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Temperature change and male infertility prevalence: an ecological study

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Abstract

Background Although the effects of climate change on human health are widely recognized, its potential role in male infertility prevalence has not been thoroughly examined. This study seeks to explore the association between changes in ambient temperature and the prevalence of male infertility.

Methods This ecological study encompassed 174 countries and regions. We utilized data from 2000 to 2019 on the age-standardized prevalence rate (ASPR) of male infertility and ambient temperature to assess their potential association. The analysis accounted for several covariates, including the Sociodemographic Index (SDI), continent, smoking prevalence, alcohol consumption per capita (APC), nitrogen dioxide (NO_2), and ozone (O_3). Annual temperature values were derived by averaging monthly temperatures, and the deviance percentage of temperature (DPT) was computed based on the 20-year mean temperature. To examine spatial and nonlinear relationships between temperature and male infertility ASPR, we applied the geographic detector approach and Restricted Cubic Spline (RCS) curves. Furthermore, linear mixed-effects models were employed to quantify the association between DPT and male infertility ASPR, and adjusted models were subsequently used to forecast changes in ASPR under projected temperature scenarios for 2020–2030.

Results From 2000 to 2019, a spatial association was identified between temperature and the ASPR of male infertility. Additionally, a U-shaped correlation emerged, indicating the lowest ASPR at 15.7 °C. Higher DPT were linked to elevated male infertility ASPR, with an adjusted β estimate of 38.770 (95% CI: 8.392, 69.162). Projections suggest that ongoing temperature increases may continue to drive up male infertility ASPR.

Conclusion Temperature change may be associated with an increased male infertility prevalence.

Keywords Climate change, Reproductive health, Male infertility, Ecological study

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Background

Male infertility is defined as the inability of the female partner to conceive naturally within one year of regular sexual intercourse without the use of contraception, due to pathological conditions in the male partner [1]. It affects approximately 7% of the global male population and is an increasingly serious public health concern [2]. Meta-analyses have shown that global semen quality is declining at an accelerating rate, with sperm concentration and total sperm count decreasing by more than 50% between 1973 and 2018 [3, 4]. Additionally, epidemiological studies reported approximately 570 million cases of male infertility worldwide in 2019, representing a 76.9% increase since 1990 [5]. The decline in male fertility imposes a substantial socioeconomic burden and contributes to the ongoing decrease in fertility rates.

Male infertility is associated with multiple causes and risk factors, which can be broadly categorized into biological/physiological/genetic, lifestyle, environmental, and sociodemographic factors [6]. Among environmental factors, there is substantial evidence that air pollution, exposure to toxic chemicals, and excessive heat exposure contribute to reduced male fertility [7]. In recent years, dramatic changes in the global climate have led to increasing impacts on the thermal environment worldwide. Whether the decline in male fertility is linked to the rise in global average temperature, or the increased frequency of extreme weather events (such as heat waves and cold waves) has attracted growing attention. Evidence from various biological populations (including guppies, chickens, mice, cattle, and pigs) indicates that the reproductive system and related reproductive physiology are highly sensitive to heat stress [8]. Moreover, studies in humans have demonstrated that spermatogenesis is particularly sensitive to temperature, with both low and high temperatures leading to reductions in semen concentration, sperm count, and sperm motility [9, 10]. Although humans can maintain thermal homeostasis within certain limits, a long-term rise in global average temperature may increase heat exposure and pose potential risks to reproductive health. Therefore, it is hypothesized that changes in environmental temperature associated with climate change may contribute to declining fertility in organisms [11, 12].

To date, direct evidence linking temperature change to the decline in male fertility remains limited. Previous studies have primarily focused on the short-term effects of environmental temperature (particularly high temperature) on semen parameters, while research investigating the long-term impact of temperature trends on male reproductive health is still scarce. Furthermore, most existing studies are based on data from experimental animals or conducted at the individual level, lacking analyses using large-scale population data, which limits the generalizability of the findings. Considering these gaps, we designed an ecological study using ERA5 (Fifth Generation ECMWF Reanalysis for the Global Climate) temperature data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and GBD (Global Burden of Disease) data on male infertility prevalence to preliminarily explore the association between temperature change and male fertility. We hypothesized that rising global temperatures may be associated with an increased burden of male infertility.

Methods

Sources of data

This study mainly relied on data from the GBD database, including the age-standardized prevalence rate (ASPR) of male infertility, smoking prevalence, estimates of air pollution exposure (nitrogen dioxide [NO_2] and ozone [O_3]), and the Sociodemographic Index (SDI). Ambient temperature information was extracted from the ERA5 dataset, while future temperature projections for 2020–2030 were obtained from the sixth phase of the Coupled Model Intercomparison Project (CMIP6). Additionally, data on age-standardized male alcohol consumption per capita (APC) were sourced from the Global Health Observatory (GHO).

The GBD database is a comprehensive resource that quantifies the burden of diseases, injuries, and risk factors in global health. It provides estimates of mortality, prevalence, and associated risk factors, offering valuable insights for public health research [13]. In this study, we collected data on ASPR male infertility from 174 countries and regions between 2000 and 2019. The list of the countries/regions included in this study is provided in Table S1, and the selection process is detailed in Figure S1.

The ERA5 reanalysis dataset is provided by ECMWF through the Copernicus Climate Change Service. ERA5 is based on the Integrated Forecasting System Cy41r2, which became operational in 2016. It provides data on atmospheric, land surface, and ocean wave variables from 1950 to date, with an hourly temporal resolution and a spatial resolution of 0.25° × 0.25° (~31 km) [14]. ERA5 has been widely applied in climate monitoring, weather forecasting, and environmental health research, and is recommended by the World Meteorological Organization (WMO) and the Intergovernmental Panel on Climate Change (IPCC) for climate-related studies. Temperature data spanning 2000 to 2019 were obtained from the ERA5 dataset for 174 countries and regions. Further details regarding the CMIP6 and GHO databases have been documented in prior publications [15, 16].

Assessment of male infertility prevalence

Within the GBD framework, infertility is identified through fertility-related questions posed in population surveys targeting married or cohabiting women. Since these surveys do not indicate which partner is infertile, estimates of male-attributable infertility were derived from a systematic literature review conducted for GBD 2010. Male infertility cases were classified using specific ICD codes: ICD-9 codes 606–606.9, V26.5, V26.52, and ICD-10 codes N46–N46.02, N46.022–N46.12, N46.122–N46.9 [17]. Couple infertility prevalence was modeled using Disease Modelling Meta-Regression (DisMod-MR 2.1) [18], and the prevalence of male infertility was subsequently calculated by applying the male-attributable proportion to the overall couple infertility estimates. Survey data were then aggregated according to GBD age groupings, and male infertility ASPR was computed using the GBD standard population structure.

Assessment of ambient temperature

In this study, we defined ambient temperature as the air temperature measured at 2 m above the surface. The data comprise global gridded information with a horizontal resolution of 0.5° x 0.5° and were sourced from the ERA5 monthly averaged data on single levels from 1940 to present dataset [19]. We utilized the GBD national administrative region shapefile to extract monthly temperature data using the zonal statistics tool in ArcGIS software. Since the GBD only provided annual prevalence estimates, the monthly temperature data were averaged over 12 months to estimate the annual temperature. The deviance percentage of temperature (DPT) served as a metric to measure how much annual temperature values deviated from the long-term average trend [20]. Specific calculation methods for DPT are outlined in the supplementary materials.

CMIP6 proposed the concept of Shared Socioeconomic Pathways (SSPs) to illustrate possible future societal trajectories without considering the effects of climate change or related policies. SSP126 reflects a sustainable development path with minimal greenhouse gas emissions, whereas SSP585 depicts a fossil fuel–driven, high-emission scenario. SSP245 and SSP370 represent intermediate pathways that lie between these two ends of the spectrum [21]. We selected data from the Community Earth System Model Version 2 (CESM2) Global Climate Model from the United States and extracted temperature data for 2020–2030 under four shared socioeconomic pathways (SSP126, SSP245, SSP370, and SSP585) using the same method as described above.

Assessment of covariates

To reduce potential confounding, we incorporated the Sociodemographic Index (SDI), lifestyle variables such as smoking prevalence and APC, as well as air pollution indicators including NO_2 and O_3. Additionally, we considered the continent of each country or region to capture broader geographic and environmental effects.

SDI is a comprehensive indicator for measuring the level of regional economic development. A higher SDI reflects a more developed economy. It is calculated as the geometric mean of three components, each indexed from 0 to 1: the total fertility rate under 25 years of age (TFU25), the average educational attainment for individuals aged 15 years and older (EDU15+), and the lagged distributed income per capita (LDI) [22]. In this study, we primarily used SDI to control for the potential impact of socioeconomic factors on male infertility prevalence.

Smoking prevalence refers to the proportion of individuals who use tobacco products either daily or occasionally. To estimate both current and former tobacco use rates, the GBD database integrates information from 3,625 nationally representative surveys using a space-time Gaussian process regression model [23].

APC is defined as the annual volume of pure alcohol consumed per individual aged 15 and above, expressed in liters. This measure combines the 3-year average of both recorded and unrecorded alcohol use, with adjustments for the 3-year average of alcohol intake by visitors. Recorded consumption is derived from official data sources such as production, trade, and taxation records, whereas unrecorded consumption pertains to alcohol not subject to governmental regulation or taxation. Visitor consumption reflects the alcohol use of tourists and citizens while abroad [24].

Furthermore, the GBD database provides estimates of NO_2 and O_3 levels using previously established calculation methods [25].

Statistical method

Continuous variables were presented as means along with their standard deviations (SDs). Based on GBD classification, SDI was categorized into five groups: Low, Low-middle, Middle, High-middle, and High [22].

The analysis was divided into two main stages. In the first stage, geographic detectors and restricted cubic spline (RCS) curves were employed to explore the spatial and nonlinear associations between average temperature and male infertility ASPR from 2000 to 2019. Geographic detectors are statistical tools designed to detect spatial heterogeneity and its potential influencing factors [26]. The method assumes that if an independent variable has a significant effect on a dependent variable, their spatial patterns will align or be correlated. In this research, we utilized the heterogeneity and factor detection components of the geographic detector method to assess the spatial variability of Y and the explanatory power of factor X, quantified by the q value—where a higher q value signifies a stronger spatial association. For further details on q value computation, see the supplementary materials. We calculated q values to evaluate the spatial relationships between temperature, SDI, smoking prevalence, APC, NO_2, O_3, continents, and male infertility ASPR. To fulfill the analytical needs of the geographic detector, quintile categorization was applied to average values of temperature, smoking prevalence, APC, NO_2, and O_3 across the 2000–2019 period. Additionally, RCS curves with three knots were constructed to analyze the nonlinear link between temperature and ASPR of male infertility, with adjustments for SDI, smoking prevalence, APC, NO_2, O_3, and continent.

Second, we assessed the relationship between DPT and male infertility ASPR from 2000 to 2019 using a linear mixed-effects model. In this model, country codes were included as random effects, while adjustments were made for SDI, smoking prevalence, APC, NO_2, O_3, and continent. Subgroup analyses were conducted by stratifying the data according to SDI and continent. Additionally, we used GBD regional classifications to investigate geographic differences in the association between DPT and male infertility ASPR [27]. In addition, we calculated the coefficient of variation of the monthly temperature data for each year to capture intra-annual temperature fluctuations, and further employed adjusted linear mixed effects models to investigate the association between annual temperature variability and male infertility prevalence.

Predicted temperature data for 2020–2030 under four SSP scenarios (SSP126, SSP245, SSP370, and SSP585) were applied to estimate the potential influence of future temperature changes on male infertility ASPR and to evaluate projected trends. These temperature projections were used to compute DPT values for each corresponding year. The resulting DPT values for 2020–2030 were then incorporated into the linear mixed-effects model described earlier to estimate future male infertility ASPR across the four SSP scenarios. To assess the impact of long-term temperature changes on the trend in male infertility prevalence, we also predicted prevalence for the years 2040, 2060, 2080, and 2100 using the same methodology described above.

To assess the robustness of our results, three sensitivity analyses were performed: (1) In the first stage of analysis, geographic detectors and RCS curves were applied to examine the relationship between temperature and male infertility ASPR at three specific time points—2000, 2010, and 2019. (2) A square root transformation was applied to the male infertility ASPR data from 2000 to 2019 to approximate a normal distribution, after which the second-stage analysis was repeated. (3) We incorporated additional data on temperature, male infertility ASPR, SDI, smoking prevalence, NO_2, and O_3 for the period 1990–1999 and repeated the primary analysis. Since APC data were not available for these years, adjustments were limited to SDI, smoking prevalence, NO_2, O_3, and continent. All statistical analyses were performed using R software (version 4.3.1) and ArcGIS (version 10.8), with a significance threshold set at $P < 0.05$.

Results

Study countries/regions characteristics

Between 2000 and 2019, the global mean temperature was 19.11 °C with a standard deviation (SD) of 8.21 °C. The average estimated exposure levels for NO_2 and O_3 were 5.37 ppb (3.60 ppb) and 40.43 ppb (9.81 ppb), respectively. Table 1 provides a breakdown of temperature and air pollution exposure values stratified by continent and SDI. During the same period, the global average male infertility ASPR was 1108.50 per 100,000 population (513.51), while the average smoking prevalence and APC were 0.31% (0.13%) and 8.95 L/year (6.82 L/year), respectively. Table 2 shows the distribution of smoking prevalence and APC by continent and SDI.

Figure 1a displays the spatial distribution of average temperature and male infertility ASPR over the two-decade period. Regions such as sub-Saharan Africa, North Africa, the Middle East, and South Asia experienced relatively higher temperatures, whereas North America, Europe, and East Asia had lower average temperatures. Meanwhile, elevated male infertility ASPR was observed in the Caribbean, sub-Saharan Africa, Europe, and East Asia. Although no direct correlation was apparent between regional temperature averages and male infertility ASPR, higher ASPR tended to be observed in warmer areas.

Table 1 The characteristics of temperature and environmental factors between 2000–2019 by continents and SDI

Variables	Temperature (℃)	NO_2 (ppb)	O_3 (ppb)
Global	19.11 (8.21)	5.37 (3.60)	40.43 (9.81)
Continents			
Africa	24.33 (3.30)	2.74 (1.70)	38.13 (7.69)
Asia	18.60 (8.39)	7.16 (4.14)	48.71 (9.72)
Europe	8.88 (4.14)	7.75 (2.23)	42.69 (5.13)
North America	22.69 (7.62)	4.88 (3.41)	36.12 (6.68)
Oceania	23.14 (5.09)	1.63 (2.14)	24.01 (6.54)
South America	20.86 (5.12)	6.34 (2.17)	31.39 (4.58)
SDI			
Low	24.17 (4.17)	2.56 (1.31)	38.20 (9.54)
Low-middle	21.09 (7.27)	4.48 (2.55)	39.80 (10.53)
Middle	19.46 (6.81)	5.67 (3.01)	40.09 (9.94)
High-middle	15.13 (8.14)	8.11 (3.66)	43.52 (9.38)
High	8.99 (7.04)	9.05 (3.30)	42.46 (7.57)

All values were calculated as the average (SD) of 2000–2019

SDI: sociodemographic index. NO_2, nitrogen dioxide. O_3, ozone

Table 2 The characteristics of male infertility prevalence and lifestyle factors between 2000–2019 by continents and SDI

Variables	Male infertility prevalence (per 100,000 population)	Smoking prevalence (%)	APC (L/year)
Global	1108.50 (513.51)	0.31 (0.13)	8.95 (6.82)
Continents			
Africa	1298.48 (696.51)	0.23 (0.10)	6.61 (5.90)
Asia	951.54 (316.31)	0.38 (0.13)	4.95 (5.46)
Europe	1089.44 (394.13)	0.37 (0.09)	17.31 (4.36)
North America	1135.83 (439.49)	0.21 (0.07)	9.11 (3.61)
Oceania	999.46 (276.44)	0.44 (0.15)	6.24 (5.80)
South America	930.84 (417.63)	0.26 (0.09)	9.68 (2.39)
SDI			
Low	1226.14 (691.31)	0.25 (0.12)	5.15 (5.54)
Low-middle	1025.51 (481.14)	0.31 (0.14)	6.96 (4.51)
Middle	1097.16 (354.93)	0.35 (0.13)	8.85 (5.76)
High-middle	1154.16 (385.46)	0.36 (0.11)	13.03 (7.67)
High	937.33 (322.47)	0.29 (0.09)	15.53 (4.72)

All values were calculated as the average (SD) of 2000–2019

SDI, Sociodemographic Index. APC, alcohol consumption per capita

Global temperatures exhibited a fluctuating upward trend from 2000 to 2019 (Fig. 1b). Male infertility ASPR showed constant fluctuations between 2000 and 2010; however, from 2010 to 2019, a notable and rapid increase was observed (Fig. 1c).

Ambient temperature and male infertility prevalence

Results from the geographic detector analysis indicated a spatial correlation between temperature and male infertility ASPR, with a q-value of 0.216 and statistical significance ($P<0.05$). However, no significant spatial associations were found between male infertility ASPR and SDI, smoking prevalence, APC, NO_2, O_3, or continent ($P>0.05$) (Fig. 2a).

Additionally, the RCS curve revealed a U-shaped nonlinear association between temperature and male infertility ASPR, with statistical evidence supporting both nonlinearity ($P<0.001$) and the overall relationship ($P=0.001$). The minimum ASPR was observed at a temperature of 15.7 °C (Fig. 2b).

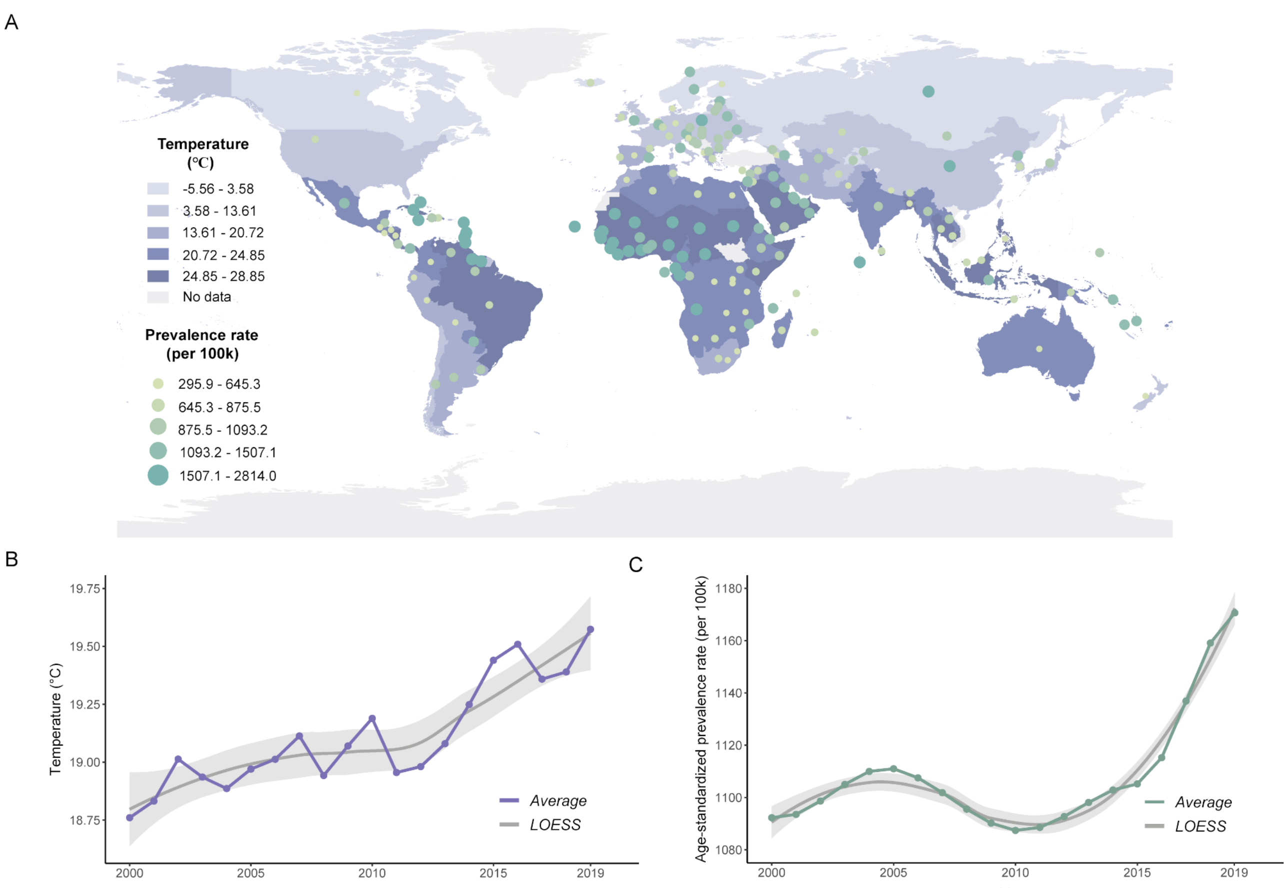

Fig. 1 Distribution and trends of temperature and male infertility prevalence from 2000 to 2019. **a**. A global map showing the local mean temperature for 2000–2019, divided into five intervals ranging from −5.56 to 28.85 °C, with color-coded dots representing the intensity of the local mean prevalence rate (ranging from 295.9 to 2814.0 cases per 100,000 population) for each country over the 2000–2019 period. **b**. The change in global temperature from 2000 to 2019. **c**. The change in global male infertility prevalence from 2000 to 2019. LOESS, locally estimated scatterplot smoothing

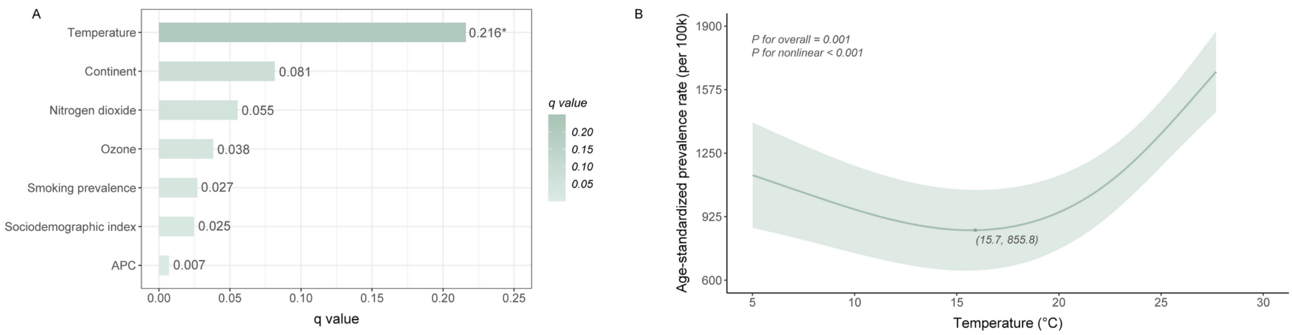

Fig. 2 Association between mean temperature and mean male infertility prevalence, 2000–2019. **a**. Spatial association between mean temperature and mean prevalence of male infertility. APC, alcohol consumption per capita. * $P < 0.05$. **b**. Nonlinear association between mean temperature and mean prevalence of male infertility

Table 3 Association between DPT and prevalence of male infertility between 2000–2019

Group	β (95% CI)[#]	*P*
Global	38.770 (8.392, 69.162)	0.013
SDI		
Low SDI	-99.716 (-217.289, 16.477)	0.098
Low-middle SDI	13.256 (-76.054, 102.723)	0.774
Middle SDI	176.588 (104.987, 249.012)	< 0.001
High-middle SDI	16.329 (-17.220, 50.033)	0.347
High SDI	22.442 (3.166, 41.926)	0.025
Continents		
Asia	81.179 (16.237, 146.244)	0.016
Europe	17.802 (-9.169, 44.784)	0.200
Africa	-40.708 (-127.549, 46.185)	0.363
North America	124.436 (49.634, 198.899)	0.002
South America	212.999 (98.873, 327.514)	< 0.001
Oceania	-2.872 (-57.341, 51.193)	0.921

Adjustments were made for SDI, Continent, Smoking prevalence, APC, NO_2, and O_3

DPT, deviance percentage of temperature

[#]Unit: per 100,000 population

DPT and male infertility prevalence

At the global level, DPT showed a positive correlation with male infertility ASPR, with an adjusted β of 38.770 and a 95% CI of 8.392 to 69.162 (Table 3). This suggests that a 1-unit increase in DPT corresponds to a rise of 38.770 cases per 100,000 population in male infertility ASPR. Results from subgroup analyses by SDI, continent, and region are detailed in Table 3 and illustrated in Fig. 3.

When stratified by SDI, the association between higher DPT and male infertility ASPR reached statistical significance only in the middle and high SDI categories. By continent, a significant association was observed in Asia and the Americas. On a regional scale, the positive link between DPT and ASPR was evident in Southeast Asia, Andean Latin America, North Africa, and the Middle East. We found no significant association between annual temperature fluctuations and the prevalence of male infertility (Table S2).

Future male infertility prevalence

Across all SSP scenarios, projections indicated a rising trend in male infertility ASPR. From 2020 to 2030, however, no notable differences in ASPR were detected among the various SSP scenarios (Fig. 4). However, over a longer time horizon, the prevalence of male infertility increased progressively across SSP126, SSP245, SSP370, and SSP585 (Figure S2). North Africa and the Middle East are projected to experience higher levels of male infertility ASPR compared to the global average, whereas Southeast Asia and Andean Latin America are expected to have lower levels (Fig. 4).

Sensitivity analysis

The sensitivity analyses further reinforce the robustness of our main findings. First, the analysis using geographic detectors and RCS curves at three time points (2000, 2010, and 2019) yielded results consistent with those of our primary analysis (Table S3, Figure S3). In addition, the relationship between DPT and male infertility ASPR remained consistent following a square root transformation (Table S4). Summary statistics for temperature, male infertility prevalence, and relevant covariates spanning 1990 to 2019 are presented in Table S5 and S6, with trend patterns visualized in Figure S4. Following the inclusion of data from 1990 to 1999, geographic detector analysis continued to support a spatial link between temperature and male infertility ASPR, and the adjusted RCS curves maintained the previously observed U-shaped nonlinear relationship (Figure S5). Although incorporating earlier data slightly reduced the statistical strength of the association between DPT and male infertility prevalence, the direction of the effect remained aligned with the initial findings (Table S7).

Discussion

This study explored the association between temperature variation and the prevalence of male infertility over the past two decades. The results indicated a spatial correlation between temperature and male infertility ASPR.

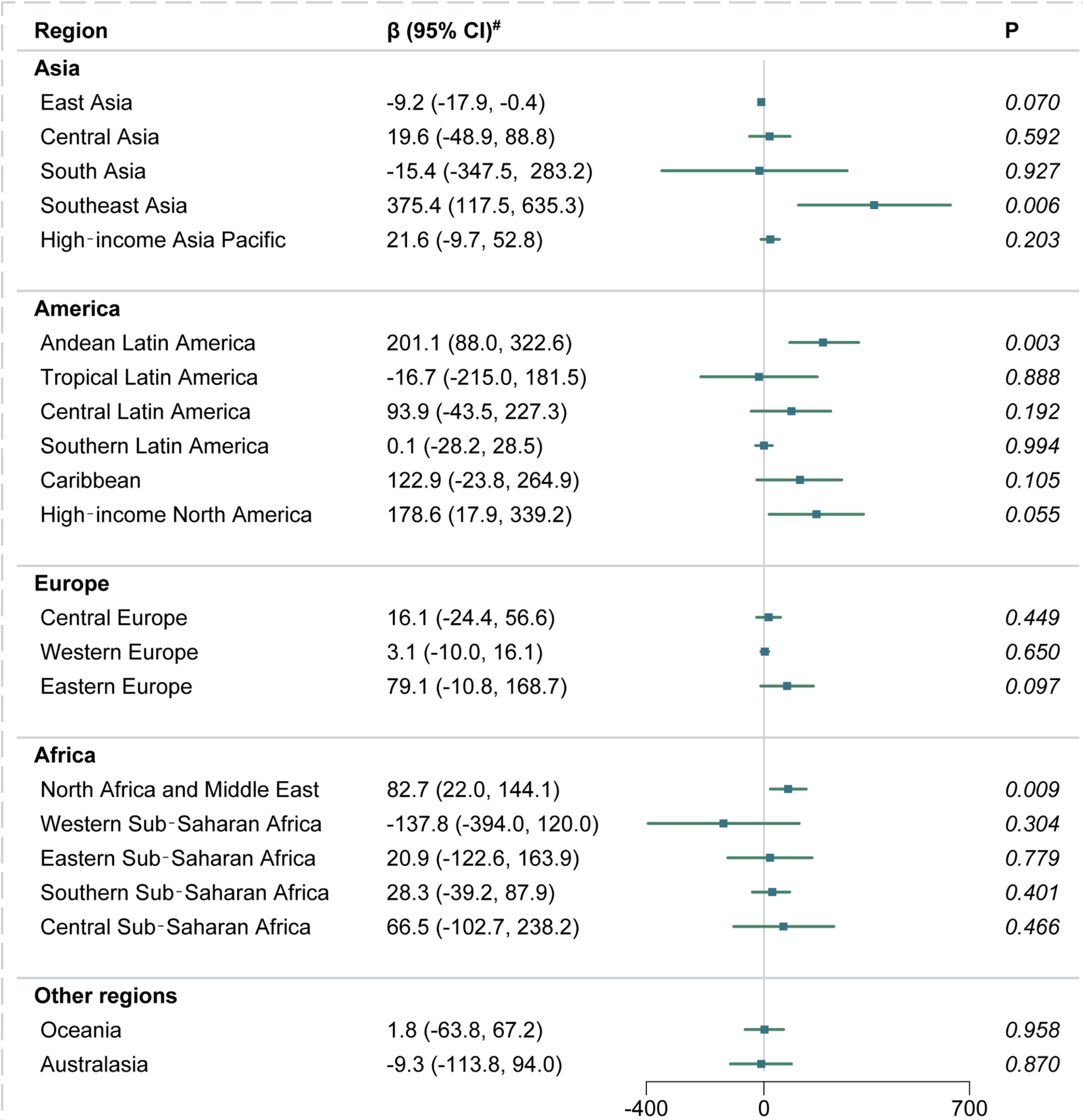

Fig. 3 Subgroup analysis of the association between DPT and prevalence of male infertility, 2000–2019. Adjustments were made for the sociodemographic index, smoking prevalence, alcohol consumption per capita, NO_2, and O_3 levels. DPT, deviance percentage of temperature. #Unit: per 100,000 population

Additionally, a U-shaped pattern was identified in the relationship between temperature and ASPR. Larger deviations in annual temperature from long-term averages were linked to higher male infertility ASPR. Projections suggest that future temperature increases may further elevate male infertility prevalence.

Unsuitable ambient temperatures may negatively affect male reproductive health. Previous studies have demonstrated that exposure to high temperatures can impair male fertility [28–30]. Additionally, Wang C et al. conducted a retrospective study analyzing semen samples from 11,877 men to investigate the exposure-response relationship between environmental temperature and semen parameters [9]. Their results indicated a U-shaped exposure-response curve, suggesting that both extremely low and high temperatures impacted semen

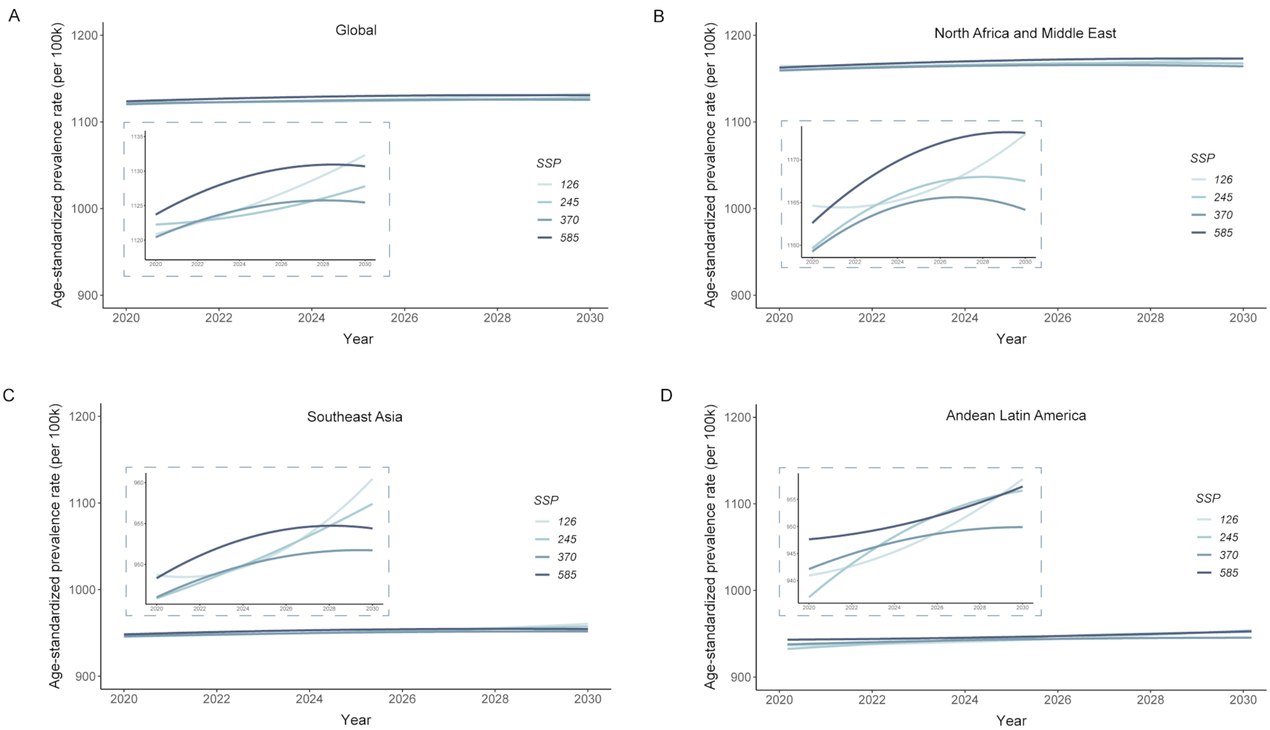

Fig. 4 Projections of male infertility prevalence changes under SSP126, SSP245, SSP370, and SSP585. **a**. Global prediction. **b**. Prediction for North Africa and the Middle East. **c**. Prediction for Southeast Asia. **d**. Prediction for Andean Latin America. The dotted box shows the enlarged image

quality adversely. Similarly, Zhou Y et al. conducted a longitudinal study involving 10,802 volunteers in China and observed that both lower and higher ambient temperature exposures, compared with the optimal temperature, were associated with decreased semen quality [10]. Consistent with previous research, our study observed a U-shaped relationship between temperature and male infertility ASPR, with the lowest prevalence occurring at moderate temperatures (approximately 16 °C). However, unlike prior studies that primarily focused on individual semen parameters or specific regional populations, our study investigated the association between temperature and male infertility prevalence at a global scale, providing insights into potential population-level factors influencing male infertility.

Studies directly examining the impact of temperature changes on male fertility remain limited, making comparisons with previous research challenging. However, Jorgensen et al. reported seasonal variations in sperm concentration and total sperm count among European men, with values in summer reduced to approximately 70% of those in winter [31]. Similar seasonal patterns were observed in studies by Gyllenborg et al. and Tjoa et al. [32, 33], suggesting that the change of environmental heat exposure may influence male fertility. Evidence from animal studies further supports this hypothesis. Souza et al. conducted a climate-controlled chamber experiment simulating the IPCC's 2100 climate scenario to assess the effects of climate change on male zebrafish reproductive function [34]. Their findings revealed a significant reduction in the gonadosomatic index, decreased sperm production, and increased germ cell shedding and apoptosis, potentially driven by oxidative stress, upregulation of pro-apoptotic genes, and DNA damage. Similarly, Breckels et al. found that rising temperatures reduced sperm length and motility in guppies, highlighting the sensitivity of sperm performance to warming conditions [35]. Although a substantial difference in species exists between fish and humans, these findings may provide valuable insights into the potential effects of climate change on male fertility.

The association between temperature change and male infertility ASPR was more pronounced in middle- and high-SDI regions, as well as in specific areas such as Southeast Asia, Andean Latin America, North Africa, and the Middle East. Several factors may explain these patterns. In higher-SDI regions, more advanced healthcare infrastructure, better diagnostic capabilities, and more comprehensive infertility reporting systems may enhance the detection of associations between environmental exposures change and male infertility. Moreover, higher levels of industrialization, greater exposure to environmental pollutants, and lifestyle factors (e.g., smoking and alcohol consumption) may amplify the adverse effects of temperature on male reproductive health. Urbanization and the urban heat island effect in these regions may further exacerbate temperature-related risks. In contrast, low-SDI regions may experience challenges such as limited healthcare access, underreporting of infertility, and incomplete data collection, potentially masking the temperature-infertility relationship. In regions such as Southeast Asia, Andean Latin America, North Africa, and the Middle East, the combination of high exposure to extreme temperatures and socio-economic disparities may increase vulnerability to heat-related reproductive health risks. Collectively, these findings underscore the need for further research to investigate the complex interplay between temperature change, environmental exposures, and social determinants of health, particularly in the context of accelerating climate change. Additionally, our study projected that future temperature increases will lead to a continued rise in male infertility ASPR. These findings suggest that public health authorities should place greater emphasis on male infertility prevention and control. Furthermore, climate change, as a potential risk factor affecting reproductive health, warrants further investigation.

Regarding climate change, the impact of rising ambient temperatures on male reproductive health remains unclear. Increased heat exposure and elevated scrotal temperature are considered important contributors to declining male fertility. Under physiological conditions, scrotal temperature is maintained at 2–4 °C lower than core body temperature, with the temperature within the testes closely reflecting the surrounding scrotal skin temperature. Any factor that elevates scrotal temperature may disrupt spermatogenesis [36]. Evidence suggests that prolonged exposure to high temperatures can impair the scrotum's thermoregulatory capacity, while even a 1–1.5 °C increase in scrotal temperature may reduce sperm production and induce abnormal sperm morphology [37, 38]. The underlying mechanisms are thought to involve increased testicular oxygen consumption, insufficient blood supply, local hypoxia, oxidative stress, and elevated sperm DNA fragmentation [39, 40]. Short-term increases in scrotal temperature may also reversibly reduce the expression of key proteins essential for sperm flagellar structure and function, thereby impairing sperm motility [41]. Furthermore, heat exposure has been shown to downregulate mitochondrial activity and decrease ATP synthesis, leading to reduced sperm motility [42]. Recent studies have reported that sub chronic increases in ambient temperature may induce epigenetic alterations in sperm, potentially affecting male reproductive function [43]. Although animal studies have demonstrated that ambient temperature can impair male fertility by disrupting sex hormone production, evidence from human studies remains limited, suggesting that hormonal changes may not represent the primary mechanism [44].

Strength and limitations

A key strength of this study is the inclusion of data from a wide range of regions and the use of high-quality, reliable datasets, which contribute to the robustness of the findings. Nonetheless, several limitations should be acknowledged: (1) As an ecological study, the observed association between ambient temperature and male infertility ASPR cannot be interpreted as causal, and further research is required to confirm any causal link; (2) The study relies on data aggregated at a broad spatial scale, which limits the ability to precisely evaluate individual-level exposure, making it necessary to exercise caution when extrapolating these results to individuals; (3) Variations in healthcare infrastructure and medical conditions across different countries or regions may influence male infertility prevalence, potentially leading to biased estimates of the temperature-ASPR relationship if such differences are not adequately controlled. Moreover, the study did not account for other environmental pollutants that may also play a role in male infertility risk. (4) Although we included temperature variability indicators to capture intra-annual temperature fluctuations, our study was limited in its ability to assess the seasonal dependence of male infertility prevalence. This limitation arises from the fact that the GBD provides only annual estimates of male infertility prevalence, preventing a direct analysis of the association between seasonal variations and male infertility prevalence. (5) In our study, we relied on a single climate model (CESM2) for predictions. Incorporating multiple climate models using a multi-model ensemble (MME) approach could help reduce uncertainty in future temperature projections and enhance prediction accuracy [45]. Additionally, the projections in this study are derived from simplified model assumptions. In reality, climate systems are more intricate, and various unmeasured factors could impact the outcomes. Therefore, these results should be viewed as indicative of possible future trends rather than exact forecasts of prevalence.

Conclusion

In summary, variations in temperature may be linked to a rise in male infertility ASPR. As such, climate change should be recognized as a potential risk factor for reproductive health and warrants greater attention. Continued research is essential to more accurately evaluate the causal relationship between ambient temperature deviations and male infertility.

Abbreviations

APC	Alcohol Consumption Per Capita
ASPR	Age-Standardized Prevalence Rate
CMIP6	Coupled Model Intercomparison Project Phase 6
DPT	Deviance Percentage of Temperature
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	Fifth Generation ECMWF Reanalysis for the Global Climate

FSH	Follicle-Stimulating Hormone
GBD	Global Burden of Disease
GHO	Global Health Observatory
HPG	Hypothalamic-Pituitary-Gonadal
ICD	International Classification of Diseases
LDI	Lagged Distributed Income Per Capita
NO_2	Nitrogen Dioxide
O_3	Ozone
RCS	Restricted Cubic Spline
SDI	Sociodemographic Index
SDs	Standard Deviations
SPP	Shared Socioeconomic Pathways
SSP126	Shared Socioeconomic Pathway scenario with low greenhouse gas emissions
SSP245	Shared Socioeconomic Pathway scenario with intermediate greenhouse gas emissions
SSP370	Shared Socioeconomic Pathway scenario with high but stabilizing greenhouse gas emissions
SSP585	Shared Socioeconomic Pathway scenario with very high greenhouse gas emissions
TFU25	Total Fertility Rate Under 25 Years of Age

Supplementary Information

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Supplementary Material 1

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Author contributions
JHQ, YHS, and QQZ drafted the manuscript. JHQ, CBM, and JYZ conducted statistical analyses and created the figures. JXM, YFW, and YHC contributed to the manuscript review. JXM and JHQ conceived the study and contributed to the manuscript review. All authors have read and approved the final manuscript.

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Data availability
The datasets used during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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References

1. Agarwal A, Mulgund A, Hamada A, Chyatte MR. A unique view on male infertility around the Globe. Reprod Biol Endocrinol. 2015;13:1–9.
2. Agarwal A, Baskaran S, Parekh N, Cho CL, Henkel R, Vij S, et al. Male infertility. Lancet. 2021;397:319–33.
3. Levine H, Jørgensen N, Martino-Andrade A, Mendiola J, Weksler-Derri D, Jolles M, et al. Temporal trends in sperm count: a systematic review and meta-regression analysis of samples collected globally in the 20th and 21st centuries. Hum Reprod Update. 2023;29:157–76.
4. Levine H, Jørgensen N, Martino-Andrade A, Mendiola J, Weksler-Derri D, Mindlis I, et al. Temporal trends in sperm count: a systematic review and meta-regression analysis. Hum Reprod Update. 2017;23:646–59.
5. Huang B, Wang Z, Kong Y, Jin M, Ma L. Global, regional and National burden of male infertility in 204 countries and territories between 1990 and 2019: an analysis of global burden of disease study. BMC Public Health. 2023;23:2195.
6. Okonofua FE, Ntoimo LFC, Omonkhua A, Ayodeji O, Olafusi C, Unuabonah E, et al. Causes and risk factors for male infertility: A Ccoping review of published studies. Int J Gen Med. 2022;15:5985–97.
7. Segal TR, Giudice LC. Systematic review of climate change effects on reproductive health. Fertil Steril. 2022;118:215–23.
8. Walsh BS, Parratt SR, Hoffmann AA, Atkinson D, Snook RR, Bretman A, et al. The impact of climate change on fertility. Trends Ecol Evol. 2019;34:249–59.
9. Wang C, Yu Q, Chu T, Wang F, Dong F, Xin H, et al. Relationship of environmental exposure temperature and temperature extremes on sperm DNA fragmentation index in men with different BMI values and the indirect effect of DNA fragmentation index on semen parameters. Sci Total Environ. 2024;916:170292.
10. Zhou Y, Meng T, Wu L, Duan Y, Li G, Shi C, et al. Association between ambient temperature and semen quality: A longitudinal study of 10 802 men in China. Environ Int. 2020;135:105364.
11. Alvero R. The third degree: climate change and reproductive health. Fertil Steril. 2022;118:213–14.
12. Martin L, Zhang Y, Mustieles V, Souter I, Petrozza J, Messerlian C. Reproductive medicine in the face of climate change: a call for prevention through leadership. Fertil Steril. 2022;118:239–46.
13. GBD 2021 Diseases and Injuries Collaborators. Global incidence, prevalence, years lived with disability (YLDs), disability-adjusted life-years (DALYs), and healthy life expectancy (HALE) for 371 diseases and injuries in 204 countries and territories and 811 subnational locations, 1990–2021: A systematic analysis for the global burden of disease study 2021. Lancet. 2024;403:2133–61.
14. Hersbach H, Bell B, Berrisford P, Hirahara S, Horányi A, Muñoz-Sabater J, et al. The ERA5 global reanalysis. Quart J Royal Meteoro Soc. 2020;146:1999–2049.
15. Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ, et al. Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. Geosci Model Dev. 2016;9:1937–58.
16. Vardell E. Global health observatory data repository. Med Ref Serv Q. 2020;39:67–74.
17. Global Burden of Disease Collaborative Network. Global burden of disease study 2019 (GBD 2019). Cause List Mapped to ICD Codes. Seattle, United States of America: Institute for Health Metrics and Evaluation (IHME). 2020. https://ghdx.healthdata.org/record/ihme-data/gbd-2019-cause-icd-code-mappings
18. Institute for Health Metrics and Evaluation (IHME). Epi Visualization. Seattle, WA: IHME, University of Washington, 2024. http://vizhub.healthdata.org/epi
19. Hersbach H, Bell B, Berrisford P, Biavati G, Horányi A, Muñoz Sabater J et al. ERA5 monthly averaged data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). 2023. https://doi.org/10.24381/cds.f17050d7
20. Closet M, Feindouno S, Guillaumont P, Simonet C. A physical vulnerability to climate change index: which are the most vulnerable developing countries? HAL. 2017;01719925v3f.
21. O'Neill BC, Tebaldi C, van Vuuren DP, Eyring V, Friedlingstein P, Hurtt G, et al. The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci Model Dev. 2016;9:3461–82.
22. Global Burden of Disease Collaborative Network. Global Burden of Disease Study. (GBD 2019) Socio-demographic Index (SDI) 1950–2019. Seattle: Institute for Health Metrics and Evaluation (IHME), 2020. https://ghdx.healthdata.org/record/ihme-data/gbd-2019-fertility-estimates-1950-2019
23. Global Burden of Disease Collaborative Network. Global Burden of Disease Study. (GBD 2019) Smoking prevalence. Institute for Health Metrics and Evaluation (IHME), Seattle, 2021;1990–2019. https://ghdx.healthdata.org/record/ihme-data/gbd-2019-smoking-tobacco-use-prevalence-1990-2019

24. World Health Organization. Global Information System on Alcohol and Health (GISAH). World Health Organization. 2016. www.who.int/data/gho/data/themes/global-information-system-on-alcohol-and-health
25. Global Burden of Disease Collaborative Network. Global Burden of Disease Study. (GBD 2019) Air Pollution Exposure Estimates 1990–2019. Seattle: Institute for Health Metrics and Evaluation (IHME), 2021. https://ghdx.healthdata.org/record/global-burden-disease-study-2019-gbd-2019-air-pollution-exposure-estimates-1990-2019
26. Jinfeng W, Chengdong X. Geodetector: principles and prospects. Acta Geogr Sin. 2017;72:116–34.
27. Global Burden of Disease Collaborative Network. Global burden of disease Study 2016 (GBD 2016) location hierarchies. Seattle: Institute for Health Metrics and Evaluation (IHME). 2017. https://ghdx.healthdata.org/record/ihme-data/gbd-2016-location-hierarchies
28. Zhang X, Fan Z, Wang Q, Deng X, Xu R, Li Y, et al. Association between ambient temperature and semen quality among sperm donation volunteers in South China. Environ Int. 2023;173:107809.
29. Thonneau P, Bujan L, Multigner L, Mieusset R. Occupational heat exposure and male fertility: A review. Hum Reprod. 1998;13:2122–5.
30. Cai H, Qin D, Peng S. Responses and coping methods of different testicular cell types to heat stress: overview and perspectives. Biosci Rep. 2021;41:BSR20210443.
31. Jørgensen N, Andersen AG, Eustache F, Irvine DS, Suominen J, Petersen JH, et al. Regional differences in semen quality in Europe. Hum Reprod. 2001;16:1012–19.
32. Gyllenborg J, Skakkebaek NE, Nielsen NC, Keiding N, Giwercman A. Secular and seasonal changes in semen quality among young Danish men: a statistical analysis of semen samples from 1927 donor candidates during 1977–1995. Int J Androl. 1999;22:28–36.
33. Tjoa WS, Smolensky MH, Hsi BP, Steinberger E, Smith KD. Circannual rhythm in human sperm count revealed by serially independent sampling. Fertil Steril. 1982;38:454–9.
34. Souza VV, Moreira DP, Braz-Mota S, Valente W, Cotta GC, Rodrigues MDS, et al. Simulated climate change and atrazine contamination can synergistically impair zebrafish testicular function. Sci Total Environ. 2024;946:174173.
35. Breckels RD, Neff BD. The effects of elevated temperature on the sexual traits, immunology and survivorship of a tropical ectotherm. J Exp Biol. 2013;216:2658–64.
36. Mieusset R, Bujan L. Testicular heating and its possible contributions to male infertility: A review. Int J Androl. 1995;18:169–84.
37. Barazani Y, Katz BF, Nagler HM, Stember DS. Lifestyle, environment, and male reproductive health. Urol Clin North Am. 2014;41:55–66.
38. Hamerezaee M, Dehghan SF, Golbabaei F, Fathi A, Barzegar L, Heidarnejad N. Assessment of semen quality among workers exposed to heat stress: A cross-sectional study in a steel industry. Saf Health Work. 2018;9:232–35.
39. Kumar N, Singh AK. Impact of environmental factors on human semen quality and male fertility: A narrative review. Environ Sci Eur. 2022;34:1–13.
40. Reyes JG, Farias JG, Henríquez-Olavarrieta S, Madrid E, Parraga M, Zepeda AB, et al. The hypoxic testicle: physiology and pathophysiology. Oxid Med Cell Longev. 2012;2012:929285.
41. Rao M, Xia W, Yang J, Hu LX, Hu SF, Lei H, et al. Transient scrotal hyperthermia affects human sperm DNA integrity, sperm apoptosis, and sperm protein expression. Andrology. 2016;4:1054–63.
42. Gong Y, Guo H, Zhang Z, Zhou H, Zhao R, He B. Heat stress reduces sperm motility via activation of glycogen synthase Kinase-3α and Inhibition of mitochondrial protein import. Front Physiol. 2017;8:718.
43. Trigg N, Schjenken JE, Martin JH, Skerrett-Byrne DA, Smyth SP, Bernstein IR, et al. Subchronic elevation in ambient temperature drives alterations to the sperm epigenome and accelerates early embryonic development in mice[J]. Proc Natl Acad Sci USA. 2024;121:e2409790121.
44. Bock SL, Chow MI, Forsgren KL, Lema SC. Widespread alterations to hypothalamic-pituitary-gonadal (HPG) axis signaling underlie high temperature reproductive Inhibition in the eurythermal Sheepshead minnow (Cyprinodon variegatus). Mol Cell Endocrinol. 2021;537:111447.
45. Chen J, Jiao Z, Liang Z, Ma J, Xu M, Biswal S, et al. Association between temperature variability and global meningitis incidence. Environ Int. 2023;171:107649.

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