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ORIGINAL PAPER

The effect of temperature on birth rates in Europe

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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 might be expected only in the long run.

Keywords Birth rates · Health at birth · Fertility · Temperature · Climate change · Europe

Introduction

There is growing evidence that human fertility and fetal development are considerably affected by heat exposure (Hajdu & 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 & 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 & Schaller, 2020; Chen et al., 2020; Deschênes et al., 2009; Grace et al., 2015; Hajdu & 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 & Schuppe, 2007; Kumar & Singh, 2022; Zhang et al., 2015), and related to

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this, a recent study reported that pre-conception heat stress results in less conception (Hajdu & 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, most previous studies concentrate on the United States (Barreca et al., 2018; Lam & Miron, 1996; Seiver, 1989). No analysis has yet been carried out for the European continent as a whole. Second, 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. Although the paper of Barreca et al. (2018) examined the changes over time, it was not possible to examine the most recent decade. Third, no previous study has examined the moderating role of humidity,[3] even though humidity is an important factor contributing to the thermal stress that people experience (Budd, 2008; Raymond et al., 2020). At 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. Fourth, the effects of heat waves are rarely examined (an important exception is Barreca et al. (2018)), 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 & Lewis, 2020; Rousi et al., 2022; Russo et al., 2017).

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[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. Seiver (1989) also restricts his analysis to effects nine months later.

[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.

[3] Although the paper of Barreca et al. (2018) examines the effect of humidity itself, they do not address the role of humidity in modifying the effect of temperature.

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 may 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 in Europe.

The rest of the paper proceeds as follows. "Data" describes the data used in the analysis. "Methods" outlines the empirical model. "Results" presents the results. "Conclusions" discusses the findings and concludes.

Data

Births at the country-month level come from 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 (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 (without weighting). 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.

Methods

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

$$\begin{aligned}\mathrm{ln}\left(\mathrm{B}_{\mathrm{ct}}\right) = {} & \sum\nolimits_{\mathrm{j}}\sum\nolimits_{\mathrm{b}=0}^{25}\beta_{\mathrm{b}}^{\mathrm{j}}\mathrm{T}_{\mathrm{c,t-b}}^{\mathrm{j}} + \sum\nolimits_{\mathrm{k}}\sum\nolimits_{\mathrm{b}=0}^{25}\gamma_{\mathrm{b}}^{\mathrm{k}}\mathrm{P}_{\mathrm{c,t-b}}^{\mathrm{k}} \\ & + \sum\nolimits_{1}\sum\nolimits_{\mathrm{b}=0}^{25}\delta_{\mathrm{b}}^{1}\mathrm{H}_{\mathrm{c,t-b}}^{1} + \rho_{\mathrm{cy}} + \theta_{\mathrm{cm}} + \tau_{\mathrm{ym}} \\ & + \pi'_{\mathrm{cm}} \times \mathrm{t} + \pi''_{\mathrm{cm}} \times \mathrm{t}^{2} + \varepsilon_{\mathrm{ct}}\end{aligned} \tag{1}$$

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%).

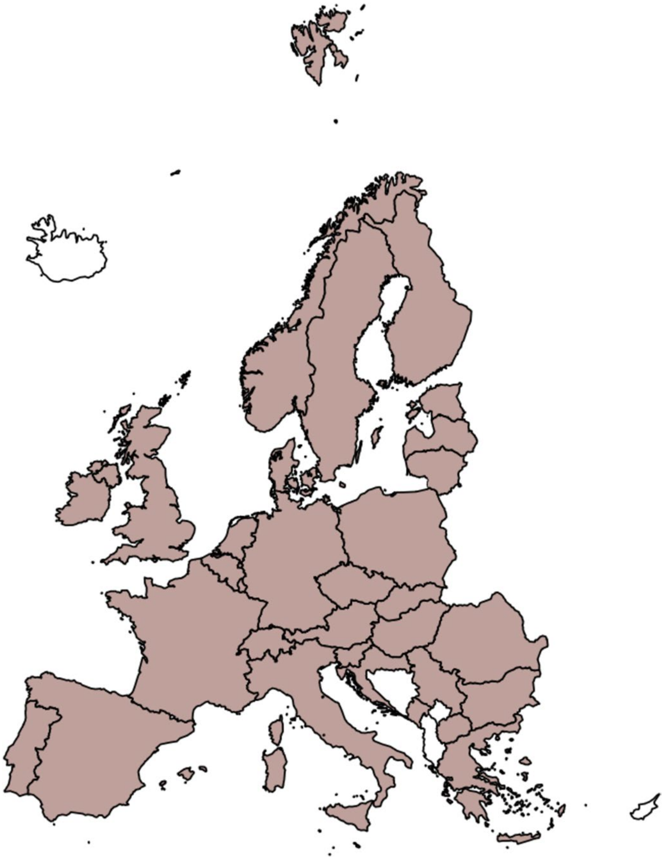

Fig. 1 Spatial coverage of the sample. Notes: Countries marked in color are included in the study: Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom

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 ($b = 0, 1, \ldots, 25$). That is, the set of coefficients $\beta_0, \beta_1, \ldots, \beta_{25}$ 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

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

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

country-by-month-specific quadratic time trends (π).[4] 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 country.

Results

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. Sexual activity may also be reduced by heat. However, it seems that seasonal activity does not decrease during the summer months, but rather is more strongly influenced by holidays and cultural/

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[4] The variable t is a discrete variable denoting time (year-month).

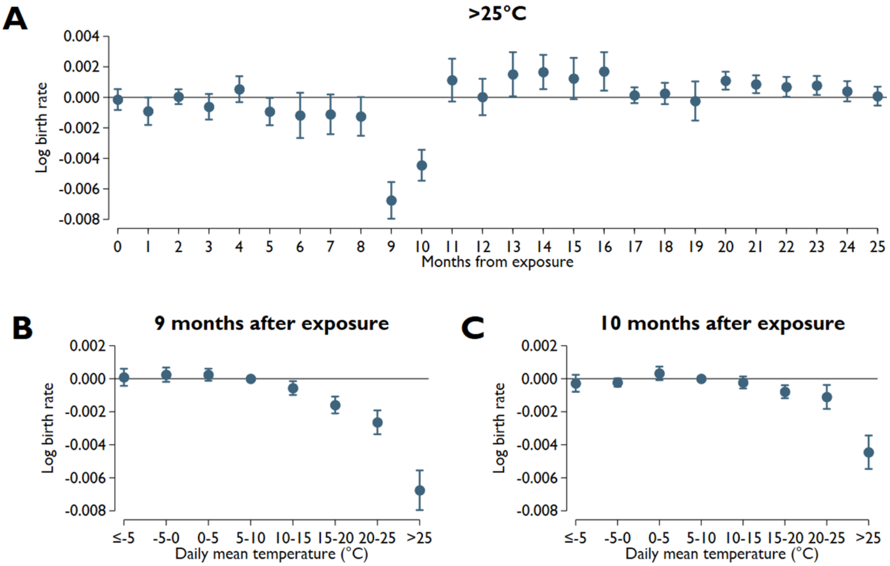

Fig. 2 The effect of temperatures on birth rates. Notes: The error bars represent 95% confidence intervals. The effects are compared to a day with a mean temperature of 5–10 °C. The model has country-by-year, country-by-month, and year-by-month fixed effects and country-by-month-specific quadratic time 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

religious celebrations (Markey & Markey, 2013; Udry & Morris, 1967; Wellings et al., 1999; Wood et al., 2017). The relationship between temperature and sexual activity has rarely been examined, and the results of the few existing studies are inconclusive (Hajdu & Hajdu, 2019; Wilde et al., 2017).

The negative effects on birth rates in the earlier months (months 5–8) may indicate that hot temperatures in early pregnancy increase the chance of fetal loss.[5] However, it is also possible that some babies who would have been premature may not be born because of exposure to high temperatures before conception. These effects are also most likely to be reflected in birth rates seven to eight months after exposure to heat. However, the proportion of very preterm infants in European countries is low (about 1% or less), so this factor is unlikely to play a role in the effects measured in the fifth to sixth month after exposure, and even in the seventh month may be of at most moderate importance.

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. These positive

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[5] 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.

effects are most likely due to the “replacement” of missed births (either due to a lack of conception or an increase in pregnancy losses). In other words, exposure to hot temperatures changes the timing of some live births, i.e. they do not completely lost, but are delayed by a few weeks/months. 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).

It should also be kept in mind that these coefficients summarize the combined effect of several factors. The duration of pregnancy is not uniformly nine months, which may affect the timing of the effects. If, for example, a fetus that would otherwise have been born premature (at 8 months) does not conceive as a result of the heat, but another pregnancy begins in the following weeks as a result, we see that the number of births decreases in month 8 after the heat, but the number of newborns increases in month 9. In contrast, delaying a normal-length pregnancy due to heat reduces the number of births 9 months later. Exposure to heat may also have a prolonged effect on reproductive health in some cases, reducing the number of births 10–11 months after exposure. However, in other cases, failure to conceive increases the number of couples who want to have children in the following months, thus increasing the number of pregnancies that start successfully and, at the same time, the number of births 10–11 months after exposure to heat. In the lack of suitable data, these and similar mechanisms cannot be examined separately, but their combined effect is reflected in the coefficients for the different months.

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 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 & Schaller, 2020; Hajdu & 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), and even in previous papers on the relationship between temperature and births (Barreca et al., 2018; Conte Keivabu et al., 2023).

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[6] 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%.[7] 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.

The conclusions remain valid even if the maximum (Fig. A6, Supplementary Materials) or minimum temperature (Fig. A7, Supplementary Materials) is used.

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 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 somewhat 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. However, the difference only reached statistical significance in the second case ($p = 0.53$ and $p = 0.03$). In sum, these effects suggest that the damage from climate change may be more severe than a simple increase in the number of hot days would imply.[8]

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[6] 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.

[7] $e^{-0.0068\times30} - 1 = -0.185$

[8] For alternative definitions of heatwave days, the results are shown in Table A4 (Supplementary Materials).

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)

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%. This means that the effect of high-humidity hot days is 0.35 percentage points (p = 0.01) and 0.22 percentage points (p = 0.09) stronger in these months. It is also worth pointing out that in months 5–8 following the temperature shock, only high-humidity hot

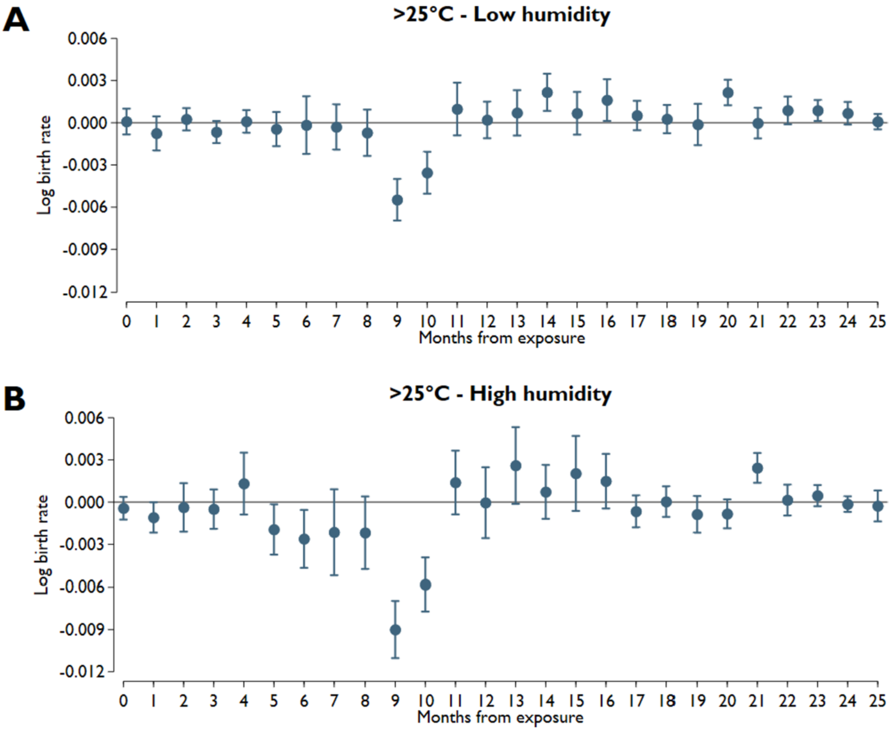

Fig. 3 The effect of heat in low humidity and high humidity conditions. Notes: The error bars represent 95% confidence intervals. The effects are compared to a day with a mean temperature of 5–10 °C. The model has country-by-year, country-by-month, and year-by-month fixed effects and country-by-month-specific 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

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.

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 annual temperature above 10 °C, while cold climate countries are defined as countries with an average annual 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

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)

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

* $p < 0.05$; ** $p < 0.01$

are somewhat smaller than previously observed, and are statistically insignificant (p = 0.40 for month 9, and p = 0.68 for month 10). However, it is worth noting that these estimates are for different periods and countries. In addition, the share of hot (> 25 °C) days is much lower in countries with cold climate than in countries with hot climate (4.5% vs. 0.3%), therefore the estimated effects have very high standard errors for the former countries.

When mild-climate countries are excluded from the analysis and warm-climate countries are defined as countries with an average annual temperature above 10.5 °C while cold-climate countries are defined as countries with an average annual temperature below 8 °C, the coefficients are more different from each other (Table A5, Supplementary Materials) and the differences are more statistically significant (p = 0.32 for month 9, and p = 0.01 for month 10).

Finally, potential adaptation over time is explored. In this exercise, each weather variable is 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 the sixteen countries for which birth rates are available for each year between 1969 and 2021.

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)

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. 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

$^{*}\ p<0.05$; $^{**}\ p<0.01$

The results for months 9 and 10 are shown in Table 4.[9] Unlike the paper by Barreca et al. (2018), this study finds no evidence for a decrease in effect sizes over time.[10] Although the two studies cover different periods—Barreca et al. (2018) cover the years 1931–2010, while the present study covers the period 1969–2021—even for the overlapping years, the estimated change in effect size differs between the two studies. Several factors may contribute to the stability of 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 on days above 25 °C and

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[9] The differences between 1969–1999 and 2000–2021 are not statistically significant (p = 0.45 for month 9 and p = 0.40 for month 10).

[10] A similar conclusion emerged even when the change over time is examined by decade (Fig. A8, Supplementary Materials). However, the uncertainty of the estimates is quite high in this specification.

the number of heatwave days, 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. It is beyond the scope of this study to explore the reasons why the change in the effect of hot temperatures differs between Europe and the US. However, it is worth mentioning some facts that may be among the possible reasons. Europe is one of the fastest-warming continents (World Meteorological Organization, 2023). This means that the average temperature of the days in the highest temperature category may have increased more in the last decades than in the US, leading to a stronger heat effect. Besides, the average age at which women give birth increased larger in most European countries than in the US.[11] If older women are more sensitive to heat, this change may partly explain the different trends over time. Temporal variations in air conditioning can also affect the difference between Europe and the US. If there was less growth in air conditioning penetration in European countries during this period (either because of higher initial penetration or for other reasons), we might expect smaller changes due to this factor.

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 suggests that high temperatures in the first few months of pregnancy may be associated with an increased risk of miscarriage, but without proper data, the effect of other mechanisms cannot be ruled out. 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 somewhat 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

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[11] see: https://www.oecd.org/els/soc/SF_2_3_Age_mothers_childbirth.pdf

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 suggest that, although temperature is not the most important determinant of birth rates, climate change may have a negative impact on the number of live births in Europe in the twenty-first century (if the historically observed relationship between temperature and birth rate remains unchanged in the near future). Especially women (and their partners) who are nearing the end of their reproductive life may be affected. In their case, “making up” for missed births due to the heat may be more difficult.

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.

Finally, some limitations of this study should be mentioned. First, the data used in this paper do not allow the identification and understanding of the mechanisms by which temperature affects birth rates. Although the timing of the effects suggests what the main mechanisms may be, it is not possible to test these directly. Second, live birth data do not include the length of pregnancy. Therefore, it is also not possible to analyze how the number of children born at term or preterm is affected by temperature and whether the temporal dynamics of these effects differ. Third, regional data would be useful to better understand the relationship between the number of births and temperature, as there may be non-negligible temperature differences within larger countries. Although these temperature differences have been taken into account, the use of regional data could increase the precision of the estimates. Finally, knowing the social background of the children born would also be necessary to investigate the heterogeneity of temperature effects. For example, women with high and low educational attainment may have different opportunities to protect themselves from the effects of hot temperatures, and these differences may be reflected in the temperature effects on their birth rates. This study could only estimate the average effects for the whole population.

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Data availability All data sources are publicly available and directly downloadable from the sources indicated in the Data section.

Declarations

Conflict of interests The author declares no competing interests.

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