Physiological and biological response to heat exposure in pregnancy: a systematic review and meta-analysis

Ana Bonell, Asma Abdul Malik Qureshi*, Andreas D Flouris, Lydia Tsoutsoubi, Amanda N Sferruzzi-Perri, Jai K Das, Jane E Hirst, Leonidas G Ioannou*

Summary

Background Pregnant women are vulnerable to extreme heat due to physiological adaptations that alter thermoregulation and metabolism; however, the underlying physiological mechanisms remain inconclusive. This systematic review and meta-analysis synthesises the effects of environmental heat on maternal, placental, and fetal physiology, identifying key biophysiological pathways.

Methods We searched PubMed and Embase from database inception to Jan 13, 2025, for studies of pregnant women exposed to heat. Observational and experimental studies conducted in laboratory or field settings were included. Grey literature was not included. Alterations in typical physiological functions resulting from heat exposure across maternal, placental, or fetal responses were considered outcomes. AB and AAMQ screened and extracted data independently. Random-effects meta-analyses and meta-regression were applied to examine associations between heat stress exposure parameters and physiological responses. The study was registered with PROSPERO (CRD42024511153).

Findings The analysis included data from 201 906 pregnant women from 27 studies. Meta-analyses of physiological changes before and after heat exposure found mean increases of 38 beats per min (bpm) in maternal heart rate (95% CI 29·3–45·8; I^2 91%; seven studies), 0·5°C in maternal core temperature (0·5–0·6; 84%; 12 studies), 1·9°C in maternal skin temperature (0·4–3·4; 99%; six studies), and 13 bpm in fetal heart rate (8·8–16·5; 78%; seven studies). On meta-regression, increased core temperature was associated with higher intensity activities and increased heat stress and inversely associated with gestational age. There were inconsistent changes in uterine and umbilical artery blood flow. However, a higher susceptibility to impaired uteroplacental blood flow was observed among pregnant women with hypertension or pre-eclampsia.

Interpretation We found consistent acute physiological stress responses to heat exposure, with evidence that these responses were worse in pregnant women with pre-eclampsia. The paucity of available data highlights the need for more research to identify the underlying biological mechanisms that mediate pregnancy outcomes with high heat exposure.

Funding Wellcome Trust.

Lancet Planet Health 2026; 10: 101431

Published Online May 13, 2026
https://doi.org/10.1016/j.lanplh.2026.101431

*Joint first authors

Medical Research Council Unit The Gambia at London School of Hygiene & Tropical Medicine, Banjul, The Gambia (A Bonell MBChB PhD); **Centre on Climate Change and Planetary Health, London School of Hygiene & Tropical Medicine, London, UK** (A Bonell); **Institute for Global Health Department, Aga Khan University, Karachi, Pakistan** (A A M Qureshi MBChB, J K Das MBChB PhD); **FAME Laboratory, Department of Physical Education and Sport Science, University of Thessaly, Trikala, Greece** (Prof A D Flouris PhD, L Tsoutsoubi PhD, L G Ioannou PhD); **Loke Centre for Trophoblast Research, Department of Physiology, Development and Neuroscience, University of Cambridge, Cambridge, UK** (Prof A N Sferruzzi-Perri PhD); **The George Institute for Global Health at Imperial College London, London, UK** (Prof J E Hirst MBChB PhD); **Department of Paediatrics and Child Health, Aga Khan University, Karachi, Pakistan** (J K Das)

Correspondence to:
Dr Ana Bonell, Centre on Climate Change and Planetary Health, London School of Hygiene & Tropical Medicine, London WC1E 7HT, UK
ana.bonell@lshtm.ac.uk

Introduction

Anthropogenic climate change has resulted in an alarming rise in global temperatures.[1,2] Heat exposure has become a crucial global health concern, with projections indicating a worsening upward trend.[3,4] This shift is intensifying the frequency, duration, and severity of extreme heat events, with serious health consequences for pregnant people.[5–7] The impacts of these extreme heat events are compounded in low-income countries, where exposures are more difficult to avoid and health systems might not be equipped to deal with the challenges brought about by the climate crisis.[8]

Pregnancy is marked by extensive physiological adaptations. These changes include metabolic, cardiovascular, endocrine, and immunological shifts, which are reflected in elevated metabolic rate, increased blood volume and heart rate, and weight gain.[9–11] Exposure to extreme heat that exceeds the thermoneutral zone of the human body—combined with the shift in maternal body surface area ratio—can affect these adaptive processes and thermoregulatory capacities, inducing physiological strain on the fetal–maternal systems.[12,13]

Heat stress exposure has been linked to increased risk of pregnancy complications across all trimesters and adverse birth outcomes.[14–17] These complications and outcomes include miscarriages,[18] congenital anomalies,[19,20] hypertensive disorders,[21] gestational diabetes,[22] preterm birth,[23,24] low birthweight,[25,26] small-for-gestational age,[27] and stillbirth.[28] Although epidemiological links are increasingly recognised, understanding of the underlying pathophysiological mechanisms remains poor.

Humans maintain a typical core body temperature of between 37°C (SD 0·2) through autonomic responses (eg, sweating and peripheral vasodilation), and behavioural adaptations (eg, seeking shade or reducing activity).[29,30] During pregnancy, thermoregulation becomes more

Research in context

Evidence before this study

Extreme heat exposure during pregnancy has been associated with adverse pregnancy and birth outcomes, including congenital anomalies, pre-eclampsia, gestational diabetes, preterm birth, low birthweight, fetal growth restriction, and stillbirth. However, underlying physiological mechanisms—particularly those involving maternal, placental, and fetal responses to environmental heat stress—remain poorly understood. To address this gap, we searched PubMed and Embase from database inception to Jan 13, 2025, using combinations of terms such as "heat stress", "temperature", "pregnancy", "maternal", "placental", "fetal", and related physiological outcomes. Eligible studies were primary research that assessed the effects of environmental heat exposure on maternal, placental, or fetal physiology during pregnancy. Although some reviews have begun to explore the effects of heat exposure on maternal and fetal physiology, no review has systematically examined the underlying pathways and biological mechanisms—including changes in maternal thermoregulation, placental function, and fetal responses to heat, nor undertaken a meta-analysis of these responses.

Added value of this study

This systematic review and meta-analysis synthesises biological responses to heat exposure during pregnancy, identifying acute thermal strain in both mothers and fetuses (especially changes in maternal core and skin temperatures), and maternal and fetal heart rate. We highlight novel insights from meta-regression showing that gestational age might modulate maternal heat strain, with physiological strain decreasing as pregnancy progresses. Additionally, this systematic review uncovers potential susceptibility among pregnant women with pre-eclampsia or hypertension, where altered uteroplacental responses and fetal distress were observed under heat exposure. The study also highlights emerging evidence of placental gene expression changes under heat and potential modulation by nutrient pathways, suggesting potential mechanisms for heat-related placental insufficiency. Despite growing literature, there is a poor understanding of the molecular, inflammatory, and epigenetic pathways that mediate heat-related pregnancy outcomes.

Implications of all the available evidence

Our findings confirm that heat exposure during pregnancy triggers acute maternal and fetal physiological stress responses and that pregnant women with hypertensive disorders might be at higher risk. However, the current evidence base is narrow, with few studies exploring endocrine and hormonal, inflammatory, or molecular mechanisms, and an understanding of the mechanisms remains blurred. Our findings call for standardised primary studies that include biomarker and mechanistic endpoints to unravel how heat impacts maternal and fetal health across pregnancy stages. From a planetary health perspective, addressing the intersection of climate exposure, undernutrition, and health system inequities is essential to protect pregnant women in climate-vulnerable regions. Future research needs to bridge these gaps and guide context-specific policy to safeguard maternal and newborn health in an increasingly warming world.

complex.[30] Although some physiological adaptations help to maintain thermal balance, such as increased plasma volume, enhanced thermal heat capacity (ie, the amount of heat required to raise the temperature by 1°C), and decrease in the threshold temperature for sweating,[31–33] some adaptations (eg, changes in body mass composition, higher metabolic rate, and altered body surface area ratio) make it more difficult for both the mother and fetus to dissipate heat. A key adaptation is the establishment of a fetal–maternal temperature gradient, where the fetus remains approximately 0·5°C warmer than the maternal core temperature in the third trimester of pregnancy[34] and dissipates heat via uteroplacental blood flow (85%) and through amniotic fluid and the uterine wall (15%).[35,36] External thermal environments can be characterised by ambient air temperature alone or through standardised heat stress indices, such as the wet bulb globe temperature (WBGT) and the universal thermal climate index. These indices integrate multiple meteorological variables—ie, air temperature, humidity, wind speed, and solar radiation—to provide a composite estimate of heat stress.[37] Previous studies have used both absolute and relative thresholds for these indices, influencing how heat exposure and stress are defined.[10,16,17] This variation affects how results are interpreted, as factors such as acclimatisation and local climate conditions can change the physiological effects of a given thermal load.

Although increased maternal core temperature could contribute to adverse pregnancy outcomes (eg, stillbirth) through heat-induced cellular stress and inflammation,[38] it is unlikely that maternal core temperature is the sole mechanism. Other factors, such as oxidative stress[11] and placental and endocrine disruption,[39] could also contribute to these outcomes. This systematic review and meta-analysis assesses the effect of an increased exposure to environmental heat stress in pregnant women on maternal, placental, and fetal physiology compared with low or no environmental heat stress. It investigates evidence from three pathways—maternal, placental, and fetal heat strain. Heat strain was defined as any biological response deviating from typical physiological function due to heat exposure. For example, maternal heat strain was defined as conditions arising from alterations in maternal physiology, activation of inflammatory pathways, or disruptions in thermoregulatory responses. Placental heat strain was defined as changes in placental blood flow, gene expression, or changes in circulating placental biomarkers. Fetal heat strain was defined as an alteration in fetal physiology, heart rate or fetal movements.

Methods

Search strategy and selection criteria

In this systematic review and meta-analysis, PubMed and Embase were searched for studies published between database inception and Jan 13, 2025.[40] Included studies met the following criteria: involved pregnant women; evaluated maternal, placental, or fetal exposure to heat; defined the source of heat exposure (eg, included ambient temperature, relative humidity, solar radiation, or physical activity); and had been granted ethics approval and were peer reviewed. The following predefined outcomes were also included: maternal, placental, or fetal cardiovascular changes; maternal temperature changes; hydration status; thermal perception; inflammatory or placental markers; and maternal hormonal changes or placental alterations.[40] Studies were excluded if published in languages other than English, or were reviews, modelling studies, animal studies, or studies where heat exposure was due to fever or infection, as these involved potentially different pathophysiological pathways. Grey literature was excluded. The detailed method is provided in the protocol.[40]

A list of seven benchmark studies, identified by a subject expert (AB), was used to validate the search algorithm developed by a second researcher (LGI), which successfully retrieved all seven studies. The full search strategies for both databases are detailed in the protocol.[40] The reference lists of all included studies and related reviews were manually screened to identify additional relevant studies and reduce the risk of publication bias.

All records retrieved from database searches were imported into Microsoft Excel for de-duplication and screening. Two reviewers (LT and LGI) independently screened titles and abstracts against predefined inclusion and exclusion criteria, and any disagreements were resolved through discussion and moderation by a third reviewer (AB). Full-text articles were obtained for all studies deemed potentially eligible and were assessed in duplicate for final inclusion, with discrepancies resolved through discussion and consultation with the third reviewer.

Data analysis

Data were extracted independently using a standardised Microsoft Excel-based data extraction template developed and finalised by AB and AAMQ. Extracted variables included: study title, authors, year of publication, country and city, climate zone, study aim, study design, sample size, maternal age, gestational age, BMI, occupation, inclusion criteria, exclusion criteria, exposure measurement and definition, exposure duration, timing of exposure by gestational age, outcome definition, outcome measurement, key findings, pregnancy outcomes, confounding variables considered, and funding sources. Discrepancies in data extraction were resolved by consensus between AB and AAMQ, and resolved by JKD. No attempts were made to contact study authors for additional information.

AB and AAMQ evaluated the risk of bias using the Risk of Bias in Non-randomized Studies-of Exposures (ROBINS-E) and the Risk of Bias in Non-randomized Studies-of Interventions (ROBINS-I) tools as appropriate.[41,42] The seven key domains were risk of bias due to: confounding, measurement of exposure, participant selection, post-exposure interventions, missing data, measurement of outcome, and reported results. Each domain was rated using standard categories (ie, low risk, some concerns, high risk, or very high risk) and then collated to an overall score for risk of bias (appendix p 12).

See Online for appendix

A meta-analysis was done to quantify acute differences in maternal, placental, and fetal outcomes before and after heat exposure, where sufficient data were available. For studies reporting data in graphical form, numerical values were extracted using WebPlotDigitiser (version 4.5, 2021). In studies where WBGT was not reported, WBGT was calculated using the Liljegren method from the reported air temperature and relative humidity.[43] Meta-regression was applied to examine the associations between exposure parameters (eg, WBGT, metabolic equivalent task [MET], and gestational age) and the pooled physiological responses across the studies included in the meta-analyses. We used unstandardised mean differences to present findings in original measurement units for both meta-analyses and meta-regression, which allowed for the more tangible interpretation of physiological changes across studies using consistent outcome measures. For missing standard deviations, we imputed values using the average coefficient of variation that was calculated from complete cases within the dataset.[44,45] Random-effects models were applied to account for between-study variability related to participant characteristics, exposure intensities, and environmental conditions. Heterogeneity was assessed using the I^2 index and further explored through meta-regression and subgroup analyses. Funnel plots were examined visually for publication bias and, where the number of studies in the meta-analysis exceeded ten, Egger's test was used to indicate the probability of asymmetrical data. Subgroup analyses of sauna-only studies allowed for isolation of the effects of external heat exposure by excluding the effect of endogenous heat production from exercise. Sensitivity analysis was undertaken to evaluate whether studies with imputed variances influenced the pooled estimate for core temperature through a leave-one-out analysis. Data analyses were undertaken in SPSS version 29.0.2.0, and meta-analyses were conducted using Python code built on the NumPy version 2.1.3 and SciPy version 1.15.3 libraries.

The study protocol is available online[40] and is registered with PROSPERO (CRD42024511153).

Role of the funding source

The funder had no role in study design, data collection, data analysis, data interpretation, manuscript writing, or decision to submit for publication.

Results

The initial search identified 4290 studies, which were imported into EndNote, and 3020 were screened after de-duplication (figure 1). 2990 studies were excluded after title and abstract screening, 30 were selected for full-text screening, and 27 were included for data extraction and analysis.

The 27 studies were published between 1961 and 2024 (table 1), and included 201 906 pregnant women, with a median of 25 women per study (IQR 14–313). Geographically, the studies were distributed across diverse climatic zones (figure 2), including tropical rainforest, tropical savannah or monsoon, humid subtropical, desert, and temperate regions. Most studies were conducted in high-income countries in Europe, North America, and Oceania. Specifically, the studies were undertaken in Sweden,[58] Finland,[46,49,51–53,55] France,[59] Germany,[66] Norway,[69] the USA,[32,47,48,50,54,57] Australia,[60,61] New Zealand,[56] and China.[63,67,68,70] In contrast, four studies originated from low-income and middle-income countries: India,[65] Pakistan,[27] and The Gambia.[62,64] Figure 2 presents the global distribution of studies, overlaid with climate zones categorised using the Köppen–Geiger climate classification, and shows a concentration of research in humid subtropical and steppe regions. Few studies are available from arid desert zones (eg, Middle East and north Africa and the south-western USA), tropical zones (both rainforest and savannah and monsoon), or from Mediterranean climates, despite their high heat vulnerability and projected temperature rise.[71]

Studies were broadly defined as heat chamber (nine studies),[32,47,48,50,54,56,58,61,69] sauna (six studies),[46,49,51–53,55] and field-based studies (12 studies).[27,57,59,60,62–68,70] In the 15 heat chamber and sauna studies, women were exposed to controlled exercise, heat, or both, with physiological measurements taken before, during, and after exposure. The duration of exposure varied from 15 min to 60 min with heat stress ranging from 15°C to 52°C WBGT, and METs varying from 1 (sitting at rest) to approximately 13 (interval training at 92% maximum oxygen consumption [VO_2 max]). Of the field-based studies, ten were prospective pregnancy cohorts[27,59,62–68,70] and two were cross-sectional.[57,60] Heat exposure was either measured acutely (six studies);[57,62–65,67] a combination of within 1 week of the outcome of interest (four studies),[57,59,60,66] allocated by trimester (five studies),[27,59,65,68,70] or whole pregnancy averages (three studies);[59,68,70] or determined using extreme percentiles (two studies).[66,68] In total, there were 355 792 pregnant women across all 27 studies. Maternal physiological response was the most frequently studied outcome, reported in 22 studies,[27,32,46–56,58,60,61,63–65,67,69,70] followed by placental outcomes (nine studies)[27,51,53,55,57,59,60,62,66] and fetal outcomes (nine studies).[49,51,55,56,58,62,64,65,68]

Maternal heart rate, core body temperature, skin temperature, and fetal heart rate were the most reported outcomes (appendix pp 2–8). Of the 16 studies that reported these outcomes using measurements taken before and after heat exposure, data were pooled for meta-analysis and additional meta-regression where possible (table 2).[32,46–49,51,52,54–56,58,61,62,64,65,69] Studies reporting outcomes that could not be included in the meta-analysis due to heterogeneity or where results were reported in only one study are given according to the predefined maternal and placental outcomes outlined in the protocol (table 3).[40] These outcomes included maternal hypertension, glucose control, placental hormones, uteroplacental blood flow, and placental gene expression. Among the 12 observational studies, confounding was the most common source of bias, with six studies considered high risk due to inadequate control over baseline or time-varying confounders (appendix p 12).[46,57,59,60,63,67] The remaining 15 studies were rated low risk or some concerns.[32,46–56,58,61,69] Exposure measurement in all 27 studies was rated low risk or with some concerns. Participant selection raised moderate concerns in 11 studies,[48,56,57,59,60,62,64,66–68,70] especially where recruitment was seasonal.[60] Meanwhile, missing data, outcome measurement, and the selection of reported results consistently received low-risk ratings. Overall, one study was categorised as low risk,[65] six studies as some concerns,[27,62,64,66,68,70] and six studies as high risk

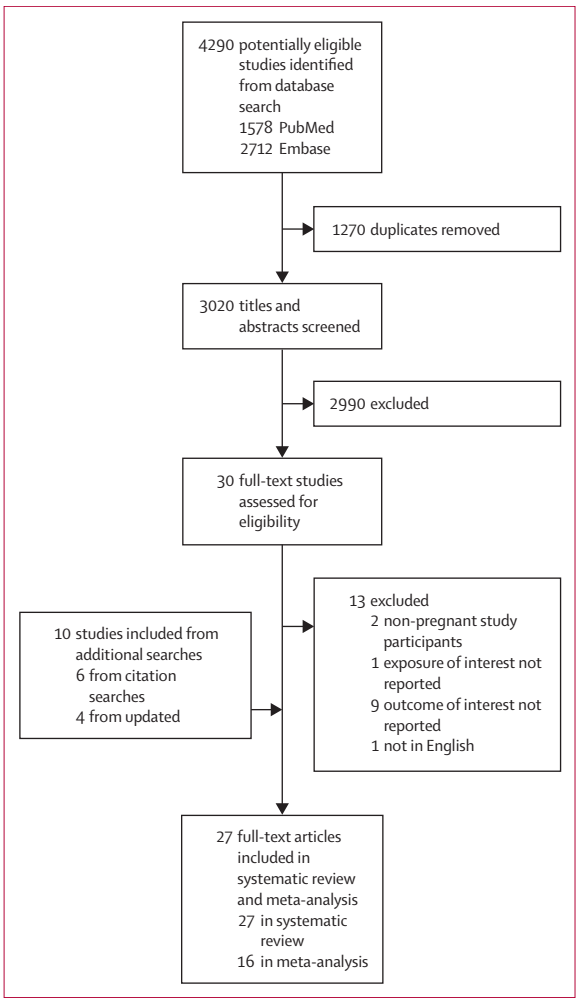

Figure 1: **Study selection**

	Study design	Location	Study setting	Participants (N)	Gestational age at exposure (weeks)	Temperature (°C)	WBGT (°C)	Metabolic equivalents	Outcome
Pystynen (1961)[46]	Experimental study	Helsinki, Finland	Sauna	60	40	64	52	1	Change in maternal blood pressure and electrolytes with sauna exposure in pregnant women with severe pre-eclampsia, mild pre-eclampsia, hypertension, or normal pregnancy
Jones and colleagues (1985)[47]	Longitudinal experimental study	Pennsylvania, USA	Heat chamber	4	12, 24, and 32	Not given	23·8	10	Change in maternal heart rate, blood pressure, core temperature, oxygen consumption, carbon dioxide production, and respiratory rate under set exercise conditions in a controlled heat chamber
Clapp and colleagues (1987)[48]	Longitudinal experimental study	Vermont, USA	Heat chamber	10	20·5 and 31·5	22	17	4–5	Change in maternal core temperature, blood glucose, and lactate level under set exercise conditions in a controlled heat chamber
Vähä-Eskeli and Erkkola (1991)[49]	Experimental study	Turku, Finland	Sauna	23	36·5	70	50	1	Change in maternal core and skin temperature, maternal heart rate, fetal heart rate, fetal movements, and uterine contractility under sauna exposure
McMurray and colleagues (1990)[50]	Longitudinal experimental study	North Carolina, USA	Heat chamber	7	15, 25, and 35	30	NA, in water	10–12	Change in maternal core and skin temperature, heat storage, convective loss, and maternal heart rate under set exercise conditions in a controlled heat chamber in the air or water
Vähä-Eskeli and colleagues (1991)[51]	Experimental study	Turku, Finland	Sauna	17	36·5	70	50	1	Change in maternal heart rate, blood pressure, uterine and umbilical pulsatile index, fetal heart rate, and fetal movements under sauna conditions
Vähä-Eskeli and colleagues (1991)[52]	Experimental study	Turku, Finland	Sauna	32	13·5 and 36·5	70	50	1	Change in maternal core temperature, skin temperature, mean arterial pressure, strove volume, cardiac output, heart rate, and peripheral vascular resistance under sauna conditions
Clapp (1991)[32]	Longitudinal experimental study	Vermont, USA	Heat chamber	18	7, 15, 23, 31, and 37	20	15·2	6	Change in maternal core temperature and exercise intensity at different gestational ages under set exercise conditions in a controlled heat chamber
Vähä-Eskeli and colleagues (1992)[53]	Experimental study	Turku, Finland	Sauna	32	37	70	50	1	Change in serum concentrations of progesterone, oestradiol, oestriol, 6-keto-prostaglandin, and thromboxane B2 under sauna conditions
McMurray and colleagues (1993)[54]	Experimental study	North Carolina, USA	Heat chamber	7	25·5	30	NA, in water	6	Change in maternal heart rate, core temperature, skin temperature, heat storage, and convective heat loss under controlled exercise conditions in a heat chamber and water chamber
Pirhonen and colleagues (1994)[55]	Experimental study	Turku, Finland	Sauna	26	34·7	70	50	1	Change in maternal heart rate and blood pressure, umbilical and uterine pulsatile index, fetal heart rate, and uterine contractility under sauna conditions
O'Neill (1996)[56]	Experimental study	Auckland, New Zealand	Heat chamber	11	35·5	22·3	22·3	5–6	Change in maternal heart rate, core temperature, fetal heart rate, and incidence of fetal heart rate accelerations under set exercise conditions in a controlled heat chamber
Sciscione and colleagues (1997)[57]	Retrospective cross-sectional study	Baltimore, USA	Field-based study	42	27–40	32·7	Not given	NA	Change in amniotic fluid index as ambient temperature increased
Lindqvist and colleagues (2003)[58]	Longitudinal experimental study	Malmö, Sweden	Heat chamber	14	8, 15, 22, 29, and 36	22	22	7–8	Change in maternal core temperature, peak temperature difference, maternal heart rate, fetal heart rate, and uterine activity at set gestational ages under set exercise conditions in a controlled heat chamber

(Table 1 continues on next page)

	Study design	Location	Study setting	Participants (N)	Gestational age at exposure (weeks)	Temperature (°C)	WBGT (°C)	Metabolic equivalents	Outcome
(Continued from previous page)									
Abraham and colleagues (2018)[59]	Cohort study	Nancy and Poitiers, France	Field-based study	668	Days 1, 2, and 3, and 1 month before delivery (calculated backwards from birth), by trimester, and whole pregnancy	5–16	3–15	NA	Ambient exposure linked to global methylation levels and gene-specific methylation in placentas
Shen and colleagues (2019)[60]	Secondary analysis of the HAPO cohort	Brisbane, QLD, and Newcastle, NSW, Australia	Field-based study	2120	24–32	Average monthly exposure 15·4–25·3	Not given	NA	Gestational diabetes incidence, fasting plasma glucose level, HbA_{1c} level, 1 and 2 h plasma glucose level, HOMA-IR score, umbilical cord C-peptide concentration, and umbilical cord glucose level
Smallcombe and colleagues (2021)[61]	Experimental study	Sydney, NSW, Australia	Heat chamber	32	30·5	32	26	4–5	Change in maternal core and skin temperature, maternal heart rate and blood pressure, whole-body thermal sensation, metabolic rate, maternal oxygen uptake, and VO_2 peak in pregnant and non-pregnant participants in a controlled heat chamber under weight-bearing and non-weight-bearing exercise conditions
Bonell and colleagues (2022)[62]	Feasibility study	West Kiang, The Gambia	Field-based study	40	28·5	31	24	3·2	Change in fetal heart rate and umbilical artery resistance index during a normal working shift in outdoor subsistence farmers with directly measured heat exposure
Peng and colleagues (2022)[63]	Cross-sectional study	Guangzhou, China	Field-based study	1043	Each antenatal visit	22–26	19–25	NA	Thermal sensation vote by trimester and ambient conditions measured in the waiting area of the obstetric department; preferred operative temperature by trimester
Bonell and colleagues (2022)[64]	Prospective observational cohort study	West Kiang, The Gambia	Field-based study	92	28·5	33·5	24·3	3·2	Change in maternal core temperature, maternal skin temperature, maternal heart rate, fetal heart rate, and fetal strain during working outdoor shift with heat exposure directly measured
Rekha and colleagues (2024)[65]	Prospective observational cohort study	Tamil Nadu, India	Field-based study	800	Directly measured for 1 day in the first, second, and third trimesters and extrapolated to trimesters and whole pregnancy	Not given	24–29	Not given	Outcomes included odds ratio of any adverse birth outcome, heat-related illnesses, heat strain indicators, and birth defects in the children of pregnant women who had been exposed to heat stress at work and pregnant women who had not been exposed to heat stress (based on standard WBGT cutoffs and threshold limit values)*
Shankar and colleagues (2023)[27]	Ancillary analysis of a subcohort within a randomised controlled study	Thatta, Pakistan	Field-based study	459	Averaged by trimester	Not given	Not given	NA	Outcomes included anthropometric measurements at birth, placental mRNA expression, placental protein expression, and maternal metabolite levels
Yüzen and colleagues (2023)[66]	Secondary data analysis from retrospective cohort study (registry study); secondary data analysis from prospective cohort study (PRINCE study)	Hamburg, Germany	Field-based study	25 624 (registry study); 386 (PRINCE study)	7 days before delivery	Not given	Not given	NA	Relative risk of preterm birth with heat wave exposure defined by different intervals (registry study); pulsatile index of the uterine and umbilical arteries linked to heat wave exposure (PRINCE study)
Wu and colleagues (2023)[67]	Cross-sectional study	Guangzhou, China	Field-based study	723	Each antenatal visit	26·4	25	06–1	Thermal sensation by trimester, ambient conditions, metabolic rate, and clothing
Wang and colleagues (2024)[68]	Prospective observational cohort study	Liaoning, Hebei, Hubei, Sichuan, Hunan, Fujian, Yunnan, and Guangdong, China	Field-based study	162 407	4 weeks before delivery, trimesters, and whole pregnancy	Not given	Not given	NA	Preterm birth and fetal heart rate; mediation analyses to explore the role of fetal heart rate as a mediator of the effects of heat exposure and risk of preterm birth

(Table 1 continues on next page)

	Study design	Location	Study setting	Participants (N)	Gestational age at exposure (weeks)	Temperature (°C)	WBGT (°C)	Metabolic equivalents	Outcome
(Continued from previous page)									
Brevik-Persson and colleagues (2024)[69]	Experimental study	Oslo, Norway	Heat chamber	15	30	20	16	11–13	Change in maternal core temperature, skin temperature, fluid loss, and thermal sensation in pregnant and non-pregnant participants under set exercise conditions in a controlled heat chamber
Wang and colleagues (2024)[70]	Prospective observational cohort study	Liaoning, Hebei, Hubei, Sichuan, Hunan, Fujian, Yunnan, and Guangdong, China	Field-based study	197 080	Trimester and whole pregnancy	Not given	Not given	NA	Hazard ratio of preterm birth risk and adjusted odds ratio of maternal hypertension linked to maternal heat exposure at different trimesters, weeks, and whole pregnancy

Experimental studies involved a defined heat exposure with or without exercise in a heat chamber with measurements taken before, during, and after heat exposure. Longitudinal experimental studies involved a defined heat exposure with or without exercise in a heat chamber with measurements taken before, during, and after heat exposure, and repeated at different gestational ages on the same participants. Sauna studies were conducted in a heat chamber that replicated the conditions of a sauna. Heat chamber studies were conducted in a heat chamber with a controlled and monitored heat exposure. Field-based studies were conducted in a real-world setting. bpm=beats per min. HbA_{1c}=glycated haemoglobin. HOMA-IR=Homoeostatic Model Assessment for Insulin Resistance score. NA=not applicable. WBGT=wet bulb globe temperature. *Threshold limit value as set by the American Conference of Governmental Industrial Hygienists.

Table 1: **Study details**

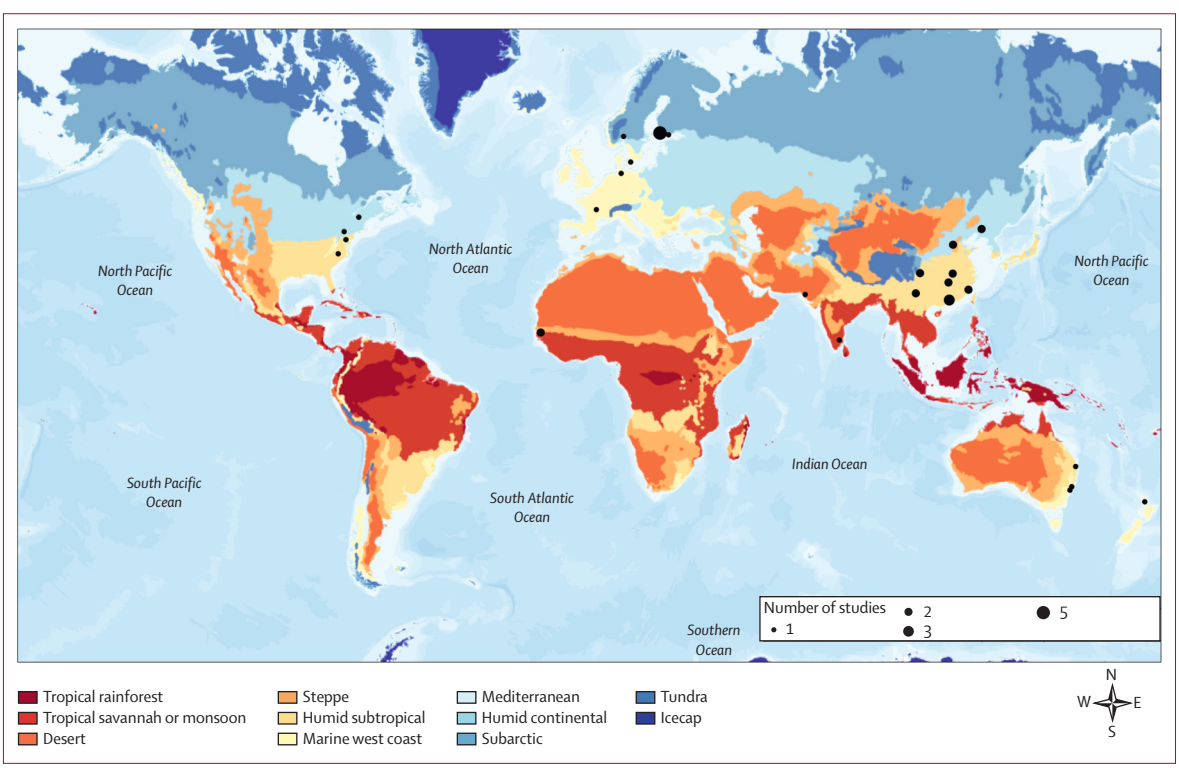

Figure 2: **Map of studies with geographical spread and climate zone**
Global distribution of the included studies by climate zone and geographical location. Each black circle represents one or more studies, with circle size scaled to reflect the number of studies conducted at that location (range 1–5).

of bias.[57,59,60,63,67] Among the 15 heat chamber and sauna studies, there was low risk of bias related to exposure measurement, outcome measurement, reporting or missing data. Six studies rated as having some concerns related to participant selection and control of confounding factors.[46–48,50,54,56] Overall, ten studies were classified as low risk,[32,49–55,61,69] four studies as having some concerns,[47,48,56,58] and one study as at high risk of bias.[46] There was moderate heterogeneity in methodological quality overall, with confounding being the main limitation across all studies (appendix pp 12–13).

Of the 22 studies reporting on maternal physiology,[27,32,46–56,58,60,61,63–65,67,69,70] seven studies reported changes in maternal heart rate and were included in the meta-analysis.[46,49,51,52,55,56,64] The random effect model found an increased pooled mean difference of 38 beats per min (bpm; SE 4·4; 95% CI 29·3–45·8) immediately after heat

	Estimate (°C or bpm)	SE	95% CI	p value
Change in maternal core temperature				
Metabolic equivalents	0·091	0·0145	0·061 to 0·121	<0·0001
Gestational age	–0·007	0·0027	–0·013 to –0·001	0·018
WBGT	0·009	0·0034	0·002 to 0·016	0·015
Change in maternal skin temperature				
Metabolic equivalents	0·051	0·0275	–0·016 to 0·118	0·114
Gestational age	–0·001	0·0093	–0·024 to 0·022	0·895
WBGT	0·174	0·0077	0·155 to 0·193	<0·0001
Change in maternal heart rate				
Metabolic equivalents	5·320	4·8275	–5·601 to 16·240	0·299
Gestational age	–0·375	0·3854	–1·247 to 0·496	0·356
WBGT	–0·291	0·6578	–1·779 to 1·197	0·668

Estimate represents the change in core temperature, skin temperature, or maternal heart rate by increase in either 1 metabolic equivalent, 1-week gestational age, or 1°C WBGT. All studies from the meta-analysis are included. WBGT=wet bulb globe temperature.

Table 2: **Meta-regression of change in maternal physiology with heat stress exposure**

exposure compared with baseline values (figure 3). There was significant heterogeneity between the studies (I^2 0·91), reflective of the diverse methods and participant characteristics of the studies. The funnel plot was symmetrical on visual inspection, indicating that publication bias was unlikely (appendix p 10). Five of the seven studies were conducted under sauna conditions,[46,49,51,52,55] with two studies including women with hypertensive disorders of pregnancy.[46,55] One study was of pregnant elite athletes and undertaken in a heat chamber on cycle ergometers,[56] and one study was of occupational heat exposure in subsistence farmers working in west Africa.[64]

Change in maternal core temperature was reported in 12 studies.[32,46–49,52,56,58,61,64,65,69] The pooled increase in core temperature immediately post-exposure was 0·5°C (SE 0·045; 95% CI 0·5–0·6; I^2 0·84) using a random effects model (figure 3). Ten studies were heat chamber or sauna studies,[32,46–49,52,54,56,58,61,69] where core temperature was measured with a rectal thermometer, and two were field-based studies,[64,65] where core temperature was measured with a tympanic thermometer. Funnel plot and Egger's test (p=0·61) indicated no evidence of publication bias.

Change in maternal skin temperature was given in six studies.[47,49,52,54,64,69] The overall estimate of change in skin temperature post heat exposure was 1·9°C (0·66; 0·4–3·4). Two studies conducted under sauna conditions (70°C, 15% relative humidity for 20 min of exposure) found large changes in skin temperature,[49,52] whereas the remaining studies (20–30°C, 38–61% reported humidity for 20–40 min of exposure),[47,54,64,69] which were conducted under heat chamber and field conditions, had more modest changes (figure 3). This was reflected in the asymmetry of the funnel plot for this analysis and an I^2 of 99%.

Meta-regression, which allows for the investigation of patient characteristics as moderators on the pooled effect, was explored for all meta-analyses. There was a statistically significant increase in change in maternal core temperature by both activity intensity (measured as MET) and WBGT exposure (table 2, appendix p 2), indicating that these parameters were statistically significantly moderating the pooled increased core temperature. There was also a statistically significant decrease in change in core temperature with increasing gestational age. With each increasing week of gestation, there was a 0·007°C decrease in the change in core temperature with heat stress exposure. This finding indicates that, as pregnancy progresses, the core temperature response to heat stress exposure reduces, contradicting general consensus over the common statement that thermoregulation is more difficult in later pregnancy, which is often stated as fact.[11,16] This finding was also shown in the six studies that conducted longitudinal experiments throughout pregnancy,[32,47,48,50,52,58] which showed that core temperature and changes in core temperature reduced as gestational age progressed.[32,47,48,58] However, only WBGT statistically significantly increased maternal skin temperature, and none of the covariates were statistically significantly associated with the change in maternal heart rate (table 2, appendix pp 3–6).

Subgroup analyses of the sauna studies found pooled mean differences of 29·4 bpm in maternal heart rate (95% CI 23·1–35·8), 0·33°C in maternal core temperature (0·24–0·42), 5·53°C in maternal skin temperature (5·33–5·73), and 10·71 bpm in fetal heart rate (7·53–13·88) before and after exposure (appendix pp 8–9).

Sensitivity analysis of the imputed variances by a leave-one-out analysis lowered the pooled effect only slightly (from 0·526°C to 0·493°C; Δ of 0·033°C). In the leave-one-out analysis, removing each imputed-variance study individually resulted in only minor shifts in the pooled estimate (range: 0·514 to 0·535°C), with all studies remaining close to the primary pooled effect with highly overlapping CIs. Together, these findings indicate that the core temperature results are robust, and no imputed-variance study exerted undue influence on the overall effect.

Three studies included participants with either hypertension or pre-eclampsia.[46,55,70] Pirhonen and colleagues compared two groups: 14 healthy pregnant women (group 1), and ten pregnant women with pregnancy-induced hypertension and two pregnant women with essential hypertension (group 2), with both groups exposed to settings similar to a sauna for 20 min (70°C, 15% reported humidity).[55] Group 2 showed a statistically significant increase in uterine artery pulsatile index during exposure, which was not observed in group 1.

Pystynen examined four groups under sauna conditions: healthy pregnancy (n=10), essential hypertension (n=4), mild pre-eclampsia (n=26; defined by albuminuria, blood pressure 140/90 mm Hg to 160/110 mm Hg with mild oedema), and severe pre-eclampsia (n=20; with additional symptoms such as headache, dyspnoea, or visual disturbances).[46] Maternal heart rate increased most in the healthy group, with a statistically significantly less reactive heart rate in those with more severe pre-eclampsia. Blood pressure dropped immediately post-exposure in participants from both mild and severe pre-eclamptic groups,

	Country	Setting (exposure)	Sample size (n)	Gestational age at exposure	Key findings
Maternal hypertension and pre-eclampsia					
Pirhonen and colleagues (1994)[55]	Finland	Heat chamber and sauna study; heat stress of 20 min, 70°C, and 15% relative humidity	14 healthy pregnant women and 12 pregnant women with hypertension	Not specified	Uterine artery pulsatility index increased significantly during heat stress in pregnant women with hypertension, but not in healthy controls; baseline pulsatility index of 0·80 (SD 0·36) *vs* 0·47 (0·11), p=0·004
Pystynen (1961)[46]	Finland	Sauna study	50 pregnant women with pre-eclampsia and 10 normal pregnant women	40 weeks	Blood pressure dropped immediately post-heat exposure in groups of pregnant women with pre-eclampsia, but not in healthy pregnant women; maternal heart rate response was highest in healthy pregnant women, and decreased with increasing severity of pre-eclampsia (26 pregnant women with mild pre-eclampsia and 20 pregnant women with severe pre-eclampsia)
Wang and colleagues (2024)[70]	China	Field study	133 515 women from a pregnancy cohort	From conception until 20 weeks	Heat stress during the first 20 weeks was associated with increased risk of maternal hypertension and both spontaneous and medically indicated preterm birth; mediation analysis showed 15·7% (spontaneous) and 33·9% (medically indicated) of this effect was attributable to maternal hypertension
Maternal glucose control					
Clapp and colleagues (1987)[48]	USA	Heat chamber, 20 min treadmill running at 21–23 °C, 30–50% relative humidity, and no wind	10 recreational runners	2 months pre-conception, 19–22 weeks, and 30–33 weeks	At 20 weeks, no significant change in glucose after exercise-induced heat stress, but by 32 weeks, a consistent drop was observed (5·3 mmol/L to 4·55 mmol/L; p<0·0001); lactate levels rose before pregnancy, but the increase was reduced and did not reach statistical significance in late pregnancy
Shen and colleagues (2019)[60]	Australia	Field study, seasonal ambient temperature	2120 women from a pregnancy cohort	24–32 weeks	Higher ambient temperatures were linked to lower maternal fasting glucose (4·4 mmol/L *vs* 4·5 mmol/L; p<0·001), 1 h (p=0·002), and 2 h glucose (p<0·001) after oral glucose tolerance test; HbA_{1c} (p<0·001) and HOMA-IR (p=0·014) declined in warmer months; umbilical cord C-peptide inversely correlated with temperature (r=–0·153; p<0·001); umbilical cord glucose was unchanged by temperature
Placental hormones and metabolic markers					
Vähä-Eskeli and colleagues (1992)[53]	Finland	Heat chamber and sauna study; heat stress of 20 min, 70°C, and 15% relative humidity	Healthy pregnant women (group 1 n=23, group 2 n=23)	13–14 weeks (group 1) and 36–37 weeks (group 2)	Minor non-significant increase in oestradiol and oestriol, progesterone unchanged; decreased thromboxane B2 in early pregnancy (p<0·005), increased 6-keto-PGF1α in late pregnancy (p<0·05); no change in uterine artery or umbilical artery flow; no increase in fetal heart rate or signs of fetal distress
Uteroplacental blood flow					
Vähä-Eskeli and colleagues (1991)[51]	Finland	Heat chamber and sauna study; heat stress of 20 min, 70°C, and 15% relative humidity	17 healthy pregnant women	36–37 weeks	No significant change in uterine artery or umbilical artery pulsatility index; minor transient increase in uterine artery resistance index score in a few cases linked to decreased maternal blood pressure
Pirhonen and colleagues (1994)[55]	Finland	Heat chamber and sauna study; heat stress of 20 min, 70°C, and 15% relative humidity	14 healthy pregnant women and 12 pregnant women with hypertension	Not specified	Baseline uterine artery pulsatility index was higher in pregnant women with hypertension *vs* healthy pregnant women (0·80 [SD 0·36] *vs* 0·47 [0·11]; p=0·004); umbilical artery pulsatility index was also elevated (1·03 [0·33] *vs* 0·82 [0·15]; p=0·037)
Yüzen and colleagues (2023)[66]	Germany	Field study	386 women from a pregnancy cohort	34–37 weeks	Heat exposure of ≥4 days exceeding 90th percentile of ambient temperature was linked to a significant decrease in uterine artery pulsatility index (β=–0·12; 95% CI –0·20 to –0·04; p=0·004); no change in umbilical artery pulsatility index
Bonell and colleagues (2022)[62]	West Africa	Field study and occupational heat exposure	40 women performing manual labour	At least 28 weeks	Umbilical artery resistance index score was consistently higher in women with adverse pregnancy outcomes at all timepoints (ie, baseline 0·68 *vs* 0·65; mid-shift 0·69 *vs* 0·67; and end-shift 0·66 *vs* 0·65); heat stress thresholds associated with placental insufficiency were a universal thermal climate index score of ≥32°C and a WBGT of ≥30°C
Effect on placental gene expression					
Shankar and colleagues (2023)[27]	Pakistan	Field study, seasonal ambient temperature	459 women from a randomised controlled trial	Throughout pregnancy	Early pregnancy exposure significantly altered the expression of 995 genes in the placenta (false discovery rate p<0·05); key gene changes were seen in pathways involved in protein synthesis, stress responses, and nutrient delivery important for fetal growth; specific stress-related genes (*XBP1*, *HSPA5*, and *ERN1*) were activated, indicating possible links to placental insufficiency and pre-eclampsia; higher ambient temperature was negatively associated with choline and positively associated with glutamine, histidine, arginine, methionine, and symmetric dimethylarginine levels (adjusted p<0·001)

(Table 3 continues on next page)

	Country	Setting (exposure)	Sample size (n)	Gestational age at exposure	Key findings
(Continued from previous page)					
Abraham and colleagues (2018)[59]	France	Field study, seasonal ambient temperature	668 women from a pregnancy cohort	At least 24 weeks	No significant association found between seasonal ambient temperature and DNA methylation for fetal side of the placenta; however, 13 differentially methylated regions mapping to eight genes were linked to humidity
Effect on amniotic fluid					
Sciscione and colleagues (1997)[57]	USA	Field study, seasonal ambient temperature	42 women from record review	27–40 weeks	Higher ambient temperatures (especially 4-day mean) were significantly associated with lower amniotic fluid index (r=–0·31; p<0·001)

6-keto-PGF1α=6-keto-prostaglandin F1 α. HbA_{1c}=glycated haemoglobin. HOMA-IR=Homeostatic Model Assessment for Insulin Resistance score. WBGT=wet bulb globe temperature.

Table 3: **Summary of narrative findings on the effects of heat stress during pregnancy on maternal and placental outcomes**

with no change in the healthy group. Fetal auscultation was typical before exposure in all groups; however, post-exposure fetal heart rate abnormalities were noted in six (30%) of 20 with severe pre-eclampsia, nine (35%) of 26 with mild pre-eclampsia, and four (40%) of ten with healthy pregnancies. One stillbirth occurred in the severe pre-eclampsia group the following day.

Wang and colleagues' study of 197 080 pregnant women found that heat exposure in the first 20 weeks of gestation was associated with increased risk of maternal hypertension and both spontaneous and medically indicated preterm birth.[70] On mediation analysis, 15·7% of the effect of heat on spontaneous birth and 33·9% of the effect of heat on medically induced preterm birth was due to maternal hypertension.

For the remaining maternal and placental outcomes, a narrative synthesis of findings is given for cases where meta-analysis was not feasible due to heterogeneity or single-study reporting (table 3). These outcomes include placental hormones,[53] glucose metabolism,[48,60] hypertension and pre-eclampsia,[46,55,70] uteroplacental blood flow,[51,55,62,66] placental gene expression,[27,59] and amniotic fluid levels (table 3).[57] Findings on changes in uteroplacental blood flow were inconsistent; however, two studies reported elevated uterine artery pulsatile indices in women with hypertension.[55,62] High ambient temperatures were associated with lower maternal fasting glucose, post-oral glucose tolerance test levels, and glycated haemoglobin. Two studies identified statistically significant changes in placental gene expression,[27,59] particularly in stress response and nutrient transfer pathways, indicating potential mechanisms of heat-related placental insufficiency.

Seven of the eight studies that monitored fetal heart rate—including 201 pregnancies—presented data that could be included in the meta-analysis.[49,51,53,55,56,62,64] The overall increase in fetal heart rate immediately post-heat stress exposure was 12·6 bpm (SE 1·79; 95% CI 8·8–16·5; figure 3). There was substantial heterogeneity (I^2=0·78), which likely reflected the variety in exposures, as four studies simulated sauna conditions, one included elite athletes, and two were based on occupational heat exposure. The funnel plot was symmetrical, indicating minimal evidence of publication bias. Meta-regression did not show any clear association between fetal heart rate change and gestational age, MET, or WBGT exposure, but there was a clear relationship with duration of exposure (appendix pp 6–8).

A multicentre, prospective cohort study of 162 014 pregnant women by Wang and colleagues examined fetal heart rate as a mediator in the pathway between heat exposure and preterm birth.[68] Participants had their fetal heart rate measured 4 weeks before delivery. Compared with term births, preterm birth was associated with whole-pregnancy and early and later gestation heat exposure, defined as temperatures exceeding the 90th percentile. Heat exposure was associated with increased fetal heart rate and, on mediation analysis, was associated with 5·14% (third trimester) and 23·19% (entire pregnancy) of the association between heat and preterm delivery.

Six studies monitored the fetus for evidence of fetal distress, defined by either reduced fetal movement, accelerations or decelerations in fetal heart rate, or increased resistance index in the umbilical artery doppler during the heat stress exposure.[46,49,51,56,62,64] In studies of healthy pregnancies, any alterations in fetal status were short-term and resolved within 1 h of termination of the heat stress exposure, except in one case, where there were persistent changes and the baby was subsequently stillborn.[62]

Discussion

This systematic review and meta-analysis describes the current evidence on the physiological and biological pathways that have been observed in pregnant women exposed to heat. Our findings suggest that available evidence is growing, yet substantial gaps remain. Acute exposure leading to maternal heat strain, as evidenced by a rise in maternal core temperature and heart rate, has been shown to occur in both field-based and laboratory-based studies. In addition, when external heat exposure was isolated from endogenous heat production, physiological changes remained. Although the pooled change in maternal heart rate dropped from 38 bpm to 29 bpm when only sauna studies were included, this finding still represents a statistically significant rise in physiological stress. When this observation is contextualised within real-world extreme

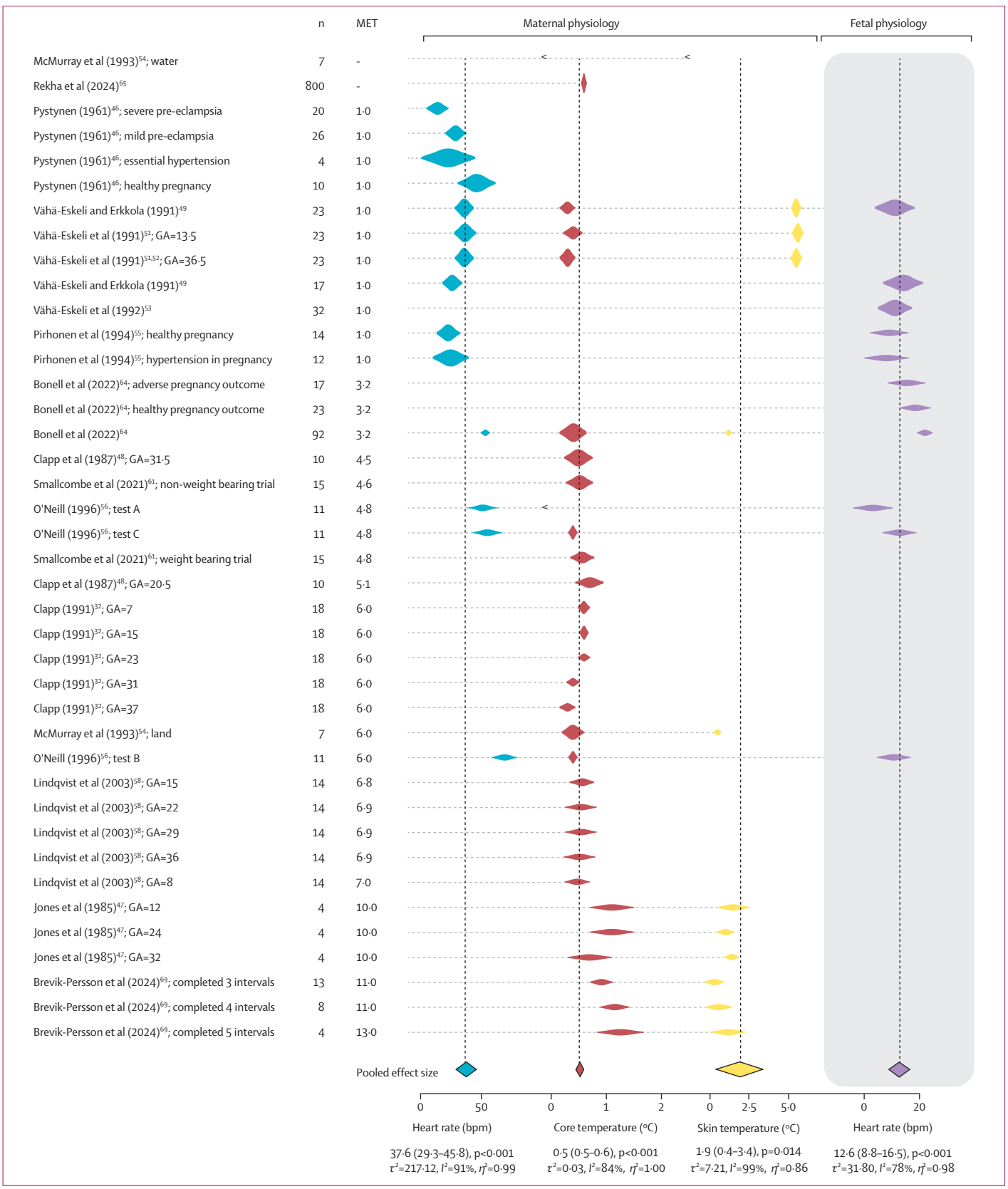
n
MET
Maternal physiology
Fetal physiology
McMurray et al (1993)[54]; water 7 -
Rekha et al (2024)[65] 800 -
Pystynen (1961)[46]; severe pre-eclampsia 20 1·0
Pystynen (1961)[46]; mild pre-eclampsia 26 1·0
Pystynen (1961)[46]; essential hypertension 4 1·0
Pystynen (1961)[46]; healthy pregnancy 10 1·0
Vähä-Eskeli and Erkkola (1991)[49] 23 1·0
Vähä-Eskeli et al (1991)[51]; GA=13·5 23 1·0
Vähä-Eskeli et al (1991)[51,52]; GA=36·5 23 1·0
Vähä-Eskeli and Erkkola (1991)[49] 17 1·0
Vähä-Eskeli et al (1992)[53] 32 1·0
Pirhonen et al (1994)[55]; healthy pregnancy 14 1·0
Pirhonen et al (1994)[55]; hypertension in pregnancy 12 1·0
Bonell et al (2022)[64]; adverse pregnancy outcome 17 3·2
Bonell et al (2022)[64]; healthy pregnancy outcome 23 3·2
Bonell et al (2022)[64] 92 3·2
Clapp et al (1987)[48]; GA=31·5 10 4·5
Smallcombe et al (2021)[61]; non-weight bearing trial 15 4·6
O'Neill (1996)[56]; test A 11 4·8
O'Neill (1996)[56]; test C 11 4·8
Smallcombe et al (2021)[61]; weight bearing trial 15 4·8
Clapp et al (1987)[48]; GA=20·5 10 5·1
Clapp (1991)[32]; GA=7 18 6·0
Clapp (1991)[32]; GA=15 18 6·0
Clapp (1991)[32]; GA=23 18 6·0
Clapp (1991)[32]; GA=31 18 6·0
Clapp (1991)[32]; GA=37 18 6·0
McMurray et al (1993)[54]; land 7 6·0
O'Neill (1996)[56]; test B 11 6·0
Lindqvist et al (2003)[58]; GA=15 14 6·8
Lindqvist et al (2003)[58]; GA=22 14 6·9
Lindqvist et al (2003)[58]; GA=29 14 6·9
Lindqvist et al (2003)[58]; GA=36 14 6·9
Lindqvist et al (2003)[58]; GA=8 14 7·0
Jones et al (1985)[47]; GA=12 4 10·0
Jones et al (1985)[47]; GA=24 4 10·0
Jones et al (1985)[47]; GA=32 4 10·0
Brevik-Persson et al (2024)[69]; completed 3 intervals 13 11·0
Brevik-Persson et al (2024)[69]; completed 4 intervals 8 11·0
Brevik-Persson et al (2024)[69]; completed 5 intervals 4 13·0
Pooled effect size
0 50
0 1 2
0 2·5 5·0
0 20
Heart rate (bpm)
Core temperature (°C)
Skin temperature (°C)
Heart rate (bpm)
37·6 (29·3–45·8), p<0·001
τ²=217·12, I²=91%, η²=0·99
0·5 (0·5–0·6), p<0·001
τ²=0·03, I²=84%, η²=1·00
1·9 (0·4–3·4), p=0·014
τ²=7·21, I²=99%, η²=0·86
12·6 (8·8–16·5), p<0·001
τ²=31·80, I²=78%, η²=0·98

Figure 3: **Rainforest plot of maternal and fetal physiological responses to heat exposure during pregnancy**
Each panel presents a separate outcome: maternal heart rate (blue), core temperature (orange), skin temperature (yellow), and fetal heart rate (purple). For each study, the width of the shape represents the 95% CI of the mean difference between pre-exposure and post-exposure values: wider shapes indicate greater uncertainty, and taller shapes indicate greater contribution to the pooled estimate. GA=gestational age. bpm=beats per min. MET=metabolic equivalent task.

heat exposure, where physical activity is necessary, we believe the combined internal and external heat-load is highly relevant. Of note, fetal distress appears to be a clear pathological response to heat stress and is particularly likely in pregnant women with pre-eclampsia.[46,55] However, almost all other hypothesised pathways—including the impacts of chronic exposure that could result in cumulative strain, long-term inflammatory activation, oxidative stress, or placental dysfunction—remain under-researched. These findings differ from those presented in existing reviews, which have mostly summarised the evidence on the impact of heat on adverse pregnancy outcomes, rather than capturing a contemporary understanding of mechanistic pathways.

The ongoing climatic shifts jeopardise recent advances in reducing maternal, fetal, and neonatal morbidity and mortality. Rooted in epigenetic and molecular mechanisms, the Developmental Origins of Health and Disease hypothesis suggests that environmental exposures during periconceptual and fetal stages induce predictive epigenetic adaptations that reprogramme gene expression and cellular function, influencing long-term susceptibility to diseases.[72] By disrupting the highly vulnerable stage of fetal development, rising ambient temperatures could not only shape the immediate course of pregnancy, but also silently programme the biological blueprint of future generations.

There remains an urgent need to raise awareness of the risks of heat exposure in pregnancy, both to the general population and medical professionals. This recognition could be reached by the acknowledgment of pregnant people and their children as vulnerable groups in heat action plans, specific guidelines, and education material developed for health-care professionals and pregnant people themselves. For example, pregnant people are not included as a high-risk group in the WHO heat and health factsheet. However, general advice given by WHO on behavioural adaptations to heat can be applied to pregnant people and will likely reduce adverse outcomes. These recommendations include avoiding being outside at the hottest time of the day, resting in cool and shaded places, wearing light and loose-fitting clothing, use of cold water sprays and showers to remain cool, and drinking cold water.[73,74] Despite these general recommendations, this systematic review and meta-analysis highlights the knowledge gap that exists, which prevents clear and evidence-based advice that is specific to pregnancy.

Although we could not define an at-risk temperature exposure at a physiological level, recent reviews of epidemiological literature indicate that temperature or heat stress exposure above the 90th or 95th exposure percentile is associated with increased risk of adverse birth outcomes. This systematic review and meta-analysis indicates that energy expenditure, coupled with heat exposure, worsened maternal core temperature rise. Therefore, it can be suggested that caution should be taken when pregnant women exercise or engage in energy-expensive activities during periods of high heat. A key priority for clinicians will be to understand who the most vulnerable pregnant people and infants are during heat events. The observation that the uteroplacental circulation in women with hypertensive pregnancy disorders might be particularly vulnerable to the additional effects of external heat stresses is important, given the increased risk of maternal and fetal complications in this group. Therefore, there is an urgent need to investigate not only fluid management under heat stress conditions, but also behavioural interventions and alternative cooling strategies to determine evidence-based interventions for this and other potentially vulnerable groups.

Although there is a clear need for extensive human studies in this field, much can be learnt from existing animal literature on the pathophysiology of heat stress in pregnant mammals. The majority of studies in sheep, mice, and rats have found that heat stress reduces both placental and fetal weight and can alter uteroplacental blood flow.[14,39,75,76] Furthermore, studies in pigs, mice, and sheep consistently show statistically significant alterations in placental anatomy, suggesting that this could be a key mechanism in altering placental function and efficiency.[77–79] Several studies have also found that placental mRNA expression is altered, although long-term implications are yet to be explored.[80,81]

Although there is little evidence on the role of the placenta in mediating the impact of heat and inconclusive evidence on the impact of heat on umbilical and uterine arterial blood flow, animal studies would indicate that this is an important area to focus on. Of note, the two field-based studies both showed an impact of heat exposure (one on the uterine artery pulsatility index[66] and the other on the umbilical artery resistance index),[62] whereas the sauna study of women with typical pregnancies showed no changes.[51] These differences could be due to several factors. The sauna study was only 20 min exposure at 70°C with 15% reported humidity, whereas the field-based studies defined exposure by either a full working shift or 4 or more days exceeding the 90th percentile of ambient temperature. The exposures in the field-based studies also differed, as one was in Germany[66] and the other in The Gambia.[62] Finally, the internal metabolic heat production was likely different in the three studies: in the sauna study in Finland,[51] participants remained seated; in the field-based study in The Gambia,[62] participants worked outdoors; and in the field-based study in Germany,[66] participants completed activities of daily living. Therefore, it would be important to understand if there is a threshold effect (either

temperature or duration of exposure), and whether this effect varies with maternal factors or acclimatisation. There is sparse evidence regarding the impact of heat on maternal hormones, with two studies reporting reduced maternal plasma glucose with increased heat exposure.[48,60] We did not find any studies that explored changes in inflammatory markers, cytokines, or heat shock proteins with heat exposure. Furthermore, there is no evidence on the difference between acute and chronic exposure and the likely differing pathways and impacts. Preliminary evidence from Shankar and colleagues[27] indicates that the effect of extreme heat on fetal growth could be attenuated by micronutrient supplementation in the 3 months before conception. This finding would suggest that improved maternal nutrition might enhance resilience to environmental stressors. This observation was also found in a study by Bonell and colleagues[82] in The Gambia, where no effect of heat stress on fetal growth was found in the group that received maternal supplementation with micronutrients in the third trimester, but was found in the group with protein-energy supplementation. Preliminary findings indicate that there could be an interaction between nutritional status and environmental stressors, although further studies are needed for confirmation.

There was substantial heterogeneity in the study designs, which minimised the ability to synthesise results. There is a need for consensus on the gold standard exposure metric, study design and reporting of risk, which would then allow comparability and reproducibility in this field. 11 studies did not report WBGT and so this had to be calculated.[32,46,48,49,51,52,55,56,58,61,69] 15 studies explored pathways other than maternal heat strain, limiting the overall findings.[27,49,51,53,55–60,62,64,65,68] The impact of air pollution, nutritional status and seasonality in the larger epidemiological studies was not always accounted for, despite evidence of a synergistic effect of air pollution and heat exposure in other studies[83,84] and the complexity of seasonal effects. This limitation should not have affected the results from the heat chamber studies, but could have underestimated or overestimated the effect of heat stress on the cohort studies. In addition, we restricted the search to English, which could have missed relevant literature published in other languages.

This systematic review and meta-analysis found consistent evidence that maternal exposure to environmental heat results in physiological strain, characterised by increases in maternal heart rate, core temperature, and fetal heart rate. Women with hypertensive disorders might exhibit heightened susceptibility. Nonetheless, insufficient and heterogeneous data on biomarkers and inflammatory pathways highlight the need for standardised, longitudinal research to clarify the biological mechanisms underlying heat-related pregnancy risks. Although heat-related health outcomes are largely preventable through appropriate interventions, existing disparities in women's rights and access to care exacerbate the existing global inequalities in the response to this crisis. Therefore, despite the urgent need to address the gaps in the scientific understanding of the physiological pathways, there is a broader need to address climate injustice on a global scale.[85]

Contributors

AB conceptualised and wrote the original draft of the manuscript, performed data curation and formal analysis, and acquired funding. AAMQ performed data curation and formal analysis, and wrote the original draft of the manuscript. ADF conceptualised the manuscript, acquired funding, and reviewed and edited the manuscript. LT performed data curation and reviewed and edited the manuscript. ANS-P acquired funding and reviewed and edited the manuscript. JKD reviewed and edited the manuscript. JEH reviewed and edited the manuscript. LGI conceptualised and reviewed and edited the manuscript, performed data curation, acquired funding, and provided software support. AB, AAMQ, and LGI verified the data. All authors had full access to the data in this study and had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

Data extracted from studies and analytical code are available from the corresponding author on reasonable request. The study protocol is available online.[40]

Acknowledgments

This project was funded by the Wellcome Trust through grants 227176/Z/23/Z, 227191/Z/23/Z, and 227190/Z/23/Z.

References

1 Intergovernmental Panel on Climate Change. Climate change 2021: the physical science basis. 2021. https://www.ipcc.ch/report/ar6/wg1/ (accessed March 4, 2023).
2 Song F, Zhang GJ, Ramanathan V, Leung LR. Trends in surface equivalent potential temperature: a more comprehensive metric for global warming and weather extremes. *Proc Natl Acad Sci USA* 2022; **119:** e2117832119.
3 Schwingshackl C, Sillmann J, Vicedo-Cabrera AM, Sandstad M, Aunan K. Heat stress indicators in CMIP6: estimating future trends and exceedances of impact-relevant thresholds. *Earth's Future* 2021; **9:** e2020EF001885.
4 Russo S, Sillmann J, Sterl A. Humid heat waves at different warming levels. *Sci Rep* 2017; **7:** 7477.
5 Ciavarella A, Cotterill D, Stott P, et al. Prolonged Siberian heat of 2020 almost impossible without human influence. *Clim Change* 2021; **166:** 9.
6 Philip SY, Kew SF, van Oldenborgh GJ, et al. Rapid attribution analysis of the extraordinary heat wave on the Pacific coast of the US and Canada in June 2021. *Earth Syst Dyn* 2022; **13:** 1689–713.
7 Van Oldenborgh GJ, Philip S, Kew S, et al. Extreme heat in India and anthropogenic climate change. *Nat Hazards Earth Syst Sci* 2018; **18:** 365–81.
8 Pörtner H-O, Roberts DC, Adams HP, et al. Climate change 2022: impacts, adaptation and vulnerability. 2022. https://www.ipcc.ch/report/ar6/wg2/ (accessed Jan 6, 2024).
9 Jukic AM, Baird DD, Weinberg CR, McConnaughey DR, Wilcox AJ. Length of human pregnancy and contributors to its natural variation. *Hum Reprod* 2013; **28:** 2848–55.
10 Baharav Y, Nichols L, Wahal A, et al. The impact of extreme heat exposure on pregnant people and neonates: a state of the science review. *J Midwifery Womens Health* 2023; **68:** 324–32.
11 Samuels L, Nakstad B, Roos N, et al. Physiological mechanisms of the impact of heat during pregnancy and the clinical implications: review of the evidence from an expert group meeting. *Int J Biometeorol* 2022; **66:** 1505–13.
12 Romanovsky AA. Thermoregulation: some concepts have changed. Functional architecture of the thermoregulatory system. *Am J Physiol Regul Integr Comp Physiol* 2007; **292:** R37–46.
13 Yüzen D, Graf I, Diemert A, Arck PC. Climate change and pregnancy complications: from hormones to the immune response. *Front Endocrinol* 2023; **14:** 1149284.

14 Ramirez JD, Maldonado I, Mach KJ, Potter J, Balise RR, Santos H. Evaluating the impact of heat stress on placental function: a systematic review. *Int J Environ Res Public Health* 2024; **21:** 1111.

15 Jiao A, Sun Y, Avila C, et al. Analysis of heat exposure during pregnancy and severe maternal morbidity. *JAMA Netw Open* 2023; **6:** e2332780.

16 Lakhoo DP, Brink N, Radebe L, et al. A systematic review and meta-analysis of heat exposure impacts on maternal, fetal and neonatal health. *Nat Med* 2025; **31:** 684–94.

17 Bonell A, Part C, Okomo U, et al. An expert review of environmental heat exposure and stillbirth in the face of climate change: clinical implications and priority issues. *BJOG* 2024; **131:** 623–31.

18 Hajdu T, Hajdu G. Post-conception heat exposure increases clinically unobserved pregnancy losses. *Sci Rep* 2021; **11:** 1987.

19 Auger N, Fraser WD, Sauve R, Bilodeau-Bertrand M, Kosatsky T. Risk of congenital heart defects after ambient heat exposure early in pregnancy. *Environ Health Perspect* 2017; **125:** 8–14.

20 Ravanelli N, Casasola W, English T, Edwards KM, Jay O. Heat stress and fetal risk. Environmental limits for exercise and passive heat stress during pregnancy: a systematic review with best evidence synthesis. *Br J Sports Med* 2019; **53:** 799–805.

21 Shashar S, Kloog I, Erez O, et al. Temperature and preeclampsia: epidemiological evidence that perturbation in maternal heat homeostasis affects pregnancy outcome. *PLoS One* 2020; **15:** e0232877.

22 Booth GL, Luo J, Park AL, Feig DS, Moineddin R, Ray JG. Influence of environmental temperature on risk of gestational diabetes. *CMAJ* 2017; **189:** E682–89.

23 Vicedo-Cabrera AM, Iñíguez C, Barona C, Ballester F. Exposure to elevated temperatures and risk of preterm birth in Valencia, Spain. *Environ Res* 2014; **134:** 210–17.

24 Chersich MF, Pham MD, Areal A, et al. Associations between high temperatures in pregnancy and risk of preterm birth, low birth weight, and stillbirths: systematic review and meta-analysis. *BMJ* 2020; **371:** m3811.

25 Wells JC, Cole TJ. Birth weight and environmental heat load: a between-population analysis. *Am J Phys Anthropol* 2002; **119:** 276–82.

26 Basu R, Rau R, Pearson D, Malig B. Temperature and term low birth weight in California. *Am J Epidemiol* 2018; **187:** 2306–14.

27 Shankar K, Ali SA, Ruebel ML, et al. Maternal nutritional status modifies heat-associated growth restriction in women with chronic malnutrition. *PNAS Nexus* 2023; **2:** pgac309.

28 Nyadanu SD, Tessema GA, Mullins B, Kumi-Boateng B, Ofosu AA, Pereira G. Prenatal exposure to long-term heat stress and stillbirth in Ghana: a within-space time-series analysis. *Environ Res* 2023; **222:** 115385.

29 Laburn HP, Faurie A, Goelst K, Mitchell D. Effects on fetal and maternal body temperatures of exposure of pregnant ewes to heat, cold, and exercise. *J Appl Physiol* 2002; **92:** 802–08.

30 Hartgill TW, Bergersen TK, Pirhonen J. Core body temperature and the thermoneutral zone: a longitudinal study of normal human pregnancy. *Acta Physiol* 2011; **201:** 467–74.

31 Abrams R, Caton D, Clapp J, Barron DH. Thermal and metabolic features of life in utero. *Clin Obstet Gynecol* 1970; **13:** 549–64.

32 Clapp JF 3rd. The changing thermal response to endurance exercise during pregnancy. *Am J Obstet Gynecol* 1991; **165:** 1684–89.

33 Dervis S, Dobson KL, Nagpal TS, Geurts C, Haman F, Adamo KB. Heat loss responses at rest and during exercise in pregnancy: a scoping review. *J Therm Biol* 2021; **99:** 103011.

34 Faurie AS, Mitchell D, Laburn HP. Peripartum body temperatures in free-ranging ewes (*Ovis aries*) and their lambs. *J Therm Biol* 2004; **29:** 115–22.

35 Wyrwoll CS. RISING STARS: The heat is on: how does heat exposure cause pregnancy complications? *J Endocrinol* 2023; **259:** e230030.

36 Schröder HJ, Power GG. Engine and radiator: fetal and placental interactions for heat dissipation. *Exp Physiol* 1997; **82:** 403–14.

37 Ioannou LG, Mantzios K, Tsoutsoubi L, et al. Indicators to assess physiological heat strain—part 1: systematic review. *Temperature* 2022; **9:** 227–62.

38 Wang LI, Liu F, Luo Y, Zhu L, Li G. Effect of acute heat stress on adrenocorticotropic hormone, cortisol, interleukin-2, interleukin-12 and apoptosis gene expression in rats. *Biomed Rep* 2015; **3:** 425–29.

39 Dreiling CE, Carman FS 3rd, Brown DE. Maternal endocrine and fetal metabolic responses to heat stress. *J Dairy Sci* 1991; **74:** 312–27.

40 Bonell A, Ioannou LG, Hirst JE, Flouris A. Understanding the physiological and biological response to ambient heat exposure in pregnancy: protocol for a systematic review and meta-analysis. *BMJ Open* 2024; **14:** e085314.

41 Higgins JPT, Morgan RL, Rooney AA, et al. A tool to assess risk of bias in non-randomized follow-up studies of exposure effects (ROBINS-E). *Environ Int* 2024; **186:** 108602.

42 Sterne JA, Hernán MA, Reeves BC, et al. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. *BMJ* 2016; **355:** i4919.

43 Liljegren JC, Carhart RA, Lawday P, Tschopp S, Sharp R. Modeling the wet bulb globe temperature using standard meteorological measurements. *J Occup Environ Hyg* 2008; **5:** 645–55.

44 Furukawa TA, Barbui C, Cipriani A, Brambilla P, Watanabe N. Imputing missing standard deviations in meta-analyses can provide accurate results. *J Clin Epidemiol* 2006; **59:** 7–10.

45 Tetzlaff EJ, Ioannou LG, O'Connor FK, Kaltsatou A, Ly V, Kenny GP. Practical considerations for using personal cooling garments for heat stress management in physically demanding occupations: a systematic review and meta-analysis using realist evaluation. *Am J Ind Med* 2025; **68:** 3–25.

46 Pystynen P. Effect of the Finnish sauna bath on the maternal blood circulation and fluid and electrolyte balance in toxemia of late pregnancy. *Acta Obstet Gynecol Scand Suppl* 1961; **40** (suppl 3)**:** 1–112.

47 Jones RL, Botti JJ, Anderson WM, Bennett NL. Thermoregulation during aerobic exercise in pregnancy. *Obstet Gynecol* 1985; **65:** 340–45.

48 Clapp JF 3rd, Wesley M, Sleamaker RH. Thermoregulatory and metabolic responses to jogging prior to and during pregnancy. *Med Sci Sports Exerc* 1987; **19:** 124–30.

49 Vähä-Eskeli K, Erkkola R. The effect of short-term heat stress on uterine contractility, fetal heart rate and fetal movements at late pregnancy. *Eur J Obstet Gynecol Reprod Biol* 1991; **38:** 9–14.

50 McMurray RG, Berry MJ, Katz VL, Graetzer DG, Cefalo RC. The thermoregulation of pregnant women during aerobic exercise in the water: a longitudinal approach. *Eur J Appl Physiol Occup Physiol* 1990; **61:** 119–23.

51 Vähä-Eskeli K, Pirhonen J, Seppänen A, Erkkola R. Doppler flow measurement of uterine and umbilical arteries in heat stress during late pregnancy. *Am J Perinatol* 1991; **8:** 385–89.

52 Vähä-Eskeli KK, Erkkola RU, Seppänen A, Poranen AK, Säteri U. Haemodynamic response to moderate thermal stress in pregnancy. *Ann Med* 1991; **23:** 121–26.

53 Vähä-Eskeli K, Erkkola R, Irjala K, Uotila P, Poranen AK, Säteri U. Responses of placental steroids, prostacyclin and thromboxane A2 to thermal stress during pregnancy. *Eur J Obstet Gynecol Reprod Biol* 1992; **43:** 97–103.

54 McMurray RG, Katz VL, Meyer-Goodwin WE, Cefalo RC. Thermoregulation of pregnant women during aerobic exercise on land and in the water. *Am J Perinatol* 1993; **10:** 178–82.

55 Pirhonen JP, Vähä-Eskeli KK, Seppänen A, Vuorinen J, Erkkola RU. Does thermal stress decrease uterine blood flow in hypertensive pregnancies? *Am J Perinatol* 1994; **11:** 313–16.

56 O'Neill ME. Maternal rectal temperature and fetal heart rate responses to upright cycling in late pregnancy. *Br J Sports Med* 1996; **30:** 32–35.

57 Sciscione AC, Costigan KA, Johnson TR. Increase in ambient temperature may explain decrease in amniotic fluid index. *Am J Perinatol* 1997; **14:** 249–51.

58 Lindqvist PG, Marsal K, Merlo J, Pirhonen JP. Thermal response to submaximal exercise before, during and after pregnancy: a longitudinal study. *J Matern Fetal Neonatal Med* 2003; **13:** 152–56.

59 Abraham E, Rousseaux S, Agier L, et al. Pregnancy exposure to atmospheric pollution and meteorological conditions and placental DNA methylation. *Environ Int* 2018; **118:** 334–47.

60 Shen EX, Moses RG, Oats JJN, Lowe J, McIntyre HD. Seasonality, temperature and pregnancy oral glucose tolerance test results in Australia. *BMC Pregnancy Childbirth* 2019; **19:** 263.

61 Smallcombe JW, Puhenthirar A, Casasola W, et al. Thermoregulation during pregnancy: a controlled trial investigating the risk of maternal hyperthermia during exercise in the heat. *Sports Med* 2021; **51:** 2655–64.

62 Bonell A, Vannevel V, Sonko B, et al. A feasibility study of the use of UmbiFlow to assess the impact of heat stress on fetoplacental blood flow in field studies. *Int J Gynaecol Obstet* 2022.

63 Peng T, Fang W, Jiang X, Yang Y, Fang Z, Zheng Z. Comparison of the thermal comfort of pregnant women at different stages of pregnancy in a subtropical region. *Build Environ* 2022; **219:** 109121.

64 Bonell A, Sonko B, Badjie J, 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. *Lancet Planet Health* 2022; **6:** e968–76.

65 Rekha S, Nalini SJ, Bhuvana S, Kanmani S, Hirst JE, Venugopal V. Heat stress and adverse pregnancy outcome: prospective cohort study. *BJOG* 2024; **131:** 612–22.

66 Yüzen D, Graf I, Tallarek AC, et al. Increased late preterm birth risk and altered uterine blood flow upon exposure to heat stress. *EBioMedicine* 2023; **93:** 104651.

67 Wu W, Fang Z, Ji X, Zheng Z. Predicted mean vote model for thermal comfort evaluation of pregnant women considering the effects of metabolic rate. *Indoor Built Environ* 2023; **32:** 667–80.

68 Wang L, Zhang C, Di J, et al. Increased risk of preterm birth due to heat exposure during pregnancy: exploring the mechanism of fetal physiology. *Sci Total Environ* 2024; **931:** 172730.

69 Brevik-Persson S, Gjestvang C, Mass Dalhaug E, Sanda B, Melau J, Haakstad LAH. Cool mama: temperature regulation during high-intensity interval running in pregnant elite and recreational athletes. *J Exerc Sci Fit* 2024; **22:** 429–37.

70 Wang L, Di J, Wang Q, et al. Heat exposure induced risks of preterm birth mediated by maternal hypertension. *Nat Med* 2024; **30:** 1974–81.

71 Malik A, Stenchikov G, Mostamandi S, et al. Accelerated historical and future warming in the Middle East and north Africa. *J Geophys Res Atmos* 2024; **129:** e2024JD041625.

72 Lacagnina S. The Developmental Origins of Health and Disease (DOHaD). *Am J Lifestyle Med* 2019; **14:** 47–50.

73 Bhandari D, Bi P, Craig JM, Robinson E, Pollock W, Lokmic-Tomkins Z. Mobilising and evaluating existing heat adaptation measures to protect maternal and child health. *Lancet Planet Health* 2024; **8:** e424–25.

74 WHO. Heat and health factsheet. 2026. https://www.who.int/news-room/fact-sheets/detail/climate-change-heat-and-health (accessed June 10, 2025).

75 Bell AW, Wilkening RB, Meschia G. Some aspects of placental function in chronically heat-stressed ewes. *J Dev Physiol* 1987; **9:** 17–29.

76 Hensleigh PA, Johnson DC. Heat stress effects during pregnancy. I. Retardation of fetal rat growth. *Fertil Steril* 1971; **22:** 522–27.

77 Zhao W, Liu F, Bell AW, et al. Controlled elevated temperatures during early-mid gestation cause placental insufficiency and implications for fetal growth in pregnant pigs. *Sci Rep* 2020; **10:** 20677.

78 Olivier K, Reinders LA, Clarke MW, et al. Maternal, placental, and fetal responses to intermittent heat exposure during late gestation in mice. *Reprod Sci* 2021; **28:** 416–25.

79 Padmanabhan R, Al-Menhali NM, Ahmed I, Kataya HH, Ayoub MA. Histological, histochemical and electron microscopic changes of the placenta induced by maternal exposure to hyperthermia in the rat. *Int J Hyperthermia* 2005; **21:** 29–44.

80 Guo H, Yang Y, Qiao Y, He J, Yao W, Zheng W. Heat stress affects fetal brain and intestinal function associated with the alterations of placental barrier in late pregnant mouse. *Ecotoxicol Environ Saf* 2021; **227:** 112916.

81 Guo H, Liu R, He J, Yao W, Zheng W. Heat stress modulates a placental immune response associated with alterations in the development of the fetal intestine and its innate immune system in late pregnant mouse. *Front Physiol* 2022; **13:** 841149.

82 Bonell A, Vicedo-Cabrera AM, Moirano G, et al. Effect of heat stress in the first 1000 days of life on fetal and infant growth: a secondary analysis of the ENID randomised controlled trial. *Lancet Planet Health* 2024; **8:** e734–43.

83 Ha S, Abatzoglou JT, Adebiyi A, et al. Impacts of heat and wildfire on preterm birth. *Environ Res* 2024; **252:** 119094.

84 Kwag Y, Kim MH, Oh J, Shah S, Ye S, Ha EH. Effect of heat waves and fine particulate matter on preterm births in Korea from 2010 to 2016. *Environ Int* 2021; **147:** 106239.

85 WHO. COP29 special report on climate change and health: health is the argument for climate action. 2024. https://cdn.who.int/media/docs/default-source/environment-climate-change-and-health/58595-who-cop29-special-report_layout_9web.pdf (accessed July 1, 2025).