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ABSTRACT

Temperature and Sex Ratios at Birth

Sex ratios at birth shape populations and are linked to maternal health and gender discrimination. We estimate the effect of prenatal temperature exposure on birth sex by linking data on 5 million births in 33 sub-Saharan African countries and India with high-resolution temperature data. We find that days with a maximum temperature above 20°C reduce male births in both regions. In sub-Saharan Africa, we observe fewer male births after high first trimester temperature exposure, consistent with increased spontaneous abortions from maternal heat stress. By contrast, in India we find second trimester temperature exposure is associated with fewer male births, consistent with reductions in induced sex-selective abortions against girls. These findings demonstrate that climate change harms maternal health, increases prenatal mortality, and reduces engagement with the health system.

JEL Classification: J13, J10, I15, I10, O13

Keywords: sex ratios at birth, temperature, prenatal exposure, maternal health, abortion

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Introduction

Human sex ratios at birth[1] (SRBs) – or the ratio of male to female offspring – have been a fascination of social scientists from at least the 1600s (Graunt, 1662; James, 1986). Over the centuries, several explanations have been proposed and dismissed to explain SRB variations (1). A consensus emerged in the mid-1900s that sex ratios at birth were likely constant, genetically determined, and invariant to social or environmental shocks (ibid., Bongaarts and Guilmoto, 2015). However, since the 1970s new theoretical biological mechanisms were proposed by which social and environmental factors could affect SRBs, most notably via male *in-utero* fragility (3). This led to a re-emergence of research in this field (4). At the same time, interest in SRBs increased dramatically among social scientists as ultrasound technology led to a rise in sex-selective abortion of girls in many countries in Asia and Eastern Europe, skewing SRBs significantly above their natural levels (2, 5).

Yet little attention has been given to the possible effects of climate change on SRBs despite the renewed interest in social, environmental, and behavioral determinants of SRBs via maternal stress and prenatal sex-selection. This is particularly puzzling given the growing literature on the effect of climate change on unintended pregnancy terminations, presumably via the channel of *in utero* stress. The current literature suggests a culling effect, i.e., higher *in utero* mortality, detected in reduced birth rates and increased pregnancy losses after heat exposure during conception and pregnancy (6–12). Given existing evidence on male *in utero* fragility and heat-induced pregnancy losses, we ask whether the effect of gestational heat exposure is sex-biased, manifesting itself in fewer male births, i.e. a lower SRB after gestational heat exposure.

In this paper, we estimate the effect of ambient temperatures during conception and pregnancy on the sex ratio at birth[1]. To assess both biophysical health and behavioral mechanisms, we conduct a comparative analysis across two major world regions with vastly different experiences with son preference and sex-selective abortion. Specifically, we compare differences in the effect of temperature exposure between India and sub-Saharan Africa. In India, son preference is strong and has inflated SRBs because of sex-selective abortion (5). By contrast, in sub-Saharan Africa fertility does not seem to be influenced by son preference and sex-selective abortion is considered minimal (13, 14). To the best of our knowledge, this is the first large-scale study on the impact of temperatures during conception and pregnancy on human SRBs.

Why should the sex ratio at birth (secondary sex ratio) respond to temperature exposure? **Fig. 1** summarizes our conceptual framework. The initial probability of conception (or the primary sex ratio) has been shown to be equal for both sexes (15). Hence, changes in the secondary sex ratio point to a prenatal mortality response after conception, under which one offspring sex is disproportionately affected by environmental stress. According to an evolutionary argument offered by Trivers and Willard's "frail male" hypothesis (3), weak males might be the ones who exhibit the lowest chances of surviving to birth under poor environmental conditions. After birth, males have lower survival probabilities than females and require greater maternal investment (16, 17). This makes frail male pregnancies not only costly for the mother but also less likely to yield further offspring. In consequence, to protect maternal resources and ultimately increase offspring, *in utero*

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[1] The sex ratio at birth (the ratio of male to female offspring) is also referred to as the secondary sex ratio. The ratio of male to female offspring at conception is referred to as the primary sex ratio.

selection may be more pronounced for males under environmental stress. Epidemiological literature suggests that heat-induced pregnancy losses are triggered by dehydration, the diversion of blood and oxygen flow away from the placenta, and hormonal dysregulation (18, 19).

Beyond the direct physiological impacts of heat on pregnancy survival, there could also be reproductive *behavioral* responses to heat, particularly in terms of induced abortion behavior. To examine one of the vastly understudied behavioral responses to heat, we exploit a comparison between sub-Saharan Africa and India. In India, sex-selective abortions – the purposeful terminations of female pregnancies – driven by son preference have led to a male-skew in the SRB. In most other countries an SRB of 103-107 boys to 100 girls is observed (5). In India, by contrast, northern states have consistently shown much higher SRBs (13, 14, 20) of around 116:100 in 2005-2016, and in the South, which is not known for sex-selection, the SRB was estimated at around 107:100 (21). The intensity of son preference, and its manifestation in prenatal sex selection, are not only more dominant in northern states of India, but also intensified at later birth orders and in families without sons (22–24). But high temperatures could impact abortion access through mobility disruptions (25–28) and by increasing financial uncertainty and reducing income generation (29, 30). Hence, we investigate heat effects on the probability of male birth for higher order births (four and higher) between sonless mothers and mothers with at least one son in northern/southern states and compare results to the sub-Saharan African placebo. We conduct this test for heat exposure in the second gestational trimester, as sex determination is possible from approximately the 13th gestational week.

Existing studies on the impact of temperatures on SRBs have several methodological limitations. These studies link annual temperature measurements to births on the country level, (31, 32) which cannot a) adequately capture variation of exposures between subnational geographic areas, b) accurately map the temperature exposure at a location to the pregnancy duration of each birth on the micro-level, c) provide insight into the potential non-linearity of the temperature-sex relationship although different temperature thresholds might have varying impacts on the SRB, and d) account for seasonality in environmental exposures, parental selection into pregnancy, underlying parental health, and other proximate and distal factors. In addition, to identify environmental determinants of the SRB, sufficient variation within and across geographic units and seasons is necessary. This has led to inconsistent findings from small-scale single-country studies (32–34) and a focus on high-income countries where large, high-quality register data is available. In the Global South, the link between temperatures and SRBs remains unexplored, despite populations' heightened vulnerability to the impacts of global warming.

We address these issues by pooling micro-level data on more than 5 million live births from 104 Demographic and Health Surveys (DHS) conducted between 2000 and 2022 in 33 countries in sub-Saharan Africa and India. We link each georeferenced birth with gridded, high-resolution daily maximum temperature data for the approximate pregnancy period, using information on the month of birth. Our fixed-effect regressions non-linearly estimate the impact days with varying temperature intensity (below 15°C, 20-25°C, 25-30°C and above 30°C) in the three approximate pregnancy trimesters on the SRB in sub-Saharan Africa and India, while accounting for seasonality, all time-constant characteristics and time trends on the subnational regional level. To infer about specific mechanisms, we use the timing of exposure, sociodemographic differentials, and cultural differences on son preference between sub-Saharan Africa and India and within India. Our study aims to provide insight into the relationship between temperatures and SRBs and the context-specific biological and behavioral determinants underpinning it.

Data and Methods

Birth and population data. We use population data from 96 Demographic and Health Surveys (DHS) conducted between 2000 to 2021 in 33 sub-Saharan African countries and India. The DHS is an important source of information on health and wellbeing for low- and middle-income country populations, particularly women and children. It provides nationally representative cross-sectional data on women of reproductive age (ages 15-54), along with information on live births and maternal characteristics, such as educational attainment and age, among others.

For the purpose of this study, we use the DHS Births Recode files and include only those surveys and births where the primary sampling unit (PSU), defined as a grouping of households typically corresponding to a city block in an urban area or a village in a rural area, is georeferenced with latitude and longitude coordinates. For each live birth, its sex, month and year of birth are recorded. Using this information on the mother's place of residence and the child's time of birth, we extract high-resolution gridded climate data for each pregnancy for the month of its birth and the previous nine months to cover its gestational period. Though the clusters are displaced spatially by up to 10km to preserve respondents' anonymity, we link the climate data to the recorded PSU location as temperature values do not vary substantially on this scale. We restrict our sample to births by women aged 15-45 at childbirth who did not migrate in the year prior to the childbirth to address exposure misclassification bias. In total, we use 5,042,494 births (3,053,730 in sub-Saharan Africa and 1,988,764 in India) from 1,631,831 women (**Table 2**). The sample covers 381 administrative divisions on the first sub-national geographical level (i.e. state, province or equivalent) in sub-Saharan Africa, and 25 states in India (see ***SI Appendix*****, Table S2** for an overview of the surveys and samples).

The outcome variable is a binary indicator of whether the child born is male. The exposure effect is then interpreted as the effect of a 1-unit change in the treatment variable (i.e. one additional day in the gestational trimester where the daily maximum temperature falls into the specified temperature bin) on the probability of the born child being male.

Climate Data. Temperature data was obtained from the National Oceanic and Atmospheric Administration's CPC Global Unified Temperature datasets (https://psl.noaa.gov/). NOAA temperature data adjustments reflect well a global warming trend (42). These gridded data provide global coverage of surface temperatures, updated daily since 1979 and projected onto a 0.5 × 0.5 grid (ca. 55 km^2). For each day in the gestational period of a child, we extract the daily maximum temperature for the grid cell that intersects with the mother's cluster location.

We define the gestational period as the month of birth and the nine months prior to birth, to also include exposure around conception. The third trimester includes the month of birth and its three lags (1-month, 2-month, and 3-month lag), the second trimester the 4-month, 5-month, and 6-month lag, and the first trimester the 7-month, 8-month, and 9-month lag. To address autocorrelation, we also include the 10-month and 11-month lag. The treatment variables then are a vector of count variables that indicate for each gestational trimester of a live birth the number of days in the trimester with daily maximum temperatures that fall into a specified temperature bin (<15°C, 15-

20°C, 20-25°C, 25-30°C, >30°C). This results in 15 treatment variables (five temperature bins for three gestational trimesters), of which we exclude the 15-20°C bins for each trimester from the regression as the reference category. The regression estimates from our linear probability model then indicate the effect of one additional day in the given exposure trimester where the daily maximum temperature falls into the given temperature bin.

By using temperature bins, we allow the temperature-sex relationship to be non-parametric, as proposed in the best-practice methodology by Dell et al. (2014). For example, the effect of an additional >30°C heat day could differ from a 20-25°C heat day. In contrast to a cruder pregnancy exposure period, the trimester exposures provide more detailed insight into sensitive exposure timings, which we exploit to infer about mechanisms. We present results by trimester instead of monthly exposures to preserve statistical power, particularly in the heterogeneity analyses by maternal and birth characteristics (in ***SI Appendix*, Figures S4** we present main results on monthly exposures). As the DHS typically provide information only on the month of birth and not the exact day, except in more recent surveys, the exposures we construct an approximated the gestational period. In reality, however, gestational length may differ substantially across births, with preterm births making up an estimated 12.3 % of live births in sub-Saharan Africa in 2010 (44). The sample of surveys where day of birth information is available is too small to identify climatic SRB determinants with micro-level linkages in our empirical strategy, given the variation necessary within and across geographical units.

In addition, we extract monthly precipitation gridded data from the Climatic Research Unit (CRU) at the University of East Anglia (45) to control for the total amount of rainfall at the PSU location measured at each exposure month.

Effect modifiers. We examine heterogeneity in the temperature-sex relationship with DHS information on maternal and birth characteristics. This helps us test hypotheses on vulnerability to heat exposure and investigate mechanisms that explain sex ratio at birth variations. For each subgroup, we run a separate regression. We examine differences by the cluster location's urban-rural classification, formal educational attainment of the mother (none or primary; secondary or higher), maternal age at birth (ages 15-24; 25-29; 30+), and birth order (1; 2; 3; 4+). To investigate effects by sibling composition, we construct a binary variable that indicates for births of parity four and higher, whether the mother previously had a male live birth or not (sonless; at least one son). For India, we also examine difference between northern and southern states (the northern states include Bihar, Delhi, Gujarat, Haryana, Himachal Pradesh, Jammu and Kashmir, Madhya Pradesh, Maharashtra, Punjab, Rajasthan, and Uttar Pradesh (38)).

Estimation Strategy. We use a linear probability model with fixed effects to estimate the relationship between gestational heat exposure and birth sex in separate regressions for sub-Saharan Africa and India and each population subgroup (see **Effect Modifiers**). We employ a region-by-calendar-month-of-birth and a region-by-year-of-birth fixed effect, where the region refers to the first administrative unit on the subnational regional level (e.g. regions, states, etc.). For a child *i* born in subnational region *r* in month *m* in year *y*, the fixed-effects model of gestational temperature exposure on the child's sex can be expressed as:

$$Male_{irmy} = \sum_{j}^{J} \sum_{k=0}^{K=11} \beta_{k}^{j}\ TEMPERATURES_{r,t-k}^{j} + rain_{rm} + \alpha_{rm} + \delta_{ry} + \varepsilon_{irmy} \qquad (1)$$

The temperature vector captures the daily maximum temperature distribution at the mother's cluster location, counting the number of days where the daily maximum temperature falls into the temperature bin *j* (<15°C, 15-20°C, 25-30°C, >30°C) in the pregnancy trimester (*t-k*, where *k*=0 up to 3). The estimated coefficients indicate the effect of one additional day in the gestational trimester *k* where the temperature falls into the temperature bin *j*, relative to a 15-20°C day, as this bin is omitted from the regression as the reference category. In the article, we present the effect for a one standard deviation change in the exposure variables to make results comparable across the samples for which we run the regressions separately.

$rain_{rm}$ is a control for the total amount of rainfall in each approximate gestational month (the month of birth and the preceding nine months). The region-by-month-of-birth fixed effect α_{rm} controls for region-specific seasonal patterns and other observed and unobserved factors that are constant within the month-region unit, as there can be substantial differences in seasonality, climatic conditions, population vulnerability, and sex ratios at births.

The estimation thus captures the effect of temperature differences on the outcome, given the location and time of the year. This fixed effect is key to our causal interpretation: It limits the temperature variation to fluctuations that occur across years (but within the same region and calendar month), making it plausibly random. The region-by-year-of-birth fixed effect δ_{ry} controls for annually time-varying factors on the subnational regional level. Alternatively, we explored region-year time trend instead of using single years, which yielded equivalent results. ε_{irmy} are the equation's error terms. This fixed effects approach requires sufficient variation between and within place-time units, which we achieve by pooling surveys across sub-Saharan Africa and India in our main specifications. Standard errors are clustered at the region level.

Results

Our analysis draws on two separate samples of live births for sub-Saharan Africa (N=3,053,730) and India (N=1,988,764) from 104 surveys at 59,087 primary sampling units (PSUs) from the DHS[2]. The baseline SRB in sub-Saharan Africa is 50.84% male (103.42 males to 100 females), whereas in India the SRB is 52.5% (110.53 males to 100 females). The PSUs in sub-Saharan Africa and India exhibit similarly high daily maximum temperatures (the mean of the daily maximum temperature in the month of birth is 30.0°C in sub-Saharan Africa and 30.3°C in India), but there is more variation between clusters in India, where the standard deviation is 6.2 (sub-Saharan Africa 4.8). Heat days above 30°C are the most common of the five bin ranges – at least 34% of all gestational days fall into this bin in all trimesters across both samples. Most births are by mothers who live in rural areas (73.4% in sub-Saharan Africa and 76.6% in India) and have no or only primary level formal education (84.1% in sub-Saharan Africa and 61.06% in India). The births are concentrated in parities three and higher in sub-Saharan Africa (56.5%) and in the first two parities in India (62.5%). Detailed descriptive statistics are in ***SI Appendix*** **Table S1** and an overview of surveys used is in **Table S2.**

Temperatures and sex ratios at birth in sub-Saharan Africa and India

Fig. 2 shows the results from two fixed effects linear probability models of male birth on temperatures at different absolute thresholds in each gestational trimester, estimated separately

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[2] DHS uses a two-stage probability sample drawn from an existing sample frame (usually the most recent census). The PSUs represent a city block in urban and a village in rural locations, comprising about 25-30 households. (35)

for the sub-Saharan Africa and India sample. The coefficients indicate the change in the probability of male birth for an additional day in the trimester where the daily maximum temperature falls into the specified temperature range (bin) in reference to a 15-20°C day, after excluding births by mothers who were not residents at the PSU location in the year prior to birth. Our results suggest that exposure to temperatures below 15°C and above 20°C is associated with decreases in male birth probability in both sub-Saharan Africa and India and these effects vary by trimester. Detailed results and a translation of effect changes to the number of male births per 100 female births are available in ***SI Appendix,*** **Table S3**.

In the first trimester (**Fig. 2A**), when ultrasonic sex determination is usually not possible yet, we find male birth reductions in both sub-Saharan Africa and India. The estimated coefficients all indicate a negative relationship between <15°C and >20°C temperature days and male birth probability, though they are only statistically significant in sub-Saharan Africa for days above 20°C. Here, an additional day in the first trimester with a daily maximum temperature of 20-25°C decreases the probability of male birth by .018 percentage points (or .33 percentage points for a 1-SD predictor change, SD=18.9, p=.035), a 25-30°C day by .019 percentage points (or .47 percentage points for a 1-SD predictor change, SD=24.6, p=.015), and a >30°C day by .017 percentage points (or .59 percentage points for a 1-SD predictor change, SD=34.7, p=.046). In the absence of sex-detection, these changes are likely driven by a physiological response in terms of maternal heat stress.

Our analysis using monthly lags instead of trimester exposures can give an indication of which approximate gestational months are sensitive to exposure *(*detailed results in ***SI Appendix*****, Table S4**). The results show that the first trimester reductions in sub-Saharan Africa appear particularly seven months before birth. The magnitude of effects is substantially larger than apparent in the analysis with aggregated trimester exposures, between -.052 percentage points for an additional 20-25°C day (or -.64 percentage points for a 1-SD predictor change, SD=6.7, p=.032) and -.051 percentage points for a 25-30°C day (or -.46 percentage points for a 1-SD predictor change, SD=9.1, p=0.035).

While in the India sample, the analysis with trimester exposure does not show statistically significant first trimester effects, there is a weak indication of consistent male birth reductions for exposure around nine months before birth, but the confidence intervals overlap with zero. For pregnancies with a standard duration of 40 weeks or nine months, the nine-month lag approximately corresponds to exposure around weeks one to four of gestation, but for shorter pregnancies the exposure might include conception[3].

In the second trimester, which is when ultrasonic sex determination becomes possible from the 13th gestational week, our results in **Fig. 2B** suggest substantial differences between sub-Saharan Africa and India. We do not identify temperature effects on birth sex in sub-Saharan Africa. Here, temperature effects are very small and statistically insignificant (-.001 to .06 percentage points for a 1-SD change, p= .66; .84; .1; .85). However, in India, our results indicate a negative relationship between temperature exposure and birth sex. The effect of a 20-25°C day is marginally statistically significant and indicates a lower male birth probability by .015 percentage points (or .24 percentage points for a 1-SD change, SD=15.8, p=.066). A 25-30°C day is association with a reduction by .017 percentage points (or .34 percentage points for a 1-SD change, SD=19.6, p=.019).

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[3] This is an approximation as most of the Demographic and Health Surveys we use to do include day of birth and gestational length information.

Again, disaggregating trimester effects by monthly exposures (***SI Appendix*, Table S4**), the second trimester male birth reductions in India appear to be driven by exposures six and five months before birth. Effects are estimated at -.02 to -.46 percentage points for a 1-SD change in the predictor, though they mostly fail to reach statistical significance. By contrast, in the adjacent monthly lags – seven and four months before birth – temperatures across all bins indicate an insignificant weak and positive relationship. These findings are suggestive of a temperature response that is concentrated in a short and specific time window of six and five months before birth (or approximately 13 to 20 weeks of gestation for a standard pregnancy duration of 40 weeks or nine months[4]), with no response thereafter. We investigate in the next sections whether these second trimester reductions in male births apparent in India – but not in sub-Saharan Africa – can be explained by a behavioral change in sex-selective abortion prevalence in response to heat.

Fig. 2C shows that in the third trimester, there is some indication that negative temperature effects on male birth probability persist in India, but not in sub-Saharan Africa. One additional 25-30°C day in the third trimester decreases male births by.013 percentage points (or .3 percentage points for a 1-SD change, SD=23.7, p=.02). The other temperature bins fail to reach statistical significance, but consistently suggest a negative relationship. Examining results for monthly exposures (***SI Appendix*, Table S4**), the third trimester effects in India are driven particularly by exposure two months before birth. Two months before birth, a 20-25°C day is associated with a lower male birth probability by .034 percentage points (or .22 percentage points for a 1-SD change, SD=6.5, p=.042) and a 25-30°C day with a .037 percentage points reduction (or .31 percentage points for a 1-SD change, SD=8.37, p=.045). In sub-Saharan Africa, our results show statistically insignificant positive temperature effects.

Our findings reveal male birth reductions in response to heat in both sub-Saharan Africa and India, but sensitive time windows of gestational exposure differ between the two regions. Across neither sample do we find evidence of a gradient in the sex response by heat intensity, i.e. the magnitude of SRB reductions is not larger for hotter temperature days. However, once the temperature coefficients are translated into the effect for a 1-SD change in the exposure variable (instead of the effect for one additional day of the exposure variable), temperatures at higher intensity have larger effects on male birth probability. This means that, considering the frequency with which days with extreme heat intensity of 25-30°C and >30°C occur, temperatures at higher intensity pose a larger risk for male birth.

Vulnerable population subgroups in sub-Saharan Africa

Based on our finding in sub-Saharan Africa of an indication of a negative relationship between heat exposure in the first trimester and child sex, we further investigate demographic heterogeneity in the temperature-sex relationship to identify vulnerable subgroups of population. **Fig. 3** shows the results for first trimester temperature effects from a separate regression for each population subgroup by the rural/urban classification of the cluster location, maternal educational attainment and age at birth, and the child's birth order. The results suggest that different sociodemographic factors may shape vulnerabilities to cold and heat exposure in sub-Saharan Africa (for results for India, see ***SI Appendix*, Figure S5**).

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[4] If exposure in the month of birth corresponds to gestational weeks 37 to 40, exposure nine months before birth should correspond to weeks one to four, eight months before birth to five to eight weeks of gestation, etc.

Fig. 3A indicates that births by mothers residing in rural areas have a lower probability of being male in response to cold and hot temperatures. A 20-25°C day in the first trimester is associated with a .028 percentage point decrease in male birth probability (or .54 percentage points for a 1-SD change, SD=19.3, p=.004) and a 25-30°C day with a .03 percentage point decrease (or .72 percentage points for a 1-SD change, SD=24.6, p=.001). The estimates for >30°C days and <15°C point to a decline, too, but are not statistically significant. For urban areas, we observe a non-significant and very small positive relationship for temperatures above 20°C, suggesting that temperatures do not affect the SRB in urban areas.

Fig. 3B compares temperature effects between births by mothers with no or primary education and by those with secondary or higher education, showing that only the former group exhibits a lower male birth probability. Mothers with no or primary educational attainment show male birth reductions by .028 percentage points for a 20-25°C day (or .52 percentage points for a 1-SD change, SD=18.7, p=.005), by .031 percentage points for a 25-30°C day (or .75 percentage points for a 1-SD change, SD=24.3, p=.001), and by .028 percentage points for a >30°C day (or .98 percentage points for a 1-SD change, SD=35.18, p=.005). Again, the estimate for <15°C days also indicates a negative relationship but is not statistically significant (p=.281). By contrast, we detect no relationships between temperatures and birth sex for births by mothers with secondary or higher education.

Fig. 3C shows that we find no remarkable difference in the temperature-sex relationship by maternal age at birth. While for all age groups the temperature effect estimates indicate a negative relationship with male births or, for the ages above 30 years, a negligible positive relationship, none of the estimates are statistically significant.

The results by birth order in **Fig. 3D** indicate an inverse U-relationship, where the second parity has an increased probability of male birth under cold and hot days, but parities one as well as above three indicate decreases. These decreases are statistically significant for parities four and higher. They are less likely to be male by .046 percentage points for one 20-25°C day (or .84 percentage points for a 1-SD change, SD=18.4, p=.003), .041 percentage points for one 25-30°C day (or .99 percentage points for a 1-SD change, SD=24.4, p=.004), and .037 for one >30°C day (or 1.28 percentage points for a 1-SD change, SD=34.7, p=.016). These results suggest larger temperature effects on the SRB in high parity births.

Prenatal sex-selection responses in India

In the following, we examine heterogeneities in the temperature-sex relationship in the second trimester in India analogously for the same sociodemographic characteristics as for the first trimester in sub-Saharan Africa, using a separate regression for each subgroup (**Fig. 4**).

First, while we find no differences in SRB responses between urban and rural locations (see ***Appendix SI*, Figure S6**), we find that births to mothers with little formal education are less male-biased (**Fig. 4A**). Only births to mothers with no or primary formal education have a lower SRB in response to heat, as opposed to births by mothers with at least secondary education, where we observe no change. The effects for days with a maximum temperature above 20°C range from -.021 to -.035 percentage points for one additional heat day (or -.4 and -.55 percentage points for a 1-SD change, 15.7, p-values <.03).

Furthermore, we find a strong indication that births of parities four and higher and to mothers of maternal ages above 30 years are less likely to be male. **Fig. 4B** shows that for birth order four and higher, male birth probability is reduced by .061 percentage points for a 20-25°C day (1.0 for a 1-SD change, SD=16.4, p=.002), .052 percentage points for a 25-30°C day (or.96 percentage points for a 1-SD change, SD=18.5, p=.001), and .044 percentage points for a >30°C day (or 1.45 percentage points for a 1-SD change, SD=32.9, p=.027). As presented in **Fig. 4C**, births with maternal ages above 30, are less likely to be male by.056 to .099 percentage points for a day above 20°C (or 1.19 to 1.87 percentage points for a 1-SD change, p-values <.01). For lower parities and maternal ages, we do not observe an association between temperatures and SRBs.

Next, we test whether the second-trimester SRB reductions in India may be driven by determinants of sex-selective induced abortion practices in India. Culturally, a preference for sons over daughters and its manifestations have been shown to be stronger in northern states of India (36–38). In addition, sex-selective abortion is practiced particularly by women who already have multiple children but no or few male children among them yet (22–24).

Based on these determinants of sex-selective induced abortion prevalence among the Indian population, we additionally test the temperature-sex relationship across four categories (in a separate regression for each): Focusing on births of parities four and higher, we compare births by sonless mothers with births by mothers who previously had at least one male birth, in both northern and southern states[5]. We find a mostly insignificant but strong association between temperatures and SRBs for births by sonless mothers in the North, and no association for the other groups. For births by sonless mothers in the North, we observe a large reduction in male birth probability by .183 percentage points for a 20-25°C day (or 2.77 percentage points for a 1-SD change, SD=15.2, p=.035). For the other heat bins, the effect estimates are similarly large (.147 and .123 percentage points) but fail to reach statistical significance (p=.091 and .167). For comparison, the temperature effect sizes are more than three times as larger in this subgroup than the parity differentials we observed in sub-Saharan Africa.

By contrast, SRBs by mothers with at least one previous male birth in the South – potentially the least likely to induce sex-selective abortion – do not respond to temperatures (p>0.3). Similarly, we identify no impact of temperatures on the SRBs by sonless mothers in the South, and mothers with at least one son in the North.

Contrasting these results with analogous models for sub-Saharan Africa as the placebo, we identify no second-trimester temperature-sex relationship in any of the subgroups by these maternal and child characteristics (see ***Appendix SI***, **Figures S7**). Although the coefficients are not statistically significant, a comparison of their direction among the subgroups even indicates the opposite pattern compared to India: Instead of a decrease in male births as seen in India, in sub-Saharan African, we observe an increase in the probability of male births among mothers with no/primary education, of higher parity, older maternal age, and those who have not had a prior male birth.

Discussion

We present evidence that temperatures before birth are associated with sex ratios at birth. Our results show a negative relationship between temperatures above >20°C and SRBs (i.e. fewer male births relative to female births) in both sub-Saharan Africa and India. However, we find

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[5] Category of northern states: Bihar, Delhi, Gujarat, Haryana, Himachal Pradesh, Jammu and Kashmir, Madhya Pradesh, Maharashtra, Punjab, Rajasthan, and Uttar Pradesh, after Kashyap and Behrman (2020).

substantive differences between the two regions. In sub-Saharan Africa, heat in the first semester decreases the SRB. The decreases are driven by births of mothers who reside in rural locations, have none or primary formal education, and are concentrated in birth orders of four and higher. In India, by contrast, where sex-selective induced abortions against girls because of son preference have led to a significant male-skew in SRBs (5), we find that heat in the second trimester decreases SRBs. Here, reductions are driven by high parities and high maternal age births. In addition, we find some indication that large SRB decreases occur in births of parities four and higher by sonless mothers in northern states of India.

Our findings indicate that both biological health responses and behavioral responses explain SRB reductions under heat. In sub-Saharan Africa we uncover social vulnerabilities to heat exposure that may be driven by direct physiological impacts on either conception or pregnancy survival (6, 8, 10, 11), but it is also highly likely that indirect mechanisms, such as temperature impacts on agricultural productivity and income generation, disease, and nutrition, also play a role (29, 30, 39) – insofar as they occur within short time lags captured in our gestational exposure period. As day of birth and gestational length information is only available in the more recent DHS, we are not able to disentangle whether temperatures are linked with a lower male conception probability under heat in the first place or intensified *in utero* mortality, but our analysis of monthly exposures points to the latter. In India, the concentrated timing of the shock (approx. 13th gestational week onwards), the heterogeneity pattern by sociodemographic characteristics, the magnitude of the effects observed for subgroups of the Indian population, and the cultural differences in son preference between India and sub-Saharan Africa suggest that fewer sex-selective induced abortions against girls take place when temperatures are above 20°C, resulting in a lower SRB.

The significant variations in SRBs following exposure to high temperatures, influenced by factors such as the mother's education, rural or urban residence, high parity, and advanced maternal age, indicate that these population subgroups are particularly vulnerable to heat stress. Our findings lend support to the Trivers-Willard hypothesis, which suggests that under adverse conditions during pregnancy – such as wars, terrorist attacks, and natural disasters – mothers are more likely to give birth to girls rather than boys (3). Although the evidence regarding the impact of maternal socioeconomic characteristics on SRBs remains mixed (40, 41), the skewed SRB observed among certain subgroups implies that mothers with lower levels of education who live in rural areas, for example, may have a reduced capacity to cope with extreme heat. As a result, they may struggle to protect their vulnerable male fetuses *in utero*.

The SRB variations we observe in response to temperatures are substantively large, given typical SRB variations both between and within populations over time (5). Additionally, our findings suggest that SRBs vary even under low levels of heat intensity from 20°C. Although temperatures at higher intensity occur frequently in the geographies under study and therefore have a relatively stronger impact on the SRB, even moderately high temperatures, measured on an absolute scale, may constitute heat stress for the maternal body and lead to behavioral responses that result in large SRB changes. Our sample has little variation in <15°C days, preventing us from identifying associations between cold and SRBs indicated in previous literature that uses data on the Global North (31).

This study has several limitations. Firstly, the survey data we use offers limited insight into individual exposure patterns, underlying health conditions, protective resources, and adaptive behaviors – factors that determine and socially stratify vulnerability to heat exposure. Secondly, the lack of information on the day of birth and gestational length may lead to exposure misclassification and prevents us from differentiating conception and in utero mortality channels, a line of inquiry hitherto unexplored. Thirdly, there may be other climatic exposures that moderate the effect of temperatures. While we include rainfall controls, future studies may explore the role of humidity, crop yields and other environmental factors in explaining SRB variations.

Overall, this study demonstrates that there is a sex-specific response to temperatures before birth driven by both biological and behavioral responses that lead to substantial impacts on reproduction and population composition. We invite scientists to further explore the potential role of moderating environmental influences, factors that buffer and increase vulnerability to exposure, and the specific direct and indirect mechanisms that link temperatures with SRBs.

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References

1. W. H. James, The human sex ratio. Part 1: A review of the literature. *Hum Biol* **59**, 721–752 (1987).
2. J. Bongaarts, C. Z. Guilmoto, How Many More Missing Women? Excess Female Mortality and Prenatal Sex Selection, 1970–2050. *Population and Development Review* **41**, 241–269 (2015).
3. R. L. Trivers, D. E. Willard, Natural selection of parental ability to vary the sex ratio of offspring. *Science* **179**, 90–92 (1973).
4. S. Song, Does famine influence sex ratio at birth? Evidence from the 1959–1961 Great Leap Forward Famine in China. *Proceedings of the Royal Society B: Biological Sciences* **279**, 2883–2890 (2012).
5. F. Chao, P. Gerland, A. R. Cook, L. Alkema, Systematic assessment of the sex ratio at birth for all countries and estimation of national imbalances and regional reference levels. *PNAS* **116**, 9303–9311 (2019).
6. A. Barreca, O. Deschenes, M. Guldi, Maybe Next Month? Temperature Shocks and Dynamic Adjustments in Birth Rates. *Demography* **55**, 1269–1293 (2018).
7. H. Cho, Ambient temperature, birth rate, and birth outcomes: evidence from South Korea. *Popul Environ* **41**, 330–346 (2020).
8. R. Conte Keivabu, M. Cozzani, J. Wilde, Temperature and fertility: Evidence from Spain. *Population Studies* 1–15 (2024). https://doi.org/10.1080/00324728.2024.2382152.
9. T. Hajdu, G. Hajdu, "Temperature, Climate Change, and Fertility" in *Handbook of Labor, Human Resources and Population Economics*, K. F. Zimmermann, Ed. (Springer International Publishing, 2020), pp. 1–25.
10. T. Hajdu, G. Hajdu, Temperature, climate change, and human conception rates: evidence from Hungary. *J Popul Econ* (2021). https://doi.org/10.1007/s00148-020-00814-1.

11. T. Hajdu, G. Hajdu, Climate change and the mortality of the unborn. *Journal of Environmental Economics and Management* **118**, 102771 (2023).
12. L. J. Marteleto, A. G. Maia, C. G. Rodrigues, Climate and fertility amid a public health crisis. *Population Studies* **77**, 437–458 (2023).
13. P. N. M. Bhat, A. J. F. Zavier, Fertility decline and gender bias in northern India. *Demography* **40**, 637–657 (2003).
14. P. N. M. Bhat, A. J. F. Zavier, Factors Influencing the Use of Prenatal Diagnostic Techniques and the Sex Ratio at Birth in India. *Economic and Political Weekly* **42**, 2292–2303 (2007).
15. S. H. Orzack, *et al.*, The human sex ratio from conception to birth. *Proceedings of the National Academy of Sciences* **112**, E2102–E2111 (2015).
16. R. Mace, R. Sear, Birth interval and the sex of children in a traditional African population: an evolutionary analysis. *J Biosoc Sci* **29**, 499–507 (1997).
17. J. C. Wells, Natural selection and sex differences in morbidity and mortality in early life. *J Theor Biol* **202**, 65–76 (2000).
18. A. Bonell, *et al.*, Environmental heat stress on maternal physiology and fetal blood flow in pregnant subsistence farmers in The Gambia, west Africa: an observational cohort study. *The Lancet Planetary Health* **6**, e968–e976 (2022).
19. D. Yüzen, I. Graf, A. Diemert, P. C. Arck, Climate change and pregnancy complications: From hormones to the immune response. *Front Endocrinol (Lausanne)* **14**, 1149284 (2023).
20. F. Chao, A. K. Yadav, Levels and trends in the sex ratio at birth and missing female births for 29 states and union territories in India 1990–2016: A Bayesian modeling study. *Foundations of Data Science* **1**, 177–196 (2019).
21. A. Singh, *et al.*, Factors Influencing the Sex Ratio at Birth in India: A New Analysis based on Births Occurring between 2005 and 2016. *Studies in Family Planning* **52**, 41–58 (2021).
22. A.-M. Aksan, Son preference and the fertility squeeze in India. *Journal of Demographic Economics* **87**, 67–106 (2021).
23. F. Arnold, M. K. Choe, T. K. Roy, Son Preference, the Family-building Process and Child Mortality in India. *Population Studies* **52**, 301–315 (1998).
24. R. D. Retherford, T. K. Roy, Effects of family composition on sex-selective abortion in Punjab, India. *Genus* **60**, 71–97 (2004).
25. L. de Montigny, R. Ling, J. Zacharias, The Effects of Weather on Walking Rates in Nine Cities. *Environment and Behavior* **44**, 821–840 (2012).
26. S. Saneinejad, M. J. Roorda, C. Kennedy, Modelling the impact of weather conditions on active transportation travel behaviour. *Transportation Research Part D: Transport and Environment* **17**, 129–137 (2012).
27. D. Samano, S. Saha, T. C. Kot, J. E. Potter, L. M. Duthely, Impact of Extreme Weather on Healthcare Utilization by People with HIV in Metropolitan Miami. *Int J Environ Res Public Health* **18**, 2442 (2021).
28. Y. Wu, T. A. Mooring, M. Linz, Policy and weather influences on mobility during the early US COVID-19 pandemic. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2018185118 (2021).
29. X. Cui, Q. Tang, Extreme heat and rural household adaptation: Evidence from Northeast China. *Journal of Development Economics* **167**, 103243 (2024).
30. F. M. Aragón, F. Oteiza, J. P. Rud, Climate change and agriculture: farmer adaptation to extreme heat. *IFS Working Papers* (2018).
31. R. Catalano, T. Bruckner, K. R. Smith, Ambient temperature predicts sex ratios and male longevity. *Proceedings of the National Academy of Sciences* **105**, 2244–2247 (2008).
32. S. Helle, S. Helama, J. Jokela, Temperature-related birth sex ratio bias in historical Sami: warm years bring more sons. *Biol Lett* **4**, 60–62 (2008).
33. M. Fukuda, *et al.*, Climate change is associated with male:female ratios of fetal deaths and newborn infants in Japan. *Fertility and Sterility* **102**, 1364-1370.e2 (2014).
34. A. Lerchl, Sex Ratios at Birth and Environmental Temperatures. *Naturwissenschaften* **86**, 340–342 (1999).
35. Guide to DHS Statistics (English). Available at:

https://dhsprogram.com/publications/publication-dhsg1-dhs-questionnaires-and-manuals.cfm [Accessed 19 September 2024].

36. S. Jayachandran, R. Pande, Why Are Indian Children So Short? The Role of Birth Order and Son Preference. *American Economic Review* **107**, 2600–2629 (2017).

37. T. Dyson, M. Moore, On Kinship Structure, Female Autonomy, and Demographic Behavior in India. *Population and Development Review* **9**, 35–60 (1983).

38. R. Kashyap, J. Behrman, Gender Discrimination and Excess Female Under-5 Mortality in India: A New Perspective Using Mixed-Sex Twins. *Demography* **57**, 2143–2167 (2020).

39. K. Grace, *et al.*, Exploring Strategies for Investigating the Mechanisms Linking Climate and Individual-Level Child Health Outcomes: An Analysis of Birth Weight in Mali. *Demography* **58**, 499–526 (2021).

40. A. Pennington, G. Maudsley, M. Whitehead, The impacts of profound gender discrimination on the survival of girls and women in son-preference countries - A systematic review. *Health & Place* **79**, 102942 (2023).

41. R. Takikawa, Y. Fukukawa, Sex differences in birth weight depending on the mother's condition: testing the Trivers-Willard hypothesis in Indian twins. *Evolution and Human Behavior* **45**, 41–47 (2024).

42. Z. Hausfather, K. Cowtan, M. J. Menne, C. N. Williams Jr., Evaluating the impact of U.S. Historical Climatology Network homogenization using the U.S. Climate Reference Network. *Geophysical Research Letters* **43**, 1695–1701 (2016).

43. M. Dell, B. F. Jones, B. A. Olken, What Do We Learn from the Weather? The New Climate-Economy Literature. *Journal of Economic Literature* **52**, 740–798 (2014).

44. H. Blencowe, *et al.*, National, regional, and worldwide estimates of preterm birth rates in the year 2010 with time trends since 1990 for selected countries: a systematic analysis and implications. *The Lancet* **379**, 2162–2172 (2012).

45. I. Harris, T. J. Osborn, P. Jones, D. Lister, Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Sci Data* **7**, 109 (2020).

Figures and Tables

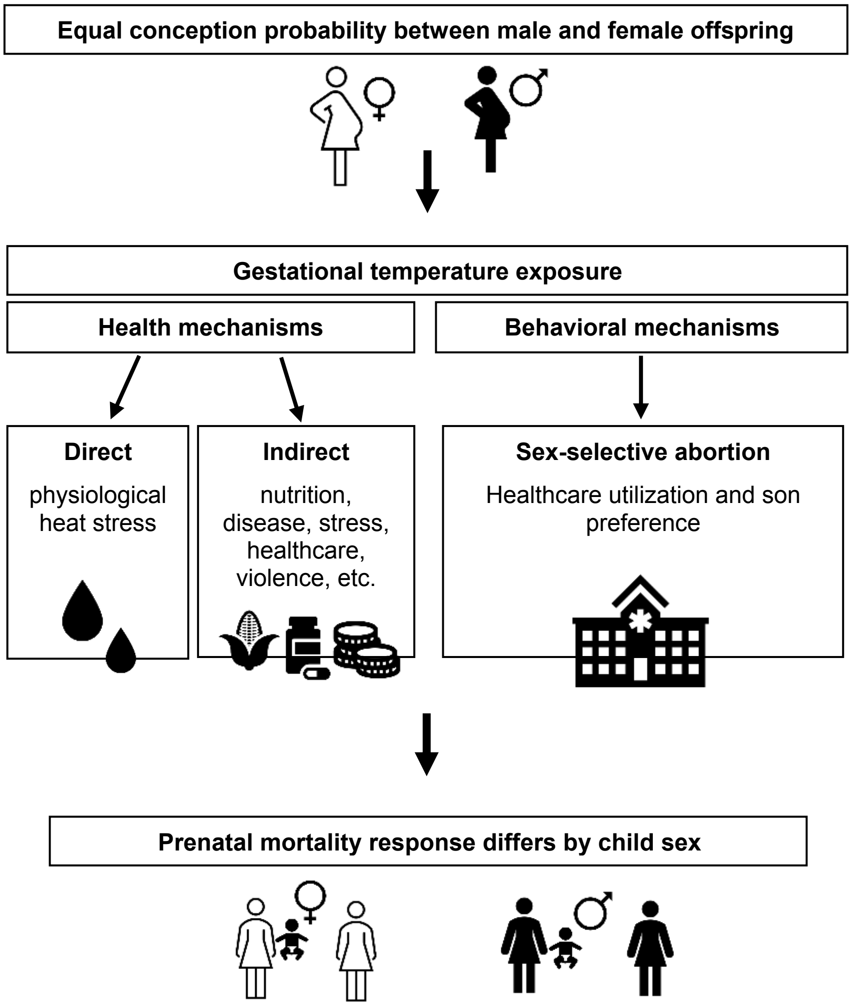

Figure 1. Conceptual framework on health and behavioral mechanisms in response to temperature exposure before birth that may cause sex-specific mortality responses

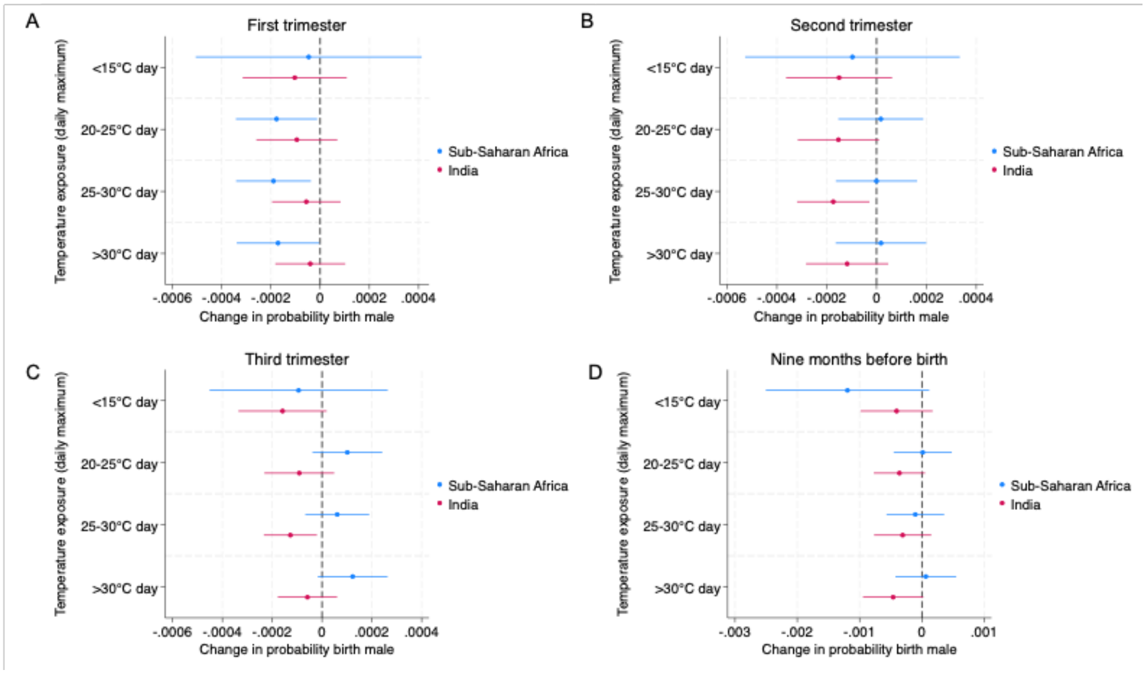

Figure 2. Associations between the number of days in the approximate gestational period that fall into a specified temperature bin and male birth in Sub-Saharan Africa and India. Estimates from a separate fixed effects linear probability model for each sub-Saharan Africa and India. Coefficients (dots) indicate the change in the probability of the birth being male, with 95% CIs (lines), for one additional day in the approximate gestational trimester where the daily maximum temperature falls into the specified temperature bin. Panel A-C show the association between temperature exposure in each gestational trimester and male birth, Panel D shows the association for temperature exposure in the month nine months before the birth month. A detailed description of methods is available in ***Data and Methods***, and detailed results in ***SI Appendix*** **Tables S3-4**.

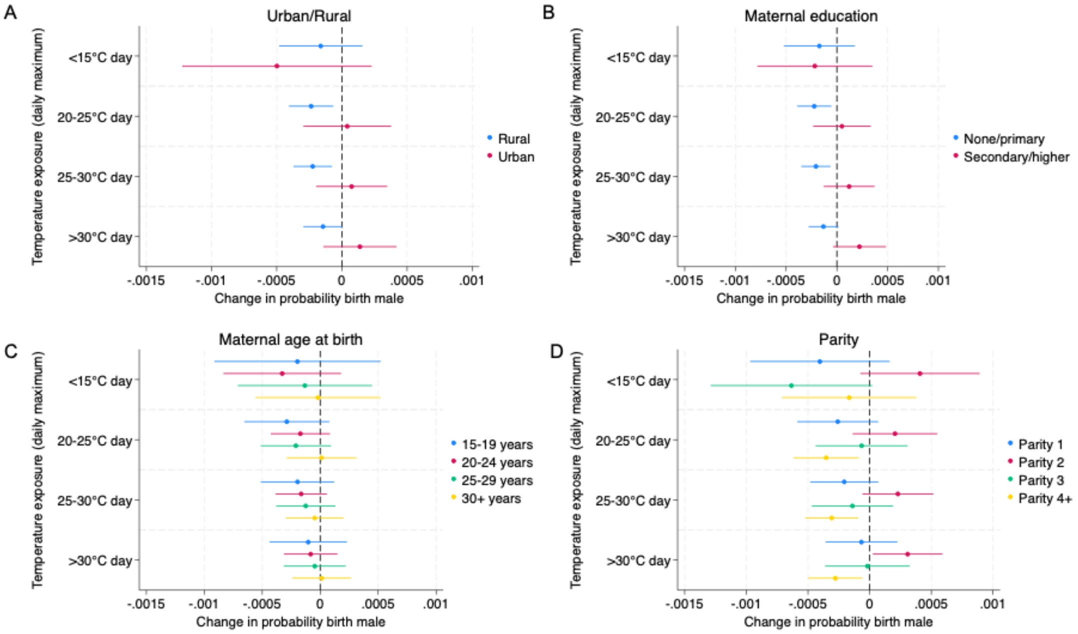

Figure 3. Associations between the number of days in the approximate first trimester that fall into a specified temperature bin and male birth in Sub-Saharan Africa by sociodemographic characteristics. Estimates from a separate fixed effects linear probability model for each sociodemographic subgroup. Coefficients (dots) indicate the change in the probability of the birth being male, with 95% CIs (lines), for one additional day in the approximate second trimester where the daily maximum temperature falls into the specified temperature bin. The panels show the association between temperature exposure in the first gestational trimester and male birth for births in urban/rural classifications of the cluster of the mother's residence (Panel A), for births by mothers with no or primary and secondary or higher educational attainment (Panel B), for births by mothers at different completed maternal ages at birth (Panel C), and by birth order (Panel D). A detailed description of methods is available in ***Data and Methods***.

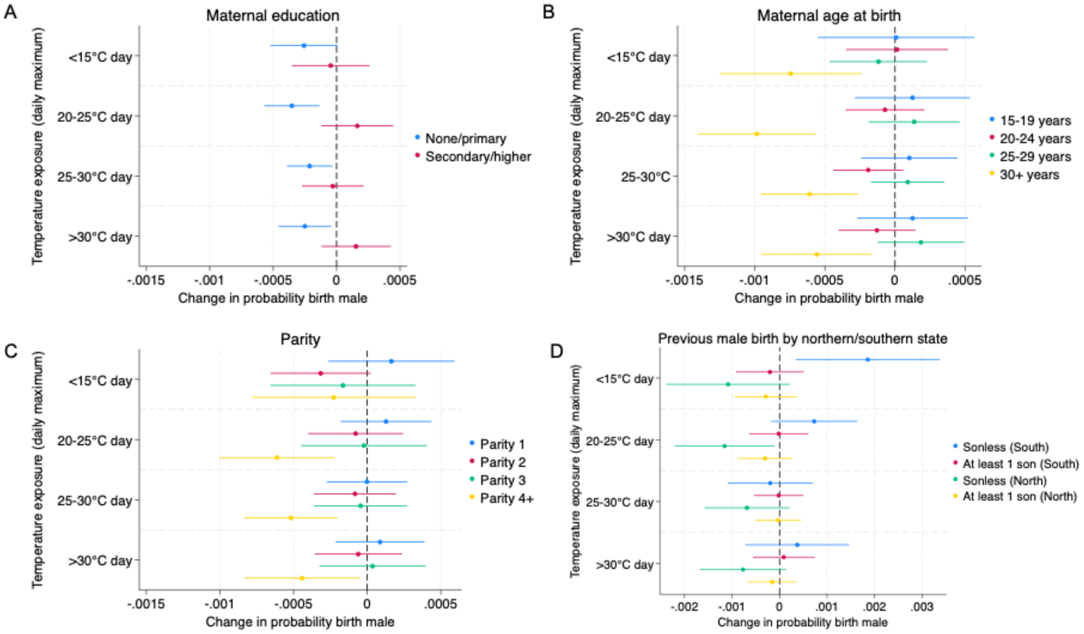

Figure 4. Associations between the number of days in the approximate second trimester that fall into a specified temperature bin and male birth in India by sociodemographic characteristics. Estimates from a separate fixed effects linear probability model for each sociodemographic subgroup. Coefficients (dots) indicate the change in the probability of the birth being male, with 95% CIs (lines), for one additional day in the approximate second trimester where the daily maximum temperature falls into the specified temperature bin. The panels show the association between temperature exposure in the second gestational trimester and male birth for births by mothers with no or primary and secondary or higher educational attainment (Panel A), for births by mothers at different completed maternal ages at birth (Panel B), by birth order (Panel C), and for sonless mothers and mothers with at least 1 previous male birth in northern/southern states of India (Panel D). A detailed description of methods is available in ***Data and Methods***.