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► **To cite this version:**

| Sophia Noel, Angela Greulich. The Effect of Heat on Fertility in France. 2025. hal-04904750

HAL Id: hal-04904750

<https://sciencespo.hal.science/hal-04904750v1>

Preprint submitted on 23 Jan 2025

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SciencesPo

CENTRE FOR RESEARCH ON
SOCIAL INEQUALITIES



n° 2025-1
January 2025

The Effect of Heat on Fertility in France

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Introduction

The accelerating pace of climate change has prompted concern regarding how climate hazards may affect population dynamics. Of all climate hazards, none is more deadly or ubiquitous than heat waves. The Intergovernmental Panel on Climate Change (IPCC) states that globally, heat waves are becoming more frequent and severe because of climate change (Intergovernmental Panel on Climate Change, 2023). Consequently, heat is forecasted to cause the largest share of the climate change death toll in coming decades (World Health Organization, 2014).

While the link between extreme heat and mortality and migration is well documented (Hunter and Simon, 2021), much less is known regarding the link between extreme heat and fertility, even though this link is also a key component in measuring the demographic implications of extreme heat. Barreca et al. (2018) make a key contribution to this field by measuring the effect of extreme heat on fertility rates in the US using a fixed-effects model that has since become standard in the literature. Similar research designs have confirmed this finding in other country contexts, including South Korea (Cho, 2020), Hungary (Hajdu and Hajdu, 2022), Brazil (Marteleto et al., 2023), the European continent (Hajdu, 2024) and Spain (Conte Keivabu et al., 2024). To our knowledge, no study has quantified the effect of heat on fertility rates in France using a similar methodology. We not only seek to fill this empirical gap, but also use France as an example to investigate in how far the estimated heat/fertility relationship depends on methodology, time, general climate regime, humidity and air pollution.

France represents a worthwhile case study within this literature because of its diverse and high-quality data on climate and on fertility at the sub-national and sub-annual level. Studying the French case may thus contribute to several active debates in this literature. First, France hosts a variety of the climates found in the European continent within a unified national context. This allows for some discussion for how adaptive behaviors at the subnational level may affect the heat/fertility relationship. Second, like Spain, air conditioning (AC) penetration rates have remained relatively low in France compared to the

US (ADEME, 2021; IEA, 2018). This permits us to contribute to an active debate in this literature on the potential role of AC and of other adaptation strategies in mitigating the link between heat and fertility. Third, the data for both meteorological and fertility data in France is available over extended time periods (from 1975 on). Therefore, our window of analysis is wider than is typically found in this literature, permitting a discussion on the temporal evolution of the relationship between heat and fertility. Comparable country specific analyses include the time period 2010-2018 (Conte Keivabu et al. 2024 on Spain), 2009-2013 (Cho 2020 on Korea) or 1980-2015 (Hajdu and Hajdu on Hungary). Barreca et al. (2018) offer a long time period (1931-2010), but here we are able to include the most recent decade of 2010-2020.

We are also able to employ humidity data of similar quality to our temperature data to explore the role of humidity within the heat and fertility association. Availability of meteorological data across several variables is not uniform across the existing literature. For example, Barreca et al. (2018) note in the case of the US that while fertility and temperature data is of high quality, the requisite humidity data is not sufficient to include it within their core analysis. In addition, we make use of detailed historical air quality data available on France (Real et al. 2022) to explore the interaction between heat and air pollution. While heat and air pollution both pose risks to reproductive health in men and women, and are often cultivated by the same atmospheric conditions, the heat/fertility literature has rarely explored the role of air pollution (notable exceptions include Conte Keivabu et al. 2024 who include particulate matter as a control variable).

We document that the French case aligns with existing research in observing a negative effect of heat on fertility rates nine to ten months after the heat shock. Overall, that this finding remains stable across different measures within and across country contexts means that this literature is coalescing around the negative effect of heat on fertility as a stylized fact. Even if the estimated effect within each country is small, its combined effect across both high- and low-income countries threatens to grow as a function of the increasing pace of global climate change.

Literature Review

In recent decades demographic inquiry has taken an increased interest on the interaction between populations and their environment. Research on the effect of heat shocks on demographic outcomes initially focused on its effects on morbidity, mortality, and migration. This research has established a wealth of evidence linking heat shocks to morbidity and mortality, and that risks and vulnerabilities are heterogeneous across and within countries according to gender, socioeconomic status, education and other social variables (Muttarak, 2021). Very recent years have seen the emergence of demographic inquiry on the effects of climate shocks on fertility. For example, a review of environmental demography by Hunter and Simon (2021) includes a section on migration and mortality, but not fertility. A more recent review of environmental demography by Hoffman et al. (2024) includes a summary on climate and fertility.

Regarding research on the specific climate shock of extreme heat on fertility, there are a few persistent findings. First, there is a statistically significant, negative relationship between heat shocks and fertility rates. Second, the short term rebound in fertility following this negative shock does not have sufficient magnitude to compensate completely for this decline in fertility rates. Third, the decline in fertility rates is most observable at a 9-to-10-month lag from the observation of a given heat shock.

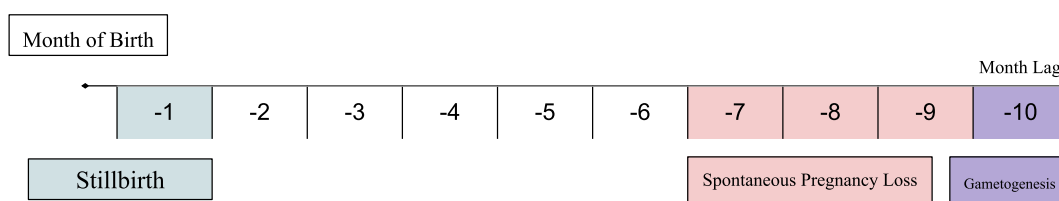
There are three direct physiological avenues through which fertility may be negatively affected by heat. First, there is evidence that heat has a negative effect on sperm quality. There is some emerging evidence that heat exposure interrupts female gametogenesis (e.g. Kulkarni and Kulkarni 2023) though since research on the effect of heat on female gametogenesis is less advanced than male gametogenesis (spermatogenesis) the heat/fertility literature is concentrated

on the disruption of male gametogenesis. Second, extreme heat may increase risk of spontaneous abortion for women in the first trimester of pregnancy. Third, there is substantial evidence that extreme heat exposure in the week before delivery increases the risk of stillbirth (Kanner, 2020. McElroy, 2022). Therefore, there are several months, lagged from birth, where heat may affect fertility rates. We therefore consider an extensive set of lags (-3, 20) in our estimation. The timing of these effects is illustrated in Figure 1.

Since previous demographic research has consistently observed a statistically significant effect at 9 and 10 months, disrupted gametogenesis and consequent decrease in likelihood in conception has emerged as the leading mechanism hypothesis explaining the link between heat and fertility (Lam and Miron 1996, Barreca et al. 2018, Régnier-Loilier 2010). It is also possible that extreme heat decreases sexual activity. The spermatogenesis mechanism hypothesis, however, is more in favor in the heat/fertility literature for the following reasons. First, though there are few studies that directly focus on the effect of heat on sexual behavior, those who have do not find a firm relationship between the two (T. Hajdu and G. Hajdu 2019; Wilde, Apouey, and Jung 2017). Second, that the effect is visible at both a nine and a ten month lag across the recent heat/fertility literature lends support to a biological, rather than behavioral response to extreme heat.

Moving from mechanisms to methodologies, Barreca et al. (2018) was one of the first demographic works to systematically explore the link between heat and fertility. Notable predecessors include the Lam and Miron (1991; 1996), Lam et al. (1994) and Seiver (1985; 1989), analyzing the case of the US. Barreca et al. make several important improvements compared to this early work. These prior studies apply their estimation strategy to each state separately and pres-

Figure 1: Extreme Heat and Individual Health Mechanisms By Months Preceding Birth Month



cribe either linear or quadratic functional forms on the relationship between heat and fertility. To address these weaknesses, Barreca et al. employ an estimation technique that divides daily temperature into bins, which permits for the possibility of a nonlinear effect shape. This work also tests larger series of lags than these previous studies to observe the possibility of a short term catch-up in births following the negative shock from extreme heat. Furthermore, Barreca et al. propose a series of fixed effects to account for underlying trends in fertility and weather that have since become standard in current literature. With this methodology, Barreca et al. find that the negative effects of heat on fertility observed at an individual level by the medical literature is visible at population level in the US.

Since then, similar studies have confirmed these findings in South Korea (Cho 2020), Hungary (I. Hajdu and G. Hajdu 2022), Brazil (Marteletto, Maia, and Rodrigues 2023), and Spain (Conte Keivabu et al. 2024). Similar studies focused on developing countries have approached similar findings, though due to data constraints in national registry data, the estimation techniques differ somewhat from the studies listed above (Grace 2017; Geruso, LoPalo, and Spears 2021; Gray and Thiede 2024).

Regarding the French case, the only article to our knowledge considering the effect of heat on fertility in France is the work of Régnier-Loilier (2010). Régnier-Loilier discusses the effect of heat waves on fertility rates in France within an article on birth seasonality. Régnier-Loilier uses an epidemiological approach, calculating the effect of heat waves on this birth deficit by comparing the anomaly month with the same month in surrounding years. He estimates a 5 to 6 percent decline in fertility rates at the national level following heat waves by comparing heat wave affected years with their surrounding years. We build upon this work by employing the fixed-effects approach that has emerged since the publishing of Régnier-Loilier's work to more comprehensively consider spatial and temporal confounders. Furthermore, the estimation technique used in this work, by the inclusion of a large series of lags permits a more substantial discussion of biological mechanisms and catch-up effects than is the case in earlier methods.

Addressing this empirical gap, we find that within the French context, for fertility rates between 1975-2020, extreme heat is associated with a decline in fertility rates 9 to 10 months later. Contrary to other country contexts, however, we observe no statistically significant rebound effect in the following months. Furthermore, we verify that these findings are consistent across several different operationalizations of extreme heat found in current literature. There are several open questions in this stream of research. First, this body of literature does not have a standard measure of a "hot" day. For example, Barreca et al. (2018) defines days with a mean temperature of 80°F (27°C) as "very hot", and Hajdu and Hajdu (2022) consider "hot" days when the mean temperature is over 25°C (77°F). Marteletto et al. (2023) classifies extreme heat relative to a historical benchmark of a 30-year monthly mean prior to the window of study for each region. We compare the outcomes of several different operationalizations concerning the same data: temperature bins, a monthly historical benchmark, the effects of consecutive hot days, and a polynomial spline. Our core findings remain stable across these specifications.

We also test our findings in light of other relevant variables such as humidity and air pollution. Demographic literature analyzing the relationship between heat and mortality has established that humidity has an antagonizing effect on observed adverse health effects due to heat (Barreca, 2012). Yet, the heat and fertility literature has not yet uniformly included humidity within its framework of analysis. Important contributions in this regard were made by Barreca et al. (2018), who includes humidity only in robustness checks due to differences in data quality between humidity and temperature, but nevertheless established humidity as a variable of interest within the heat/fertility literature. Recent work by Hajdu (2024) featuring the entire European continent has gone the farthest in integrating the role of humidity within the heat/fertility relationship.

Similarly, heat/mortality literature has found an antagonizing effect regarding the role of air pollution. Nevertheless, the interaction between heat and air pollution in the demographic literature on heat and fertility has been understudied. Notable exceptions include Conte Keivabu et al. (2024) who include PM

2.5 as a control. Since there is substantial evidence that elevated levels of air pollution such as PM 2.5, O₃, and NO₂ disrupts fertility in both men and women (cf. systematic reviews by Kumar and Singh, 2022 on male fertility and Conforti et al. 2018 on female fertility), we test here the effects of O₃ (ozone), given substantial medical research that exposure to elevated ozone levels has adverse effects to reproductive health in both men and women (Kumar and Singh, 2022; Lu et al. 2023; Ekland et al. 2017; Mendola et al. 2017; Tong et al, 2023; Carré et al. 2017).

Overall, we find that the effect of heat on fertility in France is both observable, permanent, and consistent across a variety of methodologies. This, combined with the fact that the number of extreme heat days per year has been significantly increasing over the last decades, suggests that extreme heat is a factor that should not be neglected in the long-run age structure in countries across Western Europe. This finding has increased relevance in a wider context of falling birthrates and related population aging across Europe, as well as warnings from the IPCC concerning frequent and severe heat waves globally in the near future.

Data and Methods

Fertility Data

Typically, TFR is provided on a national and annual basis, which naturally aggregates the seasonal fluctuations in fertility behavior. Consequently, data on Total Fertility Rates (TFR) on both a monthly and sub-national level is not commonly available in the European context. This data limitation means that literature on seasonal fluctuations in fertility has been confined to a handful of studies. In France, such research has been conducted only by researchers with access to INSEE data needed to calculate more granular TFR measures themselves (e.g. Regnier-Loilier 2010).

Based on data from INSEE that was requested in July 2023, we calculate TFR by month and region in the following way. For every region at each month of the analysis, the calculation is based on three measures: the monthly number of live births (defined by place of residence of the mother), the number of resident

women aged 15-49, and the number of days in the month. That number of women and number of births is both based on residence of the mother ensures continuity over these measures, and controls for short-term migration of women at the moment of delivery, though inter-regional migration a few years before or after birth is not captured here.

The first step includes dividing the number of women aged 15-49 by 35, in order to obtain the average number of women for each age within the range of 15 and 49 years old. We do not have data on the exact number of women at each age between 15-49, and only the total number within this age range. The second step is to take the average number of live births per day, and divide this, by the average number of women for each age within the range of 15 and 49 years old found in step one. This is then multiplied by 365.25 to obtain the monthly TFR. This considers the 28th of February every 4 years.

Note that this measure of fertility for each region and month so far does not account for differences in age structure between regions regarding the population of women aged 15-49. This is problematic as higher fertility observed in densely populated regions with high demographic dynamics, such as Île-de-France (Paris and the region around Paris) for example, may be caused by a higher number of women of childbearing age compared to more rural regions, rather than a substantively different fertility behavior. Even if this data still permits measurement of variation within regions under a fixed-effects methodology, we apply a post-stratification procedure to eliminate the bias caused by differences in the age structure between regions. To do so, we harmonize our monthly fertility measures by region with the annual TFR by region published by INSEE. We do so by linearly extrapolating the 12-month average of the monthly TFR to equal the annual TFR for a given region. As the annual TFR is the sum of age-specific fertility rates and is therefore not biased by the age structure, this extrapolation allows controlling for the age structure of the population of each region. Our final monthly TFR by region figures measures are therefore not only valid measures to distinguish fertility shocks lagged from extreme heat from the overarching time trends and seasonality of fertility rates within a given region, but they are also comparable between regions.

Our dataset contains monthly TFR for 22 French regions, covering the years 1975 to 2020. We exclude French overseas departments to preserve the consistency of the meteorological data source, which covers only continental Europe. Conducting this analysis at the regional level also carries the advantage of mitigating at least some bias due to mobility. In other words, overly granular spatial units could disconnect the locations at which individuals experience a heat shock (both residential and occupational settings) and the location where the birth is recorded.

Meteorological Data

Daily meteorological data for 1975-2020 is derived from the E-OBS daily gridded meteorological database distributed by the EU Copernicus Climate Data Store and compiled by Cornes et al. (2018). The use of this dataset is standard among both climatologists and social scientists in the European context. From this database we collect daily mean temperature, daily precipitation and daily relative humidity for

the entire period of study. We consider daily mean temperature to account for both the daytime high temperature and nighttime low temperature, which act in tandem upon various health risks. Across the window of analysis, around half the days in an average month have a mean daily temperature between 5-15°C. Daily mean temperatures surpassing 25°C only 0.2 days out of an average month, though such temperatures become more frequent over time. This information is collected through a rich network of in-situ weather stations and daily means are interpolated to display the data in the form of 0.1-degree cells.

The location of all the weather stations included in this dataset are illustrated in Figure 2.

This refined dataset contains meteorological data averaged to the regional level, facilitating the exposition of subnational heterogeneities in findings.

Figure 2: Copernicus Weather Stations in France

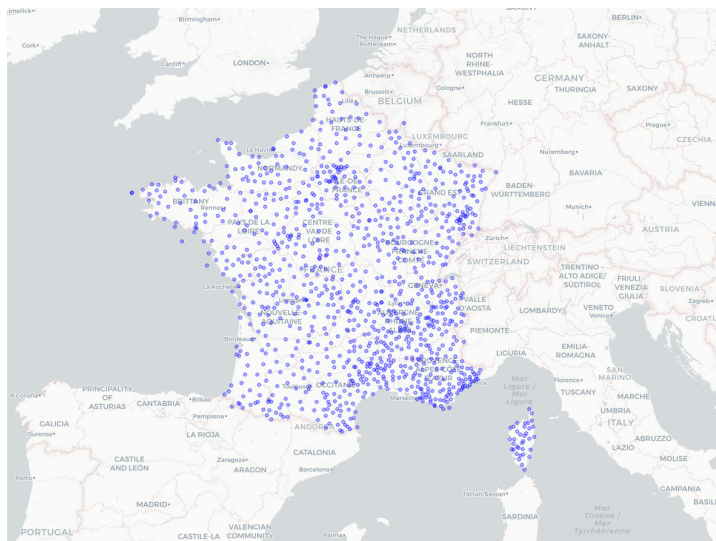
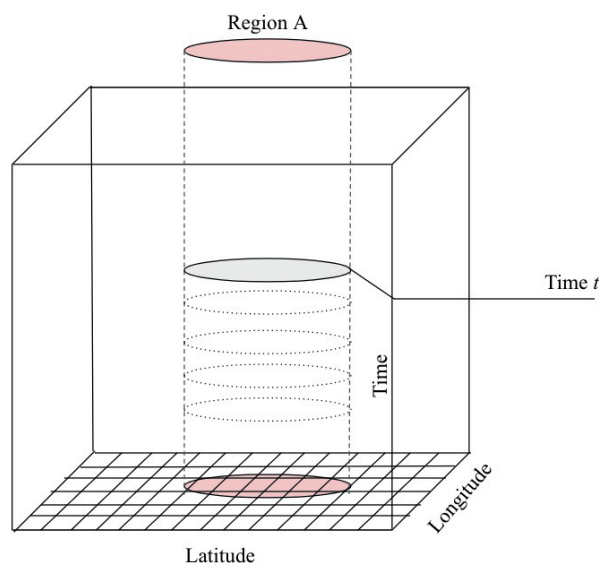


Figure 3: Copernicus Data Structure



Estimation Technique

We employ a fixed effects model estimated via OLS specified as:

$$Y_{rt} = \sum_j^J \cdot \sum_k^K \beta T_{r,t-k}^j + \sum_k^K \gamma_k P_{r,t-k} + \sum_k^K \chi_k H_{r,t-k} + \alpha_{rm} + \delta_t + \theta_{ry} + \left(\Pi_{rm}^1 \times t \right) + \left(\Pi_{rm}^2 \times t^2 \right) + \epsilon_{rt}$$

Our dependent variable of interest is TFR, (Y) by region (r) at unique month-year (t). We perform a log transformation on this variable allowing us to capture relative rather than absolute changes. Our independent variable of interest is extreme heat. The norm in this literature is to sort daily mean temperature into a series of bins, effectively transforming temperature from a continuous to a categorical variable, to facilitate interpretation on the hot days compared to other intervals (Dell, Jones and Olken 2014; Barreca, Deschenes and Guldi 2018; Hajdu and Hajdu 2022; Cho 2020; Conte Keivabu, Cozzani and Wilde 2023; Hajdu 2024). Therefore, we divide daily mean temperature into a series of bins in degrees Celsius, are as follows: <0 , $[0,5)$, $[5,10)$, $[10,15)$, $[15,20)$, $[20, 25)$, >25 . We take the bin of $[10,15)$ as the omitted category. This is denoted in the model by the term T , which contains J temperature bins in region (r) from months t to k . We calculate the days out of a given month and region where daily temperature falls within each bin and apply this to each region at all unique year-months.

We also control for precipitation by constructing bins for daily total precipitation and including them in the model as a control variable under the term P . Therefore, we consider daily precipitation assigned three bins: equal to 0, (0, 10), and equal or above 10 mm.

The literature on heat and mortality has firmly established the exacerbating role of humidity in the distribution of adverse health effects due to heat (Barreca, 2012). Yet, the heat and fertility literature does not uniformly include humidity within its framework of analysis. Important contributions in this regard were made by Barreca et al. (2018), who includes humidity only in robustness checks due to differences in data quality between humidity and temperature, but nevertheless established humidity as a variable of interest within the heat/fertility literature. Recent work by Hajdu (2024) featuring the entire European continent has gone the farthest in integrating the role of humidity within the heat/fertility relationship. We join this example, though modifying the intervals from the work of Hajdu to suit the climate of France.

The daily relative humidity within each region studied here over the entire window analysis has a median of 81.1 percent humidity (mean: 79.2 percent humidity). Therefore, we construct three humidity bins along the intervals of <75 , $[75-85]$, and >85 , to capture how many days in a given month were relatively low humidity, around median humidity, and relatively high humidity. These bins are featured over the entire range of lags (k), for each region and unique year-month ($H_{r,t-k}^1$). In a subsequent analysis, we consider the role of hot days with humidity above 85 % compared to the lower groupings.

We include temperature bin lags of -3 to 20 months ($k=-3...20$) to account for a dynamic relationship between temperatures across all the lag months for a given birth month. We also include three months of negative lag (or lead) as a placebo check, as temperatures observed after the month birth should not affect prior fertility rates ($k=-1,-2,-3$). The upper bound of 20 months allows for the observation of possible catch-up effects, where individuals may compensate for a failure to conceive around the heat wave period with conception in the following months.

We then add several fixed effects that aim to account for the regional and spatial dynamics in fertility to observe uniquely the effects of heat on fertility. First, region by month (α), which accounts for expected weather fluctuations or fluctuations in fertility behavior over the year in a given region. Second, year by month (δ), which controls for cycles encompassing all regions that affect fertility behavior such as the seasonality of marriage and birth month preference, which have been demonstrated to be relatively homogeneous at the national level (Régnier-Loilier 2010). This term also captures time-varying factors at the national scale that may affect fertility behavior such as economic or social changes. Third region by year (θ), to eliminate any long term, coincidental changes in temperature and population dynamics, such as declines in fertility seen in many western countries coinciding with a general rise in temperature attributed to climate change.

Furthermore, we include a region by calendar month quadratic and linear time trend (π) to account for possible convergences in seasonality across regions over time. We cluster standard errors by region (ε). This series of fixed-effects may be found elsewhere in the literature (Barreca et al. 2018; Hajdu and Hajdu 2022; Cho 2020; Conte Keivabu et al. Wilde 2024; Hajdu 2024).

Results

Descriptive Statistics

Fertility Data

We report a mean TFR over the observed time period of 1.82, though this varies both temporally by season and over the long term, and spatially.

Historically, seasonal fertility trends in France have been dictated by a peak of conceptions during the summer holidays, corresponding to a peak in birth rates in late spring through the 1980's (Leridon 1973). Through the 1990's the birth peak shifted later still into July, and in 2020 the peak in births is found between July and October (Papon 2020). Figure 4 displays the average seasonality of births by region for the window of this analysis (1975-2020). Over this window, the average seasonal peak of births may be observed around July.

Regarding long term fertility trends, At the national level, France has seen a significant fall in the total fertility rate from almost 3 children per woman in 1960 to just below 2 children in 1975. Fertility rates then gently declined to around 1.6 in the 1990's, before reversing direction and hitting a recent high of around 2 children per woman in 2010, before descending again slowly, and then sharply due to COVID (INSEE February 2024). The dramatic decrease has not ceased despite the abatement of the pandemic. This overarching trend, however, has not occurred to the same extent across different regions.

Beginning in the 19th century when reliable regional statistics were first available, the northern portion of France held fertility rates that were more elevated than the rest of France. This area, surrounding but not including Île-de-France, was commonly referred to as the “fertile crescent” of France. The difference between this “fertile crescent” and the rest of France has been decreasing since the 1960s, for similar reasons that have decreased the seasonality of births in France: a rise in living standards in rural communities and the decreasing influence of religion within these rural communities (Desplanques 2011).

In Figure 5, we aggregate monthly total fertility rates into 5 year periods within the observational window of this study. We isolate the year of 2020 as their own period so that the effects of COVID are distinct from the period of 2015-2019.

Figure 4: Seasonality of Births in France 1975-2020

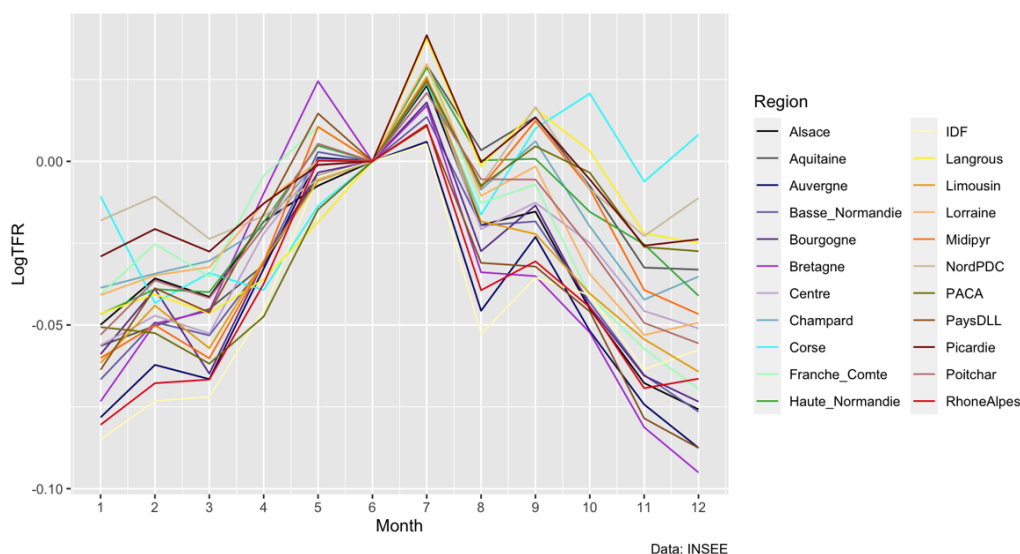
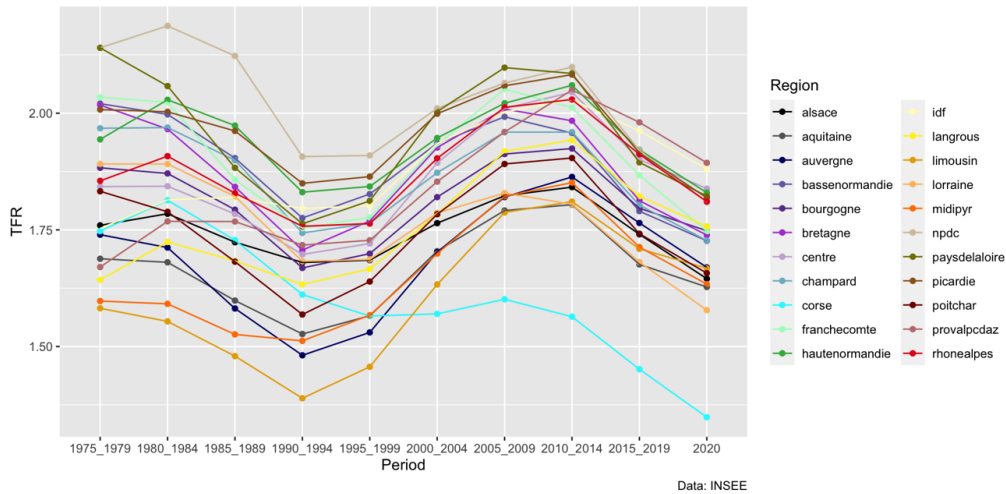


Figure 5: Fertility Rates over Time in France 1975-2020



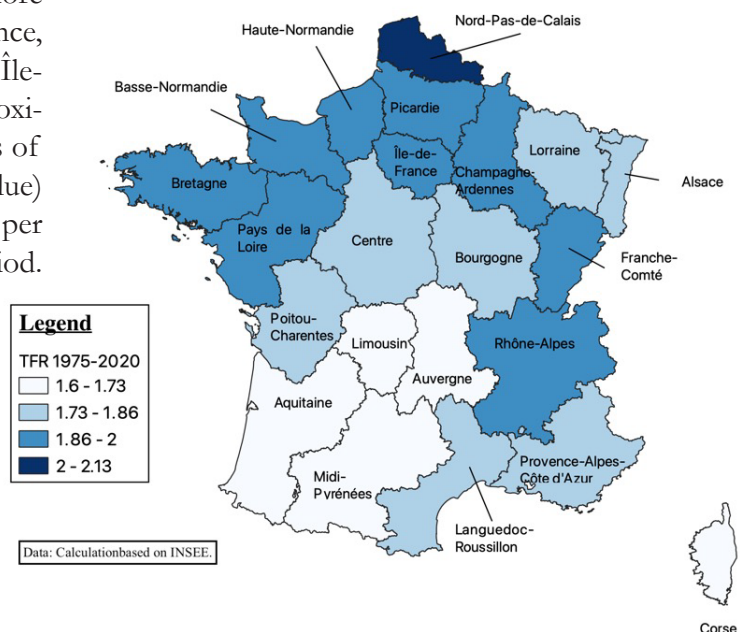
The national decrease seen in the 1970's through the 1990's was driven by comparatively large decreases in rural communes compared to urban ones. As Figure 5 illustrates, from the period of 1975-1979 to the period of 1995-1999, we observe a decrease in TFR for most regions. This is most noticeable in very rural regions such as Nord-Pas-de-Calais (tan) and Pays de la Loire (dark green), where fertility rates dropped by around 0.25 children per woman. In contrast, Île-de-France (pale yellow) during the same period remained more stable at around 1.8 children per woman.

Moving from the period of 1995-1999 until 2010-2014, most regions see a slight increase in TFR. The obvious outlier is Corse (light blue) where TFR remains stable during this period at around 1.6 children per woman. The urban-rural divide is visible during this period of TFR increase as well: several rural regions had faster TFR growth than the more stable TFR dynamic in Île-de-France. For instance, from 1995-1999 to 2010-2014, TFR increased in Île-de-France from 1.8 to 2.03: an increase of approximately 0.2 children per woman. The rural regions of Limousin (dark orange) and Auvergne (dark blue) saw increases in TFR of 0.35 and 0.33 children per woman, respectively over this same time period.

This urban-rural divide is not uniform however, as northern rural regions such as Picardie and Nord-Pas-de-Calais saw smaller increases than Île-de-France seeing an increase of 0.22 and 0.19 children per woman respectively within this specific window.

The salient point from this period of TFR increase is that even if some rural regions saw a larger increase during this time, it was not enough to compensate for the precipitous decline in rural fertility rates seen in the first decades of the window of analysis. Hence, Île-de-France's higher fertility rate compared to some other regions in France is attributable to its lack of volatility compared to other regions.

Figure 6: Regional Fertility Rates in France 1975-2020



The importance of this dynamic is visible in Figure 6. Averaged over the entire period of analysis for this work, Île-de-France has a higher TFR than some of its rural neighbors, both at the French and the European scale (Buelens 2022).

Meteorological Data

Across regions, we observe an increase in the number of warm days per year over the course of the window of analysis. In Figure 7 we display the number of days above 25°C per region per year within the meteorological data used in this analysis. In Figure 7 we see a general increase in the number of days with a mean temperature above 25°C across regions from the beginning to the end of the period of analysis. Periods of note include that of 2000-2004, in which the count of hot days from the heat wave of August 2003 are visible. Also important is the most recent period, 2015-2020, which saw a marked increase across all regions compared to the period prior.

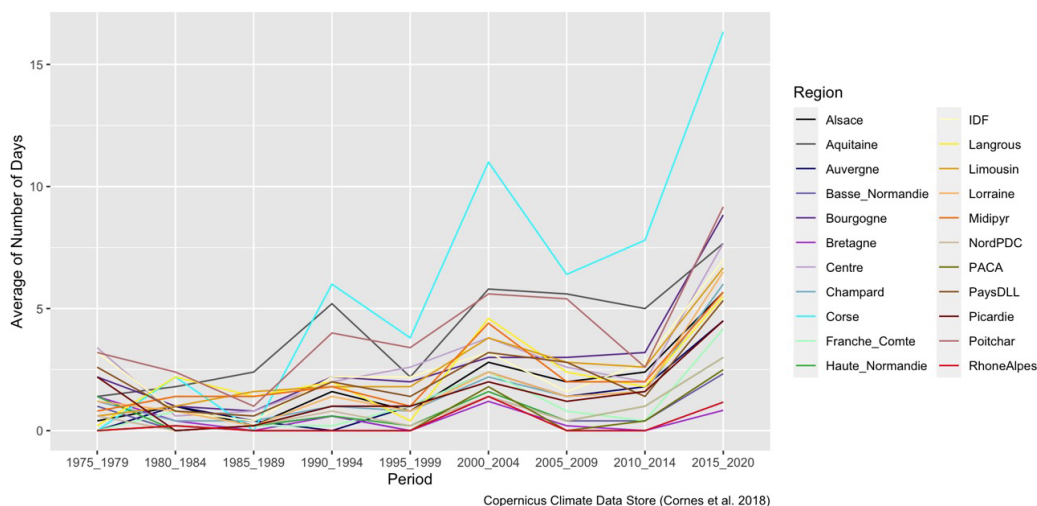
However, climate change is causing not just the random probability of an errant hot day to increase. Instead, climate change is contributing to fundamental changes in atmospheric dynamics and land/atmosphere interactions that are changing the behavior of hot weather. Hot weather is increasingly defined as the occurrence of extended, severe heat and not simply a day or two of warm temperatures.

The basic mechanism for how atmospheric dynamics contributes to especially severe heat waves is as follows. There are many currents and waves at each level

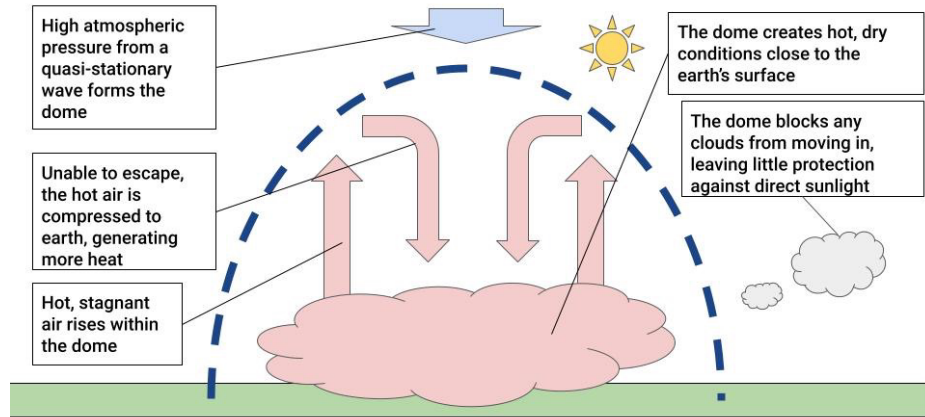
of the atmosphere that contribute to the weather we observe each day. One such phenomenon is called Rossby waves- waves in the flow of atmospheric jets in the lower levels of our atmosphere (Oxford Reference; White et al. 2022). Typically, these waves are transient. Sometimes they may become stationary (for reasons that are not perfectly defined by the scientific literature yet), with significant effects on regional meteorology. White et al. (2022) summarizes that “these quasi-stationary waves remain in approximately the same location with approximately the same phase for several days to weeks; this can lead to extreme events such as multiple days of rainfall leading to flooding, or extended heatwaves.” A key example of such an event, cited throughout the scientific literature on the subject, is the 2003 European heat wave e.g. (Petoukhov et al. 2013; Jiménez-Esteve, Kornhuber, and Domeisen 2022). The occurrence of a Rossby wave becoming a quasi-stationary wave contributes to meteorological conditions dubbed in popular media as a “heat dome” or “anti-cyclone.” Figure 8, adapted and translated from Météo-France, illustrates the effects of a heat dome.

A heat dome prompts several concurrent meteorological conditions besides high daily temperatures. These conditions include elevated nighttime temperatures, due to the persistence of hot air within the dome (Météo-France 2023). The literature on heat and mortality has consistently shown that high daytime temperatures are not a sufficient cause for a massive number of heat wave deaths. Instead, persistently elevated nighttime temperatures play a decisive role in turning a heat event into a high morbidity

Figure 7: Days Above 25C per Year by Five Year Average



**Figure 8:
Heat Dome
Mechanism**



and mortality event, because individuals do not receive a respite from the physiological effort their bodies must exert in order to compensate for the high daily temperatures e.g. (Laaidi et al. 2012). The heat dome effect also prevents cloud cover, precipitation, and wind from entering the area, all of which have cooling properties even on hot days (Météo -France 2023). The lack ventilation within the heat dome also means air pollution is trapped within the system, which in some cases may exacerbate poor health outcomes associated with heat, as has been found regarding sperm production (Kumar and Singh 2022). Because heat domes have several meteorological traits that pose risks for human health, Météo-France distinguishes between heat waves, meaning 3 or more days of heat in a row and one or two days of hot temperatures, labelled instead a “pic de chaleur” (Météo-France 2023).

There is some emerging evidence that the behaviors of stationary waves, as well as other planetary dynamics such as land/air feedback loops (Tuel and Eltahir 2021), are shifting due to climate change and will

consequently mean an increasing amount not only of hot days overall, but also hot days within heat dome events (White et al. 2022). According to Météo-France “No matter the scenario regarding the emission of greenhouse gasses, global warming will continue for several decades... The frequency of these events [in France] may double from now to 2050. By the end of the century, they may be much more severe and long, occurring in a period between the end of May and the beginning of October” (Météo-France September 2023).

In Figure 9 we plot the number of heat wave like days per region per year within the meteorological data used in this analysis, viewed within a period average. Following the example of the national benchmark, we count “heat wave” days as days where the mean 24 hour temperature is above 25°C, and the previous two or more days also had a mean temperature above 25°C. Since the Météo-France national benchmark for a heat wave is three days in a row of the mean temperature above 25.3°C, this figure is somewhat comparable to the national benchmark.

Figure 9: Days Above 25C With Two Previous Days Above 25 C per Year by Five Year Average

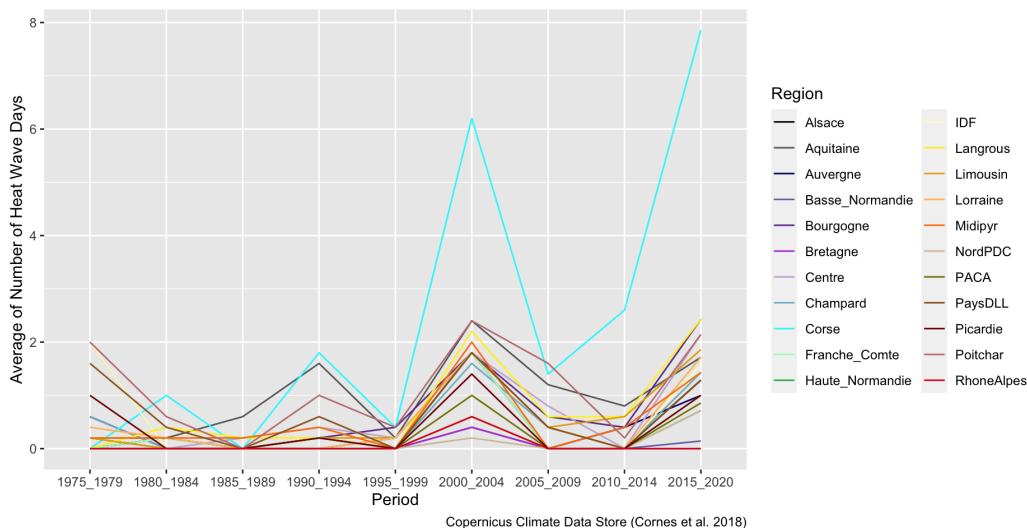


Figure 9 illustrates that for most of the window of study, the majority of regions had less than one heat wave day per year when averaged to a period, with the heat wave of 2003 existing as an anomaly across all regions. The most recent period, 2015-2020, saw a change across all regions to an average of more than one heat wave day per year as a period average.

Core Results

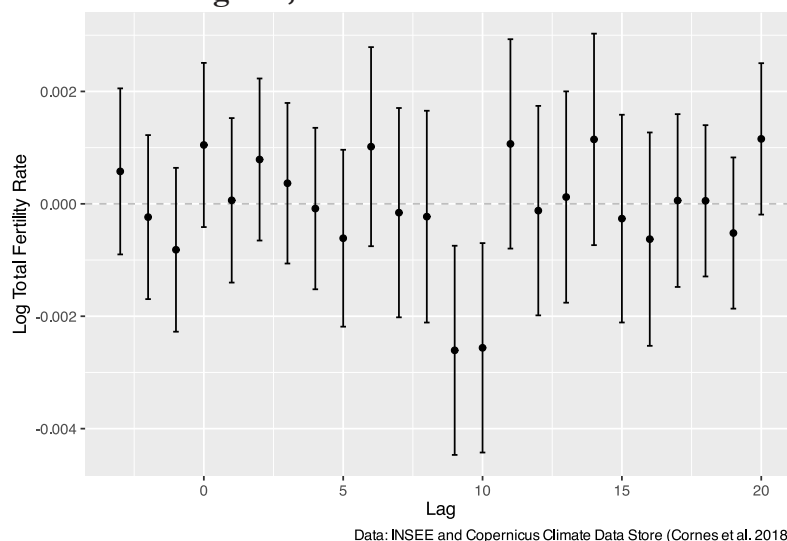
Figure 10 displays the effects of one day above 25°C compared to a day in the 10- 15°C range on log TFR across lags from -3 to +20 months. Each circle denotes the point estimate, and the brackets signify +/- 2 standard errors. Specifically, the model estimates that each day above 25°C is associated with a 0.260 and 0.256 percent decrease in fertility rates 9 and 10 months later, respectively.

That the effect is visible at both 9 and 10 months is consistent with findings in the US (Barreca et al. 2018) Spain, Europe, South Korea, Brazil and Hungary. This finding also suggests that the most visible mechanism regarding the mechanism for the heat/fertility relationship is a decrease in conception probabilities. Earlier research by Barreca et al. (2018) and Hajdu and Hajdu (2022) that is able to capitalize on weekly fertility data has pinpointed that the effect is rooted in a negative change in conception probabilities around two weeks after a heat wave. They both conclude that this small lag matches with the effect that heat has on sperm quality, as sperm exposed to heat in the earlier stages of spermatogenesis

will eventually be of lower quality at the peak of the sperm life cycle, about two weeks later. They also hypothesize that since the effect can be narrowed down to two weeks after the heat wave, a hypothesis on the role of changes in sexual behavior during the heat wave has less evidence than the spermatogenesis explanation.

Because this analysis is confined to monthly and not weekly data, we cannot definitively state if the effect seen here at 9 and 10 months comes from the spermatogenesis mechanism or a change in sexual behavior. Still, the spermatogenesis explanation appears more plausible for two reasons. First, the consistency of the mechanism seen across the literature where the data used allows a conclusion on this regard signifies that this finding is not an artifact of a particular country case. Second, that the effect seen here is of similar amplitude at both 9 and 10 months is more easily explained by the spermatogenesis mechanism than the sexual behavior mechanism. We may hypothesize, given a two week lag, that a heat wave appearing in the earliest portion of a given month would lead to a decrease in sperm quality in that same month and would therefore be observable in fertility rates within nine months. On the contrary, a heat wave appearing in the latter portion of a given month would contribute to a decrease in sperm quality in the next month due to the two week lag, and this morbidity would be observable in fertility rates nine months after this following month, for an ultimate lag of 10 months from when the heat shock was recorded.

Figure 10: Estimated Effects of One Day Above 25°C Compared to a Day of 10- 15°C on log TFR Across Lags -3 to 20. 22 French Regions, 1975-2020



Another finding is that there is no clear catch-up effect in months following the negative shock to fertility rates: that we do not observe a significant rebound in fertility rates in months afterwards suggests that the effect of fertility on birth rates may result in a permanent loss of births. Taking the sum of all statistically significant coefficients (lags 9 and 10), we estimate a net effect on TFR of -0.516 percent for each additional day above 25°C over the window of analysis. Since the mean monthly number of births in France over the window of analysis is approximately 63141 births, this net effect translates to around 325 births lost across France for each additional day above 25°C.

Figure 11 focuses on the effects of all the temperature bins at a 9-month lag. Figure 11 shows that colder days compared to the reference group do not have a significant effect on birth rates nine months later. Figure 11 also displays differences in effect regarding the two highest temperature bins. One additional day in the 20-25°C bin is associated with a 0.14 percent decline in birth rates 9 months later. In contrast, one additional day above 25°C has a larger effect, leading to a 0.26 percent decline in birth rates. That the confidence interval widens moving from the 20-25°C bin to above 25°C reflects a much smaller sample size for these hottest days.

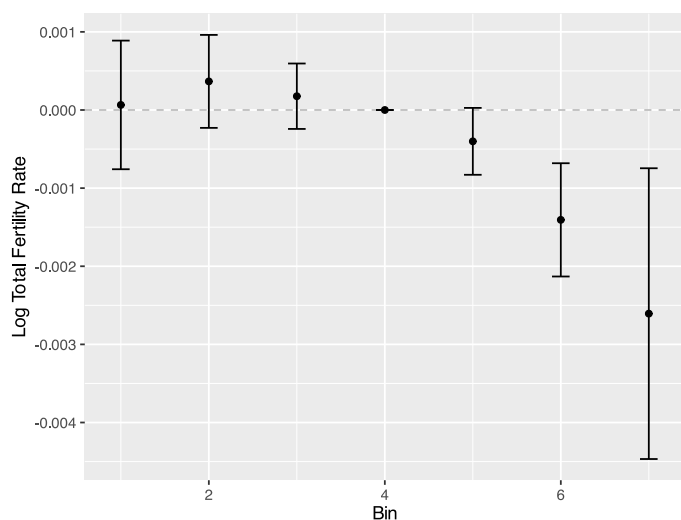
Two shortcomings of operationalizing extreme heat as a series of bins is 1) they conceive of temperature as an absolute measure rather than its relative rela-

tionship to local climates, and 2) they assume perfectly linear behavior within each bin. To address the first shortcoming, we construct a historical threshold comparing temperatures in our window of analysis to those in the prior 25 years. To explore the second shortcoming, we estimate the heat/fertility relationship using a polynomial spline. Our core findings remain stable across these different operationalizations- refer to subsequent section on alternative methodologies. These core findings are also consistent when we add weights for number of childbearing age women by region.

Results Over Time

Our observed time period is long enough to evaluate if the effect of heat on fertility has changed over time. We divide the time period into two equal portions: the first period including the years 1975-1997, and the second period including the years 1998-2020. In the case of France, we find that contrary to Hajdu's (2024) finding at the Europe level that the heat/fertility effect is stable over time, there is some temporal decrease in the size of the effect in France. For example, the coefficient for days above 25 C (bin 7) moves from -0.0042 to -0.0036 percent. Likewise, the coefficient for days between 20 and 25 C (bin 6) moves -0.0017 from -0.0012 percent.

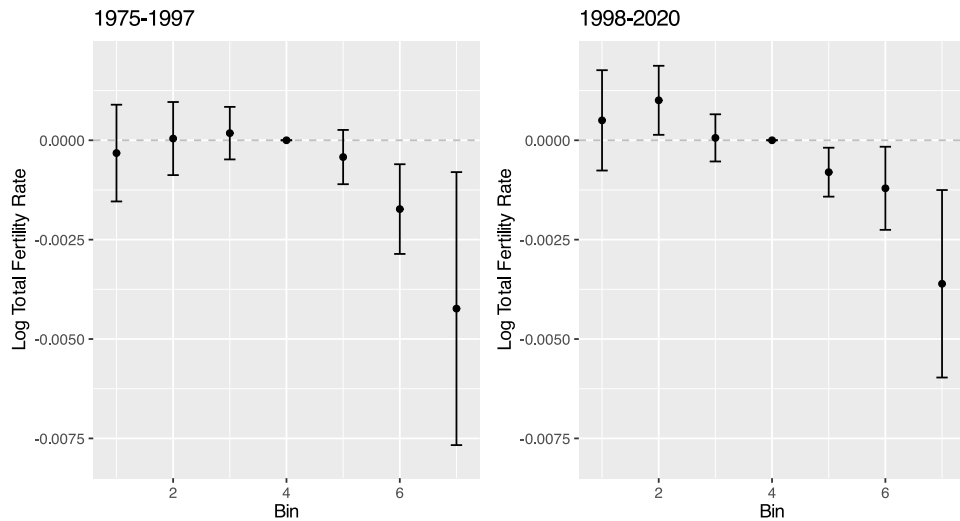
The finding is illustrated in Figure 12, which illustrates the estimated effect of all temperature bins compared to a day in the 10-15°C range on log TFR, with temperature lagged 9 months to TFR. Each circle denotes the point estimate, and the brackets signify +/- 2 standard errors.



Data: INSEE and Copernicus Climate Data Store (Cornes et al. 2018).

Figure 11: Estimated Effect of All Daily Temperature Bins Compared to a Day of 10-15°C on 9-month lagged log TFR. 22 French Regions, 1975-2020

Figure 12: Estimated Effect of All Daily Temperature Bins Compared to a Day of 10- 15°C on 9-month lagged log TFR. 22 French Regions



Data: INSEE and Copernicus Climate Data Store (Cornes et al. 2018).

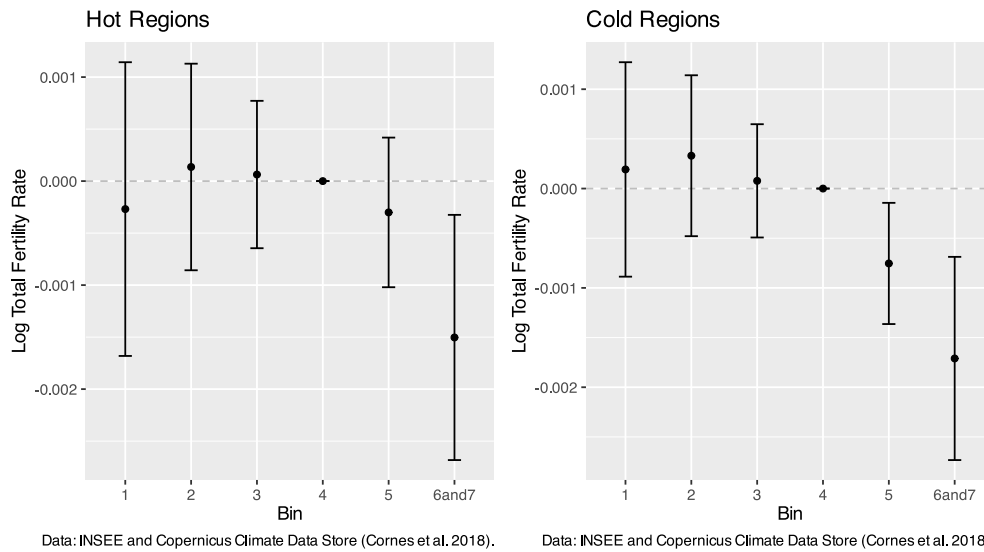
One explanation could be that France’s household air conditioning penetration rate of 25 % is higher than Europe’s overall household AC penetration rate of under 10% (ADEME 2021, pp. 27, IEA, 2018, pp. 21). It is also possible that other variables are contributing to France’s increased resilience to heat/fertility shocks over time since the severe heat wave of 2003. France has proposed some of the most ambitious heat wave resilience policies within the EU Heat wave alert systems in France include some of the most ambitious elements, as noted by Martinez et al. (2022), in a comparative review of heat health action plans in Europe, such as region-specific action plans and public outreach across a variety of channels (cf. Laaidi et al. 2012 for a review of French heat wave policy at the time period most relevant to this analysis). That these policies were not completely effective at curbing heat wave mortality does not mean we can completely rule out any latent positive effect of these heat wave alert systems at promoting resilience or popular awareness that lent resilience to heat wave fertility shocks.

Heterogeneity Across Subnational Climates

We also consider to what extent our findings vary based on typical climate regime. Previous research across country contexts has found fertility rates in historically colder parts of a given country appear to be more sensitive to heat shocks than fertility rates in warmer region due to comparative lack of adaptive infrastructures and practices (Barreca et al. 2018, Conte Keivabu et al. 2024). Overall, we reach a similar finding in the case of France.

To divide the 22 regions at hand into two equal climatic groupings, we consider the number of days in the top temperature bin (daily 24-hour mean temperature above 25° C) in each region over the entire period of study. We then find the median number of such days across these regions (89 days), and divide the observations into two groups of equal size, one containing the 11 regions that had more than 89 ”hot” days within the period of analysis, and the other containing the 11 regions that had less than 89 ”hot” days as defined here. We combine the top two temperature bins to increase sample size, allowing to obtain more consistent estimation results, especially for cooler regions where pooling by climate necessarily restricts sample size in the maximum bin of daily temperature above 25°C.

Figure 13: Estimated Effect of Temperature on 9-month lagged log TFR in Hot and Cold Regions. 22 French Regions. 1975-2020



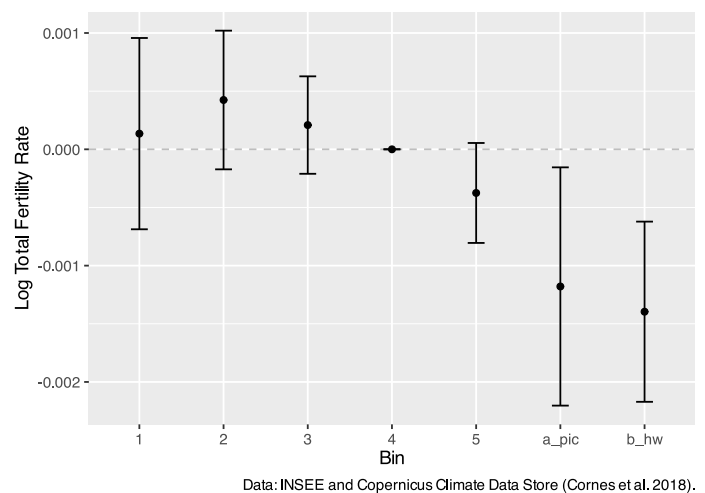
Note: Results for Figure 13 are generated from applying the core estimation technique to two subsamples of the data (hot vs. cold), based on the question if regions hosted more or less than the median number of days with a mean temperature over 25°C over the entire window of analysis. *Hot Regions*: Île-de-France, Centre, Bourgogne, Alsace, Pays de la Loire, Poitou-Charentes, Aquitaine, Midi-Pyrénées, Limousin, Languedoc-Roussillon, Corse. *Cold Regions*: Champagne-Ardennes, Picardie, Haute-Normandie, Basse-Normandie, Nord-Pas-de-Calais, Lorraine, Franche-Comté, Bretagne, Rhône-Alpes, Auvergne, Provence-Alpes-Cote-d’Azur).

We observe little difference in the estimated effect of days with a mean temperature above 20°C when comparing warmer and colder regions. The key difference in these results, instead, is in the statistical significance of bin 5 (daily mean temperature between 15° and 20°C) in colder regions whereas it is not found to be significant in the warmer regions. This finding suggests that populations in colder regions are susceptible to the effects of heat on fertility at a lower temperature threshold than populations in warmer regions of France.

The Role of Consecutive Hot Days

For this analysis, we consider how many days in a given month were “heat-wave-like” days. We consider three or more hot days in a row as the policy and academic literature has coalesced around at least this portion of a heat wave definition, even if there is some contextual variability on the exact temperature threshold. We consider hot days to be where the mean temperature is over 20°C in view of statistically significant results at the two highest temperature bins (giving a lower bound of 20°C), seen in the previous section. We then consider days over 20°C that have at least two prior consecutive days above 20°C as heat wave days.

Figure 14: Estimated effect of Heat Wave Versus Non Heat Wave Days on 9-month lagged log TFR. 22 French Regions. 1975-2020



Note: In Figure 14, we distinguish between days above 20°C where the previous two days were also above 20°C (b-hw) and days above 20°C that did not meet this condition (a-pic), matching French national policy regarding the differences between heat waves and heat spikes (a.k.a “pic du chaleur”).

Figure 15 shows that at a nine-month lag, the point estimate of a heat wave day (67b) is slightly larger than a non-heat wave day (67a) regarding their estimated effect on fertility rates (the results are very similar at a ten-month lag). Also, the confidence interval is smaller for heat wave days than non-heat wave days, signaling less variance in the results, though the estimated difference between these two groupings is not significant. These results still suggest that a single hot day even outside of a major heat wave event is a sufficient to yield significant effects on fertility rates.

The Role of Humidity

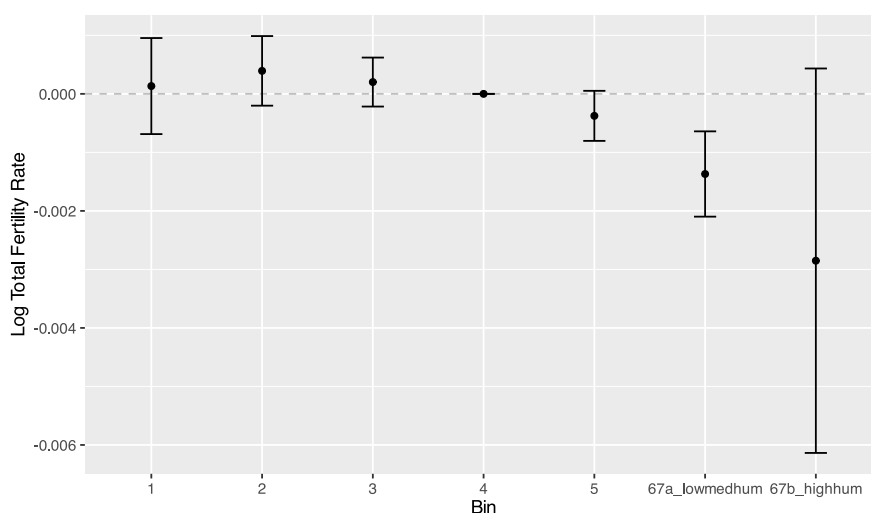
In another step, we divide days with a mean daily temperature of over 20°C into two subcategories. Those with low or medium humidity, corresponding to the first two humidity bins, and versus such days with high humidity (as defined in the core model). We find that days over 20°C have a higher estimated coefficient than days with low or medium humidity. However, we observe greater uncertainty regarding these hot and humid days, specifically because we observe no days above 25°C that are also classified as high humidity across all the regions and years included in our sample, due to the French metropolitan climate typically seeing its most humid conditions in the winter instead of the summer.

Alternative Methodologies

Spline

The previous analysis, and the heat/fertility literature at large, often uses bins to address potential non-linearity of the effect of temperature on fertility at a given lagged month. It is common in both social sciences and proximate fields like epidemiology to divide continuous variables, like income (in this case, temperature) into bins to produce more intuitive results. This method, however, is not the only way to deal with nonlinear effects. One fault of considering bins is that a critical point, a specific value in the dependent variable that may have a particularly strong threshold effect on the independent variable, within a bin may be hidden. This is especially true when the intervals are relatively large- we have considered this problem at the moment of my bin construction and for this reason the bins in the previous analysis are among the smallest intervals found in previous literature. Still, it is reasonable to consider other functional approaches as some previous studies in this literature have done in their robustness checks.

Figure 15: Estimated effect of Hot and Humid Versus Hot and Low/Medium Humidity Days on 9-month lagged log TFR. 22 French Regions. 1975-2020



Data: INSEE and Copernicus Climate Data Store (Cornes et al. 2018).

Note: In Figure 15, we distinguish between days above 20°C where the humidity level was above 85% (the highest humidity bin used in our core analysis: 67b_high), and days above 20°C where the humidity level was below 85% (encompassing the middle humidity bin of 75-85% humidity, and the lowest bin of below 75% humidity: 67a_lowmed). The median daily humidity observed in our time period is around 80%.

Figure 16: Effect of Monthly Average Temperature on Log TFR Estimated by a Polynomial Spline

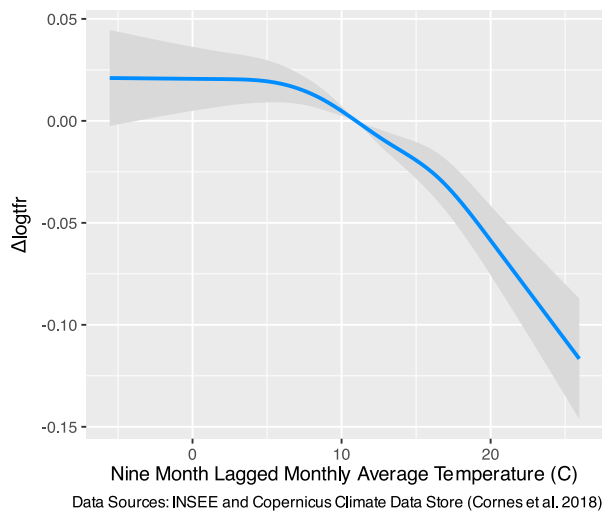


Figure 16 displays the estimated effect of the monthly average of daily temperature for a given region-month on log TFR nine months later. The estimate is plotted in blue and the shaded areas represent the 95 percent confidence interval. We use a restricted cubic spline with six degrees of freedom, which carries the advantage over natural splines as its behavior is bounded at the extremes of the function. We include fixed effects for region by month, region by year and month by year. We control for precipitation and humidity by including the daily average for a given region-month in the model. The result here is rank deficient, owing to the fact that the fixed effects capture some overlapping trends (graphing the fixed effects separately yields similar results, however, and no rank deficiency). Here, we simplify the data, including only a monthly temperature lagged nine months from total fertility rates in order to graph temperature as one variable, which is necessary for the spline input, but produces a less stable estimation.

Historical Threshold

Though constructing a series of temperature bins is becoming the most common approach in the heat/fertility literature, it is not the only method in the literature for defining extreme heat. In this section, we define heat using a regional historical threshold, as opposed to incremental bins. This serves two purposes. One, it stands as a robustness check for the results garnered above: i.e. we gain some assurance that the results so far are not only an artifact of a par-

ticular way of defining extreme heat. Two, it allows us to test these two different methods for defining extreme heat under the same data conditions.

Using a historical threshold is that it permits us to test the effects of relative heat shocks against absolute ones. It is not uniquely the absolute temperature shock that dictates health morbidity, but rather the integration between temperature and the adaptive capacity. Therefore, composing a measure of heat based on a relative threshold allows us to observe the effect of heat on fertility even after considering the local climate (and, we assume here, popular knowledge and expectations of hot weather).

One study in the heat/fertility literature have used a historical threshold to define anomalous heat events: Marteleto et al. (2023) in the case of Brazil. Marteleto et al. begin by collecting temperature data from a 30-year period prior to the window of analysis of the study. Since our window of analysis begins in 1975, we base our historical threshold on data from 1950 (the earliest data available from the Copernicus Climate Data Store) to 1974 (the year before the window of analysis begins). Next, Marteleto et al. consider dummies that indicate extreme heat events, where the average temperature in a given month is outside the historical average, plus or minus two standard deviations.

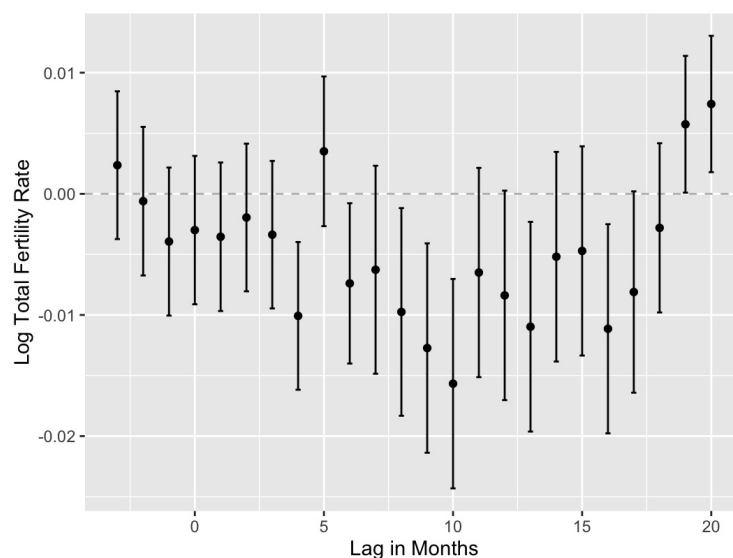
Because the seasonal climate of Brazil varies more by precipitation than temperature, we modify this measure for the French context. First, we apply the procedure only to the months of June, July, and August, which are the months in the window of analysis in which extreme heat occurs, since considering a positive temperature anomaly outside these months might falsely flag a mild winter as an extreme heat event. Next, we consider the threshold as plus two standard deviations from the historical threshold. In sum, any region-month within the period of analysis to have a mean daily temperature two standard deviations above the historical average is assigned an indicator value of 1. Any region-months that do not meet this criteria are marked zero.

We find that under this operationalization, we still observe a negative effect of temperatures on fertility rates around nine and ten months. However, the

point estimates across the lags estimated are skewed negatively compared to the core results, where they lie closer to zero. It is possible that using a binary variable here may be resulting in false negatives. That is, months just below the threshold that trigger similar health effects. At the same time, the point estimates for the lags of interest are found to be smaller here than in the core results. Statistically significant negative results at lags that have no prior explanation in the literature, such as 16, 19, may lead us to suspect these discrepancies are an artifact of the estimation technique instead of a substantive difference in findings. Despite some theoretical advantages to considering a historical deviation instead of a uniform threshold across all regions, the results obtained here are still less clear than those obtained with the bin approach.

Figure 17 displays the point estimates (circles) and and +/- 2 standard errors (brackets) of the estimated effect of a month (June, July or August) 2 standard deviations above the historical average from 1950-1974 for each month. we include lagged effects up to 20 months following exposure, as well as placebo checks at -1,-2,-3. We include fixed effects for region by month, year by month, and region by year. We also include linear and quadratic time trends. We control for precipitation and humidity. Standard errors are clustered by region.

Figure 17:
Estimated Effects of Monthly Average Temperature 2 Standard Deviations Above a Historical Threshold on log TFR Across Lags -3 to 20



Data: INSEE and Copernicus Climate Data Store (Cornes et al. 2018).

Outlook: Investigating the Role of Air Quality in the Heat/Fertility Relationship

In this section, we explore the possibility that air pollution affects the heat/fertility association. There are several reasons to consider the role of heat and air pollution in tandem regarding their effect on fertility. First, the same atmospheric conditions that often contribute to persistently hot weather also serve to exacerbate air pollution due to the overarching heat dome conditions previously discussed. Second, there is substantial evidence that elevated levels of air pollution such as PM 2.5, O3, and NO2 disrupts fertility in both men and women (cf. systematic reviews by Kumar and Singh, 2022 on male fertility and Conforti et al. 2018 on female fertility). Notwithstanding this overlap, the interaction between heat and air pollution in the demographic literature on heat and fertility has been understudied. Notable exceptions include Conte Keivabu et al. (2024) who include PM 2.5 as a control. We test here the effects of O3 (ozone), given substantial medical research that exposure to elevated ozone levels has adverse effects to reproductive health in both men and women (Kumar and Singh, 2022; Lu et al. 2023; Ekland et al. 2017; Mendola et al. 2017; Tong et al, 2023; Carré et al. 2017). Ozone also is of particular interest to the case of France as it is the only pollutant to increase in prevalence over recent decades, especially concerning urban areas (Sicard et al. 2016). This prevalence is occurring despite some policy attention devoted to air quality from the EU and France over the same time period (Ministère de la Transition Écologique et de la Cohésion des Territoires, 2022; 2023).

On its own, ozone pollution may negatively affect reproductive health through a variety of mechanisms. In men, a literature review by Kumar and Singh (2022) reports that ozone exposure contributes to decreased sperm quality. Lu et al. (2023) finds that spermatogenesis at stages I and II are most susceptible to adverse effects due to ozone exposure. This approximates to sperm produced the month before a hypothetical conception month (i.e. approximately 10 months lagged from birth). A systematic review by Carré et al. (2017) concludes that existing literature supports that air pollutants disrupt gametogenesis in both men and women, but studies on men are more common due to the ease of obtaining samples.

Moving from gametogenesis to adverse pregnancy outcomes, a meta-analysis on 30 European countries reports that ozone concentration increases the risk of preterm birth (Ekland et al. 2021). Another meta-analysis by Rappazzo et al. (2021) finds that ozone exposure in both the first and second trimester is associated with increased likelihood of preterm birth. A systematic review by Conforti et al. (2018) reports that evidence that O₃ exposure is detrimental to live birth rates specifically among IVF women. Mendola et al. (2017) estimate that approximately 8000 stillbirths in the US annually may be attributable to ozone exposure.

Regarding an interaction between both ozone and high temperature, Tong et al. (2023) finds that in the US, both ozone exposure and high temperature increase risk of pregnancy loss (including miscarriage and still birth), and furthermore that the presence of high temperature amplifies the negative effect of ozone exposure on these outcomes. While the literature is approaching a consensus on the adverse effects of both high temperature and ozone on pregnancy outcomes separately, Tong et al. note their study is among the first to consider an antagonizing interaction between the two. This notion is not unfamiliar to the wider literature on ozone exposure risks. For example, in a systematic review, Areal et al. (2021) notes that adverse respiratory health outcomes from ozone exposure are amplified during warm temperatures.

Methodology

Ozone functions differently than temperature because there is no consensus on what level, if any, can be considered totally risk free from a human health standpoint. Literature on the subject is moving towards the notion that adverse health effects can be found at levels lower than previously expected. For example, based on a systematic literature review, WHO guidelines lowered their threshold from 2005 to 2021 (WHO, 2021). Furthermore, general guidelines are commonly constructed based on either non-accidental mortality rates, respiratory mortality rates, or both (WHO, 2021). As a result, it is possible that other morbidities, such as sperm quality or pregnancy loss are visible below these levels. For example, French and EU thresholds are 120 µg/m³, and Tong et al. (2023) report their effect visible at 104 µg/m³, even when paired with their classification of “low temperature” of daily mean temperature below 18°C.

We employ a historical air pollution dataset constructed by Real et al. (2022) covering mainland France from 2000-2020 at a resolution of about 4 km. We extract the average daily maximum values of O₃ pollution within the 22 regional boundaries included in this analysis. We pair the average maximum ozone recorded within the boundary of each region with the temperature of that same day.

With this combined dataset, we observe that 73 % of the region-days in our sample above 25°C registered ozone pollution levels higher than the French and EU health threshold level of 120 µg/m³. 35 % percent of the days in our sample between 20 and 25°C registered a daily maximum ozone level of above 120 µg/m³. Overall, days with levels of ozone pollution 120 µg/m³ constitute only 6.3 % of the days in our sample. Regarding days that register above a maximum level of 100 µg/m³ (WHO 8 hour mean threshold), 18 % of all region-days register ozone levels above this amount. Out of days with a mean daily temperature above 25°C (bin 7), 95 % of them register ozone above 100 µg/m³. Out of days with a mean daily temperature between 20 and 25°C (bin 6), 68 % of them register ozone levels above 100 µg/m³.

Given that ozone levels in France are elevated compared to international benchmarks, we also analyze ozone levels by the tertile of daily ozone level observed across all regions from 2000-2020. One third of the days in the window of analysis registered a daily maximum of below $66.61658 \mu\text{g}/\text{m}^3$, another third between $66.61658 \mu\text{g}/\text{m}^3$, and $86.63152 \mu\text{g}/\text{m}^3$, and the upper third of days above $86.63152 \mu\text{g}/\text{m}^3$.

Figure 18 describes the percentage of days in each ozone tertile in each temperature bin used in the core analysis, divided by region. Across all regions, all days with a mean 25 C temperature also registered a maximum ozone level in the upper third of all days measured. Across all regions, a majority days with a mean temperature between 20 and 25 C also saw ozone levels among the upper third of the sample. Therefore, it is possible that ozone levels play a role in co-creating the effects of heat on fertility rates observed in the core results. In other words, there are no cases in any region in any time from 2000-2020 where heat may be observed in the absence of meaningful levels of air pollution, in order to claim definitively that extreme heat as operationalized in the core results is sufficient to affect fertility rates.

Preliminary Air Pollution Results

Given the significant overlap between hot weather and air pollution, we also employ a case crossover approach similar to what has been used in recent epidemiological studies that seek to disentangle the role of air pollution and heat on various health outcomes including adverse effects on pregnancy (Tong et al. 2023) and respiratory and cardiovascular deaths (Azzouz et al. 2024). We divide daily temperature and ozone and ozone levels into tertiles, and then construct a typology with nine categories based on if a given region was in the first, second or third tertile for both ozone and temperature. We then place these nine categories within the model structure used for the core results above (i.e. the fixed effects remain unchanged). We omit the category of low ozone and low temperature.

Figure 18. Ozone Tertile and Temperature Bin by Region

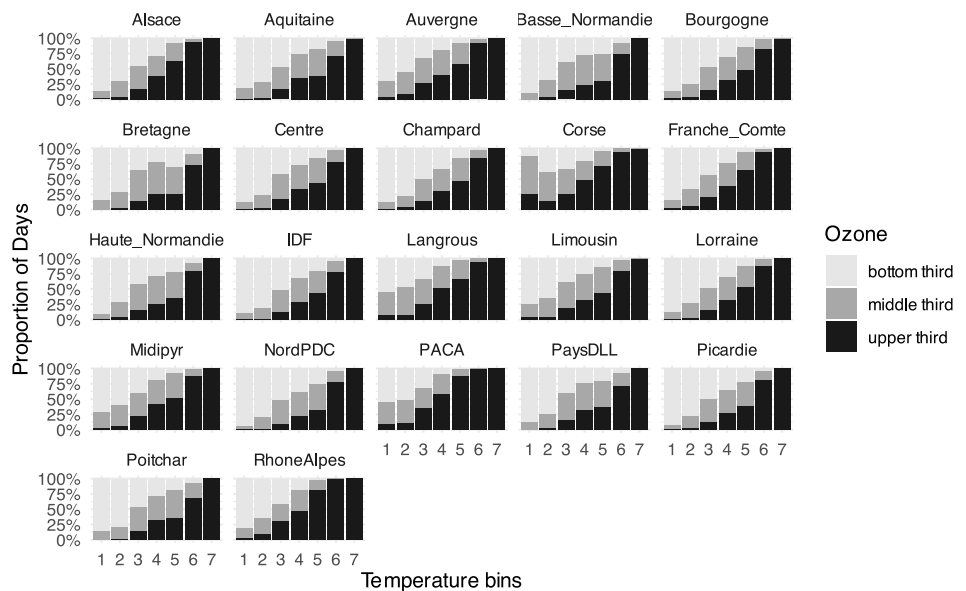
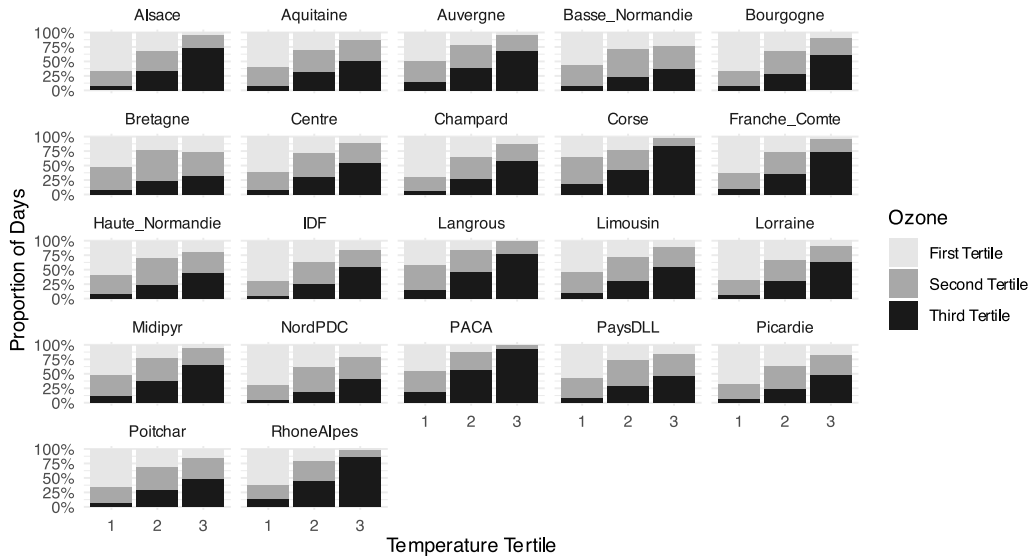


Figure 19. Ozone Tertile and Temperature Tertile by Region



The temperature tertiles used here are below 8.296271°C , in between 8.296271°C and $14.974454^{\circ}\text{C}$, and above $14.974454^{\circ}\text{C}$ (the lower bound for bin 5 in the core analysis is 15, so effectively this pools days in temperature bins 5, 6 and 7 as employed in the core analysis).

While existing literature supports the notion that heat and air pollution may contribute to adverse pregnancy outcomes, we do not observe statistically significant results across any of the categories at zero or lagged one month from birth. This is likely due to technical limitations rather than a substantial finding: generally, literature on adverse pregnancy outcomes is anchored in detailed hospital records and we employ region level fertility rates. We do, under this operationalization, continue to observe significant results at 9 and 10 months lagged from birth.

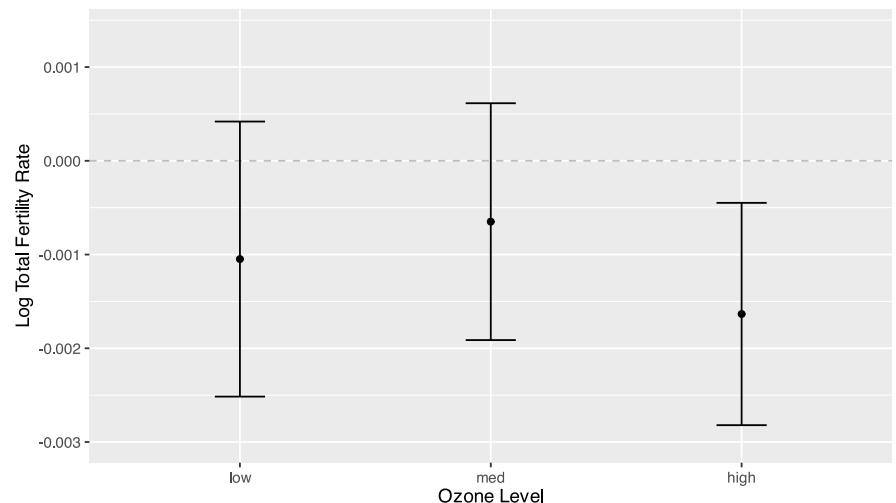
Figure 20 displays the point estimates (circles) and ± 2 standard errors (brackets) of the estimated effect of one day of high temperatures at all ozone levels compared to a day with low ozone and low temperature/. We include lagged effects up to 20 months following exposure, as well as placebo checks at -1,-2,-3, but display the results at lag 9 since earlier analysis yielded this as the lag of most interest. We include fixed effects for region by month, year by month, and region by year. We also include linear and quadratic time trends. We control for precipitation and humidity. Standard errors are clustered by region.

Table 1: Number of Days By Tertile Category

Low Temperature Low Ozone	33627
Low Temperature Medium Ozone	17499
Low Temperature High Ozone	5128
Medium Temperature Low Ozone	16086
Medium Temperature Medium Ozone	22387
Medium Temperature High Ozone	17781
High Temperature Low Ozone	6541
High Temperature Medium Ozone	16367
High Temperature High Ozone	33346

Figure 20 displays the estimated effect of one day of high temperatures at all ozone levels compared to a day with low ozone and low temperature.

Figure 20: The Effect Of High Temperature Days Crossed with Low Medium and High Ozone By Sample Tertile Lagged 9 Months from Birth



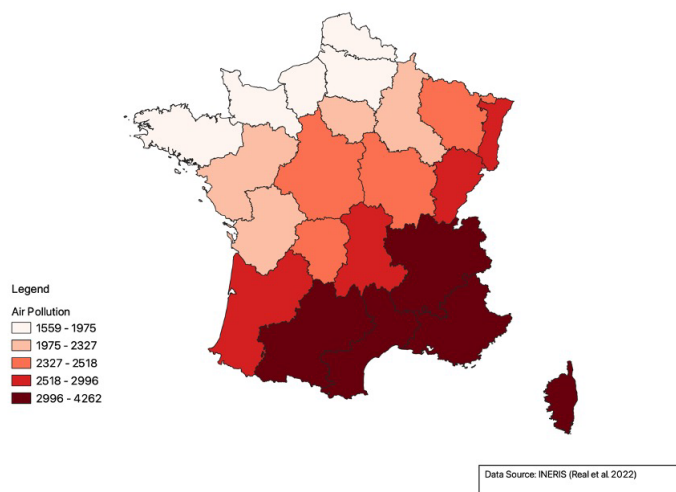
Data: INSEE, Copernicus Climate Data Store (Cornes et al. 2018) and and INERIS (Real et al. 2022). Lag = 9

This operationalization suggests that ozone may exacerbate the link between heat and fertility, especially 9 months lagged from birth. At lag 9, days with high temperatures but with low and medium ozone levels produce statistically insignificant results, while days with high temperatures and high ozone levels do: the estimated coefficient of high temperature days with high ozone levels has a larger magnitude (-0.0016) compared to high temperature days with medium ozone levels (-0.0006) and high temperature days with low ozone levels (-0.0010).

Persistent presence of air pollution where heat appears also alters the policy ramifications of the heat/fertility literature. If the effect of heat on fertility was uniquely an effect of heat, seeking cooler indoor areas during warm periods of the day would be an appropriate public health message. Staying indoors during periods of bad air quality, though, does not eliminate the risk of bad air quality due to the transfer of outdoor pollutants to indoor spaces (ANSES, 2019). This may be part of the explanation for why we observe similar estimates across warmer and cooler regions: even if the built environment and habits in warmer regions are more adapted for warm weather, that these warmer areas are also more polluted than cooler areas may negate any adaptive advantages to heat alone (Figure 21).

Diversifying variables of interest in the heat fertility literature emphasizes the possibilities for case specific pathways in each country that mediate the rela-

Figure 21. Number of Days in Upper Ozone Tertile of Maximum Daily Ozone Exposure By Region From 2000-2020



tionship between heat and fertility, even if the overall outcome is similar. For instance, in France heat may interact with air pollution to produce an effect of heat on fertility. In other countries, high temperature may interact with humidity (Hajdu 2024), even if due to the prevailing climate in France the heat and humidity rarely coincide. Therefore, it is possible that the relative composition of different hazards is responsible for relatively similar results at lags 9 and 10 across countries. In sum, even if across countries we consistently observe around a -0.5 percent net effect, the mechanism may vary according to local climate and population makeup, and future research may account that heat/fertility mechanisms are not identical between country contexts.

Conclusion

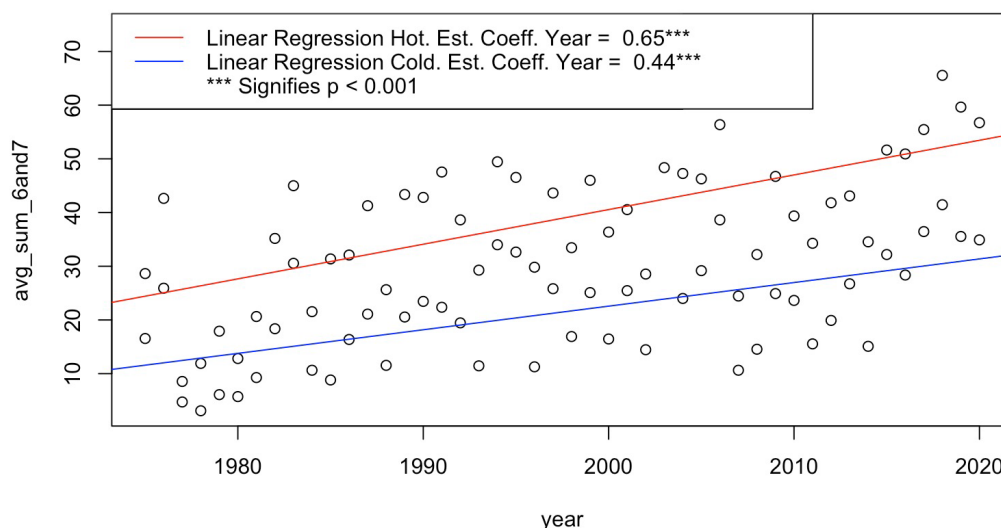
This study finds that extreme heat is associated with a negative effect on fertility rates in France. A decline in monthly TFR may be linked to extreme heat nine and ten months prior to the month of birth. These findings must be viewed in light of several limitations of this research. First, the temporal granularity of this study is limited by fertility data being available by month, and not by week. Previous work in this research stream that relies on weekly fertility data is able to go further than this study in discussing possible mechanisms that lead to decreased conception probabilities. Second, the regional level of the fertility data constrains the spatial granularity of the study. Meteorological variables, even on a given day, may vary with regions and taking a simple mean overlooks this heterogeneity.

Furthermore, we do not weigh the meteorological variables in accordance with heterogeneities in population at the sub regional level. Therefore, temperatures experienced by urban populations, as a larger proportion of the region as a whole, are underrepresented. The urban heat island effect further complicates measuring extreme heat experienced by urban populations. Weather stations included in the EU Copernicus database used here are commonly located in parks or airports outside the city center, which may be several degrees cooler than temperatures in the city center (cf. regarding the Paris case: (APUR 2012)).

We also do not account for migration between regions between the timing of conception and of birth. This is especially relevant in this case since heat waves often come during the period of vacances in France, a period of exceptional internal migration. Furthermore, we are able to measure directly the role of socioeconomic status at the individual level in mediating the connection between heat and fertility. Individuals of higher socioeconomic status may be more likely to take vacations outside hot city centers. One could also hypothesize on the role of indoor versus outdoor labor in subtracting or adding daily heat exposure heterogeneously according to socioeconomic status at the sub-regional level.

We observe that this effect is heterogeneous over space and time. Here, we emphasize that, since our estimation technique is in terms of one additional hot day, our finding that the negative effect of heat on fertility decreases in magnitude over time does not necessarily indicate that the net effect is decreasing as well. Climate change has caused an increase in the number of days where temperatures are high enough to affect fertility rates (over 20°C) in France. For example, over the first five years of our observed time period (1975-1980), French metropolitan regions experienced an average of around 15 days above 20°C per year. For the last five years of the analysis (2015-2020), the regions experienced an average of around 46 days above 20°C per year. Figure 9 illustrates this trend, and further describes how this increase is more marked in the warmer climates of France than in the colder ones. While climate change stands as a relatively minor factor in the French fertility decline today, the accelerating pace of climate change means its relative importance among other factors is likely to increase in coming decades, both in France and globally.

Figure 22. Time trend of Yearly Number of Days above 20 C Grouped by Climate Over Time. 22 French Regions. 1975-2020



Results for Figure 22 are generated based on the question if regions hosted more or less than the median number of days with a mean temperature over 25 C over the observed time period. *Hot Regions*: Île-de-France, Centre, Bourgogne, Alsace, Pays de la Loire, Poitou-Charentes, Aquitaine, Midi-Pyrénées, Limousin, Languedoc-Roussillon, Corse. *Cold Regions*: Champagne-Ardennes, Picardie, Haute-Normandie, Basse-Normandie, Nord-Pas-de-Calais, Lorraine, Franche-Comté, Bretagne, Rhône-Alpes, Auvergne, Provence-Alpes-Cote-d’Azur).

Our finding of a negative impact of climate change on fertility must therefore be set within two broader trends: the first is a general fertility decline below replacement level - a trend observed over the last decade in many high-income countries, including France. The second is the acceleration of climate change. Fertility decline below replacement level in high income countries with carbon intensive lifestyles could initially be interpreted as a net positive for the global environmental outcomes. This conclusion is strained when we consider that recent the fertility decline in high income countries has been coupled with relatively stable fertility intentions around replacement level (Toulemon and Testa, 2005; Testa 2014). Fertility decline therefore carries a possible loss of social wellbeing in not achieving anticipated life projects. The acceleration of climate change means that environmental factors, either through physiological or psychological pathways, may play a relatively larger role in driving unmet fertility intentions and related fertility decline in coming decades.

Discussion: Future Research on Heat and Fertility

The main areas of improvement for this specific work and demographic research on heat and fertility in general is to 1) further develop the mechanisms that are responsible for this link, and 2) develop a more comparative perspective, especially with regards to low and middle income countries that are more vulnerable to the risks of climate change. These two notions are linked: different data availabilities across different country contexts have led to a fragmentation of the mechanisms explored in this literature.

Regarding the mechanisms determining the link between climate and fertility, Hoffmann et al. (2024) outline that demographic research proceeds along three general pathways. 1) direct physiological consequences of climate shocks affecting fertility rates and pregnancy outcomes 2) indirect consequences of climate shocks on fertility rates and pregnancy outcomes due to limited resources and 3) climate change concerns shifting fertility preferences (e.g. Rose and Testa, 2015, Helm et al. 2021).

Owing to country specific data constraints, research on different country contexts tends to focus on one mechanism over the others, even if there may exist interdependences between these pathway across contexts. Hoffman et al. (2024) note that research on the indirect consequences of climate shocks on fertility rates are confined to low and middle income countries. Additionally, research on climate anxiety and fertility intention is often confined to high income countries.

We can take this work at hand as an example for how available data shapes the mechanisms that are able to be explored. These findings are based on monthly total fertility rates. Research on other high income countries often is based on monthly or weekly fertility rates. Using monthly or weekly fertility rates as the dependent variable permits researchers to pinpoint the temporal delay between the heat shock and effects on fertility, and thus which physiological mechanisms may be responsible. Yet, the overall window of analysis used in analyzing this data (around 20 months before the time of birth) still does not permit the exploration of these physiological mechanisms within a wider picture of concurrent mechanisms such as shifts in fertility intentions. For example, it unclear to what extent the short term loss in births we observe here endures through completed fertility. This may be the case either involuntarily via the loss of a decisive reproductive year at the end of a woman's child-bearing years, or voluntarily via an increase in climate anxiety due to experiencing a dramatic climate event such as the European heat wave of 2003. Relatedly, more research is needed on how individuals interpret or explain this delay in conceptions.

Some research has gone further than this work in linking multiple heat/fertility mechanisms. In a study of 59 low and middle income countries, Gray and Thiede (2024) make use of Demographic and Health Survey (DHS) data, which contains information both on fertility outcomes and future intentions. They report that positive temperature anomalies have a positive effect on births, but a larger negative effect on reported fertility intentions. In urban areas, positive temperature anomalies were found to have no effect on births, but a negative effect on fertility intentions. Since the demographic data here is not available at the sub annual level, it is not possible to trace the

temporal lag between the heat shock and its effect on fertility, and therefore the possible physiological mechanisms. However, it goes much further in considering the simultaneous effects of heat on fertility outcomes *and* intentions than similar research in higher income countries.

Future research may seek to harmonize the temporal detail of fertility rate based studies done in Europe and US and the multidimensionality of DHS based research. This objective also serves to further the comparative power of heat/fertility research, bridging the gap between methods and findings that currently exist between higher and lower income countries on this topic. Regarding demographic data, DHS data could be used to compute subnational and sub annual fertility rates in low and middle income countries as does a work in progress by Cheritel et al. (2023). On the part of meteorological data, satellite data used for low and middle income countries contains more uncertainty than data anchored in in-situ measures but carries the advantage of being easily harmonized across country contexts. For a more comprehensive review of data sources currently available for measuring the effects of climate on fertility in low and middle income countries, see Grace (2017).

In sum, harmonizing the methodological basis for research on climate and fertility across high and low income countries stands as one of the biggest challenges for future research in this field. Such harmonization, however, would support a more comprehensive investigation on the various mechanisms that may connect climate shocks and fertility rates, and further analysis on within and between country differences in this relationship.

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Abstract

We estimate the effects of heat on monthly fertility rates in 22 French region from 1975-2020. We find that days with a mean daily temperature above 25 C have an estimated effect of -0.260 and -0.256 percent on Total Fertility Rates nine and ten months later, respectively. We find that the negative association has become somewhat smaller over the window of analysis, and is heterogeneous at the sub-national level, with fertility rates in colder regions being affected at lower temperatures than in hot regions. We also find that the negative association is relevant across alternate methodologies. We furthermore discuss the potential role of humidity and air pollution in modifying the association between heat and fertility. Our findings suggest that the heat/fertility association is an important factor in debates on population aging in Europe and on the diversity of health risks posed by climate change.

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Keywords

Climate change, fertility, heat wave, population ageing, humidity, air pollution

JEL Codes

J13 - Q54

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Pour citer cet article | Cite this paper

Sophia Noel, Angela Greulich, "The Effect of Heat on Fertility in France", *CRIS Papers*, n° 2025-1, January 2025.

DOI: 10.25647/cris.papers.03

Édition de ce numéro | Editorial board

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Responsable de la publication :
Carlo Barone

