INSTITUTE OF ECONOMICS
Centre for Economic and Regional Studies

HUN-REN
Hungarian Research Network

Közgazdaság- és Regionális Tudományi Kutatóközpont
KÖZGAZDASÁG-TUDOMÁNYI INTÉZET

KRTK-KTI WORKING PAPERS | KRTK-KTI MŰHELYTANULMÁNYOK

The effect of temperature on birth rates in Europe

TAMÁS HAJDU

KRTK-KTI WP – 2023/32

November 2023

INSTITUTE OF ECONOMICS, CENTRE FOR ECONOMIC AND REGIONAL STUDIES
HUNGARIAN RESEARCH NETWORK (HUN-REN)
BUDAPEST

ABSTRACT
Using data from 32 European countries for nearly 244 million live births between 1969 and 2021, this paper examines the effects of temperatures on birth rates. The results show that exposure to hot days slightly reduces birth rates five to eight months later, while much stronger negative effects are observed nine to ten months after exposure to hot temperatures. Thereafter, a partial recovery is observed, with slightly increased birth rates. This study also shows that the effect of high-humidity hot days is much stronger than that of hot days with low humidity. Besides, the effect of heatwave days has been found to be more severe than that of hot days that are not preceded by other hot days. This study finds that some adaptation to heat can only be expected in the long run, which suggests that climate change may have a negative impact on the number of live births in the twenty-first century.

JEL codes: I12, J13, Q54
Keywords: birth rates, fertility, temperature, climate change, Europe

Tamás Hajdu
HUN-REN Centre for Economic and
Regional Studies
hajdu.tamas@krtk.hun-ren.hu

A hőmérséklet hatása a születések számára Európában

HAJDU TAMÁS

ÖSSZEFOGLALÓ

A tanulmány a hőmérsékletnek a születési rátára gyakorolt hatását vizsgálja 32 európai ország 1969 és 2021 közötti közel 244 millió élveszületésre vonatkozó adatainak felhasználásával. Az eredmények azt mutatják, hogy az extrém meleg napoknak való kitettség enyhén csökkenti a születési rátát öt-nyolc hónappal később, míg kilenc-tíz hónappal a forró hőmérsékletnek való kitettség után sokkal erősebb negatív hatások figyelhetők meg. Az ezt követő néhány hónapban részleges helyreállás figyelhető meg; a születési ráta enyhén emelkedik. A tanulmány azt is megmutatja, hogy a magas páratartalmú forró napok hatása erősebb, mint az alacsony páratartalmú forró napoké. Emellett a hőhullámos napok hatása erősebb, mint az olyan forró napoké, melyeket közvetlenül nem előznek meg más magas hőmérsékletű napok. A hőséghez való részleges alkalmazkodás csak hosszú távon várható, ami arra utal, hogy az éghajlatváltozás negatív hatással lehet az élveszületések számára a XXI. században.

JEL: I12, J13, Q54

Kulcsszavak: születések, termékenység, hőmérséklet, éghajlatváltozás, Európa

The effect of temperature on birth rates in Europe

Tamás Hajdu

HUN-REN Centre for Economic and Regional Studies, hajdu.tamas@krtk.hun-ren.hu

Abstract

Using data from 32 European countries for nearly 244 million live births between 1969 and 2021, this paper examines the effects of temperatures on birth rates. The results show that exposure to hot days slightly reduces birth rates five to eight months later, while much stronger negative effects are observed nine to ten months after exposure to hot temperatures. Thereafter, a partial recovery is observed, with slightly increased birth rates. This study also shows that the effect of high-humidity hot days is much stronger than that of hot days with low humidity. Besides, the effect of heatwave days has been found to be more severe than that of hot days that are not preceded by other hot days. This study finds that some adaptation to heat can only be expected in the long run, which suggests that climate change may have a negative impact on the number of live births in the twenty-first century.

JEL codes: I12, J13, Q54

Keywords: birth rates, fertility, temperature, climate change, Europe

Acknowledgment

This work was supported by the Hungarian National Research, Development and Innovation Office – NKFIH (grant no. FK 134351) and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. The sources of funding had no role in study design; in the collection, analysis, and interpretation of data; in the writing of the article; and in the decision to submit it for publication. I acknowledge the E-OBS dataset from the EU-FP6 project UERRA (http://www.uerra.eu) and the Copernicus Climate Change Service, and the data providers in the ECA&D project (https://www.ecad.eu).

1. Introduction

There is growing evidence that human fertility and fetal development are considerably affected by heat exposure (Hajdu and Hajdu 2022a), as is that of our fellow mammals (Hansen 2009). On the one hand, several studies demonstrated that post-conception exposure to hot temperatures increases the chance of pregnancy losses (Basu et al. 2016; Bonell et al. 2023; Davenport et al. 2020; Hajdu and Hajdu 2021a, 2023; McElroy et al. 2022; Sexton et al. 2021), leads to shorter gestation and lowers the health of newborns (Andalón et al. 2016; Barreca and Schaller 2020; Chen et al. 2020; Deschênes et al. 2009; Grace et al. 2015; Hajdu and Hajdu 2021b; Sun et al. 2019). On the other hand, others have found that heat impairs spermatogenesis and has a negative effect on various sperm parameters (Garolla et al. 2013; Jung and Schuppe 2007; Kumar and Singh 2022; Zhang et al. 2015), and related to this, a recent study reported that pre-conception heat stress results in less conception (Hajdu and Hajdu 2022b).

Some recent papers have examined the temporal dynamics of the relationship between temperature and birth rates at the monthly level, rather than looking specifically at the effect of pre- or post-conception heat stress on different aspects of human fertility (Barreca et al. 2018; Cho 2020; Conte Keivabu et al. 2023). These studies have explored how the temperature in a given month affects birth rates in that month and in subsequent months.[1] The general finding is that heat strongly decreases the birth rate eight and ten months later. At the same time, heat also appears to slightly reduce birth rates in the few months after exposure, indirectly suggesting that fetal losses increase when pregnant women are exposed to hot weather. Barreca et al. (2018) also showed that after the initial (within 10 months) heat-induced decline in the birth rate, there is a significant rebound, offsetting about half of the decline. However, others have either not examined this issue (Cho 2020) or have failed to find a similar decline (Conte Keivabu et al. 2023). A consistent finding in the literature is that, unlike heat, the effect of cold temperatures is small.[2]

Despite the growing empirical evidence on the relationship between ambient temperature and birth rates, some limitations and unanswered questions remain in the literature. First, no previous study has examined the role of humidity, even though humidity is an important factor contributing to the thermal stress that people experience (Budd 2008; Raymond et al. 2020). At

---

[1] An earlier study by Lam and Miron (1996) uses a similar approach to investigate this question, but focuses only on birth rates nine and ten months after heat exposure.

[2] Thiede et al. (2022) examines a similar question with annual data of African countries and is therefore unable to analyze the detailed dynamics of the relationship. In addition, since the annual average of the maximum temperature was used, temperature extremes and their effects could not be fully captured. Nevertheless, they also find that the higher the temperature, the lower the birth rate.

a given temperature, the higher the humidity, the lower the ability of the human body to cool itself through sweating, and therefore the higher the risk of adverse health consequences. Exploring the role of humidity in influencing the effect of heat on births may be important for a better understanding of the potential consequences of climate change. Second, the effects of heat waves are rarely examined, despite the fact that one important consequence of climate change is a dramatic increase in the number and duration of prolonged periods of extreme heat (Perkins-Kirkpatrick and Lewis 2020; Rousi et al. 2022; Russo et al. 2017). Third, most of the studies analyzed the temperature effects over a period of less than ten years, which makes it impossible to explore how the relationship between temperature and birth rates has changed over time. Again, such an analysis may provide important insight regarding the impacts of climate change. Fourth, the geographical coverage of most of the previous studies is limited, with the exception of studies on the United States, which cover almost half of a continent (Barreca et al. 2018; Lam and Miron 1996). Examining data from small geographical areas makes it difficult to estimate how the effect of temperature varies with local climatic conditions. Although this is not impossible if the climatic conditions within the area are sufficiently diverse, as demonstrated by Conte Keivabu et al. (2023) using Spanish regional data.

This study contributes to the literature by examining the impact of temperature on birth rates in Europe over a period of 53 years. Using data from 32 European countries, the level of spatial coverage is similar to studies using US data, while only one other study (Barreca et al. 2018) is comparable in terms of the time coverage of this paper. Furthermore, the relationship between temperature and birth rates has not been examined in any study from a full European perspective. The results of empirical analysis show that heat has adverse effects on birth rates. Birth rates decline modestly 5 to 8 months after exposure, but the strongest effects are observed nine and ten months after the heat shock. Specifically, one day with an average temperature of >25°C, relative to one day between 5°C and 10°C, decreases the monthly birth rate by 0.68% nine months later and by 0.45% ten months later. Birth rates recover somewhat thereafter, especially in the 11-16 months after exposure. This paper also shows that when heat meets with high humidity the negative effects on birth rates are more severe, as they are on hot days that are preceded by other hot days. An important result regarding the potential impacts of climate change is that long-term adaptation can mitigate the effects of heat to some extent, but short-term adaptation (over a few decades) does not appear to be occurring based on historical data.

The rest of the paper proceeds as follows. Section 2 describes the data used in the analysis. Section 3 outlines the empirical model. Section 4 presents the results. Section 5 discusses the findings and concludes.

2. Data

Births at the country-month level come from Eurostat (Eurostat 2023a). This database provides information on the number of births from 1960 onwards, but as birth rates are available for relatively few countries in the first years, the analysis is limited to the years 1969-2021. Birth rates are defined as the number of births per 100,000 women in a given country-month. The number of women (at the beginning of the year) for every year and country also comes from Eurostat (Eurostat 2023b), and the mid-year female population is used as the denominator in the calculation of birth rates.

Information on weather is drawn from the European Climate Assessment & Dataset project (Cornes et al. 2018). The E–OBS 27.0e dataset (The ECA&D Project Team 2023) used for this analysis contains daily temperatures, relative humidity, and precipitation information for Europe with a spacing of 0.25° × 0.25° in regular latitude/longitude coordinates starting 1950.

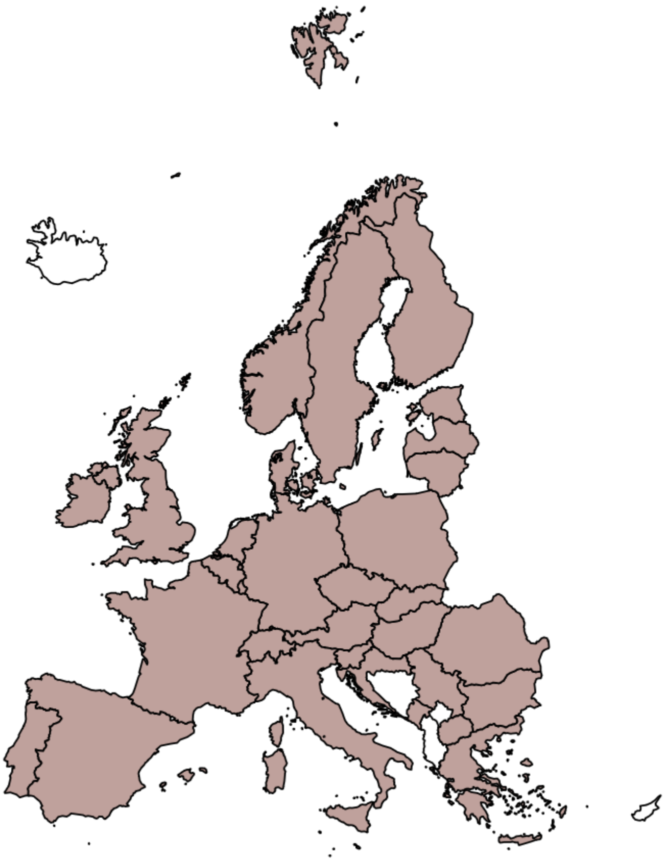
To describe the daily weather conditions at each grid point, eight binary temperature variables based on the mean temperature (≤−5°C, −5–0°C, 0–5°C, 5–10°C, 10–15°C, 15–20°C, 20–25°C, >25°C), five precipitation variables indicating the amount of precipitation (0 mm, 0–3 mm, 3–5 mm, 5–10 mm, over 10 mm) and six humidity variables (≤50%, 50-60%, 60-70%, 70-80%, 80-90%, >90%) were created. Next, these grid-point level weather variables were averaged to the country level. Defining the weather indicators first for the grid points and only thereafter aggregating them ensures that the weather variations within the country are preserved as much as possible. Finally, the monthly number of days with different temperature, humidity, and precipitation levels were calculated by summing the daily level data.

For the hottest days, a further distinction was made between high- and low-humidity days, and between heatwave and non-heatwave days. High-humidity hot days were defined as days with relative humidity above 60% and mean temperature >25°C, while low-humidity hot days were defined as >25°C days with relative humidity below 60%. A heatwave is defined as a period of at least three consecutive days where the daily mean temperature exceeds 25°C on each day. Accordingly, heatwave days are those >25 °C days that are preceded by at least two other >25 °C days, and non-heatwave days are those extremely hot days where the two days preceding them are not both >25°C days.

It is worth pointing out that heat exposure is measured by the average daily temperature. This means that on days with an average temperature above 25°C, the heat stress is high. On these days the maximum temperature is typically well above 30°C, with an average of 33.9°C.

The final dataset covers 32 countries (Fig. 1) and includes 15,624 country-month observations, containing aggregated information on nearly 244 million live births. The temporal coverage for each country is shown in Table A1 in Supplementary Materials, while Table 1 summarizes the main variables in the analysis sample. The mean monthly birth rate is around 181 births per 100,000 women. On average, there are 2.6 days in a month with an average temperature between 20 and 25°C and 0.6 days with an average temperature above 25°C. About two-thirds of the latter days are low humidity days and one-third are high humidity days. Furthermore, the share of heatwave and non-heatwave hot (>25°C) days is almost equal.

Fig. 1: Spatial coverage of the sample



Notes: Countries marked in color are included in the study.

Table 1: Descriptive statistics

	Mean	SD	Min	Max	N
Birth rate	181.41	38.82	38.57	420.61	15,624
≤−5°C days	0.86	2.85	0	29.66	15,624
−5 to 0°C days	2.01	3.61	0	23.62	15,624
0 to 5°C days	5.06	5.79	0	27.98	15,624
5 to 10 days	6.95	6.15	0	28.17	15,624
10 to 15°C days	7.01	6.29	0	28.79	15,624
15 to 20°C days	5.32	6.31	0	29.60	15,624
20 to 25°C days	2.61	4.86	0	25.82	15,624
>25°C days	0.62	2.08	0	20.74	15,624
>25°C days with low humidity	0.40	1.53	0	18.26	15,624
>25°C days with high humidity	0.22	0.86	0	10.84	15,624
>25°C: non-heatwave days	0.28	0.80	0	7.90	15,624
>25°C: heatwave days	0.33	1.37	0	16.46	15,624

Notes: Units of observations: country-by-month. Weighted by the countries' female population at the beginning of the year.

3. Methods

To identify the effect of temperatures on birth rates, the following equation is estimated:

$$\ln(B_{ct}) = \sum_j \sum_{b=0}^{25} \beta_b^j T^j_{c,t-b} + \sum_k \sum_{b=0}^{25} \gamma_b^k P^k_{c,t-b} + \sum_l \sum_{b=0}^{25} \delta_b^l H^l_{c,t-b} + \rho_{cy} + \theta_{cm} + \tau_{ym} + \pi'_{cm}\times t + \pi''_{cm}\times t^2 + \varepsilon_{ct} \quad (1)$$

where B is the birth rate in country *c* at time *t* (year *y*, month *m*). T stands for temperature bins (≤−5°C, −5–0°C, 0–5°C, 5–10°C, 10–15°C, 15–20°C, 20–25°C, >25°C). In the analysis, the temperature bin of 5–10°C is the omitted category. P denotes the number of days when the amount of daily precipitation falls in precipitation bin *k* (0 mm, 0−3 mm, 3−5 mm, 5−10 mm, over 10 mm). H stands for relative humidity categories (≤50%, 50-60%, 60-70%, 70-80%, 80-90%, >90%).

In this specification, coefficient β^j shows the effect of one additional day when the daily mean temperature falls into temperature bin *j* on the logarithm of the monthly birth rate (relative to a day with a mean temperature of 5–10°C). To study the dynamics of the temperature-birth rate relationship, it is allowed that the birth rate at time *t* to be affected by weather up to 25 months earlier (b = 0, 1, …, 25). That is, the set of coefficients β_0, β_1, …, β_{25} shows effect of temperature at time *t* on current and future birth rates.

Country-by-year fixed effects (ρ) controls for unobserved country-specific factors at the year level that may influence birth rates. Country-by-month fixed effects (θ) controls country-specific seasonality. Year-by-month fixed effects (τ) control for time-varying factors affecting birth rates in the same way for all countries. In addition, country-specific seasonality is allowed to change over time by adding country-by-month-specific quadratic time trends (π).[3] This kind of fixed effects approach is widely used in the literature and allows a causal interpretation of temperature coefficients (Dell et al. 2014).

The regressions are weighted by the countries' female population at the beginning of the year, and standard errors are clustered by county.

4. Results

4.1. Main results and robustness

Panel A of Fig. 2 shows the estimated effects for the highest temperature category (>25°C), relative to a day with a mean temperature of 5–10°C. Similar to the previous studies (Barreca et al. 2018; Conte Keivabu et al. 2023), the strongest effects are observed nine and ten months after exposure. One additional day with an average temperature of >25°C decreases the monthly birth rate by 0.68% nine months after exposure and by 0.45% ten months after exposure. However, it is also worth highlighting that there is also a noticeable drop in birth rates 5-8 months after the heat shock. In these months, the heat-induced decline is between 0.09% and 0.13%. The effects observed in the ninth and tenth months suggest that heat has a detrimental effect on reproductive health in the pre-conception period, while the negative effects on birth rates in earlier months indicate that hot temperatures in early pregnancy increase the chance of fetal loss.[4]

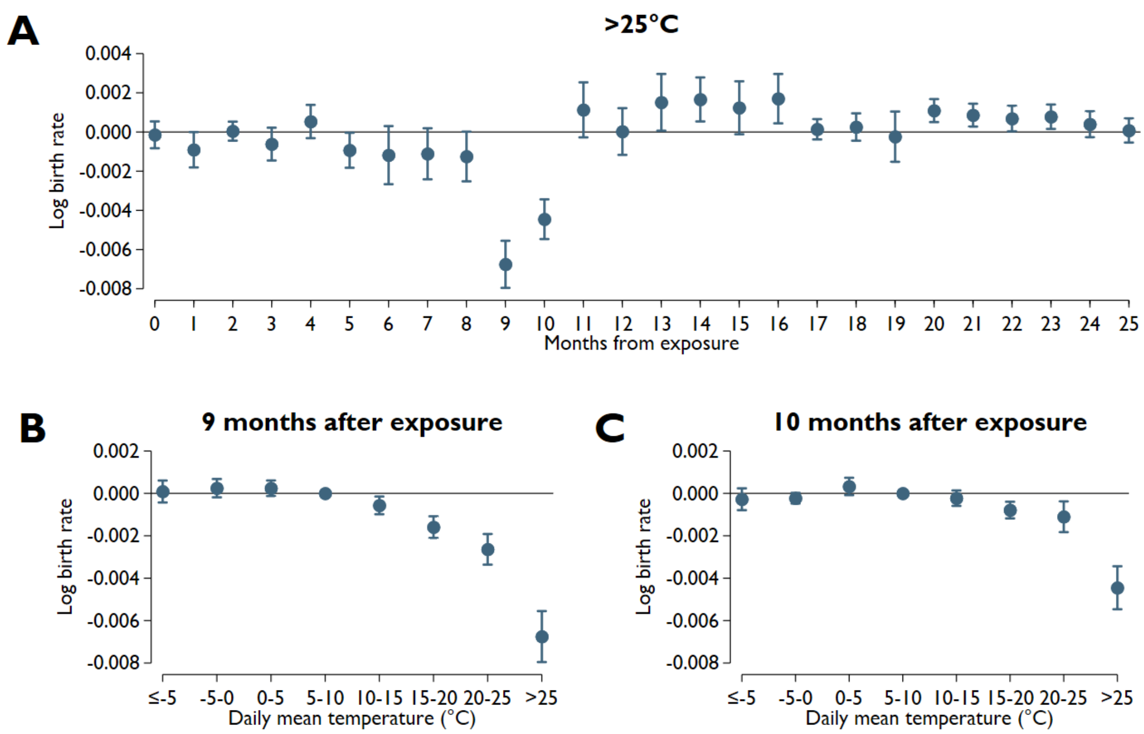
From the eleventh month onwards, positive effects are seen, most strongly between months 11 and 16. In five of these six months, the estimated impacts range from 0.11% to 0.17%. Overall, roughly two-thirds of the cumulative effect of −1.7 log points observed in months 0-10 after exposure "disappears" between months 11 and 25. The cumulative effect in this latter period is 1.1 log points. The overall pattern of the effects is very similar for the 20-25°C temperature category, but the estimated coefficients are lower (Fig. A1, Supplementary Materials)

Panel B and C in Fig. 2 looks in detail at months 9 and 10 after exposure to temperatures, where the greatest impact of extreme heat is observed. It is evident that temperature has a non-linear effect on birth rates. In month 9, there are no apparent differences between the effects of the

[3] The variable t is a discrete variable denoting time (year-month).
[4] The latter simply follows from the fact that, for example, a ceteris paribus increase in miscarriages in the second month of pregnancy will result in a decrease in live births about seven months later.

temperature categories below 10°C. However, as the daily mean temperature rises above 10°C, birth rates start to fall, and this fall is significantly stronger for the hottest days, suggesting that the marginal effect of temperature is increasing. A similar pattern emerges for month 10, but the estimated effects are somewhat weaker. This 90-degree rotated J-shaped relationship is not unexpected, as non-linear temperature effects have been shown in a number of other cases, ranging from health at birth (Barreca and Schaller 2020; Hajdu and Hajdu 2021b) through sleep (Hajdu 2023; Minor et al. 2022) and mortality (Barreca et al. 2016; Carleton et al. 2022; Heutel et al. 2021) to productivity (Burke et al. 2015; LoPalo 2023) and cognitive performance (Graff Zivin et al. 2018; Park et al. 2020).

Fig. 2: The effect of temperatures on birth rates



Notes: The error bars represent 95% confidence intervals. The effects are compared to a day with a mean temperature of 5–10°C. The model has country-by-year, country-by-month, and year-by-month fixed effects and country-by-month-specific quadratic time trends. Precipitation and relative humidity are controlled for. The regressions are weighted by the countries' female population at the beginning of the year. Standard errors are clustered by country. N=15,624.

The sensitivity of the results is assessed through a series of robustness tests, including the use of alternative fixed effects, the exclusion of precipitation and humidity, alternative clustering of standard errors, and the estimation of an unweighted regression (Table A2, Supplementary Materials). None of these changes alter the main conclusion. For month 9, the effect of a >25°C day ranges between −0.58% and −0.73%, while for month 10, it is between −0.34% and −0.54%. These coefficients are highly significant in all cases. The results are also robust to restricting the sample to countries with full coverage for the years 1969-2021 (Fig. A2, Supplementary Materials), to using the population of women aged 15–44 as the denominator in the calculation of birth rates (Fig. A3, Supplementary Materials), or to using the log number of births as the dependent variable (Fig. A4, Supplementary Materials).

The estimation of the temperature effects using 2°C-wide temperature categories above 20°C strengthens the conclusion that the higher the temperature, the lower the birth rate at 9 and 10 months after the temperature shock (Table A3, Supplementary Materials). This specification shows that one additional >28°C day decreases the monthly birth rate by 0.70% nine months after exposure and by 0.56% ten months after exposure.

The main results remain the same even if the monthly mean temperature is used instead of the temperature categories in a restricted cubic spline approach (Fig. A5 ,Supplementary Materials). In this specification, the estimated effect of a monthly mean temperature of 27°C[5] is −15.5% nine months after exposure, relative to a monthly mean temperature of 7.5°C. This is slightly lower than the effect of 30 hot days in the baseline specification, which is −18.5%.[6] For month 10, these effects are −10.7% and −12.6%, respectively. These differences are due to the fact the effect of temperature is non-linear and the monthly mean temperature masks the difference between, for example, a month with 30 days of mild temperatures and a month with 15-15 days of hot and cold temperatures. In other words, the specification using monthly mean temperatures biases the estimate of the effect of heat downwards.

4.2. Heatwaves, heterogeneity by humidity and climate, and change over time

Given climate change and the increase in the number of heatwave days, an important question is whether the effect of heatwave days is stronger than that of similarly hot but not heatwave days. In this analysis, heatwaves are defined as periods of three or more consecutive days where the daily mean temperature exceeds 25°C on each day. Accordingly, heatwave days are those hot (>25°C) days that are preceded by at least two other hot days. Table 2 summarizes the estimation, in which >25°C days are distinguished according to whether they can be considered

[5] For a fair comparison with the base model, the value of 27°C is used. On days above 25 °C, the average temperature is approximately 27°C.

[6] $e^{-0.0068\times 30} - 1 = -0.185$

a heatwave day or not. The estimated effects are shown for months 9 and 10, where the largest coefficients are observed. Heatwave days seem to have stronger effects on birth rates both nine and ten months later. For month 9, the estimated effect of a heatwave day is −0.73%, while the effect of a similarly hot but not heatwave day is −0.59%. For month 10, these effects are −0.55% and −0.22%, respectively. In sum, the effect of hot days is stronger when they are preceded by other hot days, suggesting that the damage from climate change may be more severe than a simple increase in the number of hot days would imply.

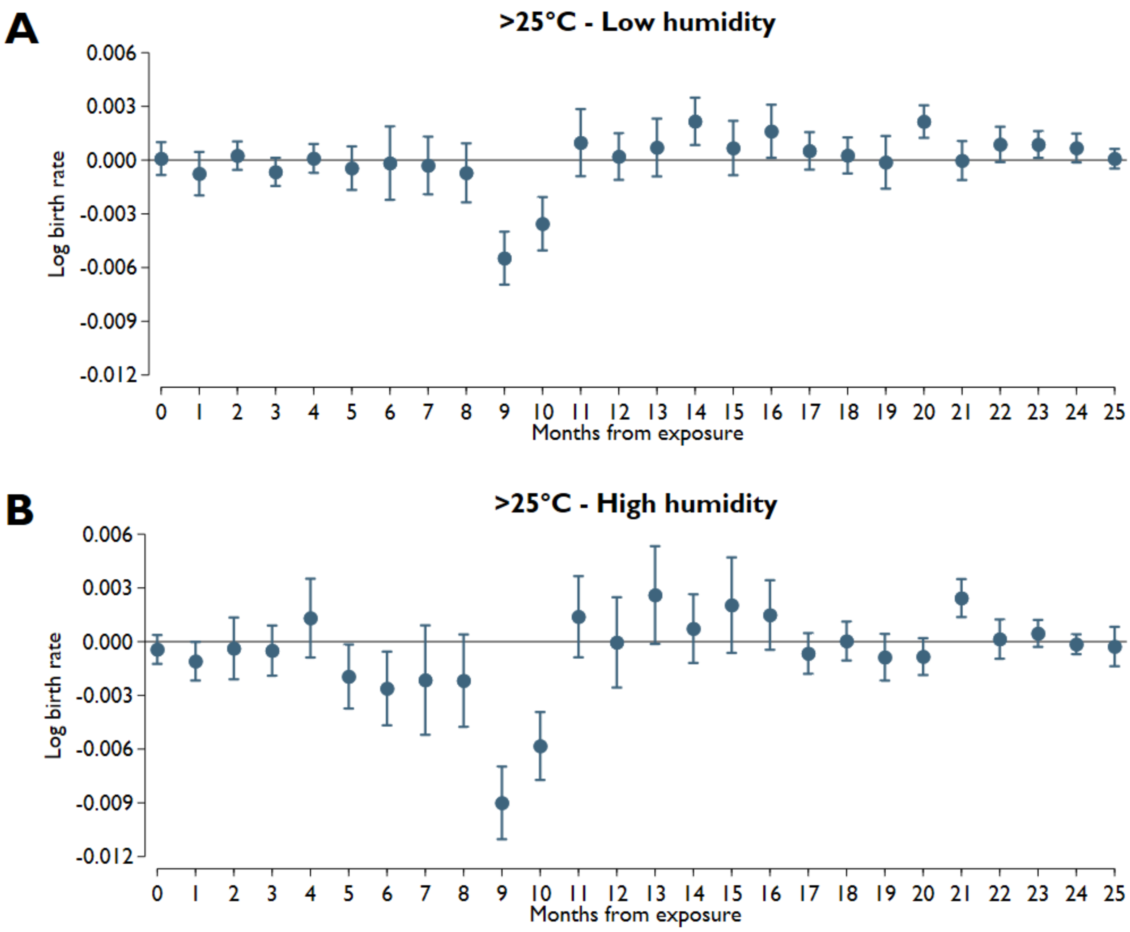
Table 2: The effect of heatwave days

Daily mean temperature (°C)	(1)
9 months from exposure	
≤−5°C	0.0001 (0.0002)
−5-0°C	0.0002 (0.0002)
0-5°C	0.0002 (0.0002)
5-10°C	ref. cat.
10-15°C	-0.0006^{**} (0.0002)
15-20°C	-0.0016^{**} (0.0003)
20-25°C	-0.0027^{**} (0.0004)
>25°C: non-heatwave day	-0.0059^{**} (0.0020)
>25°C: heatwave day	-0.0073^{**} (0.0005)
10 months from exposure	
≤−5°C	−0.0003 (0.0002)
−5-0°C	−0.0002 (0.0001)
0-5°C	0.0003 (0.0002)
5-10°C	ref. cat.
10-15°C	−0.0002 (0.0002)
15-20°C	-0.0008^{**} (0.0002)
20-25°C	-0.0013^{**} (0.0003)
>25°C: non-heatwave day	−0.0022 (0.0014)
>25°C: heatwave day	-0.0055^{**} (0.0004)

Notes: Dependent variable: log birth rate. The model includes lags 0-25 but only lags 9 and 10 are shown (see Eq. 1). The model has country-by-year, country-by-month, and year-by-month fixed effects and country-by-month-specific quadratic time trends. Precipitation and relative humidity are controlled for. The regressions are weighted by the countries' female population at the beginning of the year. Standard errors are clustered by country. N=15,624.
* p<0.05, ** p<0.01

Next, the moderating role of humidity on the effect of heat is examined. In this specification, rather than simply including the number of hot (>25°C) days in the model, a distinction was made between high-humidity and low-humidity hot days. As previously described, high-humidity hot days are those days with an average temperature >25°C where the relative humidity is above 60%, while low-humidity hot days are those days with a similar average temperature where the humidity is below 60%. These results are shown in Fig. 3. It is clearly seen that although low-humidity hot days have non-negligible effects on birth rates, the impact of high-humidity hot days is much stronger. For months 9 and 10, the estimated effects of low-humidity hot days are −0.55% and −0.36%, respectively. In contrast, for high-humidity hot days, these coefficients are −0.90% and −0.58%. It is also worth pointing out that in months 5-8 following the temperature shock, only high-humidity hot days have clear negative effects. This suggests that the risk of fetal death in early pregnancy is mainly increased by exposure to hot days with relatively higher humidity that cause more intense heat stress.

Fig. 3: The effect of heat in low humidity and high humidity conditions



Notes: The error bars represent 95% confidence intervals. The effects are compared to a day with a mean temperature of 5–10°C. The model has country-by-year, country-by-month, and year-by-month fixed effects and country-by-month-specific quadratic time trends. Precipitation and relative humidity are controlled for. The regressions are weighted by the countries' female population at the beginning of the year. Standard errors are clustered by country. N=15,624.

Previous studies have reported that the effect of hot days is stronger in geographic regions with colder climates than in regions with hotter climates (Barreca et al. 2018; Conte Keivabu et al. 2023). To check for this difference, in this study countries are divided into two groups based on the average temperature between 1969 and 2021. Hot climate countries are defined as countries with an average temperature above 10°C, while cold climate countries are defined as countries with an average temperature below 10°C. Next, all the weather variables (temperature, precipitation, humidity) are interacted with the climate variables of the countries, and consequently different temperature effects are estimated for hot and cold climates. The results are summarized in Table 3, which shows the temperature coefficients for months 9 and 10. Consistent with previous results, the effect of heat appears to be stronger in colder climates, but the differences are somewhat smaller than previously observed. However, it is worth noting that these estimates are for different periods and countries.

Table 3: The effect of temperature on log birth rates by climate

Daily mean temperature (°C)	(1) Hot climate	(2) Cold climate
9 months from exposure		
≤−5°C	0.0003 (0.0015)	0.0002 (0.0002)
−5-0°C	−0.0006 (0.0007)	0.0004 (0.0003)
0-5°C	0.0007 (0.0004)	0.0003 (0.0002)
5-10°C	ref. cat.	ref. cat.
10-15°C	−0.0010* (0.0005)	−0.0001 (0.0003)
15-20°C	−0.0020** (0.0004)	−0.0012** (0.0003)
20-25°C	−0.0025** (0.0005)	−0.0026** (0.0007)
>25°C	−0.0068** (0.0007)	−0.0092** (0.0029)
10 months from exposure		
≤−5°C	−0.0001 (0.0017)	−0.0001 (0.0003)
−5-0°C	−0.0013 (0.0008)	0.0000 (0.0002)
0-5°C	0.0005 (0.0004)	0.0004* (0.0002)
5-10°C	ref. cat.	ref. cat.
10-15°C	−0.0007 (0.0005)	0.0003 (0.0003)
15-20°C	−0.0014** (0.0004)	−0.0003 (0.0004)
20-25°C	−0.0011 (0.0006)	−0.0008 (0.0006)
>25°C	−0.0049** (0.0007)	−0.0060* (0.0025)

Notes: Dependent variable: log birth rate. The model includes lags 0-25 but only lags 9 and 10 are shown (see Eq. 1). The model has country-by-year, country-by-month, and year-by-month fixed effects and country-by-month-specific quadratic time trends. Precipitation and relative humidity are controlled for. The regressions are weighted by the countries' female population at the beginning of the year. Standard errors are clustered by country. N=15,624. * p<0.05, ** p<0.01

Finally, potential adaptation over time is explored. In this exercise, each weather variables are interacted with indicators for 1969-1999 and 2000-2021. As the number of countries in the sample changes over time, this estimate is restricted to countries for which birth rates are available for each year between 1969 and 2021. The results for months 9 and 10 are shown in Table 4. Unlike the paper by Barreca et al. (2018), this study finds no evidence for a decrease in effect sizes over time. If there has been any change, it is rather a weak increase in the effect of heat. Several factors contribute to the change in the estimated impacts over time. Some of these factors tend to reduce the impacts. For example, the spread of air conditioning. However, other factors may lead to an increase in the estimated impacts. For example, since not only the number of days above 25°C has increased over the half-century considered in this analysis, but also the average temperature of days above 25°C[7], ceteris paribus, the effect of a hot day is likely to be stronger at the end of the period than at the beginning. The net effects of these factors are reflected in the estimated coefficients in Table 4, and the forces in the two directions appear to cancel each other out.

Table 4: Changes in the effect of temperature on log birth rates over time

Daily mean temperature (°C)	(1) 1969-1999	(2) 2000-2021
9 months from exposure		
≤−5°C	0.0009* (0.0003)	0.0001 (0.0006)
−5-0°C	0.0011** (0.0004)	−0.0009* (0.0003)
0-5°C	0.0007 (0.0003)	−0.0002 (0.0003)
5-10°C	ref. cat.	ref. cat.
10-15°C	−0.0003 (0.0003)	−0.0011** (0.0003)
15-20°C	−0.0011* (0.0005)	−0.0021** (0.0005)
20-25°C	−0.0019** (0.0005)	−0.0019** (0.0006)
>25°C	−0.0059** (0.0008)	−0.0063** (0.0008)
10 months from exposure		
≤−5°C	−0.0001 (0.0003)	0.0004 (0.0004)
−5-0°C	0.0002 (0.0003)	−0.0016* (0.0007)
0-5°C	0.0003 (0.0002)	0.0006* (0.0003)
5-10°C	ref. cat.	ref. cat.
10-15°C	−0.0004 (0.0003)	−0.0004 (0.0003)
15-20°C	−0.0008* (0.0003)	−0.0011** (0.0002)
20-25°C	−0.0014* (0.0006)	−0.0004 (0.0007)
>25°C	−0.0040** (0.0006)	−0.0048** (0.0009)

Notes: Dependent variable: log birth rate. Only countries with full coverage between 1969 and 2021 are included. The model includes lags 0-25 but only lags 9 and 10 are shown (see Eq. 1). The model has country-by-year, country-by-month, and year-by-month fixed effects and country-by-month-specific quadratic time trends.

[7] Furthermore, for example, the number of heatwave days has also increased significantly.

Precipitation and relative humidity are controlled for. The regressions are weighted by the countries' female population at the beginning of the year. Standard errors are clustered by country. N=10,176. * $p<0.05$, ** $p<0.01$

5. Conclusions

This paper examined the effect of temperature on birth rates. This is the first study in the literature that has analyzed this issue from a European perspective, using data from 32 countries for nearly 244 million live births between 1969 and 2021. The results show that nine and ten months after exposure to hot days (daily average temperature >25°C), birth rates drop substantially. The effect of exposure to one additional hot day is −0.68% and −0.45% at months 9 and 10, respectively, compared to a day with an average temperature of 5–10°C. At the same time, it was also shown that the number of live births decreases slightly even 5-8 months after a heat shock. This implies that high temperatures in the first few months of pregnancy are causing an increased risk of miscarriage. However, a substantial part (two-thirds) of the decline observed in the first 10 months is offset by a rebound in the subsequent months, mainly due to increased birth rates 11-16 months after the heat exposure.

One notable finding of the study is that humidity plays a major role in the impact of hot days on birth rates. The effect of a hot day with high humidity is much stronger than another hot day with low relative humidity. From the perspective of the potential impact of climate change, it is also worth noting that hot days that are preceded by other hot days have a greater negative effect on birth rates than hot days that are preceded by non-hot days.

Regarding the potential for future adaptation, the study presented two important findings. The effect of heat is smaller in countries with a hotter climate than in countries with a cooler climate, although negative effects are observed in both groups of countries. This suggests that long-term adaptation to a warmer climate (most likely on a century scale) may alleviate somewhat the effect of heat. At the same time, no difference was observed in the heat effects between 1969-1999 and 2000-2021, indicating that short-term adaptation might be less effective in mitigating the effects of hot weather on birth rates. These results suggests that climate change may have a negative impact on the number of live births in the twenty-first century.

From a public policy perspective, the results of this study suggest that it may be useful to raise awareness among pregnant women and people (men and women) considering having children about the harmful effects of high temperatures. To be more effective, this could be combined with a warning system that provides information on expected heat waves. These policies may already reduce the negative impact of extreme heat on birth rates in the short term.

References

Andalón, M., Azevedo, J. P., Rodríguez-Castelán, C., Sanfelice, V., & Valderrama-González, D. (2016). Weather Shocks and Health at Birth in Colombia. *World Development*, *82*, 69–82. https://doi.org/10.1016/j.worlddev.2016.01.015

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. *Journal of Political Economy*, *124*(1), 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*(4), 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*(1), 77–82. https://doi.org/10.1038/s41558-019-0632-4

Basu, R., Sarovar, V., & Malig, B. J. (2016). Association Between High Ambient Temperature and Risk of Stillbirth in California. *American Journal of Epidemiology*, *183*(10), 894–901. https://doi.org/10.1093/aje/kwv295

Bonell, A., Part, C., Okomo, U., Cole, R., Hajat, S., Kovats, S., et al. (2023). An expert review of environmental heat exposure and stillbirth in the face of climate change: Clinical implications and priority issues. *BJOG: An International Journal of Obstetrics & Gynaecology*. https://doi.org/10.1111/1471-0528.17622

Budd, G. M. (2008). Wet-bulb globe temperature (WBGT)—its history and its limitations. *Journal of Science and Medicine in Sport*, *11*(1), 20–32. https://doi.org/10.1016/j.jsams.2007.07.003

Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature*, *527*(7577), 235–239. https://doi.org/10.1038/nature15725

Carleton, T., Jina, A., Delgado, M., Greenstone, M., Houser, T., Hsiang, S., et al. (2022). Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits. *The Quarterly Journal of Economics*, *137*(4), 2037–2105. https://doi.org/10.1093/qje/qjac020

Chen, X., Tan, C. M., Zhang, X., & Zhang, X. (2020). The effects of prenatal exposure to temperature extremes on birth outcomes: the case of China. *Journal of Population Economics*, *33*(4), 1263–1302. https://doi.org/10.1007/s00148-020-00768-4

Cho, H. (2020). Ambient temperature, birth rate, and birth outcomes: evidence from South Korea. *Population and Environment*, *41*(3), 330–346. https://doi.org/10.1007/s11111-019-00333-6

Conte Keivabu, R., Cozzani, M., & Wilde, J. (2023). Temperature and Fertility: Evidence from Spanish Register Data. IZA Discussion Papers 16110. https://www.iza.org/publications/dp/16110/temperature-and-fertility-evidence-from-spanish-register-data

Davenport, F., Dorélien, A., & Grace, K. (2020). Investigating the linkages between pregnancy outcomes and climate in sub-Saharan Africa. *Population and Environment*, *41*(4), 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. *Journal of Economic Literature*, *52*(3), 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*(2), 211–17. https://doi.org/10.1257/aer.99.2.211

Eurostat. (2023a). Live births (total) by month (demo_fmonth). https://ec.europa.eu/eurostat/databrowser/view/demo_fmonth/default/table. Accessed 31 August 2023

Eurostat. (2023b). Population on 1 January by age group and sex (demo_pjangroup). https://ec.europa.eu/eurostat/databrowser/view/demo_pjangroup/default/table. Accessed 31 August 2023

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. *Human Reproduction*, *28*(4), 877–885. https://doi.org/10.1093/humrep/det020

Grace, K., Davenport, F., Hanson, H., Funk, C., & Shukla, S. (2015). Linking climate change and health outcomes: Examining the relationship between temperature, precipitation and birth weight in Africa. *Global Environmental Change*, *35*, 125–137. https://doi.org/10.1016/j.gloenvcha.2015.06.010

Graff Zivin, J., Hsiang, S. M., & Neidell, M. (2018). Temperature and Human Capital in the Short and Long Run. *Journal of the Association of Environmental and Resource Economists*, *5*(1), 77–105. https://doi.org/10.1086/694177

Hajdu, T. (2023). Temperature exposure and sleep duration: evidence from time use surveys. KRTK-KTI Working Papers - 2023/25. https://kti.krtk.hu/wp-content/uploads/2023/09/KRTKKTIWP202325.pdf

Hajdu, T., & Hajdu, G. (2021a). Post-conception heat exposure increases clinically unobserved pregnancy losses. *Scientific Reports*, *11*(1987). https://doi.org/10.1038/s41598-021-81496-x

Hajdu, T., & Hajdu, G. (2021b). Temperature, climate change, and birth weight: evidence from Hungary. *Population and Environment*, *43*(2), 131–148. https://doi.org/10.1007/s11111-021-00380-y

Hajdu, T., & Hajdu, G. (2022a). Temperature, Climate Change, and Fertility. In K. F. Zimmermann (Ed.), *Handbook of Labor, Human Resources and Population Economics* (pp. 1–25). Cham: Springer. 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. *Journal of Population Economics*, *35*(4), 1751–1776. https://doi.org/10.1007/s00148-020-00814-1

Hajdu, T., & Hajdu, G. (2023). Climate change and the mortality of the unborn. *Journal of Environmental Economics and Management*, *118*, 102771. https://doi.org/10.1016/j.jeem.2022.102771

Hansen, P. J. (2009). Effects of heat stress on mammalian reproduction. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1534), 3341–3350. https://doi.org/10.1098/rstb.2009.0131

Heutel, G., Miller, N. H., & Molitor, D. (2021). Adaptation and the Mortality Effects of Temperature across U.S. Climate Regions. *The Review of Economics and Statistics*, *103*(4), 740–753. https://doi.org/10.1162/rest_a_00936

Jung, A., & Schuppe, H.-C. (2007). Influence of genital heat stress on semen quality in humans. *Andrologia*, *39*(6), 203–215. https://doi.org/10.1111/j.1439-0272.2007.00794.x

Kumar, N., & Singh, A. K. (2022). Impact of environmental factors on human semen quality and male fertility: a narrative review. *Environmental Sciences Europe*, *34*(1), 6. https://doi.org/10.1186/s12302-021-00585-w

Lam, D. A., & Miron, J. A. (1996). The effects of temperature on human fertility. *Demography*, *33*(3), 291–305. https://doi.org/10.2307/2061762

LoPalo, M. (2023). Temperature, Worker Productivity, and Adaptation: Evidence from Survey Data Production. *American Economic Journal: Applied Economics*, *15*(1), 192–229. https://doi.org/10.1257/app.20200547

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. *Environment International*, *158*, 106902. https://doi.org/10.1016/j.envint.2021.106902

Minor, K., Bjerre-Nielsen, A., Jonasdottir, S. S., Lehmann, S., & Obradovich, N. (2022). Rising temperatures erode human sleep globally. *One Earth*, *5*(5), 534–549. https://doi.org/10.1016/j.oneear.2022.04.008

Park, R. J., Goodman, J., Hurwitz, M., & Smith, J. (2020). Heat and Learning. *American Economic Journal: Economic Policy*, *12*(2), 306–339. https://doi.org/10.1257/pol.20180612

Perkins-Kirkpatrick, S. E., & Lewis, S. C. (2020). Increasing trends in regional heatwaves. *Nature Communications*, *11*(1), 3357. https://doi.org/10.1038/s41467-020-16970-7

Raymond, C., Matthews, T., & Horton, R. M. (2020). The emergence of heat and humidity too severe for human tolerance. *Science Advances*, *6*(19), eaaw1838. https://doi.org/10.1126/sciadv.aaw1838

Rousi, E., Kornhuber, K., Beobide-Arsuaga, G., Luo, F., & Coumou, D. (2022). Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia. *Nature Communications*, *13*(1), 3851. https://doi.org/10.1038/s41467-022-31432-y

Russo, S., Sillmann, J., & Sterl, A. (2017). Humid heat waves at different warming levels. *Scientific Reports*, *7*(1), 7477. https://doi.org/10.1038/s41598-017-07536-7

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. *Environmental Research*, *197*, 111037. https://doi.org/10.1016/j.envres.2021.111037

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*(6), 067005. https://doi.org/10.1289/EHP4648

The ECA&D Project Team. (2023). A European daily high-resolution gridded dataset (E-OBS), 27.0e. https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php. Accessed 31 August 2023

Thiede, B. C., Ronnkvist, S., Armao, A., & Burka, K. (2022). Climate anomalies and birth rates in sub-Saharan Africa. *Climatic Change*, *171*(1), 5. https://doi.org/10.1007/s10584-021-03273-z

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-spicific proteinases 3 changes in fertile men. *Journal of Assisted Reproduction and Genetics*, *32*(5), 747–755. https://doi.org/10.1007/s10815-015-0451-0

Supplementary Materials for

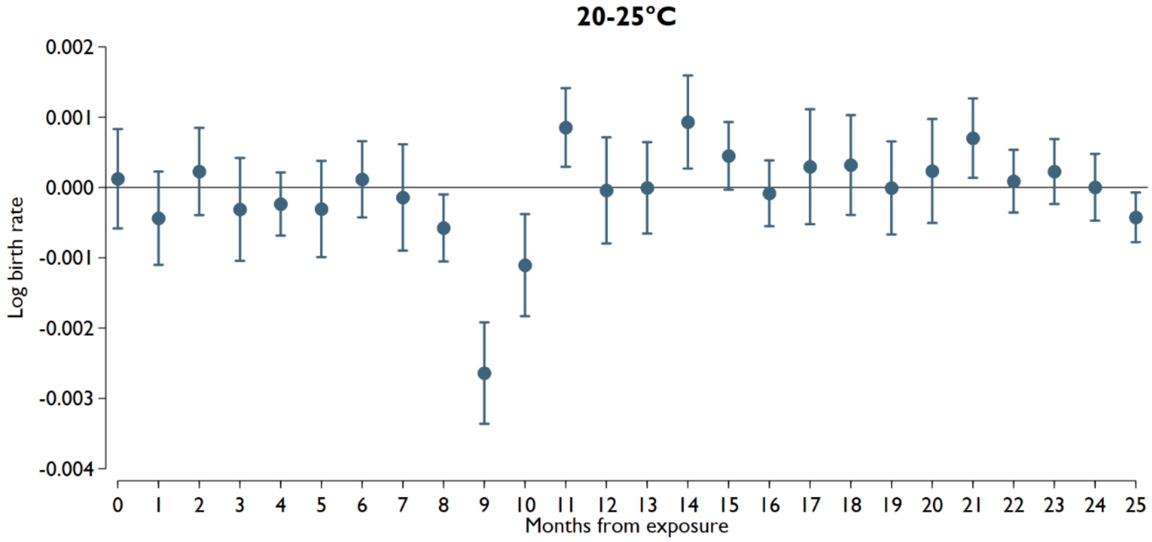
The effect of temperature on birth rates in Europe

This PDF file includes:

Fig. A1-A4

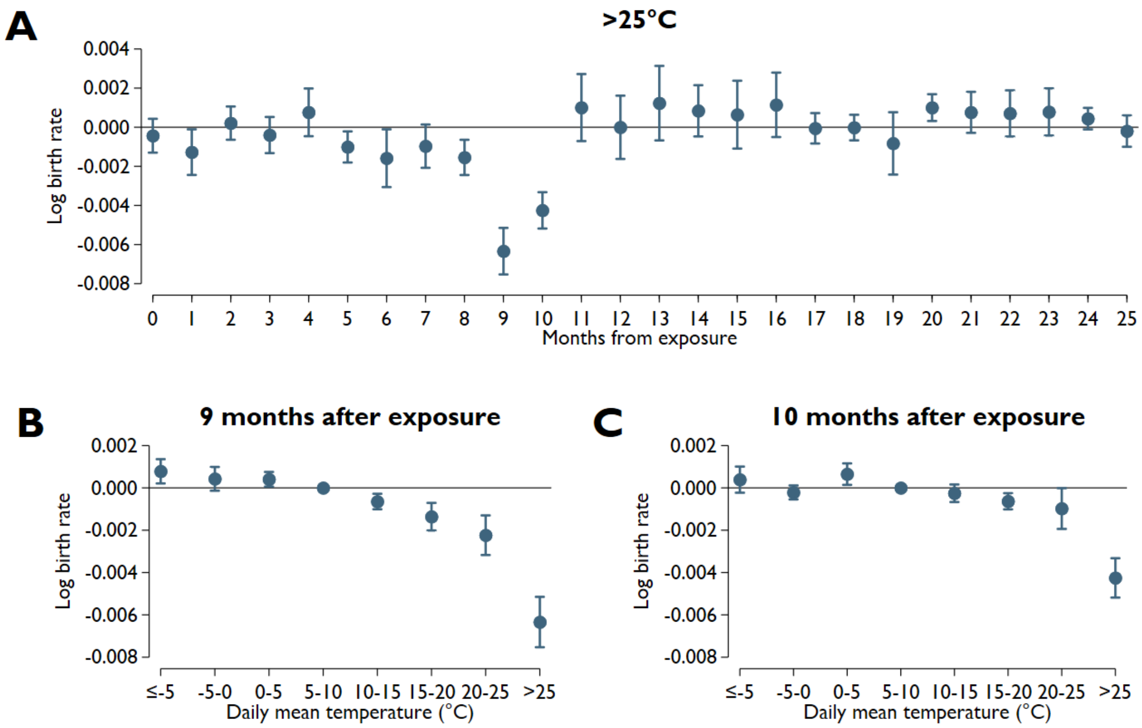
Table A1-A3

Fig. A1: The effect of a 20-25°C day on birth rates



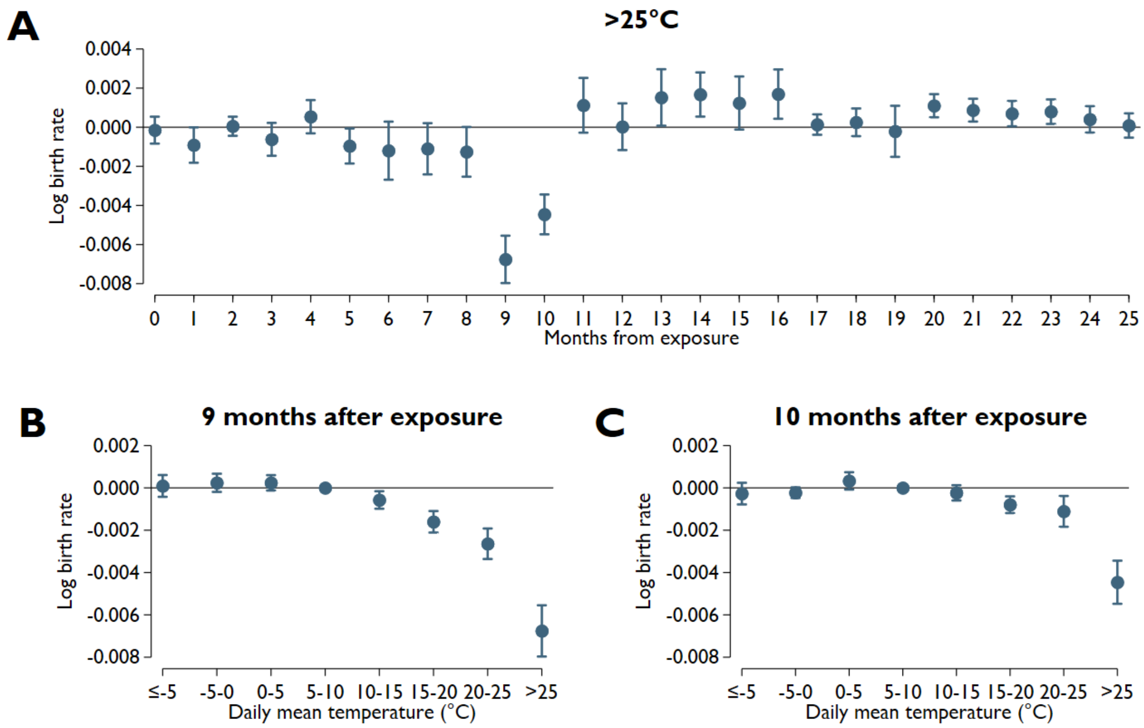
Notes: The error bars represent 95% confidence intervals. The effects are compared to a day with a mean temperature of 5–10°C. The model has country-by-year, country-by-month, and year-by-month fixed effects and country-by-month-specific quadratic time trends. Precipitation and relative humidity are controlled for. The regressions are weighted by the countries' female population at the beginning of the year. Standard errors are clustered by country. N=15,624.

Fig. A2: Estimations based on a balanced panel of countries



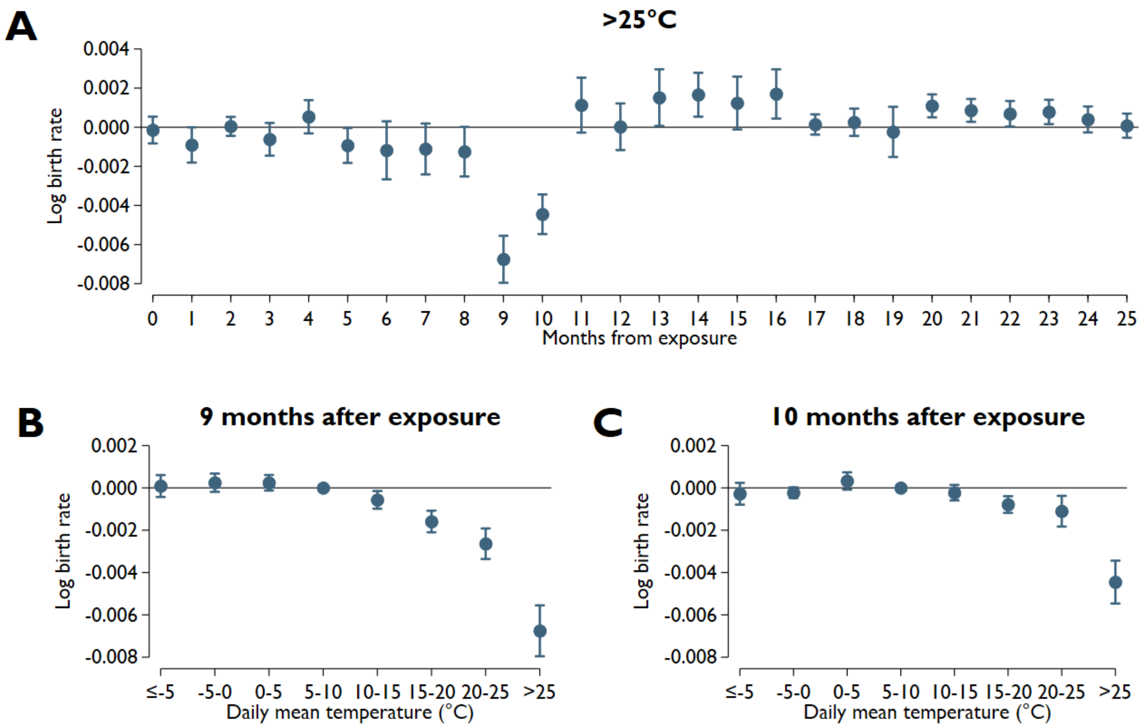
Notes: Only countries with full coverage between 1969 and 2021 are included. The error bars represent 95% confidence intervals. The effects are compared to a day with a mean temperature of 5–10°C. The model has country-by-year, country-by-month, and year-by-month fixed effects and country-by-month-specific quadratic time trends. Precipitation and relative humidity are controlled for. The regressions are weighted by the countries' female population at the beginning of the year. Standard errors are clustered by country. N=10,176.

Fig. A3: Estimations using the log number of births per 100,000 women aged 15-44 as the dependent variable



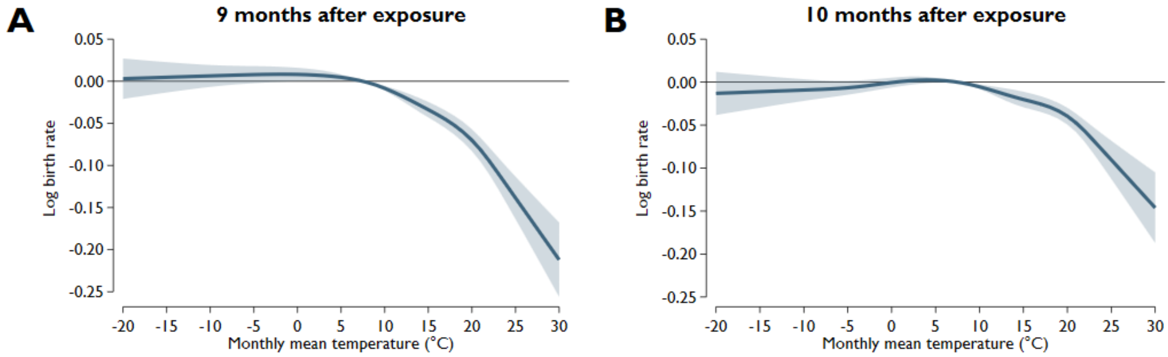
Notes: The error bars represent 95% confidence intervals. The effects are compared to a day with a mean temperature of 5–10°C. The model has country-by-year, country-by-month, and year-by-month fixed effects and country-by-month-specific quadratic time trends. Precipitation and relative humidity are controlled for. The regressions are weighted by the countries' female population at the beginning of the year. Standard errors are clustered by country. N=15,540.

Fig. A4: Estimations using the log number of births as the dependent variable



Notes: The error bars represent 95% confidence intervals. The effects are compared to a day with a mean temperature of 5–10°C. The model has country-by-year, country-by-month, and year-by-month fixed effects and country-by-month-specific quadratic time trends. Precipitation and relative humidity are controlled for. The regressions are weighted by the countries' female population at the beginning of the year. Standard errors are clustered by country. N=15,624.

Fig. A5: Estimations using the monthly mean temperature



Notes: The temperature estimates come from restricted cubic spline functions with six knots. The shaded areas represent 95% confidence intervals. The reference temperatures are 7.5 °C. The model has country-by-year, country-by-month, and year-by-month fixed effects and country-by-month-specific quadratic time trends. Precipitation and relative humidity are controlled for. The regressions are weighted by the countries' female population at the beginning of the year. Standard errors are clustered by country. N=15,624.

Table A1: Spatial and temporal coverage of the sample

Country	Years
AUT	1969-2021
BEL	1969-2021
BGR	1994-2021
CHE	1969-2021
CZE	1992-2021
DEU	1969-2021
DNK	1969-2021
ESP	1969-2021
EST	1969-2021
FIN	1969-2021
FRA	1994-2021
GBR	1973-2018
GRC	1969-2021
HRV	1994-2021
HUN	1994-2021
IRL	1969-2021
ITA	1969-2021
LIE	1980-2021
LTU	1994-2021
LUX	1969-2021
LVA	1996-2021
MKD	1994-2021
MNE	2005-2021
NLD	1969-2021
NOR	1969-2021
POL	1995-2021
PRT	1969-2021
ROU	1995-2021
SRB	2005-2021
SVK	1996-2021
SVN	1994-2021
SWE	1969-2021

Table A2: Sensitivity tests

Daily mean temperature (°C)	(1) Baseline	(2) C-Y-S FE	(3) R-Y-M FE	(4) Unweighted	(5) Excl. precipitation and humidity	(6) SE clustering: C + YM
9 months from exposure						
≤−5°C	0.0001 (0.0003)	−0.0004 (0.0003)	0.0004 (0.0003)	0.0011 (0.0007)	0.0001 (0.0002)	0.0001 (0.0003)
−5-0°C	0.0002 (0.0002)	−0.0001 (0.0002)	0.0000 (0.0002)	−0.0006 (0.0005)	0.0005* (0.0002)	0.0002 (0.0003)
0-5°C	0.0002 (0.0002)	0.0002 (0.0002)	0.0005** (0.0002)	0.0003 (0.0002)	0.0003 (0.0002)	0.0002 (0.0002)
5-10°C	ref. cat.	ref. cat.	ref. cat.	ref. cat.	ref. cat.	ref. cat.
10-15°C	−0.0006** (0.0002)	−0.0008* (0.0003)	−0.0005* (0.0002)	0.0004 (0.0005)	−0.0005* (0.0002)	−0.0006* (0.0002)
15-20°C	−0.0016** (0.0003)	−0.0018** (0.0003)	−0.0015** (0.0004)	−0.0013** (0.0003)	−0.0014** (0.0002)	−0.0016** (0.0003)
20-25°C	−0.0026** (0.0004)	−0.0031** (0.0006)	−0.0023** (0.0004)	−0.0028** (0.0003)	−0.0022** (0.0002)	−0.0026** (0.0004)
>25°C	−0.0068** (0.0006)	−0.0073** (0.0008)	−0.0060** (0.0006)	−0.0059** (0.0006)	−0.0058** (0.0005)	−0.0068** (0.0007)
10 months from exposure						
≤−5°C	−0.0003 (0.0003)	−0.0006 (0.0003)	−0.0002 (0.0003)	0.0009 (0.0009)	−0.0003 (0.0002)	−0.0003 (0.0003)
−5-0°C	−0.0002 (0.0001)	−0.0006* (0.0002)	−0.0005 (0.0003)	0.0003 (0.0005)	−0.0001 (0.0002)	−0.0002 (0.0002)
0-5°C	0.0003 (0.0002)	0.0000 (0.0002)	0.0001 (0.0002)	0.0008 (0.0005)	0.0002 (0.0002)	0.0003 (0.0002)
5-10°C	ref. cat.	ref. cat.	ref. cat.	ref. cat.	ref. cat.	ref. cat.
10-15°C	−0.0002 (0.0002)	−0.0006 (0.0003)	−0.0003 (0.0002)	0.0004 (0.0004)	−0.0003 (0.0002)	−0.0002 (0.0002)
15-20°C	−0.0008** (0.0002)	−0.0011** (0.0002)	−0.0008** (0.0003)	−0.0002 (0.0003)	−0.0008** (0.0002)	−0.0008** (0.0002)
20-25°C	−0.0011** (0.0004)	−0.0013* (0.0005)	−0.0009* (0.0004)	−0.0009 (0.0008)	−0.0011** (0.0002)	−0.0011** (0.0004)
>25°C	−0.0045** (0.0005)	−0.0054** (0.0009)	−0.0034** (0.0005)	−0.0035** (0.0008)	−0.0040** (0.0005)	−0.0045** (0.0006)
Fixed effects	C-Y, C-M, Y-M	C-Y-S, C-M, Y-M	C-Y, C-M, R-Y-M	C-Y, C-M, Y-M	C-Y, C-M, Y-M	C-Y, C-M, Y-M
Time trend	C-M-specific quadratic	C-M-specific quadratic	C-M-specific quadratic	C-M-specific quadratic	C-M-specific quadratic	C-M-specific quadratic
Precipitation and humidity	Yes	Yes	Yes	Yes	No	Yes
SE clustering	C	C	C	C	C	C + Y-M
Weighted	Yes	Yes	Yes	No	Yes	Yes

Notes: Dependent variable: log birth rate. C-country, R-region, Y-year, S-season, M-month. Regions: (i) Southern Europe = Portugal, Sapin, Italy, Greece, Croatia, Montenegro, North Macedonia, Serbia, Slovenia; (ii) Eastern Europe = Bulgaria, Czech Republic, Hungary, Slovakia, Romania, Poland; (iii) Northern Europe = Sweden, Norway, Finland, Denmark, Estonia, Lithuania, Latvia, Ireland, United Kingdom; (iv) Western Europe = Germany, France, Netherlands, Belgium, Luxembourg, Liechtenstein, Switzerland, Austria. N=15,624. * $p<0.05$, ** $p<0.01$

Table A3: Estimation using 2°C temperature categories above 20°C

Daily mean temperature (°C)	(1) 9 months from exposure	(2) 10 months from exposure
≤−5°C	0.0001 (0.0002)	−0.0003 (0.0003)
−5-0°C	0.0002 (0.0002)	−0.0002 (0.0001)
0-5°C	0.0003 (0.0002)	0.0003 (0.0002)
5-10°C	ref. cat.	ref. cat.
10-15°C	−0.0005** (0.0002)	−0.0002 (0.0002)
15-20°C	−0.0016** (0.0003)	−0.0008** (0.0002)
20-22°C	−0.0030** (0.0006)	−0.0012* (0.0006)
22-24°C	−0.0015 (0.0009)	−0.0004 (0.0012)
24-26°C	−0.0058** (0.0015)	−0.0038* (0.0016)
26-28°C	−0.0063** (0.0021)	−0.0035 (0.0019)
>28°C	−0.0070** (0.0019)	−0.0056** (0.0018)

Notes: Dependent variable: log birth rate. The model includes lags 0-25 but only lags 9 and 10 are shown (see Eq. 1). The model has country-by-year, country-by-month, and year-by-month fixed effects and country-by-month-specific quadratic time trends. Precipitation and relative humidity are controlled for. The regressions are weighted by the countries' female population at the beginning of the year. Standard errors are clustered by country. N=15,624. * $p<0.05$, ** $p<0.01$