distribution of disappearing and re-appearing live births due to climate change by calendar week of conception

Notes: To determine the distribution of disappearing live births due to climate change by the calendar week of conception, we simply calculate the projected change in conception rates for the period of 2040–2059 (RCP 8.5) using only the coefficients of the temperature lags 0 to 5 from Equation (3). We use these lags to estimate the approximate distribution of disappearing live births as our estimations suggest that exposure to heat has a six-week-long deteriorating effect on conception rates. That is, we estimate the following:

$$CL_{wm}^D = \left[\exp \left(\sum_{k=0}^5 \sum_j \beta_k^j \left(T_{(w-k)m}^{j,2040-2059} - T_{(w-k)m}^{j,1986-2005} \right) \right) - 1 \right] \times Y_w^{1986-2005} \quad (11)$$

where CL^D is the change in conception rate for calendar week w , climate model m (or in our terminology: the disappearing live births by calendar week). β is the estimated historical relationship between temperature bin j and the conception rate for lag k ($k = 0, 1, \dots, 5$). $T^{2040-2059}$ shows the projected temperature distribution in the period of 2040–2059 for calendar week w , climate model m (RCP 8.5). Similarly, $T^{1986-2005}$ shows the retrospectively simulated temperature distribution in the period of 1986–2005 for calendar week w , climate model m . $Y^{1986-2005}$ is the conception rate based on pregnancies ending in live births in the period of 1986–2005. In other words, the first term in the square bracket is the percentage change in conception rate, and it is multiplied by the baseline of conception rate.

To determine the distribution of re-appearing live births by calendar week of conception, we follow a similar procedure, but we use temperature coefficients for lags 6 to 25:

$$CL_{wm}^R = \left[\exp \left(\sum_{k=6}^{25} \sum_j \beta_k^j \left(T_{(w-k)m}^{j,2040-2059} - T_{(w-k)m}^{j,1986-2005} \right) \right) - 1 \right] \times Y_w^{1986-2005} \quad (12)$$

where CL^R is the distribution of re-appearing live births.

We account for regression uncertainty by bootstrapping the β coefficients (500 times, sampling with replacement), as discussed in the Methods. For this graph, we use the median of 10,500 projections (500 coefficient estimations multiplied by 21 climate models). For simplicity, values for calendar weeks with very small changes are set to be zero.

Tables

Table A1. Impacts of changing seasonality of conceptions ending in live births on the in utero temperature exposure of the affected newborns

Temperature	Exposure during the 2 nd and 3 rd trimesters (days)			Exposure during the whole pregnancy (days)		
	Re-appearing births	Disappearing births	Difference	Re-appearing births	Disappearing births	Difference
≤−5°C	1.1	3.0	−1.9	3.1	3.2	−0.1
−5 to 0°C	7.4	20.3	−12.9	20.8	22.8	−2.0
0 to 5°C	20.9	50.6	−29.7	51.9	59.4	−7.5
5 to 10°C	24.9	41.3	−16.4	43.8	52.3	−8.5
10 to 15°C	29.3	31.4	−2.1	38.5	47.1	−8.6
15 to 20°C	37.2	21.8	15.4	43.3	41.1	2.2
20 to 25°C	42.8	11.2	31.6	49.9	34.1	15.8
>25°C	18.3	2.4	15.9	21.8	13.1	8.7
Total	182	182	0	273	273	0

Notes: The table shows the estimated average in utero temperature exposures for live births with changing conception dates due to climate change. The figures represent temperature exposures in days assuming 39-week-long pregnancies. The exposures are calculated using the average projections of the calendar week-level temperature distribution of the 21 climate models for the period of 2040–2059 (RCP 8.5). For the exact definition of disappearing and re-appearing live births see Fig. A9. The figures show average exposures of these groups. The exposure of disappearing live births is a crude estimation of the “original” exposures of those births whose conception is delayed as the result of future warming. The exposure of re-appearing live births is a crude estimation of the “new” exposures of these live births. Therefore, the “Difference” column approximates how the average exposure changes due to the shift in the timing of conception of these live births.