Climate change, maternal health and birth outcomes: how does environmental heat affect pregnancy and birth outcomes in The Gambia?

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Declaration:

I confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated within the thesis.

[redacted]

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Date: 22nd November 2022

Abstract

Extreme heat exposure is linked to poor maternal and child health. With anthropogenic climate change, global annual temperatures have risen to 1.2°C above pre-industrial levels and are predicted to reach around 2.7°C by the end of the century. West Africa is high-risk for the impacts of climate change, including extreme heat, both in terms of exposure, health risks and adaptation options.

This thesis explores the impact of extreme heat on maternal and fetal physiology to improve understanding of the pathophysiological pathways and examines the longer-term impacts of heat on growth in the first 1000 days of life. Firstly, a prospective cohort study was conducted of heat stress, heat strain and fetal strain in pregnant subsistence farmers in West Kiang, The Gambia. Additionally qualitative work explored the lived experiences of pregnant subsistence farmers, to include how working in the heat whilst pregnant feels, what adaptation options are available, and their concerns for the future. Secondly, an analysis of robust data from a randomized controlled trial of nutritional supplementation characterizes the relationship between chronic heat exposure and growth faltering in the first 1000 days of life, also in West Kiang, The Gambia. Thirdly, I engaged schools across The Gambia to identify climate or environmental issues in their areas, develop solutions to these local problems and brought everyone together for a festival to share climate change solutions.

The findings showed a worrying level of heat exposure already being experienced. Acute impacts on maternal and fetal physiology were high. Long term impacts of heat on growth faltering were significant for weight-for-age and weight-for-height z-scores.

This thesis highlights the ongoing risk to maternal and child health of rising global temperatures, but also demonstrates strong youth and community drive to alter the current trajectory.

Acknowledgements

Firstly, I must thank my amazing supervisors and advisory team. Andrew has been a fantastically supportive supervisor at every stage – helping with navigating the details of running a project at MRCG, and working with insightful and careful thought and very quickly on any manuscript! Additionally, he delivered world-record breaking pastoral care to myself and my family throughout the PhD, especially when we lived in Keneba. His kindness and generosity cannot be overstated, and the children love him. I cannot begin to express how grateful I am to Andy, who from the very outset has given me time, respect and kindness. In essence he has demonstrated what a perfect supervisor should be. His support for my decisions around clinical work and COVID, and his time to discuss the difficult choices we, as a family had to make regarding heading back to The Gambia during the first wave of the pandemic, were incredibly valuable. It goes without saying that he has opened many doors for me during my PhD and I hope that I can follow his example and one day be such an amazing supervisor. Neil's engagement in the work, has from the outset been fantastic. Ever since he got a random email from someone based in Vietnam and we had our first chat, he has been fully supportive and onboard at every step. I am grateful for his calm and sensible advice and for finding the time to spend an afternoon with myself and the children at the sea – that was really special. During the course of my PhD, Ana has reached stellar status with her work on heat and mortality and it is a great privilege to know her. I have enjoyed learning from her epidemiological and statistical knowledge, and I am a better scientist for her guidance. I really hope we can work together on future projects. Jane brings absolutely invaluable expertise and advice to the group and it's safe to say that the work would have been impossible without her input and guidance. Finally, I have to say a huge thank you to Kris. He leads the Planetary Health team at MRCG and has built a small but close-knit and incredibly supportive group. His door is always open and he never gets annoyed (at least not obviously) when I bother him with problems from coding in R to existential crisis regarding the futility of working on the climate crisis – thanks for always listening!

I must also thank all participants in the studies. I am especially grateful to the women in the prospective cohort study who allowed us to follow them around, experience a snap-shot of their lives and humored me when I wanted to “help” – digging the ground (ineffectually), weeding the rice fields (hopefully weeds, although they look very similar) and hauling water from the wells (sometimes a full bucket would reach the top). I feel privileged that I was given the opportunity to meet such a wonderful group of women.

I would also like to say a huge thank you to the study team. It was great to work on the project together and it was especially great to work with Jainaba who has developed over the last few years and will hopefully start studying for her Masters soon. I would also like to thank everyone in MRCG especially in MRC Keneba where everyone was so welcoming and kind.

Within LSHTM I have had the great privilege of being part of the amazing Planetary Health Network and Centre on Climate Change and Planetary Health, both of which have been fun and inspirational.

Finally, I would like to thank my family and friends. To my parents for always being my champions, retweeting every tweet and letting us stay in your house way more that I’m sure you expected your adult child to be doing. To Fatou for her dedication to the family and the kids, and for her words of wisdom and her wonderful company – I would never have been able to do my fieldwork without her. To my children - Leyla and Rafi, who’s endless joy in everything made the transition to rural Africa easy, and the sudden relocation to the UK during covid an unexpected treasure of family time. They continually surprise me with their "can do" attitude and openness to new people and experiences. Finally, thank you to my wonderful husband Baz, who has from the beginning believed in me more than I have believed in myself, has patiently given me advice (even when I didn't want to hear it), and has travelled around the world on this adventure with me and put my needs first – thank you!

Preface

This thesis is presented in a research paper style format. Supplementary material for each paper is presented in the appendix for that chapter. Published papers are included in their published format.

Chapter 1 Describes the background on climate change and maternal health with an updated systematic review on the impact of heat on stillbirth, low birth weight and preterm birth. I outline the key knowledge gaps in both the global epidemiology and the pathophysiological mechanisms. I discuss the additional risk of occupational heat exposure placed in the study context of The Gambia and discuss the need for public engagement and advocacy to ensure action on climate change considers and includes the voice of the youth.

Chapter 2 describes the rationale for the PhD, the aims and objectives and study designs. All outputs are presented.

Chapter 3 is a published paper of the study protocol: A protocol for an observational cohort study of heat strain and its effect on fetal wellbeing in pregnant farmers in The Gambia. *Wellcome Open Research.*

Chapter 4 is a published paper: A feasibility study of the use of UmbiFlow™ to assess the impact of heat stress on fetoplacental blood flow in field studies. *International Journal of Gynecology and Obstetrics.*

Chapter 5 is a paper in press: Environmental heat stress on maternal physiology and fetal blood flow in pregnant subsistence farmers in The Gambia, West Africa: an observational cohort study. *Lancet Planetary Health.*

Chapter 6 is a published paper: The Challenges of Working in the Heat Whilst Pregnant: Insights From Gambian Women Farmers in the Face of Climate Change. *Frontiers in Public Health.*

Chapter 7 is a prepared paper: Assessing the impact of heat stress on growth faltering in the first 1000 days of life in rural Gambia. Submitting to *Nature Climate Change.*

Chapter 8 is a published paper of the public engagement work: Grassroots and youth-led climate solutions from The Gambia. *Frontiers in Public Health.*

Chapter 9 is a discussion of the overall thesis to include main findings, limitations and recommendations for future work.

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5. Supplementary material for “Assessing the impact of heat stress on growth faltering in the first 1000 days of life in rural Gambia”.
6. Supplementary material for “Grassroots and youth-led climate solutions from The Gambia”.
7. Accepted commentary in Lancet Planetary Health on the public engagement work: “Towards equity and impact in planetary health education initiatives”
8. Published paper in Frontiers in Public Health “Impact of personal cooling on performance, comfort and heat strain in healthcare workers in PPE, a study from West Africa”.

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Abbreviations

APO	Adverse Pregnancy Outcome
ARDS	Acute Respiratory Distress Syndrome
BMI	Body Mass Index
CDC	Centres for Disease Control and prevention
DIC	Disseminated Intravascular Coagulation
DHS	Demographic Health Surveillance
DNA	Deoxyribonucleic Acid
GPR61	G Protein-coupled Receptor 61
HIC	High Income Country
HSP	Heat Shock Protein
IPCC	Intergovernmental Panel on Climate Change
IUGR	Intrauterine Growth Restriction
LMIC	Low-Middle Income Country
LBW	Low Birth Weight
MUAC	Mid-Upper Arm Circumference
PROM	Premature Rupture of Membranes
PSI	Physiological Strain Index
PTB	Preterm Birth
RF	Risk Factor
RI	Resistance Index
SIRS	Systemic Inflammatory Response Syndrome
SSA	Sub-Saharan Africa
TBW	Total Body Water
USS	Ultrasound Scan
UTCI	Universal Thermal Climate Index
WBGT	Wet Bulb Globe Temperature

Glossary of Key Terms

Heat stress: refers to the overall heat load an individual is exposed to and includes metabolic heat as well as external environmental conditions such as air temperature, humidity, radiant heat and wind/air speed.

Heat stress Indices: over 100 heat stress indices exist to attempt to characterize the impact of the combination of heat stress factors on human physiology.

Heat strain: refers to the physiological impact of heat stress and can lead to symptoms of heat illness and eventually heat stroke and death.

COVID-19 impact statement

My PhD was significantly impacted by COVID-19. In March 2020 I was seven months into my field work and on track to meet my recruitment of 125 participants by the end of May with the rest of the year dedicated to follow-up visits and collecting birth outcomes. However, as borders rapidly closed, and my husband was unable to join us from the UK, I had one day's notice before myself and my children took one of the last flights out of The Gambia. The following week, MRCG stopped all field activities as dictated by the Gambian government. For the study this meant we were unable to collect repeated field visits in 62/92 participants and had to rely on the existing clinics and healthcare facilities to record birth outcome data for the remaining deliveries.

Personally, I found myself in London unexpectedly and felt that the only moral course of action at this point was to go back to clinical work. I worked for the next few months in the intensive care unit at University College London Hospital. This was some of the most challenging clinical work I have ever done. This was in part because I had been out of clinical work for six years by this point and was back working as a registrar in ICU, but also because the patients themselves were incredibly sick and unstable, and the emotional burden of speaking to relatives over the phone rather than in person was unexpectedly difficult. Once numbers in ICU returned to within capacity, I stepped out of my clinical role and back to working on my PhD. However, we still could not return to The Gambia at this stage as there were no commercial flights. In August 2020 we were able to return to The Gambia, where I again paused my PhD to work clinically at the hospital on MRCG campus. As one of the few people in country with experience of both treating COVID-19 patients and with delivering ventilatory support, I again felt that I had to offer my clinical skills over continuing with my PhD. I was tasked with training the clinical staff in management of COVID-19, to include management of the acutely unwell patient and the treatment of acute respiratory failure. I had experienced the discomfort of wearing personal protective equipment (PPE) for hours during my time in ICU in the UK and was extremely concerned for my colleagues here who would be wearing PPE in hot, humid conditions that far exceed recommended exposures. Therefore, during the training and simulation sessions I also ran a randomized controlled trial of cooling on performance, comfort and heat strain in healthcare workers in PPE (see appendix 7). It was a great privilege to work with the wonderful healthcare workers at the Clinical Services Department.

I am eternally grateful that the COVID-19 pandemic did not hit The Gambia in the same way as the UK as the healthcare system would have been overwhelmed within days.

CHAPTER 1

BACKGROUND TO THESIS

SUMMARY OF CHAPTER

In this chapter I provide a background and justification to this thesis. I discuss the climate crisis and future predictions. I briefly explore the health impacts of climate change on maternal health before focusing the work on the impact of heat. I first present the epidemiological evidence of the impact of heat on pregnancy and pregnancy outcomes and include an update on a recently published systematic review. I then cover the physiology of thermoregulation and specific considerations in pregnancy and highlight knowledge gaps. I discuss the dual risk of occupational heat and pregnancy, and describe the existing literature on this, to include qualitative studies on perception of risk. Finally, I introduce the importance of raising awareness of the climate crisis, the need for youth engagement and the power of advocacy in shaping our responses to climate change.

1.1. Climate change

Climate change is described as the greatest threat to human health in the 21st century,[1,2] with the impacts unequally distributed around the world. Often those countries that have least contributed to the problem suffer with the most extreme effects.[3] Rising global temperatures have been clearly attributed to human-induced climate change with estimations that annual global temperatures would be approximately 1.2°C lower without human activity, and 37% of heat-related deaths can be attributed to human-induced climate change, based on extensive real-world data.[4] The latest climate models predict global annual temperature rises of around 2.7°C by 2100 if we do not drastically cut emissions, giving a bleak picture for a large part of the global population, who will be at risk of extreme heat in the near future.[5] Therefore action on climate change and more broadly on improving planetary health by reversing biodiversity loss, environmental degradation, virgin land encroachment and environmental pollution is increasingly urgent.[6] The latest results from the Intergovernmental Panel on Climate Change (IPCC) clearly document the impacts on both the natural systems that humans depend upon, and also on human health directly, with a limited timeframe to prevent catastrophic changes.[7]

1.1.1. Heat and maternal health

There are multiple pathways in which climate change can impact upon maternal health both directly (e.g. through extreme heat, air pollution, vector borne diseases) and indirectly (e.g. through migration, food insecurity, violence),[8] as visualised in Figure 1.

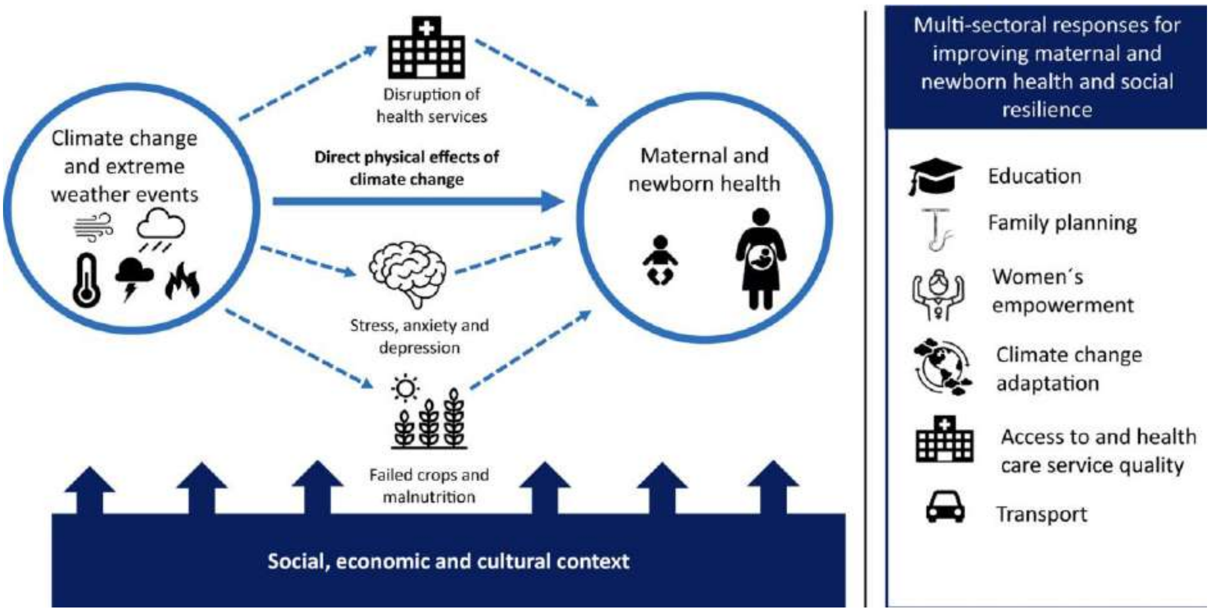


Figure 1: framework of the direct and indirect effects of climate change on maternal and neonatal health.[8]

The focus of the ongoing work is heat and the impact of heat on pregnancy and pregnancy outcomes with the understanding that this is part of a larger scheme of impacts being experienced due to climate change.

Direct effects of heat on pregnancy have been shown to increase the risk of miscarriage,[9] congenital anomalies,[10] stillbirths,[11,12] preterm births,[13,14] low birth weight,[15,16] gestational diabetes,[17] pre-eclampsia[18] and premature rupture of membranes.[19]

1.1.2. Heat and first trimester impacts

Whilst there is clear evidence that in the first trimester an increase in maternal core temperature is linked to increased rates of miscarriage, congenital anomalies, fetal resorption and failure to implant,[9,20] the relevance of this to high ambient temperature exposure is less clear. However recent large-scale studies have found an increased risk of cardiac anomalies in mothers exposed to high ambient temperatures. Auger et al. examined 704,209 fetuses and found a prevalence ratio for atrial septal defect of 1.37 (95% CI 1.1;1.7) in those exposed to >15 days above 30°C from 2-8 weeks post-conception.[10] A further study by Miao et al. of 4,787,356 fetuses found an increased risk of all congenital anomalies associated with increasing temperature variability exposure, with the strongest effect on the 5th week of gestation. At gestational week 5 there was a risk ratio (RR) of 1.06 (95% CI 1.02;1.10) with each 1°C increase in the standard deviation of the daily temperature on all congenital anomalies.[21] However, there remains equipoise in the literature due to several negative studies. There is in general a paucity of evidence to form definitive conclusions and so this remains an area in need of further research.[22]

1.1.3. Heat and preterm birth

The link between ambient heat exposure and preterm birth (PTB) is the most commonly assessed adverse birth outcome in epidemiological studies.[23] In Chersich et al's systematic review they found a large variety in statistical methodology and definitions of heat exposure, making a single estimate of effect impossible.[24] Instead there were several metrics used to combine the results, e.g. on meta-analysis, exposure to a heatwave increased the OR of PTB by 1.16 (95% CI 1.10;1.23), see Figure 2.

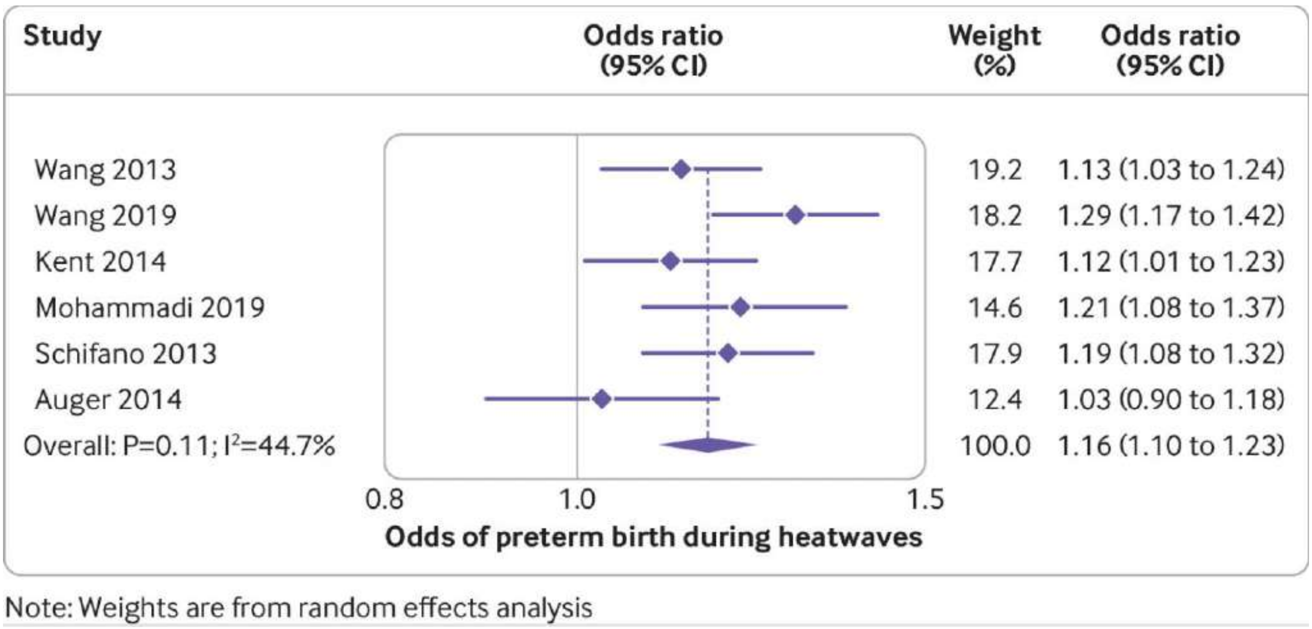


Figure 2: Meta-analysis of odds of preterm birth during a heatwave.[24]

The literature search in this review was conducted in September 2019 and I ran an updated search to April 2022 and found a further 42 relevant articles published since September 2019. Of these, 25 explored the impact of heat on pre-term birth. Again, there is a large variety in both statistical methodologies and in definitions of heat exposure. Table 1 gives a brief description of each study.

Table 1: Studies of ambient temperature exposure and PTB published between September 2019-April 2022.

First Author	Title	Country	Findings
Balvier F[25]	Effect of air temperature on human births, preterm births and births associated with maternal hypertension	Belgium and French Reunion	Increase by 1°C increased PTB by 2.6% at 4 days lag. Those with hypertension increased by 5.7%
Cheng P[26]	Short-term effects of ambient temperature on preterm birth: a time-series analysis in Xuzhou, China	China	Increase risk of PTB in cold temperatures compared to median.
Cushing L[27]	Extreme heat and its association with social disparities in the risk of spontaneous preterm birth	USA	HR of PTB on extremely hot days (AT $\geq$ 40°C) was 1.15 (95% CI 1.01;1.30)
Gat R[28]	Differences in environmental factors contributing to preterm labor and PPROM – Population based study	Israel	High temperature 2 days prior to admission increased PTB (RR=1.08, 95%CI 1.02;1.15) and PROM (RR=1.19, 95%CI 1.03;1.37) in Bedouin but not Jewish population.
Gong Y[29]	Effects of ambient temperature on the risk of preterm birth in offspring of adolescent mothers in rural henan, China	China	Risk of PTB increased by 20.7% (OR 95% CI 1.10;1.32) for each 1°C increase in mean temperature exposure throughout the whole pregnancy
Gronlund C[30]	Time series analysis of total and direct associations between high temperatures and	USA	10.6% of PTB attributed to AT of 24.9C vrs 18.6°C RF: <20yrs, >30yrs and non-black

	preterm births in Detroit, Michigan		
Huang M[31]	Acute associations between heatwaves and preterm and early-term birth in 50 US metropolitan areas: a matched case-control study	USA	OR 1.05 (1.02;1.08) in black women exposed to extreme heat. Non-significant when all ethnicities together
Ilango S[32]	Extreme heat episodes and risk of preterm birth in California, 2005-2013	USA	HR from 1.01 (0.997;1.02) to 1.13 (1.05;1.21) depending on definition of heat episode
Jegasothy E[33]	Maternal factors and risk of spontaneous preterm birth due to high ambient temperatures in New South Wales, Australia	Australia	Exposed to 95th percentile vrs daily median gave RR 1.14 (1.07;1.21).
Kwag Y[34]	Effect of heat waves and fine particulate matter on preterm births in Korea from 2010 to 2016	South Korea	2nd trimester exposure to heatwaves >88th percentile gave OR 1.17 (1.12;1.22) compared to no exposure
Li C[35]	Temperature variation and preterm birth among live singleton deliveries in Shenzhen, China: A time-to-event analysis	China	Explored temperature variation. Risk highest in 2nd trimester: 5.8% (3.3;8.3) increased risk with each 1°C increase in daily temperature range
Liu X[36]	Associations of maternal ambient temperature exposures during pregnancy with the risk of preterm birth and the effect modification of birth order during the new baby boom: A birth cohort study in Guangzhou, China	China	PTB risk peaked at 24/40 gestation HR=1.83 (1.27;2.62)
McElroy S[37]	Extreme heat, preterm birth, and stillbirth: A global analysis across 14 lower-middle income countries	Angola, Benin, Burundi, Ethiopiia, Haiti, Malawi, Nepal, Nigeria, Philippines, South	Increased preterm and stillbirth above 20°C exposure. Impact of reduction in diurnal variation with increased risk of preterm below 16°C variation.

		Africa, Tajikistan, Timor-Leste, Uganda, Zimbabwe	
Ranjbaran M[38]	Ambient temperature and air pollution, and the risk of preterm birth in Tehran, Iran: a time series study	Iran	Exposure to ambient heat at 99th and 95th percentile at lag 0 gave RR of 1.17 (1.05;1.31) and 1.16 (1.04;1.29) respectively for PTB
Smith M[39]	Association of Summer Heat Waves and the Probability of Preterm Birth in Minnesota: An Exploration of the Intersection of Race and Education	USA	Heat wave defined as heat index > 99th percentile for 7 days. Black women with college degrees had a RR of 2.97 (1.5;6.1) PTB compared to white women with college degrees when exposed to a heat wave
Son J[40]	Exposure to heat during pregnancy and preterm birth in North Carolina: Main effect and disparities by residential greenness, urbanicity, and socioeconomic status	USA	HR for 1°C increase in temperature for 7 days prior to deliver was 1.01 (1.00;1.02). Increased risk in urbanised areas, low SES and low greenness.
Song J[41]	Short-term effects of ambient temperature on the risk of premature rupture of membranes in Xinxiang, China: A time-series analysis	China	RR of PROM when exposed to 99th percentile (32°C) = 2.16 (1.24;3.76) compared to median temperature.
Spolter F[42]	Prenatal exposure to ambient air temperature and risk of early delivery	Israel	HR of 1.31 (1.11;1.56) for PTB exposed to highest quintile of temperature compared to 3rd quintile.
Sun Y[43]	Examining the joint effects of heatwaves, air pollution, and green space on the risk of preterm birth in California	USA	Additive interaction between heatwave and high air pollution levels on PTB HRs.
Vilcins D[44]	The Association of Ambient Temperature with Extremely Preterm Births	Australia	Extreme PTB OR = 1.03 (1.01;1.05) with each 1°C increase in maximum temperature

Wang Q[45]	Independent and Combined Effects of Heatwaves and PM2.5 on Preterm Birth in Guangzhou, China: A Survival Analysis	China	HR ranged from 1.10 (1.01;1.20) to 1.92 (1.39;2.64) depending on heatwave definition.
Wang Y[46]	Ambient temperature and the risk of preterm birth: A national birth cohort study in the mainland China	China	HR of 1.55 (1.48;1.61) when exposed to 95th percentile of ambient temperature.
Ward A[47]	The impact of heat exposure on reduced gestational age in pregnant women in North Carolina, 2011-2015	USA	Increased minimal temperature by 2°C increased odds of PTB from 1.01 (1.01;1.02) to 1.06 (1.05;1.07)
Yang D[19]	Influence of ambient temperature and diurnal temperature variation on the premature rupture of membranes in East China: A distributed lag nonlinear time series analysis	China	No increased risk of preterm PROM with heat exposure, but increased risk of term PROM – RR 1.08 (1.01;1.16) exposed to 97.5th percentile of ambient temperature.
Zhou G[48]	Preconception ambient temperature and preterm birth: a time-series study in rural Henan, China	China	>90th percentile ambient temperature exposure 2 weeks prior to conception increased risk of PTB – RR 1.47

AT = Apparent Temperature; CI = Confidence Interval; HR = Hazard Ratio; OR = Odds Ratio; PROM = Premature Rupture of Membranes; PTB = Preterm Birth; RR = Risk Ratio

Most of the studies published from before and after 2019 come from high income countries (HIC) in temperate regions. An important development is the study by McElroy et al. which estimated the effect of ambient temperature exposure on PTB and stillbirths in 14 low-middle income countries (LMICs).[37] This is the first study to document risk of PTB linked to ambient temperature exposure in low income countries (LICs). Ambient temperature from global gridded data and defined as maximum temperature, minimum temperature and diurnal temperature variation was linked to demographic health surveillance (DHS) data to give individual exposure estimates. Despite several tropical countries (with high mean annual temperatures and likely an acclimatised population) being included in the analysis, an exposure above 20°C was linked with an increased risk of PTB.

Further interesting considerations identified in the more recent studies include a synergistic effect of air pollution and heat,[38,49] with increasing risks in several studies and identification of at risk groups (those more likely to be affected by the exposure), to include those with complications of pregnancy, socio-economic factors and ethnic differences.[27,28,33] Additionally, there is growing evidence of an impact of green space on the risk of heat and preterm birth, with less access to green space increasing the negative impact of heat.[40,43]

1.1.4. Heat and stillbirth

All eight studies included in Chersich et al's review on heat and stillbirth found an association between increasing temperature and increasing risk of stillbirth. However, all these studies came from HIC. The updated review included a further 8 studies, most of them again from HIC but with the addition of McElroy et al.'s study on extreme heat and preterm birth and stillbirth from 14 LMICs.[37] Stillbirth risk increased with exposure of 20-30°C maximum temperature, with 20°C as the reference. Stillbirth risk also increased with a decrease in diurnal temperature below 16°C (reduced diurnal temperature indicates a rise in night-time temperature), with a RR of 2.1 (95%CI 1.01;4.02) for a single day below 16°C in the week prior to birth, see Figure 3.

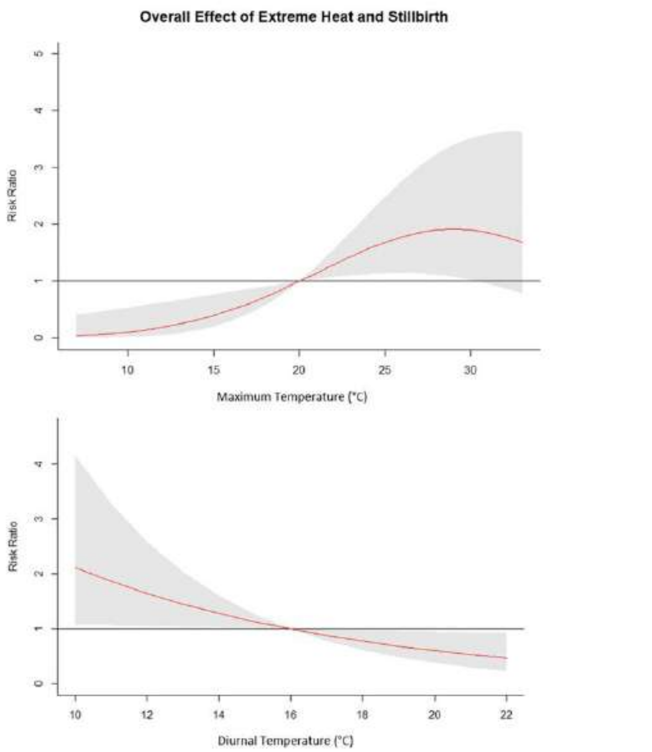


Figure 3: Modelled estimates of association between maximum temperature (reference 20°C) and diurnal temperature range (reference 16°C) and still birth.[37]

Three studies from the USA all found an increased risk of stillbirth with increasing temperature exposure. Kanner et al analysed 112,005 pregnancy outcomes and found an OR of 5.06 (95% CI 3.34;7.68) increased risk of stillbirth for whole pregnancy exposure to extreme heat and on a case-crossover analysis found a 7% increased risk of stillbirth with each 1°C increase during the final week of pregnancy.[50] The two further studies from the USA both used case-crossover methods. This method involves using each individual as their own case and control and evaluating the likelihood of the event (stillbirth) occurring based on the temperature exposure during the case or preceding control weeks. Rammah et al found OR of 1.45 (95% CI 1.18;1.77) increase risk of stillbirth with 5.6°C increase in apparent temperature in the preceding week,[12] and Savitz et al found similar overall levels and when stratified by socio-economic status found OR 2.4 (95% CI 1.2;5.2) in those in the lowest SES quartile vs the highest.[51] In Iran, an area where temperature variation throughout the year is large and summer temperatures can reach as high as 50°C, two studies explored the impact of heat and stillbirth. Khodadadi et al found an increased risk of stillbirth in the last 2 weeks of pregnancy in those exposed to the 99th percentile of heat stress compared to the 75th percentile, OR of 2.0 (95% CI 1.0-4.2).[52] Ranjbaran et al.'s time-series study from Tehran based on data on 3460 stillbirths from 2015-2018 found no significant impact of heat, using a variety of different definitions for exposure.[53] The final two studies were based on historic data from the 1800s in Sweden and although they are unlikely to be directly generalisable due to changes in healthcare generally and in particular antenatal and perinatal care, introduction of antibiotics, alterations in society to include women's rights and gender equality, and environmental and climatic alterations to present day, both studies found an increased risk of stillbirth in hot exposures.[54,55]

1.1.5. Heat and low birth weight

In Chersich et al, 18 out of 28 studies demonstrated an impact of heat on birth weight.[24] No meta-analysis was performed on the studies that assessed risk of low birth weight (LBW) due to the wide variation in effects. The studies that explored changes in birth weight found only small changes (between -10 to -20g) effects, with minimal effect in LMICs. The updated search found a further ten studies exploring heat and low birth weight, all but one of which found a negative impact of heat on birth weight. The study with no significant findings was based in China and explored the impact of temperature and humidity separately.[56] There was no significant association between temperature and birthweight in the adjusted model, but reduced birth weight was associated with low humidity. Again, there was a large heterogeneity in definitions of exposures and outcomes used. One study from Iran found an OR of 2.86 (1.05;7.79) for LBW when mothers were exposed to the 99th percentile Physiological Equivalent Temperature (a heat stress index) two weeks prior to birth.[15] Two studies from USA and Peru, with birth weight as a continuous measure, found the biggest impact of heat in the 3rd trimester with similar reductions in birthweight, - 19.3g (95% CI -27.04;-11.57) and -23.7g (95% CI -28.0;-19.5) respectively.[57,58] Four studies explored the impact of heat on term LBW with slightly increased impact,[59-61] e.g. a study from Israel of 624,940 births found a decrease of 65g (95% CI 72;58) for those exposed to temperatures above the 90th percentile during pregnancy, compared to those exposed to the 41-50th percentile.[62]

Two further studies explored pathophysiological mechanisms linking heat to low birth weight. Wang et al studied the impact of temperature exposure on placental weight, placental volume and placental-weight-to-birth-weight ratio (a proxy of placental efficiency, with increasing values indicating placental dysfunction).[63] Exposure to the 95th percentile

(29°C) versus the mean (20°C) in late pregnancy reduced placental weight -6.03g (-11.28g; -0.78g); reduced placental volume, -16.15cm^3 (-26.24cm^3;-6.07cm^3) and increased placental weight to birth weight ratio, 0.26 (0.07;0.45).

Li et al assessed the level of G protein-coupled receptor 61 (GPR61) methylation status in both mother and neonate on birth weight.[64] GPR61 deficiency has been found to link to increasing body mass index.[65,66] They found significant associations of relative humidity and diurnal temperature range with GPR61 methylation and birth weight, suggesting a possible epigenetic mechanism for the impact of heat on birth weight.

1.2. Heat stress indices

Multiple heat stress indices have been developed over the last 100 years to quantify the heat strain risk with the goal of reducing the morbidity and mortality associated with heat illness.[67] Unfortunately to date there is no gold-standard heat stress index and so in determining the health impacts of heat exposure, many different indices are used and this leads to difficulties in interpreting results, pooling outcomes and calculating accurate estimates of effect.[24]

In this thesis two heat stress indices are used – the Wet Bulb Globe Temperature (WBGT) and the Universal Thermal Climate Index (UTCI). The WBGT was developed in the 1950's in an attempt to reduce heat stress deaths in military training camps in the USA, and was very successful.[67] It is still the most widely used heat stress index and is used to determine occupational safety settings for heat illness risk, in military training and in sports events. The WBGT is based on three parameters: the natural wet bulb temperature (T_{nwb}), black globe temperature (T_g) and the dry bulb temperature (T_{db}). The natural wet bulb temperature is the temperature of a thermometer covered in a wet cotton wick that is exposed to ambient wind and radiation. The black globe temperature is the temperature at the centre of a 15cm diameter black sphere. In the absence of solar radiation this will be the same temperature as the ambient air temperature, but in the presence of solar radiation this will exceed the ambient air temperature. Both the natural wet bulb temperature and the black globe temperature are affected by air movement and the natural wet bulb is additionally affected by the relative humidity. The dry bulb temperature is shielded and so is only affected by air temperature.[67] The WBGT is defined as:

$$WBGT = 0.7T_{nwb} + 0.2T_g + 0.1T_{db}$$

The UTCI was developed by the International Society of Biometeorology and the European Union COST-action 730 in recognition of the need for a universal index that addressed the following needs: 1) short-term weather forecasting and disaster planning; 2) public health evaluations on the impact of environmental conditions and health outcomes; 3) monthly or seasonal forecasting to aid near-future planning; 4) and long-term planning for impacts of climate change.[68] The UTCI-Fiala's multi-node thermophysiological model was selected as the basis upon which to translate actual climate conditions into UTCI values. Fiala's model is based on an "average" person: weight of 73.4kg, fat content of 14% and estimated surface area of 1.85m^2 working at 2.3 MET.[69] This model was then extensively tested and validated both on simulations and using existing datasets to give a UTCI value.[70] This UTCI value is defined as the air temperature of the reference conditions (as described above) causing the same physiological response as the actual conditions.[68] However it is important to note that neither of these indices have any adaptation for pregnancy where the assumptions for an "average" person are unlikely to be met.

1.3. Thermoregulation in pregnancy

Humans maintain their core temperature within a narrow range of 35.5 to 37.5°C.[71] This ensures optimal functioning of the many systems within the body, to include those occurring both intra- and extra-cellularly, e.g. protein folding, catalytic enzyme actions, maintenance of tight junctions between cells to preserve blood brain and intestinal barrier integrity.[72] Heat balance is maintained when heat loss equals heat gain.[73] Heat gain occurs from both internal (metabolic) and external (environmental) sources and heat loss relies on both behavioural and physiological mechanisms (Figure 4). Our behavioural options are many, but the physiological mechanisms to lose heat are limited to three – diversion of blood to the skin to increase radiative and convective heat loss, sweating to enable evaporative heat loss, and reduction in metabolic rate to limit heat production.[72]

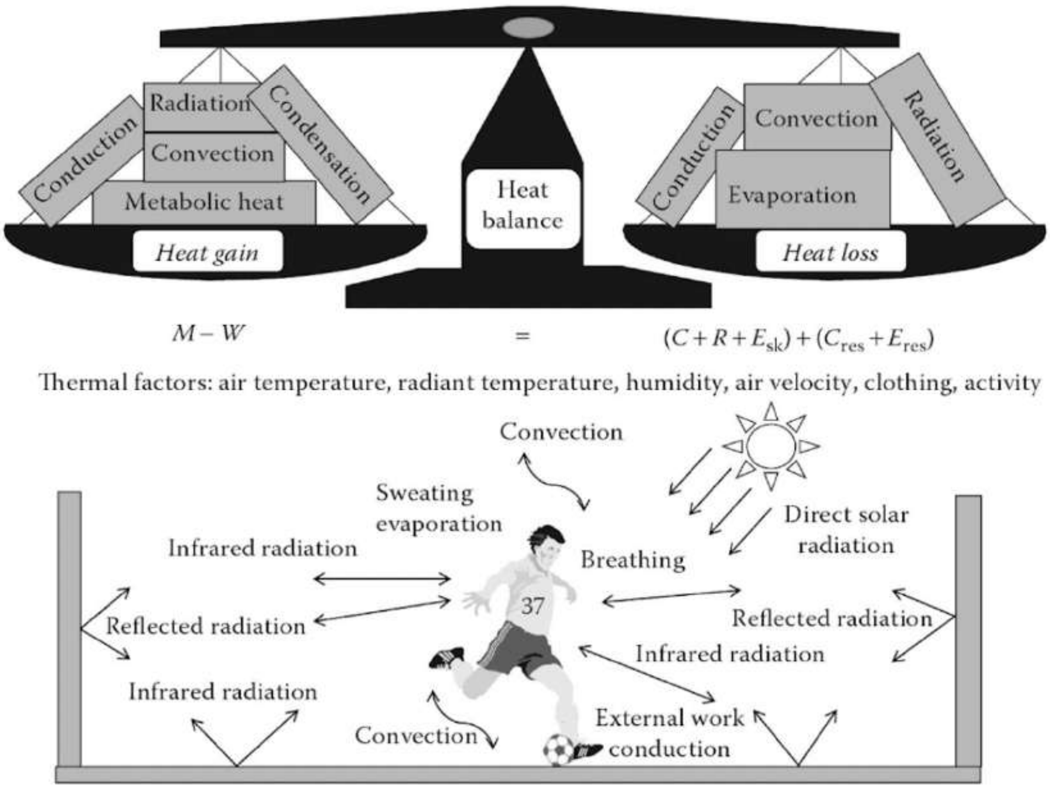


Figure 4a: Representation of heat balance equation to maintain thermal homeostasis.[74]

There are multiple physiological changes that occur during a human pregnancy that could affect thermoregulation. Cardiac output and plasma volume increase by up to 50% by the third trimester and although red blood cells increase, there is a dilutional anaemia.[75] The increase in basal metabolic rate and decrease in body mass to surface area ratio is balanced by lowering of the sweat threshold and a steady decrease in core temperature as pregnancy progresses.

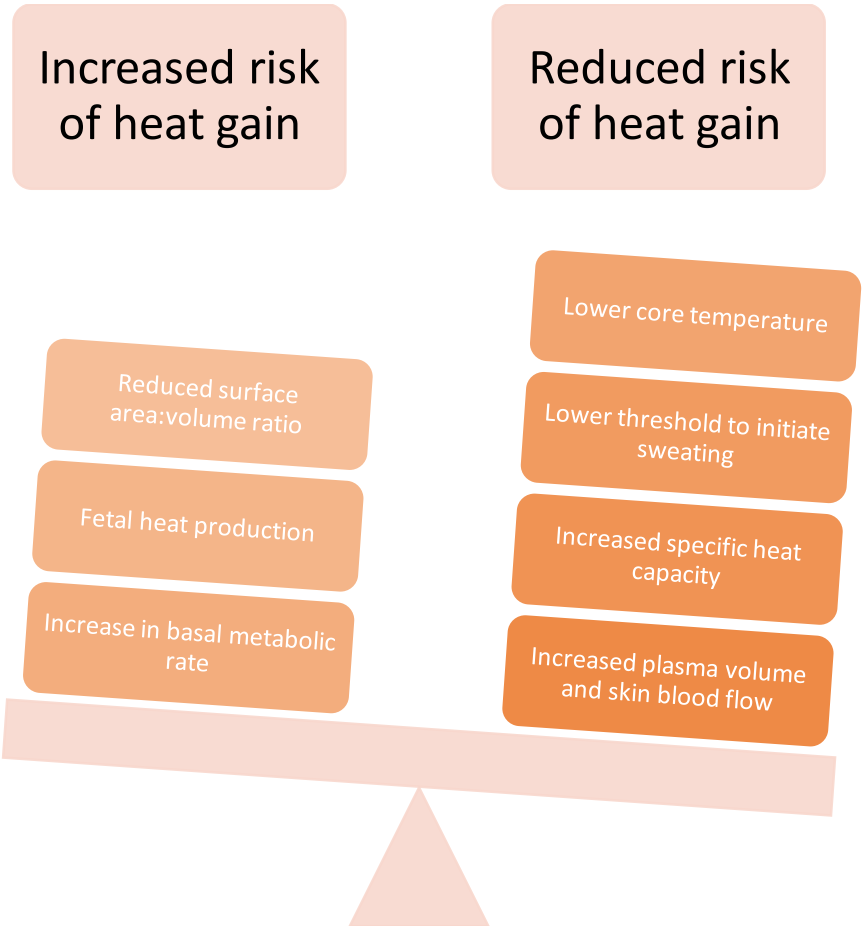


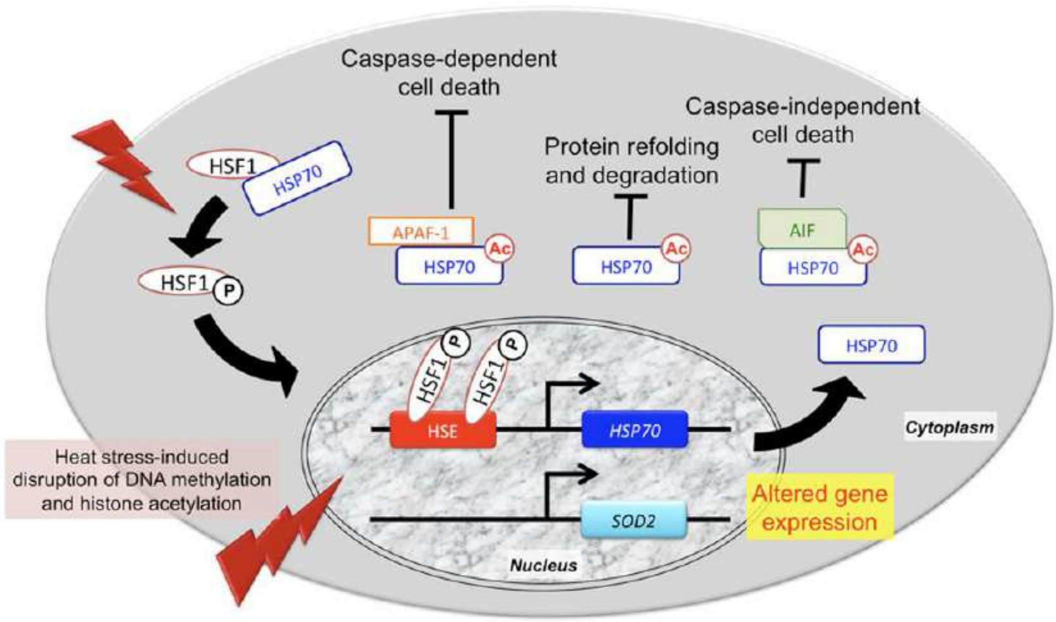
Figure 4b: representation of the physiological alterations in pregnancy that influence thermoregulation.

These physiological changes were previously thought to impair thermoregulation, however there is growing evidence that, in humans, maintaining thermal homeostasis is no more challenging in pregnancy than when not pregnant.[76-78] However, despite thermoregulation being conserved there is a clear link between heat exposure and poor pregnancy outcomes as described above.

1.4. Hypothesised pathophysiological mechanisms

The key pathophysiological mechanisms proposed in the literature for the impact of heat on pregnancy include: maternal heat strain,[73,79] dehydration,[30] reduction in placental blood flow,[80,81] oxytocin and prostaglandin release,[14] heat shock proteins,[82,83] endotoxin and inflammatory cytokine release and DNA methylation (epigenetic changes).[84] Most of these mechanisms although plausible from a theoretical and animal physiological understanding, remain hypothetical as detailed studies in humans are lacking.[77] It is important to note that although pathophysiological mechanisms of reducing fetal size may overlap with preterm birth or stillbirth, there may be other additional pathways to consider for each outcome. For example, details from mammalian studies show that acute heat stress can reduce blood flow to the placenta by up to 30% and when chronically heat stressed in late gestation the placental size can be reduced and nutrient and oxygen transport impaired.[85,86] Therefore, heat stress may reduce blood flow to the placenta and trigger preterm birth or, in a chronic state, result in impaired placental function. However, heat shock proteins are also potentially implicated in preterm birth and therefore it is likely that the pathophysiological pathways are complex and interconnected.[83,87] Heat shock proteins are a broad group of inducible proteins, produced by cells as a response to potentially damaging stimuli, e.g. ischaemic or oxidative or heat stress and often act as intercellular stabilisers.[88] In heat acclimation, heat shock protein levels increase in keeping with the phenotypical changes that are also induced (lowered core body temperature, cardiovascular stability, lowered sweating threshold and improved heat-loss).[89,90] In pregnancy there is no clear consensus on their role,[91] although there is some evidence of differential expression in placentas of those with adverse pregnancy outcomes, such as small-for-gestational age.[83,87]

Hypothesised epigenetic changes associated with maternal heat strain are mostly extrapolated from animal studies. The epigenome is responsible for differential gene expression - genes may be switched on and off in different cell types and at different times in complex organisms such as humans.[92] Defective epigenetic changes can result in severe health implications, such as increased risk of type II diabetes, cardiovascular disease and metabolic disorders.[93,94] Evidence from mammalian studies indicate that epigenetic modifications are sensitive to heat exposure and potentially reduce antioxidant defence capacity amongst other effects (visualised in Figure 5),[84,92] however human data is still lacking. Activation of HSP70 to stabilise the intracellular environment has been shown in mammals whilst in utero with potential implications for long-term heat vulnerability or resilience.[95] The implications of these potential changes in humans remains unclear.



Molecular Reproduction Devel, Volume: 85, Issue: 11, Pages: 810-820, First published: 29 June 2018, DOI: (10.1002/mrd.23040)

Figure 5: Hypothetical model of epigenetic defense mechanisms in heat stressed embryos.[92]

1.5. Occupational heat exposure in pregnancy

The majority of those at risk of extreme heat live in tropical and sub-tropical regions around the world (Figure 6),[96] and West Africa is at high risk to not only extreme heat but also the compounding impacts of food insecurity, vector borne diseases, water scarcity and flooding due to climate change.[97]

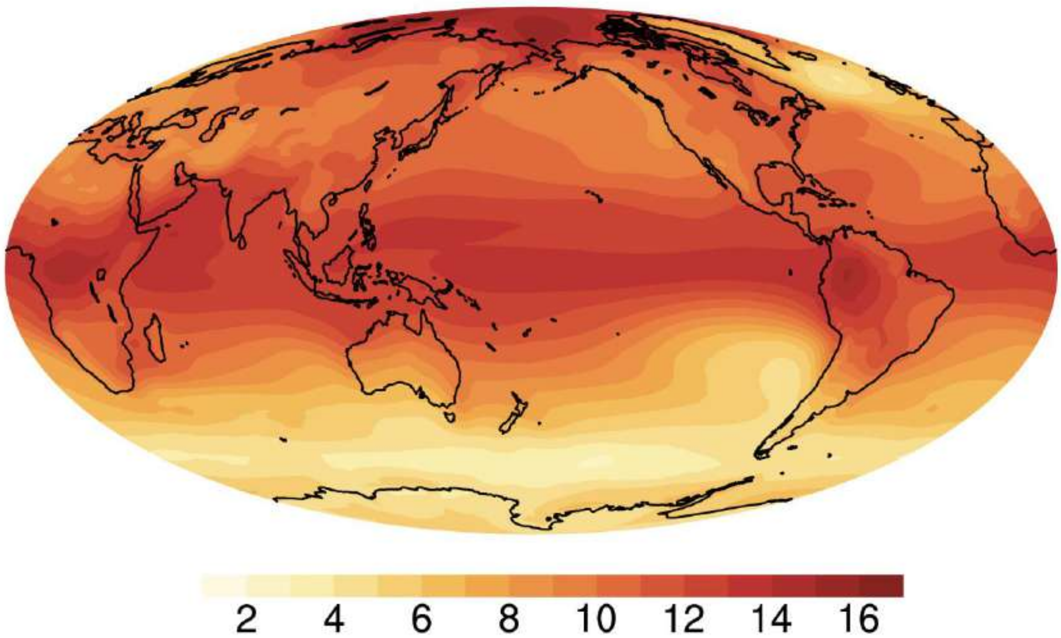


Figure 6: Change in surface equivalent potential temperature (surface temperature, humidity and latent energy) between 2080-2099 and current (1980-1999).[98]

In Sub-Saharan Africa an estimated 50% of the agricultural workforce are female and many will work during pregnancy.[99] Even if not in formal employment, women in these regions are responsible for much of the subsistence farm-work, fetching water, chopping and carrying firewood – all of which incur significant physical strain and continue during pregnancy. A systematic review of occupational heat strain found an estimated 35% of workers at risk of the health impacts of heat stress.[100] However, there remains minimal data available on occupational heat health in pregnant women. One study from Florida, USA found that pregnant agricultural workers were aware of the risks of heat exposure in pregnancy but felt they lacked the agency to alter their exposure.[101] Although data is scarce, there is no reason to suggest that pregnant workers would be protected from the impacts of heat. Indeed, a pilot study from Bangladesh found women construction workers' core temperatures rose during their day of work significantly more than those who worked indoors.[102]

1.6. Advocacy for action on climate change

It has been stated time and again that the climate crisis poses the greatest threat to human health and that there is absolute urgency in the need for action.[6] Despite this, global government action, policy and legislation are lagging far behind. Children, especially children in SSA, are already being harmed by climate change and this will only worsen as global temperatures increase.[103] However, we have seen over recent years that the youth have a powerful voice, are passionate about change and can bring pressure to the international community to act.[104] In The Gambia there is strong government commitment to meet the Paris Accords targets,[105] but in order for this to occur, there must also be strong commitments from the communities. In addition, understanding the impacts of climate and environmental degradation through a child/youth lens, allowing them to consider solutions they would like to see, gives those that will live through this crisis the opportunity to explore an alternative future.

1.7. Study context: The Gambia

Climate change presents a major challenge to The Gambia. West Africa in general is at high risk of the impacts of climate change in terms of extreme heat, drought, and flooding.[106] Salt intrusion, reduction in crop yield and water scarcity risk overturning progress on food security in the region.[107] Additionally, infrastructure to ensure climate resilience within the health service are lacking, adding to the vulnerability. This is all occurring despite the fact that The Gambia has contributed almost nothing to greenhouse gas emissions.

Women and girls are often stated as more vulnerable to the impacts of climate change than men, due in part to poverty, but also due to societal constraints and lack of agency.[108] Despite this, women can be strong defenders of the environment and powerful agents of change, given the information and tools to make this possible. The impact of heat on pregnancy outcomes is well documented in temperate regions and the Global North, however there are sparce data from SSA. This PhD will explore the impact of heat stress on maternal and fetal physiology, how longer-term heat stress exposures impact growth in utero and up to 2 years of age and how pregnant farmers experience and adapt to heat stress in the face of climate change.

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CHAPTER 2 - THESIS OVERVIEW

SUMMARY OF CHAPTER

In this chapter I present the rationale, aims and objectives of this thesis. I also declare the sources of funding and list additional publications and outputs.

2.1 PhD Rationale

With increasing global temperatures, and heat stress exposure linked to poor pregnancy outcomes and early childhood mortality, a greater understanding of the pathophysiological mechanisms and long-term outcomes can help develop evidence-based adaptations and interventions.

There are three main pillars to this thesis. Firstly, I focused on heat impacts on pregnant subsistence farmers in rural Gambia. This work targeted a group that were highly likely to be exposed to heat stress. This rationale was based on the following factors: 1) pregnant women are highly under-represented in physiology studies, leading to a paucity of human evidence;(1) 2) subsistence farmers are recognised as an at risk group to both heat and other impacts of climate change, but again are often missing from occupational health research or recommendations;(2) 3) physiological changes due to heat impacts on pregnant farmers had never, to my knowledge, been described; 4) The Gambia is at high risk of extreme heat and this will worsen;(3) 5) by utilising the natural exposure that was already occurring, we could gain understanding of the pathophysiological changes that otherwise would be impossible to study.

Furthermore, to develop interventions to alleviate heat exposure, I felt that in addition to understanding the physiological and biological impact of heat on pregnant subsistence farmers, it was imperative to also understand the following: the experience of heat and climate change that the women were living with; what actions they were already taking to adapt to the heat; and what actions they might be interested in having access to in the future.

The second pillar of the PhD explored the impact of heat on growth in the first 1,000 days of life (from conception to aged 2 years). There is growing recognition that almost all children (>99%) are currently impacted by climate or environmental hazards and those highly exposed live in Africa.(4) This environmental epidemiological analysis linked data from a previously conducted randomised control trial with global gridded climate data. The study was conducted because 1) there is a gap in the understanding of how heat impacts early childhood;(5) 2) by exploring the impact of heat on child growth in The Gambia, the impacts of the climate crisis can be focused on child health and development;(4) 3) there was a unique opportunity to utilise the data from the clinical trial (with robust repeated measures from in utero to 2 years on individuals exposed to high heat stress) to study this impact in detail whilst controlling for important confounders including seasonality and infectious episodes, which has not previously been possible.

The third pillar of the PhD involved public engagement work with school children and youth in The Gambia. I have been impressed by the ability of youth advocates to focus global attention on the climate crisis and the need for action and wanted to understand what the climate crisis and environmental degradation means to the youth of The Gambia. Therefore, I have engaged with them to encourage both an understanding of the harms of climate change/environmental degradation and to identify solutions for the problems they themselves view as imperative for their communities. This engagement work was a two-way learning experience and gave me and the wider planetary health group here at MRCG an insight into a youth-centred understanding of climate change related issues which I hope will help to direct future work.

My final hope is this work can be used to help develop effective and evidence-based interventions to allow adaptation to climate change in communities severely affected.

2.2 PhD Aims and Objectives

This thesis aims to contribute to the evidence base on the impact of heat on maternal and child health through characterising potential pathophysiological pathways of heat stress on maternal and fetal physiology and describing the relationship between heat stress and early growth. Specific objectives include:

- Determine the heat stress exposure of pregnant agricultural workers in The Gambia
- Determine the maternal physiological response to heat stress exposure
- Determine the acute effect of heat stress on the fetus
- Determine the perception of heat risk in pregnancy amongst pregnant subsistence farmers in The Gambia and what adaptation options are available
- Determine the chronic effect of heat stress on growth faltering in the first 1000 days of life in The Gambia
- Engage and listen to the Gambian youth on their problems and solutions to environmental degradation and climate change.

2.3 Ethics

All studies presented were approved by the Gambia government/MRC Joint ethics committee and the London School of Hygiene and Tropical Medicine Ethics Advisory Board in accordance with the Declaration of Helsinki (2013).

2.4 Funding

This thesis was funded by the Wellcome Trust through the Wellcome Trust Global Health PhD Fellowship awarded to myself (216336/Z/19/Z). The funders had no role in any of the study designs, data collection, analysis, or manuscript writing.

2.5 PhD Publications and Additional Outputs

PhD published papers

Bonell A, Hirst J, Vicedo-Cabrera AM, Haines A, Prentice AM, Maxwell NS. A protocol for an observational cohort study of heat strain and its effect on fetal wellbeing in pregnant farmers in The Gambia. Wellcome Open Res. 2020 Mar 31;5:32. doi: 10.12688/wellcomeopenres.15731.2. PMID: 32292825; PMCID: PMC7141168.

Bonell A, Vannevel V, Sonko B, Mohammed N, Vicedo-Cabrera AM, Haines A, Maxwell NS, Hirst J, Prentice AM. 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 Sep 27. doi: 10.1002/ijgo.14480

Spencer S, Samateh T, Wabnitz K, Mayhew S, Allen H, **Bonell A**. The Challenges of Working in the Heat Whilst Pregnant: Insights From Gambian Women Farmers in the Face of Climate Change. Front Public Health. 2022 Feb 10;10:785254. doi: 10.3389/fpubh.2022.785254. PMID: 35237548; PMCID: PMC8883819.

Bonell A, Badjie J, Jammeh S, Ali Z, Hydara M, Davies A, Faal M, Ahmed AN, Hand W, Prentice AM, Murray KA, Scheelbeek P. Grassroots and Youth-Led Climate Solutions From The Gambia. Front Public Health. 2022 Apr 7;10:784915. doi: 10.3389/fpubh.2022.784915. PMID: 35462834; PMCID: PMC9021377.

PhD papers in press (accepted)

Bonell A, Sonko B, Badjie J, Samateh T, Saidy T, Sosseh F, Sallah Y, Bajo K, Murray KA, Hirst J, Vicedo-Cabrera AM, Prentice AM, Maxwell NS, Haines A. A Cohort study assessing the effect of environmental heat stress on maternal physiology and fetal blood flow in pregnant subsistence farmers in The Gambia, West Africa. Lancet Planet Health

PhD prepared manuscript (submitted)

Bonell A, Vicedo-Cabrera AM, Murray KA, Moirano G, Sonko B, Moore S, Haines A, Prentice AM. Assessing the impact of heat stress on growth faltering in the first 1000 days of life in The Gambia. Nature Climate Change

Additional outputs

Below are additional outputs based on the research outputs above.

Media articles

- Heat stress and its severity during pregnancy: The worsening realities of heat stress for pregnant women in West Africa. Physiology News, Issue 127, Autumn 2022. https://www.physoc.org/magazine-articles/heat-stress-and-its-severity-during-pregnancy/
- A Gambian midwife's perspective on extreme heat and pregnancy. Wellcome News, 21st June 2022. https://wellcome.org/news/the-gambia-midwife-perspective-extreme-heat-and-pregnancy
- Seen and heard: Why young people's voices must be listened to and acted upon to tackle climate change. Expert Opinion, 7th April 2022.

https://www.lshtm.ac.uk/newsevents/expert-opinion/seen-and-heard-why-young-peoples-voices-must-be-listened-and-acted-upon

- Gambia's labouring farmers show why premature births may boom in a warmer world. Thomas Reuters Foundation News, 6th Feb 2020. https://news.trust.org/item/20200206142604-qegop/

Poster presentations

- Using UmbiFlow™ to assess heat stress on fetoplacental bloodflow. RCOG World Congress, Jun 2022
- Impact of heat stress on pregnant subsistence farmers in West Africa. Geneva Health Forum, April 2022

Conference talks

- Climate Change and Maternal and Neonatal Health Outcomes: New Methods to Address Heat Impacts in Vulnerable Populations. Symposium at International Society of Environmental Epidemiology, Aug 2021
- Hotter and hotter: effects of extreme heat on maternal and fetal health in The Gambia. Symposium at American Society of Tropical Medicine & Hygiene, Nov 2020
- Heat and Health: a Learning Lab. Planetary Health Conference, Banjul, The Gambia, January 2020

Podcasts

- S5E3: Climate change solutions in The Gambia: Coproduction approaches with pregnant women, schoolchildren and farmers. Connecting citizens to science, Liverpool School of Tropical Medicine
- S1E9: Climate Change and Health. Emissions: Impossible? UK Research and Innovation

- S2E6: What if we can't handle the heat? LSHTM Viral

Webinars

- LSHTM Pre-COP27 Climate & health symposium: moving from evidence to action, Oct 2022
- Burning up: what is extreme heat doing to our planet & our health? London International Development Centre, July 2022
- The Climate Emergency: Funding, Research Gaps and Policy Priorities. The Physiological Society, June 2022
- Our planet, our health: driving action towards a healthy, sustainable future for all. LSHTM, April 2022
- Maternal health, Climate change, and birth outcomes: Environmental and Reproductive Justice Intersections, June 2020

Additional publications

Bonell A, Badjie J, Faal LB, Jammeh S, Ali Z, Hydara M, Davies A, Faal M, Ahmed AN, Hand W, Prentice AM, Murray KA, Scheelbeek P. Towards equity and impact in planetary health education initiatives. Lancet Planet Health, *in press*

Samuels L, Nakstad B, Roos N, **Bonell A**, Chersich M, Havenith G, Luchters S, Day LT, Hirst JE, Singh T, Elliott-Sale K, Hetem R, Part C, Sawry S, Le Roux J, Kovats S. 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 Aug;66(8):1505-1513.

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Bonell A, Nadjm B, Samateh T, Badjie J, Perry-Thomas R, Forrest K, Prentice AM, Maxwell NS. Impact of Personal Cooling on Performance, Comfort and Heat Strain of Healthcare Workers in PPE, a Study From West Africa. Front Public Health. 2021 Sep 1;9:712481. doi: 10.3389/fpubh.2021.712481. PMID: 34540787; PMCID: PMC8440920.

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2.6 References

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CHAPTER 3 – A protocol for an observational cohort study of heat strain and its effect on fetal wellbeing in pregnant farmers in The Gambia

SUMMARY OF CHAPTER

In this chapter I present the published study protocol of an observational cohort study on heat stress in pregnant farmers in The Gambia. I include the rationale for the study, details on the study setting, population, sample size calculation and methodology and outline the statistical analysis plan. A full summary of the chapter can be found in the abstract for the paper.

I include here the published version.

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RESEARCH PAPER COVER SHEET

Please note that a cover sheet must be completed for each research paper included within a thesis.

SECTION A – Student Details

Student ID Number	215963	**Title**	Dr
First Name(s)	Ana		
Surname/Family Name	Bonell		
Thesis Title	Climate change, maternal health and birth outcomes: how does environmental heat affect pregnancy and infant growth in The Gambia?		
Primary Supervisor	Professor Andrew Prentice		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

SECTION B – Paper already published

Where was the work published?	Wellcome Open Research		
When was the work published?	31st March 2020		
If the work was published prior to registration for your research degree, give a brief rationale for its inclusion	NA		
Have you retained the copyright for the work?*	**Yes**	Was the work subject to academic peer review?	**Yes**

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SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	I proposed the idea for this study when I applied for funding for my PhD. In consultation with my supervisors and scientific advisors, we worked on developing the study protocol. I wrote the complete first draft of the paper for the co-authors to review. I produced all figures in this paper and led the submission process and responses to reviewers.

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First published: 18 Feb 2020, **5**:32 https://doi.org/10.12688/wellcomeopenres.15731.1

Check for updates

STUDY PROTOCOL

REVISED **A protocol for an observational cohort study of heat strain and its effect on fetal wellbeing in pregnant farmers in The Gambia** [version 2; peer review: 2 approved]

Ana Bonell[1], Jane Hirst[2], Ana M. Vicedo-Cabrera[3,4], Andy Haines[5], Andrew M. Prentice[1], Neil S. Maxwell[6]

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Abstract
Introduction: Climate change predictions indicate that global temperatures are likely to exceed those seen in the last 200,000 years, rising by around 4°C above pre-industrial levels by 2100 (without effective mitigation of current emission rates). In regions of the world set to experience extreme temperatures, women often work outside in agriculture even during pregnancy. The implications of heat strain in pregnancy on maternal health and pregnancy outcome are not well understood. This protocol describes a study to assess the physiological response of pregnant women to environmental heat stress and the immediate effect this has on fetal wellbeing.
Methods and analysis: The study will be performed in West Kiang district, The Gambia; a semi-arid zone in West Africa with daily maximum temperatures ranging from approximately 32 to 40°C. We will recruit 125 pregnant women of all ages who perform agricultural work during their pregnancy. Participants will be followed every two months until delivery. At each study visit fetal growth will be measured by ultrasound scan. During the course of their working day we will take the following measurements: continuous maternal physiological measurements (heart rate, respiratory rate, chest skin temperature and tri-axis accelerometer data); intermittent maternal tympanic core temperature, four point skin temperature, blood pressure; intermittent fetal heart rate and, if eligible, umbilical artery doppler; intermittent environmental measurements of air temperature, humidity, solar radiation and wind speed. Venous blood

Open Peer Review

Approval Status ✓ ✓

	1	2
version 2 (revision) 31 Mar 2020		✓ view
version 1 18 Feb 2020	✓ view	? view

1. **Matthew F. Chersich**, University of the Witwatersrand, Johannesburg, South Africa
2. **Beth Holder**, Imperial College London, London, UK

Any reports and responses or comments on the article can be found at the end of the article.

and urine will be collected at beginning and end of day for biomarkers of heat strain or fetal distress and hydration status.

Keywords
heat stress, pregnancy, climate change, maternal, subsistence farmer

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Author roles: Bonell A: Conceptualization, Funding Acquisition, Writing – Original Draft Preparation; **Hirst J**: Methodology, Writing – Review & Editing; **Vicedo-Cabrera AM**: Methodology, Software, Writing – Review & Editing; **Haines A**: Conceptualization, Supervision, Writing – Review & Editing; **Prentice AM**: Conceptualization, Supervision, Writing – Review & Editing; **Maxwell NS**: Methodology, Supervision, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: The project is supported by the Wellcome Trust. AB is supported by a Wellcome Clinical PhD Fellowship (203905).
The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

How to cite this article: Bonell A, Hirst J, Vicedo-Cabrera AM *et al.* **A protocol for an observational cohort study of heat strain and its effect on fetal wellbeing in pregnant farmers in The Gambia [version 2; peer review: 2 approved]** Wellcome Open Research 2020, **5**:32 https://doi.org/10.12688/wellcomeopenres.15731.2

First published: 18 Feb 2020, **5**:32 https://doi.org/10.12688/wellcomeopenres.15731.1

REVISED **Amendments from Version 1**

This version clarifies the inclusion criteria, the details of obstetric and medical risk factors that will be collected and how gestation will be taken into account in the analysis.

There is also a limitations section, outlining the methodological flaws inherent with field studies where gold-standard laboratory based measurements are not possible.

Any further responses from the reviewers can be found at the end of the article

Introduction

The world is getting hotter and current projections show no sign of this warming slowing down[1,2]. This global increase in heat comes with increases in both number and duration of heat waves[3]. A recent study described the "temperature of equivalence" concept, which quantified the heterogeneity of surface temperature by geographical regions and demonstrated that low-income countries will bear a greater burden of severe heat events compared to high-income countries, even if target temperatures of less than 1.5°C are met[4,5].

Pregnancy is a vulnerable time. Hyperthermia in the first trimester is teratogenic[6–8] and there is epidemiological evidence of increased preterm births, low birth weight (LBW) and stillbirths following maternal exposure to heat stress[9–13], though data from Africa are sparse and contradictory[14–16].

In temperate regions, a case-crossover study from California found an 8.6% increase in prematurity with every 5.6°C increase in ambient temperature exposure[17]. An intra-population analysis quantified the effect of heat on birth weight and found that heat explained 9.6% of the difference in birth weight between populations[18,19].

Heat stress (a combination of ambient temperature, humidity, solar radiation and wind speed) and the consequent heat strain (the physiological response to heat stress) have not been studied in pregnant women in the field. Heat strain presents as a spectrum from perceived discomfort to death[20]. There is almost no field-based physiology studies concerning the impact of heat stress on maternal physiology or the impact that it has on the developing fetus.

Temperature regulation

Healthy human bodies maintain a core temperature of around 37°C[21]. On a cellular level, this ensures an ideal environment for processes necessary for life, for example enzymes to work optimally and proteins to fold in the required configuration[22]. Heat balance is maintained when heat is lost at a similar rate to which it is produced or absorbed, as visualized in Figure 1[23].

Heat loss can be altered by two mechanisms, autonomic thermoregulation where physiological processes take place without conscious effort, or behavioural thermoregulation, where conscious action is used to reduce body temperature. In certain situations the heat burden cannot be entirely avoided, for example agricultural workers and therefore in these situations the physiological mechanisms act to try and ensure heat balance is maintained. Thermal homeostasis is controlled by the

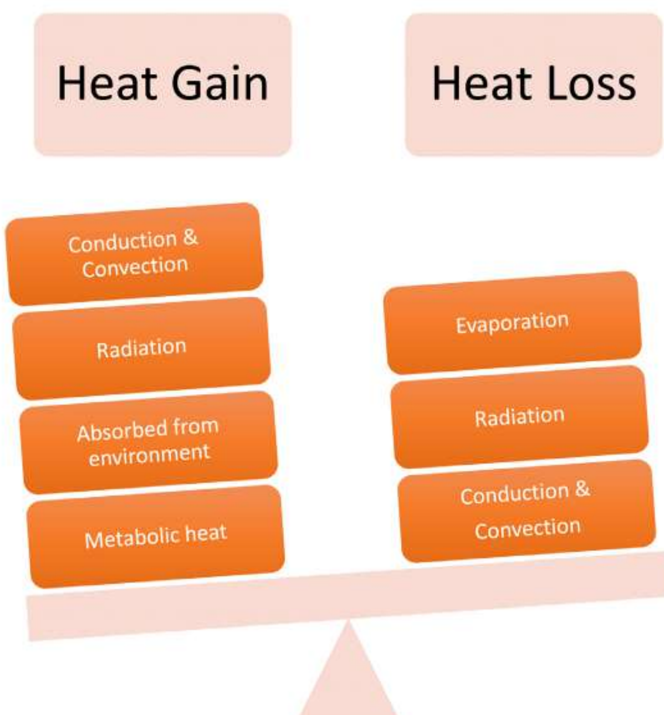

Figure 1. **Thermal factors involved in the maintenance of the heat balance of a body.**

preoptic anterior hypothalamus which receives afferent signals from thermal sensors in the skin and visceral core[24]. The efferent signals stimulate cutaneous vasodilation and sweating. These increase conductive, convective, radiative and evaporative heat loss, see Figure 2.

In contrast to behavioural thermoregulation, which has a near-infinite capacity to regulate body temperature, physiological responses to environmental heat stress have a finite capacity[25]. Heat acclimation (physiological adaptations due to repeated laboratory based heat training) and acclimatization (physiological adaptations due to repeated exposure to heat in the natural environment) improves a body's response to heat stress; however, at a certain point even these mechanisms will be overwhelmed and core body temperature will rise[26,27].

When the internal heat production increases due to increased metabolic demand and/or mechanical work, there is a delay in the body's response to the additional heat stress. On average it takes 45 minutes for a body to reach equilibrium, and prior to this there is heat storage in the body[27]. This is also followed by a post-exercise attenuation of heat dissipation, such that it may take 2 hours for a body to return to thermal equilibrium after exercise[28]. The impact of this on maternal and fetal physiology and health is unknown.

Pathophysiology of heat strain

When a body's capabilities to alleviate heat stress by thermoregulatory mechanisms are overwhelmed then heat strain develops, see Figure 3.

When cutaneous vasodilation is stimulated, blood supply to the skin increases from around 1% of cardiac output to as high as 70% (6-8 L/min)[24,29]. This necessitates a large reduction in blood flow to internal organs, in particular the splanchnic and renal arteries, as well as a reduced venous return. If the heat stress continues, then hypovolaemia due to water and salt loss in sweat exacerbates the reduction in cardiac output and the consequent reduction in blood supply to internal organs. If this continues, there is a risk of acute kidney injury, and splanchnic and cerebral blood flow insufficiency. Interruption of the splanchnic blood flow has been shown to result in ischemia of the gastrointestinal membrane, which potentially results in translocation of gut bacteria and endotoxins[30]. If the heat stimulus is removed at this point, there is still the risk of developing systemic inflammatory response syndrome (SIRS), acute respiratory distress syndrome (ARDS), disseminated intravascular coagulopathy (DIC), multi-organ failure and death due to the stimulation of the pro-inflammatory cascade[31].

Specific considerations in pregnancy

During pregnancy, maternal physiological changes are dramatic. Plasma volume increases by almost 50% in the third trimester, red blood cells increase by a lesser extent, giving a dilutional anaemia, and cardiac output also increases by around 50%[32,33]. The placental blood flow in the third trimester is 600–700 mL/min and is regulated by local vasoactive mechanisms rather than central neuronal command[34].

In terms of thermal regulation, thermal capacity increases, core temperature decreases, heat production increases and

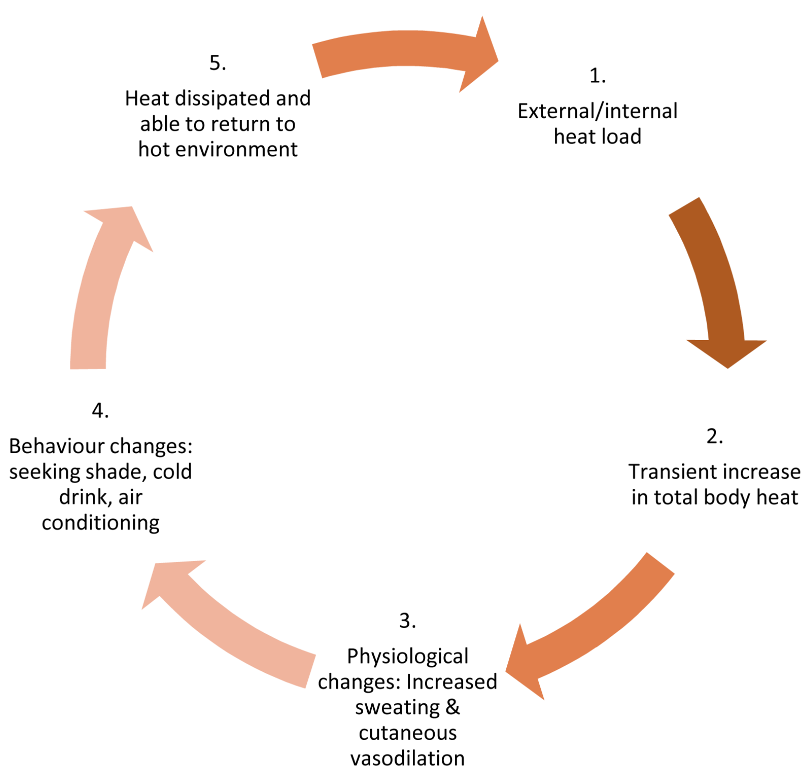

Figure 2. Normal physiological response to heat.

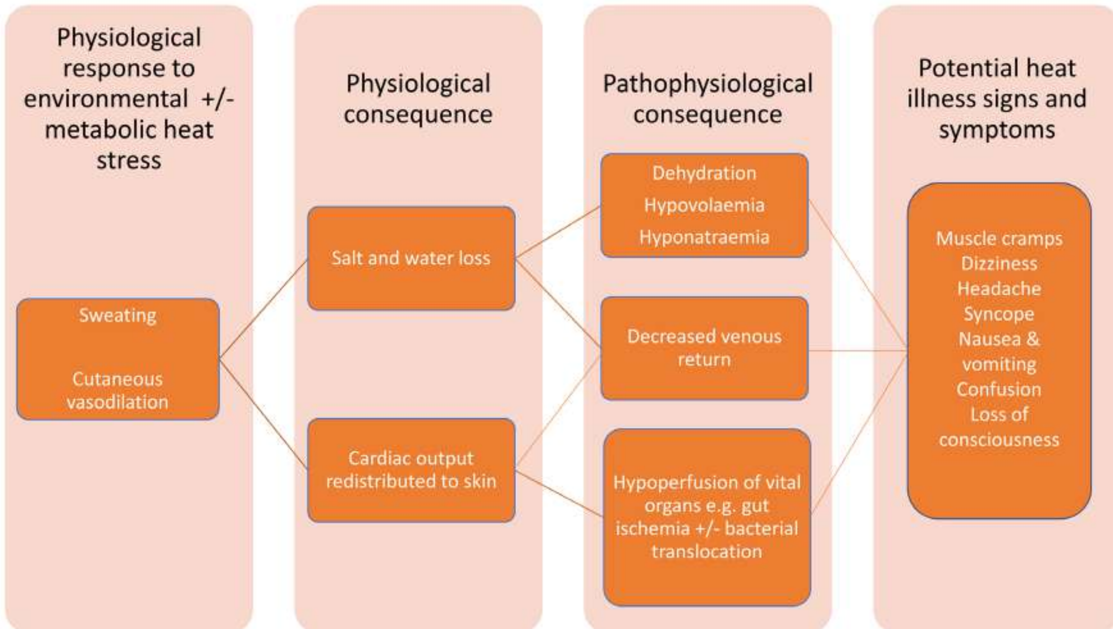

Figure 3. Pathophysiology of heat strain.

surface-area-to-volume ratio decreases over the course of pregnancy[35]. Although some of these act to protect the pregnant woman, the overall impact of these mechanisms is a reduction in the ability to dissipate heat and an increased risk of heat strain in pregnancy. The fetal heat balance is dependent on fetal heat generation (metabolic rate), maternal temperature and uterine blood flow; however, the fetus itself has no ability to actively loose heat[8]. Heat loss occurs mainly through the umbilical artery, although some heat is lost to the amniotic fluid. The fetus is usually 0.4-0.6°C hotter than maternal core temperature, but in situations where maternal core temperature rises, this will result in heat transfer to the fetus[36,37]. The impact of heat on fetal development has been a difficult area to study. Women with pyrexia, usually from an infection, experience several other factors that affect the fetus, namely microbial factors, immune responses and maternal physiological response. Owing to the difficulty in isolating the effect of heat strain in human pregnancy little is known about the changes in placental blood flow, release of heat shock proteins and other chemical responses to heat strain and what these mean for fetal wellbeing. What is known is largely taken from the animal literature and heat stress has been shown to reduce birth weight in a variety of mammals. In particular, a large body of work has examined heat stress in ewes, where placental weight and size was diminished, blood flow to the uterine artery reduced and intrauterine growth retardation (IUGR), similar to stunting, was seen in animals in a chronic heat stress environment[38–41]. The impact of heat stress varied with trimester, with increased rates of first trimester miscarriage and congenital abnormalities. Heat stress in the second and third trimesters resulted in IUGR and increased the incidence of stillbirth[42]. These studies give an insight into what may be occurring in humans; however, in many cases, it is difficult to directly transfer to the human condition due to large differences in the volume to surface area ratio, and in the relative mass of the products of conception. Consequently, the pregnant ewe has often be considered to be the optimal animal model but still has important differences (the rumen and fleece for instance) and therefore conclusions must be viewed with caution.

Figure 4 gives an overview of the hypothetical impact of heat stress by trimester.

Climate change, occupational health and pregnancy

The knowledge gap relating to pregnancy in humans and exposure to heat stress is of current and growing concern as present conditions can be extreme for pregnant women and climate change predictions put the global temperature at levels not experienced in the last 200,000 years (i.e. the timespan modern humans have inhabited the earth). The burden of that heat stress will be mostly felt in low income countries with the least opportunity for adaptation[5]. It will also occur in areas where women make up almost 50% of the agricultural work force and work throughout pregnancy[43,44].

Aims and objectives

We aim to assess whether heat strain in pregnant farmers in The Gambia acutely alter fetal wellbeing. The aims of this study are to:

1. Determine the heat stress exposure of pregnant farmers.

2. Determine the prevalence of heat strain by trimester and heat stress exposure in pregnant farmers.

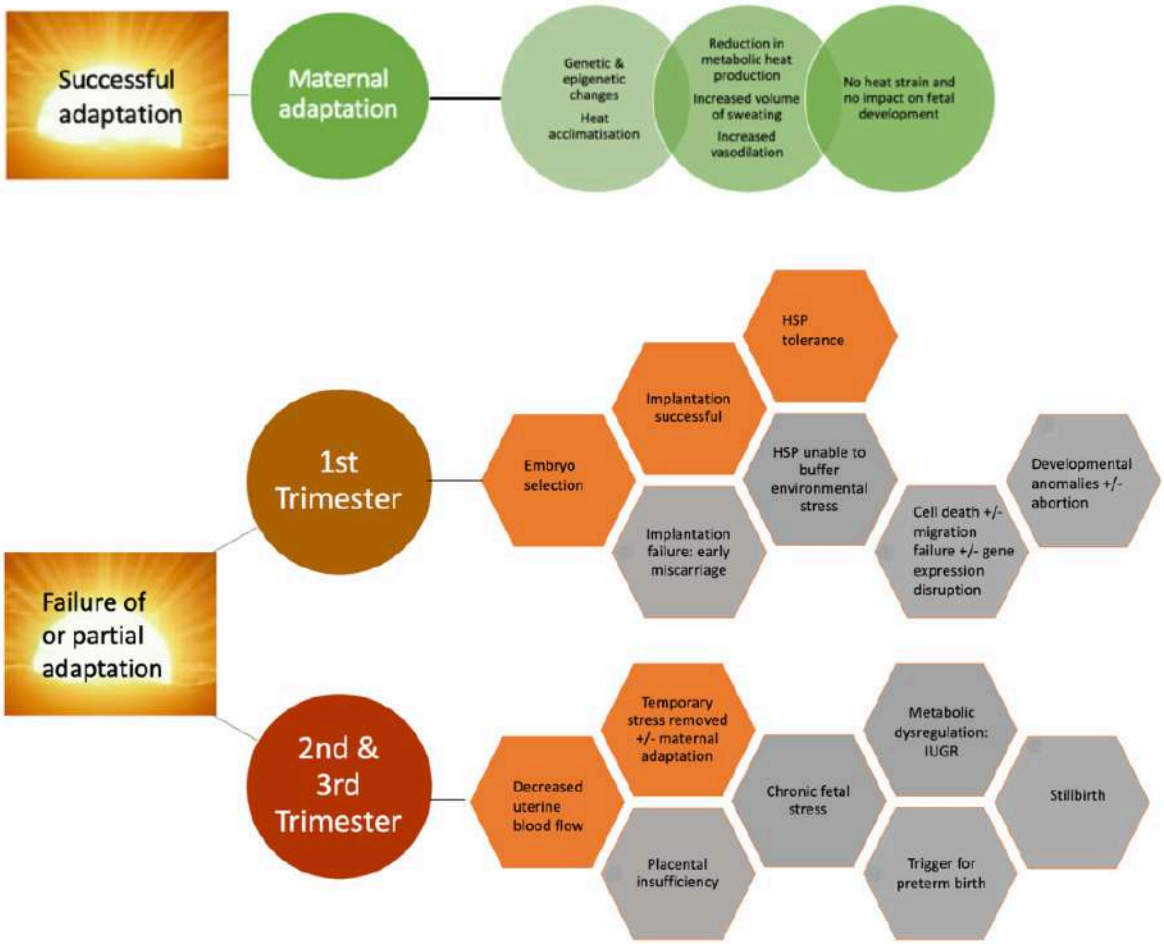

Figure 4. Theoretical framework of impact of heat stress on pregnancy. Orange hexagons indicate physiological impact of heat that does not necessary result in harm. Grey hexagons indicate harmful changes to the fetus. HSP, heat shock protein, IUGR, intrauterine growth retardation.

3. Determine if biomarkers of heat strain correlate with physiological measurements in pregnant farmers.
4. Determine if maternal heat strain has an immediate impact on fetal heart rate or blood flow as an indication of fetal wellbeing.
5. Determine if biomarkers of feto-placental function are altered by maternal heat strain.

Methods

Study design

This is a prospective observational cohort study of pregnant women who perform outdoor agricultural work during pregnancy, which has been recruiting since August 2019.

Setting

This study will be conducted at Keneba field station, Medical Research Council Unit The Gambia at London School of Hygiene and Tropical Medicine (MRCG @ LSHTM).

MRC Keneba is a rural field station based 2.5 hours inland from the coast, in Kiang West region where mostly subsistence agriculture is practiced. The climate in this area has two distinct seasons, the wet and dry season, which run from July to October and November to July, respectively. Farming of rice and groundnuts occur during the wet season and relies mostly on rainfall. In the dry season there are large “gardens”, which are used to grow a variety of vegetables. These tend to be watered by hand. Farming is a gender specific activity, with men growing the cash crops and women mainly growing food for household consumption or selling at the local markets. All agricultural work practiced by women in the region is done manually – planting, transplanting, weeding, harvesting, clearing, tilling and watering. Previous work in The Gambia has assessed the energy expenditure of pregnant women during different agricultural activities and also assessed the amount of time spent on these activities. These studies show that women will work between 50% to 83% of a 9-hour day on agricultural work, depending on the season, even when pregnant[45–48].

The mean monthly temperatures in 2017 varied from 25.4–30.3°C and maximum monthly temperatures from 31.5–39.5°C. The maximum monthly Wet Bulb Globe Temperature (WBGT) varied from 24.7–29.3°C. This gives the exposure during the hottest times of the day. This exposure is at a level that international guidelines would identify as at risk of heat illness. The annual average temperature rise since 1980 is just below 1°C (REF). Most villages do not have electricity and therefore no access to air conditioning or electric fans. Water is mostly supplied through public bore holes, although some homes do have tapped water.

Participants and recruitment

Community sensitization and discussion will occur in each village prior to any visits. Once agreement and consent from the village elders has been obtained, we will recruit 125 participants.

Pregnant women will be approached and informed about the study in their preferred language. Inclusion and exclusion criteria are set out below.

Inclusion criteria:

1. Confirmed pregnancy with live single fetus
2. Provision of written informed of consent or witnessed thumbprint
3. Live and work within the region
4. Spend time during pregnancy in any of the following activities; working as an agricultural labourer; outside labour on a small-hold farm; gardening for at least 3 hours
5. Willingness and ability to provide demographic and clinical information, blood and urine samples and wear a non-invasive portable device for continuous physiological monitoring

Exclusion criteria:

1. In immediate need of medical attention or emergency obstetric care
2. Diagnosed with pre-eclampsia or gestational diabetes in this pregnancy
3. History of cardiac disease

Sample size

Previous studies on physiological changes in pregnant women working in heat have not been completed. Based on published literature, we expect around 35% of agricultural workers to experience heat strain and assume this incidence risk remains at least as high in pregnancy[49,50]. Assuming an unexposed incidence risk of fetal distress to be 5% with an alpha of 0.05, we will need to recruit 99 participants to be powered to detect an exposed incidence risk of 30% with fetal distress. Taking into account drop-out rates due to fetal loss, we will recruit 125 participants.

Study procedures

Pregnant women, of any gestation, identified by the demographic surveillance system (DSS), antenatal clinics or village assistants will be approached and consented if eligible. They will attend the Keneba antenatal clinic where socio-economic, demographic, medical and obstetric details will be collected These will include any past medical history, past obstetric history including previous miscarriages, stillbirths, premature births or low birth weight infants. A baseline ultrasound will be performed by a trained member of staff. Gestational age will be determined based on an early ultrasound scan (under 28 weeks gestation) using biparietal diameter. If an early ultrasound scan has not been performed then biparietal diameter will still be used but with the expectation of reduced accuracy in the estimation of gestation. In women between 28–34 weeks we will perform an UmbiFlow™ scan. The UmbiFlow™ device was designed in South Africa for use in low-resource settings to identify women at risk of poor birth outcomes due to placental pathology. It measures the resistance index (RI) in the umbilical artery and plots this on a normogram based on gestational age (see Figure 5 for an example). This device is designed for use by unskilled practitioners and requires minimal training. It has been validated for gestational ages 28–34 weeks[51,52].

Within the next 2 weeks, on the day they are working outside, they will attend Keneba field station where they will have baseline anthropometry, physiology readings and blood and urine collection. They will be fitted with an Equivital™ LifeMonitor device. This is a portable, multi-parameter telemetry device that sits within a Lycra chest belt with inbuilt fabric sensors[53]. Once wearing the LifeMonitor device they will complete a 6-minute walk test to determine cardiovascular reserve and calibrate the device[54].

During the working day (duration recorded) we will record their tympanic temperature and the ambient conditions every hour. At middle and end of day we will assess fetal heart rate ± umbilical artery flow. Maternal measurements will include a four-point skin temperature using an infrared, non-contact thermometer. Measurements are taken from four-left-hand sided points from 20 cm away; chest, mid-tricep, mid-thigh and mid-calf[55]. A Perfect®Prime thermal imaging camera IR10019 with a resolution of 320 x 240 and pixels of 76,800 will be used to take two pictures per time point; from the waist up (with head-dress removed), and from the waist down (with legs revealed). Heart rate and blood pressure will be measured with an automatic OMRON M3 Intellisense device. Standardised ratings for thermal sensation and comfort will be recorded. At the end of the participant's normal working day we will collect end line blood and urine and take a final measurement of weight and bioimpedence. Participants will be followed every 2 months during the course of their pregnancy. Figure 6 and Figure 7 give an overview of study processes and timing.

After delivery, data will be collected on birth outcome, birth weight, gestational age, infant sex and maternal and newborn status.

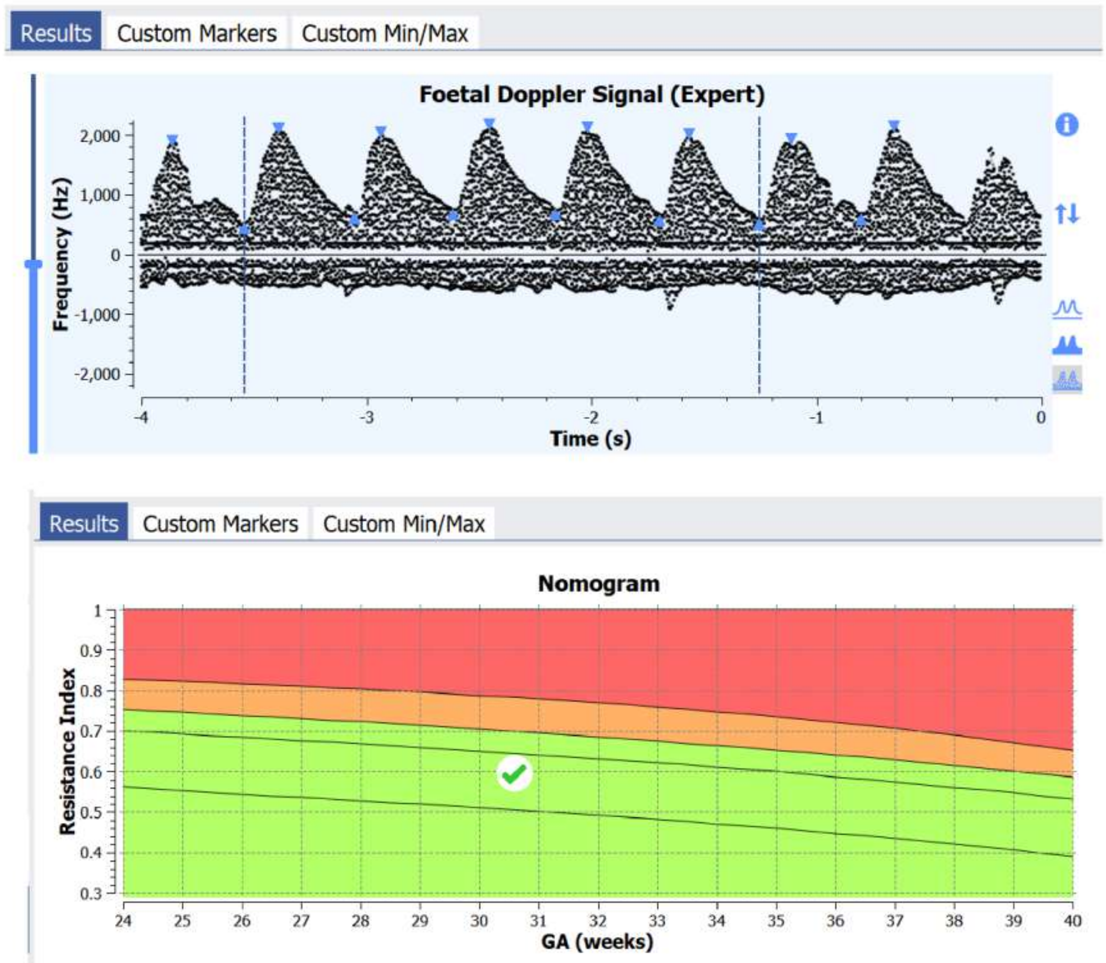

Figure 5. Fetal Doppler signal and associated normogram produced when using the UmbiFlow™ device.

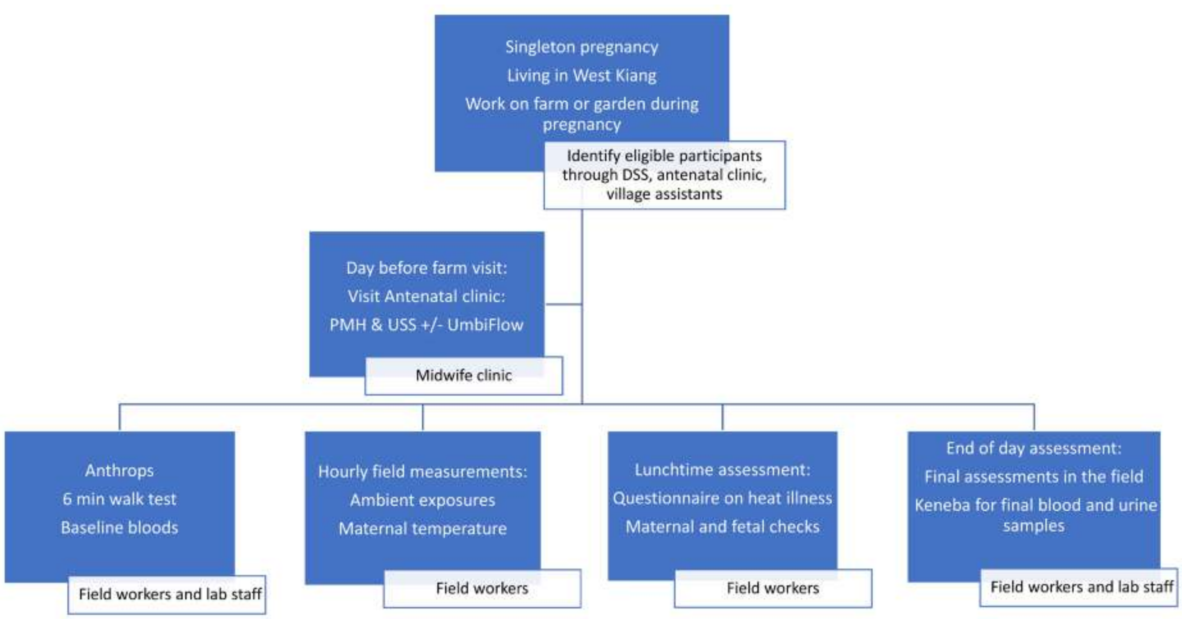

Figure 6. Study scheduling. DSS, demographic surveillance survey; PMH, past medical history; USS, ultrasound scan.

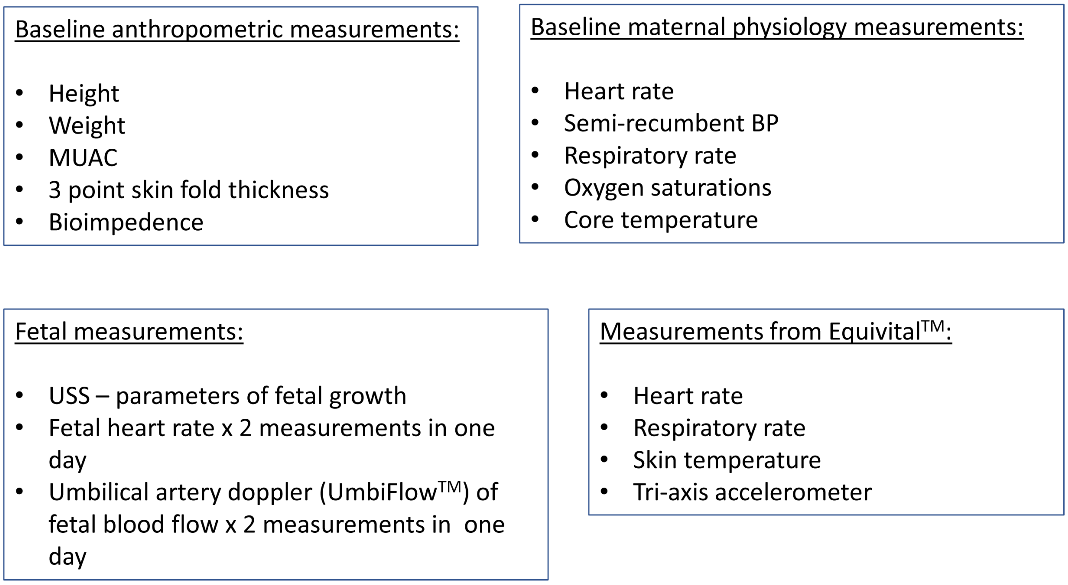

Figure 7. Data collection of anthropocentric, maternal, fetal and physiological measures. MUAC, mid-upper arm circumference; BP, blood pressure; USS, ultrasound scan.

Recruitment will be over a 12-month period to ensure different seasonal exposure to work and heat. By recruiting over the course of a year and repeating measures every two months we will capture different trimesters for the same women. This will give us an estimate of the physiological changes that occur at different heat exposures and by different trimesters and identify if these alterations lead to altered fetal wellbeing.

Primary outcome measures

The primary outcome is a measurement of fetal distress. We define compromised fetal wellbeing as either: (i) a baseline fetal heart rate above 160 bpm or below 115 bpm; and/or (ii) if the fetus is 28–34 weeks gestation, then UmbiFlow™ above the 75th percentile of established resistance index graphs, or absent end diastolic flow, in keeping with the findings from South Africa and the developers of UmbiFlow™[51,52].

Laboratory sample collection and processing

Study staff will collect a venous blood and urine sample for each participant for use in study laboratory procedures. All samples aim to identify maternal heat strain or fetal wellbeing. Table 1 gives the laboratory sampling and justification. Whole blood samples from each participant will be used to prepare six dried blood spots of 10 µl each on filter paper and stored for biomarker testing. Serum samples will be separated and stored at -80°C for future analysis.

Statistical analyses

Statistical analysis will be performed using R. Appropriate descriptive analysis will be used to present maternal characteristics and environmental heat stress exposures. Data will be assessed for normality and skewed data will be appropriately transformed.

Derived values

Metabolic rate and energy expenditure will be determined from the raw accelerometer and heart rate data using complex non-linear modelling. The 6-minute calibration test will allow development of individual and trimester specific estimates of metabolic rate. These will be cross-checked against historic data on energy expenditure of pregnant women in West Kiang per activity type.

Heat strain will be determined by either the physiological strain index (PSI) or the Center for Disease Control (CDC) recommended signs and symptoms score.

The PSI model is based on changes in heart rate and core body temperature and therefore gives an indication of the combined thermal and cardiovascular load:

$$PSI = 5 \times (T_{core1} - T_{core0})/(39.5 - T_{core0})) + (5 \times (HR_1 - HR_0) \times (180 - HR_0))$$

Where 0 indicates baseline and 1 indicates rate or value during exposure[20]. This has been used in multiple studies on physiological changes in exercise and/or heat but not in pregnancy[56,57].

The CDC method is based on a series of symptoms related to heat illness, which vary from heat rash to heat stroke[58]. We will include those related to heat stroke, heat exhaustion and heat cramps or a core temperature above 38°C, but will not include symptoms of heat rash or sunburn as these are not related to the physiological changes we are interested in. There are several heat stress indices we will calculate based on the direct field measurement we will take. These will include the

Table 1. Laboratory tests.

Investigation	Purpose of the test	When to be taken
Haemoglobin & haematocrit	Identify if anaemic Indication of change in hydration status during activity	Beginning and end of day
Urea & creatinine	Indication of renal function and hydration status	Beginning of day
CRP	Inflammatory markers that are known to alter acutely in heat strain and/or in fetal distress[59–62]	Beginning and end of day
IL-6, IL-8, IL-10		
TNF		
Lipopolysaccharide	Increases when gastrointestinal permeability increases in heat strain[29,30,63]	
Intestinal fatty acid binding protein		
Heat shock protein 70	Intra and extracellular heat shock proteins are altered in heat strain and may play a role in placental function[56,64,65]	
Glucose	Alter in response to physiological stress of exercise and/or heat	
Cortisol		
Urine specific gravity and osmolality	Indication of hydration status	Beginning and end of day
Alphafetoprotein, apoliprotein C-II & III	Indication of placental function[59]	Beginning and end of day

CRP- C-reactive protein; IL-6 interleukin-6; TNF, tumor necrosis factor.

WBGT, the Universal Thermal Climate Index, the apparent temperature and the heat index.

Primary outcome analysis

A mixed-effect linear model will be run, using lme4 package in R to allow fixed and random effects to be incorporated appropriately.

The expected final model will be of the form: Fetal distress(ij) = fixed part [heat stress index + PSI/heat strain + maternal age + gestational month (or trimester) + nutritional status + metabolic rate + cardiac reserve + heat illness symptoms + ΔHct + Δbioimpedence] + random term [individual participant]

Fetal compromise(ij) = presence or absence of fetal distress as defined above for individual i at gestational month j (1…9).

Secondary outcome analysis

Different commonly used heat stress indices as described above will be validated against heat strain data for clinical correlation. Changes in fetal heart rate from baseline, stratified by trimester will be explored. Heart rates > 170 and > 180 will also be used as cut offs for fetal distress, although the numbers may be small. Changes in biomarkers of heat strain or feto-placental function will be analysed by ANOVA stratified by trimester and heat stress exposure.

Safety and ethical considerations

This study has been approved by the Gambia government/MRC Joint ethics committee (ref: 16405) and the London School of Hygiene and Tropical Medicine Ethics Advisory Board.

Written informed consent and information sheets will be provided to all participants. A trained study staff member will conduct individual screening interviews and informed consent procedures in the preferred language of the participant. If the participant is unable to write, her fingerprint will be used as substitute for a signature, and an impartial adult witness to the entire consent procedure will provide their signature.

Potential participants will be able to ask questions and discuss the study with study staff at any time during and after study activities. Participants are free to withdraw consent at any time during the course of the study and this will not impact on future care provision.

Risks associated with participating in this study are minimal. Participants will be screened at the start of the day and should they demonstrate any signs or symptoms of illness or concern they will be advised to seek the attention of the Keneba health clinic and participation in the study will be delayed until they are well. Should a participant be hypertensive but not pre-eclamptic then may still enter the study, but we will refer them to antenatal services for treatment of their hypertension. Should a participant develop pre-eclampsia after recruitment, diagnosed at antenatal clinic or on subsequent visits, they will be referred to Keneba antenatal services and not included in the daily assessment of maternal heat strain and fetal wellbeing. However, if they are willing to remain in the study, pregnancy outcome data will still be collected.

Participants will have additional venous blood samples taken using aseptic technique with universal precautions to minimize the risk of infection, personal discomfort, transient bleeding and bruising that may result. An ultrasound scan is part of routine antenatal care and an additional scan adds no harm to maternal or fetal health. The risks of wearing the portable recording devices include chaffing of the skin and discomfort, which we will minimize by ensuring a good fit at the beginning of the day and checking for any skin irritation at the end of the day.

During the 6-minute walk test the participant can stop at any point during the course of the exercise and standardised feedback was collected. Additionally, this test will be performed at Keneba field station, close to the clinic area and if any untoward symptoms are experienced, they will assess and treat the participant as required.

During the course of the day, if a significant heat load is experienced and the maternal core temperature increases beyond 38.5°C (see below) the guidelines on treatment of heat strain will be followed with some additional considerations. In non-pregnant individuals, heat strain is determined to be a life-threatening emergency requiring immediate treatment when core temperature reaches 40.5°C[31]. In pregnancy, heat is known to be teratogenic in the embryonic period, and throughout pregnancy compensatory mechanisms may be compromised. Hence we do not think it is ethical to allow the temperature to reach such a high level. Therefore, should maternal core temperature reach 38.5°C, this would result in an immediate review and treatment of heat strain would be commenced. This would include an overall clinical assessment of the women and fetus, immediate measures to treat the women and if these did not result in improvement within 30 minutes, consideration of transfer to the health facility.

If during the intermittent measurements of fetal wellbeing, there are any concerns with fetal heart rate (either >160 or <115)[66], or regarding the Doppler results, then the participant will be assessed, encouraged to rest in the left lateral position, consume water, and have observations of fetal movement and maternal blood pressure taken. If after 30 minutes, the baseline heart rate has not returned to the normal range, the Doppler remains abnormal, or there are any clinical concerns, the women will be offered transport to the health clinic for further review and treatment. Any such events will be recorded as an incident case of fetal distress as per the primary outcome of this study.

Limitations

This is a field-based study in rural West Africa and therefore there are several limitations when comparing it to a laboratory based heat chamber study. We aim to characterize the physiological response of pregnant women to heat stress. Due to ethical considerations, this is an observational study only. Therefore if the women are not exposed to extreme heat in their usual work, we will not be able to measure this effect. However, from previous work in this setting, women were working in the heat during pregnancy and therefore we are confident that the exposure will occur.

Since we are recruiting women who work in the gardens or farms during pregnancy, we are aware that our sample may be biased towards those in the lowest socio-economic group, which may affect the generalisability of the result. However, we consider this group to be of particular importance as they are likely to have little options for modification of behaviour or development of adaptation strategies. We will use Demographic Health Surveillance Data to compare our sample with the wider pregnant community over the time period of our study to determine the representation in the sample and any significant sources of bias.

Our physiology measurements do not include continuous core temperature monitoring as would be the gold standard, due to practical constraints of field work. We therefore use tympanic temperature as a measure of core temperature, recognising the deficiencies in this measurement. Due to well documented measurement errors in this method, we are likely to underestimate the true temperature rise. Additionally the Equivital device measurements, heart rate, respiratory rate, skin temperature and tri-axis accelerometer will all have measurement errors. We will attempt to minimise these by removing impossible values, cleaning the signal and using the inbuilt algorithms for percentage confidence in the results.

Due to the practicalities of accessing remote rice fields, and transporting all necessary equipment we will be unable to accurately assess water intake. Our assessment of hydration therefore is at the physiological level, but this is a limitation in the methodology especially considering that hydration is an important aspect of thermoregulation.

Confidentiality and access to data

All participants will be allocated a unique identifying number (UIN) at recruitment. Data generated by the wearable sensors will be downloaded from the devices at the end of the day, linked to the UIN and then wiped. During the study day, data will be collected on tablets using the REDCap application. On return to Keneba field station the tablets are synced, allowing transfer of encrypted data to the designated server.

All data will be backed up regularly by the IT department in accordance with MRC SOP-INT-001. The database is centrally stored, data is secure and encrypted and held by MRC/LSHTM. No personal identifiable information will be available in any shared or published document. Primary data outputs will be in XML format. All study documents will be filed and stored for at least 10 years.

Dissemination

The results of the study will be analysed and prepared for publication in open-access peer-reviewed international journals, staggered over time. At the end of the project a community event will be held to disseminate results to all those communities that participated in the study. We will comply with international standards and guidelines regarding open access of research data.

Conclusion

This study will be the first to characterize the heat stress, heat strain and fetal status in pregnant farmers and with these results we hope to describe the problem, measure the incidence of significant threats to fetal well-being, and to highlight the need for ongoing work in this area with an ultimate aim of developing adaptation interventions to mitigate the problem.

Data availability

No data are associated with this article.

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Open Peer Review

Current Peer Review Status: ✓ ✓

Version 2

Reviewer Report 07 April 2020

https://doi.org/10.21956/wellcomeopenres.17328.r38292

✓

Beth Holder
Institute of Reproductive and Developmental Biology, Department of Metabolism, Digestion and Reproduction, Imperial College London, London, UK

I am happy with the response and revisions, and approve this study for indexing.

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 09 March 2020

https://doi.org/10.21956/wellcomeopenres.17244.r37960

?

Beth Holder
Institute of Reproductive and Developmental Biology, Department of Metabolism, Digestion and Reproduction, Imperial College London, London, UK

This is an ambitious and timely study, particularly given growing interest in the effects of extreme heat on pregnancy outcome. The Keneba field station in The Gambia is an ideal place to run this study, and the planned wide-range measurements will address some important questions and generate useful data. The overall study design is very good, with the following caveats/considerations:

1. More information is needed on the exact gestation that will be studied. This should be clearly stated in the inclusion/exclusion criteria. It is not stated when women will be approached and consented, and hence what gestation the 2-week study period will cover. It is only mentioned that the UmbiFlow will be performed on women between 28-34 weeks. Is this the target gestational period that will be studied?

2. Related to the above, including a wide range of gestations could impact on the required sample sizes, as gestation could play an impact on either physical exertion (i.e. the mother resting more in later gestation), or on the sensitivity of the fetus to stress. I would like to know a bit more about the range of gestation that will be studied, and how gestational age will be considered in the analysis (i.e. will stratification be performed).

3. Will liquid intake be monitored? This could have an impact on maternal wellbeing, and also impact on urine and blood analyses. Perhaps water could be provided in reusable bottles, and the amount left over at the end of the day recorded.

4. Will blood samples at the beginning of the day be fasted samples, or after eating? Same for the end of the day sample - will the time since their last meal be recorded?

5. Normal fetal heart rate varies with gestation. It would be good to consider this in the study. It would also be good to include HR >170 and >180 in the secondary analysis.

6. Accurate estimation of gestation could be quite important in this study. It is not clear how often early ultrasounds will be performed. Has capability been built in this area? Are there designated individuals who will perform ultrasounds?

7. Related to the above, I am concerned that LMP and biparietal diameter (BPD) will be used interchangeably. In how many women is LMP expected to be used? Will LMP also be recorded for those with BPD measurements to see how they compare?

8. How will the gestation at ultrasound scan be considered? My understanding is that at 12-26 weeks, it is accurate +/- 10-11 days, and after 27 weeks, it is accurate +/- 2-3 weeks. It would be good to give some detail on the limitations of using a single BPD measurement. If possible, paired BPD measurements at two timepoints would improve the accuracy of estimating gestational age.

9. Will hypertensive women be included? It is not mentioned in the exclusion criteria, but presumably anyone who is identified as hypertensive at time of consent will be excluded?

10. Will participants be blinded to their measurements, or will it be fed back to them each day? I wonder how they many adapt their behaviour in subsequent days if they are aware of their previous measurements (of course exempting when there are concerns of maternal/fetal wellbeing, which will rightly result in intervention).

11. Finally, there is not much detail provided on what clinical parameters will be recorded that may be important to consider in any analysis. E.g. maternal age, ethnicity, BMI, parity, gravidity, previous pregnancy pathologies (e.g. miscarriage, stillbirth, pre-eclampsia,

preterm birth, gestational diabetes).

Is the rationale for, and objectives of, the study clearly described?
Yes

Is the study design appropriate for the research question?
Yes

Are sufficient details of the methods provided to allow replication by others?
Partly

Are the datasets clearly presented in a useable and accessible format?
Not applicable

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Pregnancy, maternal-fetal health, placental biology, immunology, maternal vaccination, extracellular vesicles

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 18 Mar 2020

Ana Bonell, Medical Research Council Gambia @ London School of Hygiene and Tropical Medicine, Fajara, The Gambia

Thank you for your time and effort in providing the feedback on the paper. We are very grateful for the scientific review and hope that the changes we have made in response to the suggestions make the article stronger scientifically.

1. More information is needed on the exact gestation that will be studied. This should be clearly stated in the inclusion/exclusion criteria. It is not stated when women will be approached and consented, and hence what gestation the 2-week study period will cover. It is only mentioned that the UmbiFlow will be performed on women between 28-34 weeks. Is this the target gestational period that will be studied?

We decided to include any gestation. Since we repeat our field measurements every two months, we hope to get at least 2 visits per participant. Due to the variation in climate exposures we did not want to limit the gestation we would explore at the start of the project since those environmental conditions (hot and humid) only last 3 months. If we limited the recruitment to early gestation then we would not have late pregnancies exposed to those conditions. This has been made clearer in the manuscript.

2. Related to the above, including a wide range of gestations could impact on the required sample sizes, as gestation could play an impact on either physical exertion (i.e. the mother

resting more in later gestation), or on the sensitivity of the fetus to stress. I would like to know a bit more about the range of gestation that will be studied, and how gestational age will be considered in the analysis (i.e. will stratification be performed).

Gestation will be included in the analysis. We will begin by exploring the results stratified by trimester, but will consider using a fixed effect of gestational weeks or months in the full model. Stratification by trimester will be used for analysis of heat strain, biochemistry changes and changes in osmolality.
This has been made clearer in the manuscript

3. Will liquid intake be monitored? This could have an impact on maternal wellbeing, and also impact on urine and blood analyses. Perhaps water could be provided in reusable bottles, and the amount left over at the end of the day recorded.

This is a very important point. Unfortunately our study has taken us to remote areas where our 4WD is unable to reach. We have then had to carry all our equipment out into the field. Due to these constraints we have been unable to do this.
I will add this as a limitation

4. Will blood samples at the beginning of the day be fasted samples, or after eating? Same for the end of the day sample - will the time since their last meal be recorded?

Blood samples will not be taken fasted

5. Normal fetal heart rate varies with gestation. It would be good to consider this in the study. It would also be good to include HR >170 and >180 in the secondary analysis.

This will be added to our secondary analysis. Additionally we will also look at the change in fetal heart rate from at rest in a cool room to when working in the field and so use individual resting rates as our baseline.

6. Accurate estimation of gestation could be quite important in this study. It is not clear how often early ultrasounds will be performed. Has capability been built in this area? Are there designated individuals who will perform ultrasounds?

Ultrasound scans will be performed by 1 midwife or 1 doctor who have undergone training in fetal scanning and dating measurements.
This has been clarified in the manuscript

7. Related to the above, I am concerned that LMP and biparietal diameter (BPD) will be used interchangeably. In how many women is LMP expected to be used? Will LMP also be recorded for those with BPD measurements to see how they compare?

This has been altered as you suggest. LMP is very unreliable in this setting. Therefore we will use BPD only for dating.

8. How will the gestation at ultrasound scan be considered? My understanding is that at 12-

26 weeks, it is accurate +/- 10-11 days, and after 27 weeks, it is accurate +/- 2-3 weeks. It would be good to give some detail on the limitations of using a single BPD measurement. If possible, paired BPD measurements at two timepoints would improve the accuracy of estimating gestational age.

Gestational dating will be based on ultrasound. Most participants will have had an ultrasound prior to 28 weeks (giving an accuracy to +/- 14 days). If the participant has not been identified early enough then this will be recorded and gestational dating will be based on BPD but with the caveat of reduced accuracy.
This has been altered in the protocol to make clearer

9. Will hypertensive women be included? It is not mentioned in the exclusion criteria, but presumably anyone who is identified as hypertensive at time of consent will be excluded?

If participants are hypertensive but not pre-eclamptic they will be included. If they develop pre-eclampsia then they will be excluded.
This has been made clearer in the manuscript

10. Will participants be blinded to their measurements, or will it be fed back to them each day? I wonder how they many adapt their behaviour in subsequent days if they are aware of their previous measurements (of course exempting when there are concerns of maternal/fetal wellbeing, which will rightly result in intervention).

Participants will be made aware of concerns to fetal wellbeing or raises in core temperature above 38.0 degrees. Otherwise they will not have measurements fed back to them

11. Finally, there is not much detail provided on what clinical parameters will be recorded that may be important to consider in any analysis. E.g. maternal age, ethnicity, BMI, parity, gravidity, previous pregnancy pathologies (e.g. miscarriage, stillbirth, pre-eclampsia, preterm birth, gestational diabetes).

All these parameters will be collected. This has been added to the manuscript to make it clear.

Competing Interests: None

Reviewer Report 02 March 2020

https://doi.org/10.21956/wellcomeopenres.17244.r37958

Matthew F. Chersich
Wits Reproductive Health and HIV Institute, Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, South Africa

The study covers key topic of growing concern. Pregnant women may well be now of the highest risk groups for heat exposure in LMICs, and occupational exposure is especially problematic as women may continue to work even when they feel heat stress. The biological measures are detailed, will provide much information.

A few comments:

1. I think more is needed to distinguish between subsistence farming and farming done done for income.

2. It is also not clear if there will be a set of questions asked about heat behaviours, for example, changes in work hours as gestation progresses, changes in kinds of activities done depending on temperature, changes in behaviours, like starting earlier in the day. Changes in gender roles with gestation or temperature? Do men do more when it is hot? Is drinking water accessible?

3. There is a line which is problematic 'almost no data and no field studies concerning impact of heat stress on maternal physiology...; there is a lot written about thermoregulation in pregnancy, and it is fascinating.

4. The claim about hyperthermia being a teratogen in humans is perhaps over-stated. As I understand there is still a controversy about this in terms of saunas etc.

5. I wonder if it might be better to target the physiological measurements to days above a certain temperature threshold, based on forecasting. That is the key question I think, It depends what your question is: impact of total heat burden during pregnancy, or impact of 'extreme heat'. If it is the later then measures on days with Tmax >90th percentile might make more sense.

6. The ability of women to thermoregulate in pregnancy is remarkable I think, their relative 'hypothermia' and shifting of blood away from the fetus means that you may not detect any major impact, a major missed opportunity

7. I wonder if you need a limitations section, the one limitation under participants did not make sense to me. How much will behaviours change with the presence of a field worker? The hourly tympanic membrane measure seems excessive intrusion that may alter the behaviour you are trying to asess. I really dount the core temp will rise, certainly not by the hour! She may have heat stress and discomfort but for that to raise her temperature is unlikely I imagine.

8. The sample size refers to the 30% increases incidence in the primary outcome?

Is the rationale for, and objectives of, the study clearly described?

Yes

Is the study design appropriate for the research question?
Yes

Are sufficient details of the methods provided to allow replication by others?
Partly

Are the datasets clearly presented in a useable and accessible format?
Not applicable

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Cimate change and health; reproductive health, maternal health, HIV

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 18 Mar 2020

Ana Bonell, Medical Research Council Gambia @ London School of Hygiene and Tropical Medicine, Fajara, The Gambia

Thank you for your time and effort in providing the feedback on the paper. We are very grateful for the scientific review and hope that the changes we have made in response to the suggestions make the article stronger scientifically.
1. I think more is needed to distinguish between subsistence farming and farming done done for income.

In the Gambia there is a clear gender divide in farming. Men work on the cash crops and women grow what they use themselves with the potential to sell at the village markets.This has been added into the background context to aid understanding of the local situation.

2. It is also not clear if there will be a set of questions asked about heat behaviours, for example, changes in work hours as gestation progresses, changes in kinds of activities done depending on temperature, changes in behaviours, like starting earlier in the day. Changes in gender roles with gestation or temperature? Do men do more when it is hot? Is drinking water accessible?

These questions will not be asked as part of this study, however additional qualitative work is planned to explore these questions to complement this work.We specifically ask about heat illness symptoms, thermal comfort and sensation, thirst and perceived exertion.

3. There is a line which is problematic 'almost no data and no field studies concerning impact of heat stress on maternal physiology...; there is a lot written about thermoregulation in pregnancy, and it is fascinating.

I completely agree, there is a lot of data on thermoregulation in pregnancy, but field-based physiology studies in heat stressed human pregnancies are lacking. I have rephrased the sentence to more accurately reflect this.

4. The claim about hyperthermia being a teratogen in humans is perhaps over-stated. As I understand there is still a controversy about this in terms of saunas etc.

Hyperthermia is a teratogen in the first trimester, as shown from fever studies and studies with documented prolonged rises in core temperature.
I have clarified that it is a teratogen in the first trimester in the manuscript.

5. I wonder if it might be better to target the physiological measurements to days above a certain temperature threshold, based on forecasting. That is the key question I think, It depends what your question is: impact of total heat burden during pregnancy, or impact of 'extreme heat'. If it is the later then measures on days with Tmax >90th percentile might make more sense.

This would give us a detailed idea of extreme heat. However without the ability to compare to physiological changes at cooler times it would be difficult to differentiate the heat from the exercise effects. This was the rational to recruit throughout the year.

6. The ability of women to thermoregulate in pregnancy is remarkable I think, their relative 'hypothermia' and shifting of blood away from the fetus means that you may not detect any major impact, a major missed opportunity

The ability to thermoregulate is impressive, however the conditions here in The Gambia are extreme in terms of what we as humans can adapt to. In particular if occupational guidelines were followed the max WBGT is often above the level at which outdoor work is advised. Therefore even with a starting relative hypothermia we expect to see some changes. Additionally, the shifting of the blood away from the fetus is a very important physiological change to document as a starting point to understand the impact of heat in pregnancy.
I have added detail on the max WBGT we expect the women to be exposed to and how this puts them at risk of heat illness according to the ACGIH

7. I wonder if you need a limitations section, the one limitation under participants did not make sense to me. How much will behaviours change with the presence of a field worker? The hourly tympanic membrane measure seems excessive intrusion that may alter the behaviour you are trying to asess. I really dount the core temp will rise, certainly not by the hour! She may have heat stress and discomfort but for that to raise her temperature is unlikely I imagine.

A limitations section has been added.
The taking of hourly tympanic membrane measurements was a compromise as we were unable to measure continuous core temperature as would have been the gold standard in heat strain studies. Rectal temperature was impossible and core telemetry pills have yet to be proved safe in pregnancy. In heat chamber studies, volunteers will put their core temperature up within 20 mins of exercise in a hot/humid environment and this will return to baseline relatively quickly which is the rational for the hourly measurements.

8. The sample size refers to the 30% increases incidence in the primary outcome?

Yes, this is for the primary outcome
I have clarified this in the manuscript

Competing Interests: none

CHAPTER 4 – A feasibility study of the use of UmbiFlow™ to assess the impact of heat stress on fetoplacental blood flow in field studies

SUMMARY OF CHAPTER

In this chapter I present a published study describing the use of a low-cost portable device (UmbiFlow™) in field studies to assess the dynamic changes to umbilical artery resistance index under heat stress conditions. This paper details the results of a subset of participants from the prospective cohort study who were able to be scanned in the field. Forty participants were included in the study and a potential threshold value to placental insufficiency at 32°C Universal Thermal climate index or 30°C by wet bulb globe temperature was found.

The full summary of the chapter can be found in the abstract of the paper. Supplementary material for this paper can be found in Appendix 2

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RESEARCH PAPER COVER SHEET

Please note that a cover sheet must be completed <u>for each</u> research paper included within a thesis.

SECTION A – Student Details

Student ID Number	215963	**Title**	Dr
First Name(s)	Ana		
Surname/Family Name	Bonell		
Thesis Title	Climate change, maternal health and birth outcomes: how does environmental heat affect pregnancy and birth outcomes in The Gambia?		
Primary Supervisor	Professor Andrew Prentice		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

SECTION B – Paper already published

Where was the work published?	International Journal of Gynecology & Obstetrics		
When was the work published?	27th September 2022		
If the work was published prior to registration for your research degree, give a brief rationale for its inclusion	NA		
Have you retained the copyright for the work?*	**Yes**	Was the work subject to academic peer review?	**Yes**

*If yes, please attach evidence of retention. If no, or if the work is being included in its published format, please attach evidence of permission from the copyright holder (publisher or other author) to include this work.

SECTION C – Prepared for publication, but not yet published

Where is the work intended to be published?	
Please list the paper's authors in the intended authorship order:	

Stage of publication	Choose an item.

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	I wanted to explore and expand on the description of the umbilical artery resistance index data and so designed this study in consultation of my supervisors and scientific advisors. I ran the analysis, produced all figures and images and wrote the complete first draft for all co-authors to comment and edit. I led the sumbssion process and led the responses to reviewer comments.

SECTION E

Student Signature	Ana Bonell
Date	17th November 2022

Supervisor Signature	Andrew Prentice
Date	21st November 2022

Received: 28 March 2022 | Revised: 9 September 2022 | Accepted: 26 September 2022

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CLINICAL ARTICLE

A feasibility study of the use of UmbiFlow™ to assess the impact of heat stress on fetoplacental blood flow in field studies

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Abstract

Objective: To evaluate the use of UmbiFlow™ in field settings to assess the impact of heat stress on umbilical artery resistance index (RI).

Methods: This feasibility study was conducted in West Kiang, The Gambia, West Africa; a rural area with increasing exposure to extreme heat. We recruited women with singleton fetuses who performed manual tasks (such as farming) during pregnancy to an observational cohort study. The umbilical artery RI was measured at rest, and during and at the end of a typical working shift in women at 28 weeks or more of pregnancy. Adverse pregnancy outcomes (APO) were classified as stillbirth, preterm birth, low birth weight, or small for gestational age, and all other outcomes as normal.

Results: A total of 40 participants were included; 23 normal births and 17 APO. Umbilical artery RI demonstrated a nonlinear relationship to heat stress, with indication of a potential threshold value for placental insufficiency at 32°C by universal thermal climate index and 30°C by wet bulb globe temperature.

Conclusions: The Umbiflow device proved to be an effective field method for assessing placental function. Dynamic changes in RI may begin to explain the association between extreme heat and APO with an identified threshold of effect.

KEYWORDS
Africa, climate change, fetoplacental circulation, heat, pregnancy

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1 | INTRODUCTION

With the ongoing climate crisis, global extreme heat exposure is progressively increasing with, for example, 30% of the world's population already exposed for 20 or more days annually to levels of heat sufficient to cause excess mortality and up to 74% predicted to be exposed by 2100.[1] Sub-Saharan Africa, South Asia, and Southeast Asia have been identified as regions at high risk of climate-change-related extreme weather events, despite contributing almost nothing to the problem.[2] In The Gambia, West Africa, extreme heat, defined as above the 90% centile compared with the average temperature for that region (>39.4°C), occurred on average for 50 days per year, from 2016 to 2019 (from local weather station data). The double burden of deadly heat exacerbated by climate change and existing health inequalities make this a critical location to study.

The burden of adverse pregnancy outcomes (APOs) are mainly felt in low- to middle-income countries, for example an estimated 15 million preterm births (PTB) occur per year, with more than 80% occurring in Asia and sub-Saharan Africa.[3] PTB is linked to high rates of both perinatal mortality (the cause of up to 24% of neonatal deaths in sub-Saharan Africa) and morbidity with long-term implications.[4] Triggers for preterm labor are complex and multifactorial, but recent environmental epidemiologic studies demonstrate that maternal exposure to extreme heat increases the risk of PTB.[5,6] Stillbirths, a neglected tragedy, are again mainly felt in low- to middle-income countries, with increasing rates and have also been linked to extreme heat exposure.[7]

The impact of heat on pregnancy depends on the intensity, duration, and exposure window. First-trimester exposure leads to increased embryonic death, and cardiac and neurologic anomalies.[8] In the second and third trimester, maternal exposure to ambient heat has been shown to increase the risk of PTB, stillbirths, and low birth weight in multiple settings.[6,9,10] Despite strong environmental epidemiologic evidence of the association between heat and APO, there remains limited understanding of the pathophysiologic mechanism associated with these poor outcomes.[11] One of the proposed hypotheses is that thermoregulatory changes to blood flow prioritize heat loss through cutaneous vasodilatation over other homeostatic mechanisms. For example, in non-pregnant individuals during exertional heat strain, mesenteric and renal blood flow can be reduced to such an extent that gut permeability or acute kidney injury may occur.[12] In pregnancy, where blood flow to the uterus and placenta depends on cardiac output, with no autoregulation, there is evidence from animal studies that this occurs,[13] but human studies are lacking.[11] However, utero-placental insufficiency is implicated in the pathophysiologic mechanisms of stillbirth, PTB, and intrauterine growth restriction.[14] Heat stress could potentially impact on fetal well-being if the placenta is unable to buffer the effects of the reduction in blood flow leading to transient utero-placental insufficiency.

Direct measurement of blood flow to the placenta through the uterine arteries can be challenging because it requires highly specialized non-portable equipment in conjunction with fluid dynamic modeling.[15] However, the umbilical artery Doppler waveform gives an indication of the fetoplacental circulation function, and so indicates how effectively the fetus is receiving oxygen and nutrients, and removing waste products, and can be used as a surrogate for direct blood flow measurement. The UmbiFlow™ device, a low-cost portable continuous-wave Doppler device, was designed and developed in South Africa and has been validated for use to identify placental insufficiency based on the resistance index (RI) of the umbilical artery, with accuracy comparable to commercial units.[16,17] It has not yet been used to explore dynamic changes in the RI under different physiologic conditions. We hypothesize that heat stress will impact on umbilical artery RI, and those who have APO are more likely to have placental insufficiency under heat stress. Therefore, the following study objectives were defined:

- to determine if the UmbiFlow™ identifies a change in umbilical artery resistance index under heat stress; and
- to determine the practical considerations needed to use UmbiFlow™ in the field.

2 | MATERIALS AND METHODS

This feasibility study follows the guidelines on reporting non-randomized pilot and feasibility studies (checklist can be found in the Supplementary material, Table S1).[18] It was part of a larger prospective cohort study on heat strain in pregnant subsistence farmers and the physiologic impact on their fetuses.[11] The study was approved by the Gambia Government/MRC Joint ethics committee and the London School of Hygiene and Tropical Medicine Ethics Advisory Board (ref: 16405) in accordance with the Declaration of Helsinki (2013).

Briefly, pregnant women living in West Kiang, The Gambia, participated in an observational cohort study of maternal heat strain and the assessment of the dynamic changes in maternal and fetoplacental blood flow during a day of field work from August 2019 to March 2020, with follow up until December 2020.[19] Participants were identified through the antenatal clinic or the health and demographic surveillance system in place in West Kiang and were eligible if they were pregnant with a singleton fetus, undertook farming or manual tasks during pregnancy, and did not have pre-eclampsia or eclampsia at the time of recruitment. Gestational age was determined using last known menstrual period when known, or if unknown, by biparietal diameter on ultrasound scan before 28 weeks of gestation. The feasibility study visits occurred in those with gestational age of 28 weeks or more. Exposure to external environmental conditions (air temperature, relative humidity, solar radiation, wind speed) were measured hourly using the HT200: Heat Stress WBGT Meter, Extech® and the Extech® AN100 thermo-anemometer (Extech Instruments, Nashua, NH, USA). Measurements were taken within 1 metre of participants to record exact exposure conditions. Two thermal indices were calculated from these measures—the Wet Bulb Globe Temperature (WBGT) and the Universal Thermal Climate Index (UTCI). These are composite measures of thermal stress taking into account heat, humidity, solar radiation, and wind speed.[20]

UmbiFlow™ measures the blood flow velocity in the umbilical cord and calculates the RI as (systolic velocity – diastolic velocity)/systolic velocity. The hand-held probe attaches to a laptop/tablet, signal processing occurs within the specialized software to give both a waveform and an audible umbilical artery blood flow. Validated reference values by gestational age indicate if the RI is within a normal, intermediate, or high-risk risk range (RI below 75th centile, between 75th and 95th centiles, and above the 95th centile, respectively, for gestational age). On a single occasion for each participant the RI was measured at baseline in an air-conditioned environment with the participant supine at rest, and with abdominal lateral tilt, and then at two time points during her working day—determined based on the length of the work shift to correspond with a mid-point and end-point of the manual tasks. At each time point, two measurements were taken, assessed for quality (signal quality assessed by expert trained by the South African team), mean values were taken when good/moderate quality and discarded if poor quality. The risk category was recorded at each reading as well as the exact value of the RI. Fetal heart rate was measured concurrently, and average values over 5 min were taken. When fetal heart rate or umbilical artery RI was identified as high risk during the study and did not resolve within 30 min, participants were referred for urgent care. This involved being assessed by the rural antenatal clinic (staffed by a midwife and four doctors), with the option to be referred to a tertiary center should they identify a clinical need. All participants were followed until after delivery and data on birth outcome were collected. APOs were defined as follows: stillbirth—pregnancy longer than 20 weeks where the baby was born dead; PTB—live birth before the completion of 37 weeks of pregnancy; low birth weight—birth weight less than or equal to 2.5 kg; small for gestational age—birth weight 10% below expected weight for gestational age based on Intergrowth-21 standardized curves.

To determine practical considerations, the study team recorded any issues with the software, the use of UmbiFlow in the field, and the results generated.

All analyses were performed in R version 4.1.0. Descriptive characteristics are presented as mean ± standard deviation or median (interquartile range) by outcome, depending on distribution. The relationship between UTCI, fetal heart rate, and umbilical artery RI were explored using linear and non-linear models. Non-linear models were tested across different spline definitions and different knots placed at the median and 90th centile. The lowest Akaike information criterion was used to determine best model fit. Change in fetal heart rate by UTCI was best explained by a linear model. RI *Z* score (which is age adjusted) or change in RI by UTCI was best explained by a non-linear model with a cubic spline with one knot at the median.

A multilevel linear regression model, with individual as random effect, of the association between umbilical artery RI *Z* score and heat stress was explored both with and without cubic splines, with the best fit determined by Akaike information criterion. The final model is shown as:

$$Z\ \text{score}_{ij} \sim b_0 + b_1 {}^{*}\text{heat stress}_{ij}.$$

where *Z* score is umbilical artery RI *Z* score for individual *i* at time *j* and heat stress is UTCI for individual *i* at time *j*.

Multilevel model assumptions were assessed by examining the normality of residuals and performing Levene tests for homogeneity of variance. The simr package was used to run a simulation-based power analysis on the multilevel model to give estimations of sample size requirements to detect a difference in umbilical artery RI *Z* score under heat stress.

3 | RESULTS

Full umbilical artery Doppler was completed on 40 participants the field. Of these 40 participants, 17 had APO and 23 did not. Of those with APO, three experienced stillbirths, seven delivered preterm (spontaneously), six were low birth weight, and eight had SGA. Descriptive characteristics of all participants are presented in Table 1, with detailed description of those with stillbirths in Table 2.

Environmental conditions and physiologic parameters at baseline, during the work shift, and at the end of the work shift are presented in Table 3 (full exposures can be found in the Supplement Material, Figure S1). All participants were exposed to "extreme heat stress" (based on the UTCI value), which has been shown to increase risk of mortality in other populations and settings.[21] Average physical energy expenditure for the working shift was equivalent to moderate intensity exercise such as a brisk walk.[22] There was no significant difference between working environmental conditions or estimated energy expenditure in those who went on to have an APO compared with those who did not.

Fetal heart rate demonstrated a linear relationship with heat stress, giving an increase of 10.7 (95% confidence interval [CI] 7.5–13.8) beats/min for each 10°C UTCI increase and 13.4 (95% CI 9.5–17.2) beats/min for each 10°C WBGT increase (Figure 1). However, there was no clear linear or nonlinear relationship between fetal heart rate and maternal tympanic temperature. Change in RI from cool baseline to working conditions reduced with increasing heat

TABLE 1 Demographic, social, obstetric, and anthropometric characteristics of those with adverse pregnancy outcomes and those without[a]

Characteristics	Adverse pregnancy outcome (*n* = 17)	No adverse outcome (*n* = 23)
Age, year	32.3 ± 7.6	31.6 ± 7.3
Occupation: farmers/other	16/1	16/7
Marital status		
Married	17	21
Single	0	1
Widowed	0	1
Gravida	5 (5.0)	5 (3.5)
Parity	3 (4.0)	4 (3.0)
GA at study visit	31.1 ± 3.1	30.5 ± 2.9
Height, cm	161.2 ± 5.4	162.6 ± 6.3
Weight, kg	62.3 ± 7.7	64.8 ± 12.1
BMI	24.0 ± 2.9	24.5 ± 3.9
Blood pressure	108/72	115/72
Hb, g/dL	11.3 ± 1.1	11.0 ± 1.6
Infection during pregnancy	7/17 (41%)	13/23 (57%)
Pre-eclampsia/eclampsia	1/17 (6%)	5/18 (28%)
Gestational age at birth, wk	38.4 ± 3.3	40.1 ± 1.7
Birth weight, kg	2.8 ± 0.5	3.4 ± 0.4
Adverse outcomes		
Stillbirths	3/40 (7.5%)	
Preterm births	7/40 (17.5%)	
Low birth weight	6/40 (15%)	
Small for gestational age	8/40 (20%)	

Abbreviations: BMI, body mass index (calculated as weight in kilograms divided by the square of height in meters); GA, gestational age; Hb, hemoglobin.

[a]Data are presented as mean ± standard deviation, median (interquartile range) or as number (percentage).

stress exposure up to 32°C UTCI/30°C WBGT and then appears to begin to increase with rising heat stress (Figure 2). There was no statistical difference in association between RI and heat stress in those with APO versus without APO (see Supplementary Material, Figure S2). Based on these findings, several simulation-based power calculations are given in Table 2. Model diagnostics for normality of residuals and homogeneity of variance (using Levene test) did not indicate gross violation of model assumptions.

Practical considerations for use in the field included ensuring a comfortable and private area to scan—which was provided by local vegetation or screens; protection from extreme weather—provided by portable shade/rain protector; and need for accurate gestational age to calculate RI *Z* scores. Several challenges were identified: software compatibility, delay in loading of the program when in the field, and interference with the signal when using Windows 7. The programming for the software can only run on Windows and is incompatible with Apple devices. It also required a laptop versus a tablet so requiring multiple electronic devices to be carried into the field because all study records were taken directly onto tablets. There was a delay in loading the software at each start up, which required planning for especially considering the need to capture dynamic changes. We also struggled with interference in the signal when using Windows 7, which resolved on upgrading to Windows 10, but made measurements difficult. All these issues were worked through and we were able to successfully record umbilical artery RI in the field at all the required time points. Furthermore, the manufacturers of UmbiFlow™ are working to resolve many of the points raised.

4 | DISCUSSION

We show that the UmbiFlow™ device is highly suited to field work, being light and compact, and that the measurement of umbilical artery Doppler in field conditions is possible and shows promising evidence of potentially enhancing the understanding of the fetoplacental circulation response to heat stress. Under heat stress conditions below 32°C UTCI/30°C WBGT there was a reduction in the umbilical artery RI from baseline, which would indicate increased blood velocity within the fetoplacental circulation as we would expect. However, above these temperature thresholds there appears to be a trend towards increasing RI, which would indicate insufficiency in the fetoplacental circulation. The response to heat stress may be different in those individuals that went on to have an APO as shown in the difference in z-scores presented in Table 3; however, the present study was not powered to determine this with statistical significance.

There are few studies exploring the impact of heat on uterine or placental blood flow. A study from Sweden on sauna use (20 min at 70°C) in late pregnancy found a reactive increase in fetal heart rate, but no change in umbilical artery blood flow.[23] This study is not immediately translatable to other settings because of both the inactivity and the extreme heat, but could be reassuring in terms of short bursts of unavoidable extreme heat exposure. Other studies have mainly focused on thermoregulation in pregnancy and there are several studies with encouraging evidence that thermoregulation is not compromised.[24,25] Although there is clear evidence that moderate intensity exercise is of benefit in pregnancy,[26] these studies are in temperate conditions and so not transferable to our setting. Additionally, in extreme cases (Olympic athletes exercising at more than 90% maximum maternal heart rate) there can be compromised fetal well-being.[27] This extreme physiologic strain may be similar to that experienced under extreme heat and warrants further investigation.

The study has several limitations. The sample size was reduced because the COVID-19 pandemic halted all field work activity from March 2020, limiting the scope of analysis available. Maternal core temperature could not be measured in the field (impractical to use rectal thermometer and lack of evidence on safety for core telemetry pills) and therefore the less accurate and less precise tympanic temperature was measured. Additionally, pregnancy and neonatal outcomes in the general population of The Gambia are worse than

TABLE 2 Details of participants who had stillbirths

	Case A	Case B	Case C
Maternal age	40–45 years	40–45 years	25–30 years
Gravida/Parity	12/7	10/9	2/1
Previous stillbirth	Yes	No	No
Previous miscarriage	Yes	No	No
Previous neonatal death	No	Yes	No
GA at visit	31 + 6	34 + 5	32 + 1
UA RI – baseline RC	High risk	Low risk	Low risk
UA RI – during work RC	High risk	High risk	Low risk
UA RI – after work RC	High risk	High risk	Low risk
Action	Referred for urgent care	Referred for urgent care	Normal care
GA at delivery	37 + 1	40 + 1	42 + 2
Outcome	Stillbirth	Stillbirth	Likely intrapartum death

Abbreviations: GA, gestational age; RC, risk category (low risk, intermediate risk, high risk based on *z*-score); UA RI, umbilical artery resistance index.

TABLE 3 Environmental conditions, maternal tympanic temperature, fetal heart rate, and umbilical artery resistance index[a]

	Baseline		Mid-way		End of shift	
	APO	No APO	APO	No APO	APO	No APO
UTCI, °C	23.1 ± 1.3	22.1 ± 2.2	34.2 ± 4.0	33.6 ± 4.2	34.1 ± 3.2	34.5 ± 2.7
WBGT, °C	19.3 ± 1.0	18.6 ± 1.8	27.3 ± 4.1	27.2 ± 4.5	27.3 ± 3.6	27.7 ± 2.7
Air temp., °C	24.0 ± 1.5	22.9 ± 2.0	34.2 ± 3.6	33.9 ± 4.1	34.4 ± 3.2	34.8 ± 3.0
T_{tym}, °C	36.9 ± 0.2	36.9 ± 0.2	37.2 ± 0.4	37.1 ± 0.3	37.1 ± 0.3	37.3 ± 0.3
PAEE, kcal/kg/h	—	—	—	—	3.1 ± 0.9	3.1 ± 0.7
FHR, beats/min	128.4 ± 8.4	126.4 ± 7.8	142.2 ± 14.4	147.3 ± 7.1	143.7 ± 11.8	144.9 ± 11.5
RI	0.68 ± 0.10	0.65 ± 0.08	0.69 ± 0.10	0.67 ± 0.05	0.66 ± 0.05	0.65 ± 0.07
Z score	0.74 ± 1.59	0.43 ± 1.23	0.964 ± 1.58	0.52 ± 0.74	0.51 ± 0.89	0.23 ± 1.13

Abbreviations: APO, adverse pregnancy outcomes; FHR, fetal heart rate; PAEE, physical activity energy expenditure; RI, umbilical artery resistance index; T_{tym}, tympanic temperature; UTCI, universal climate thermal index; WBGT, wet bulb globe temperature.
[a]Data are presented as mean ± standard deviation.

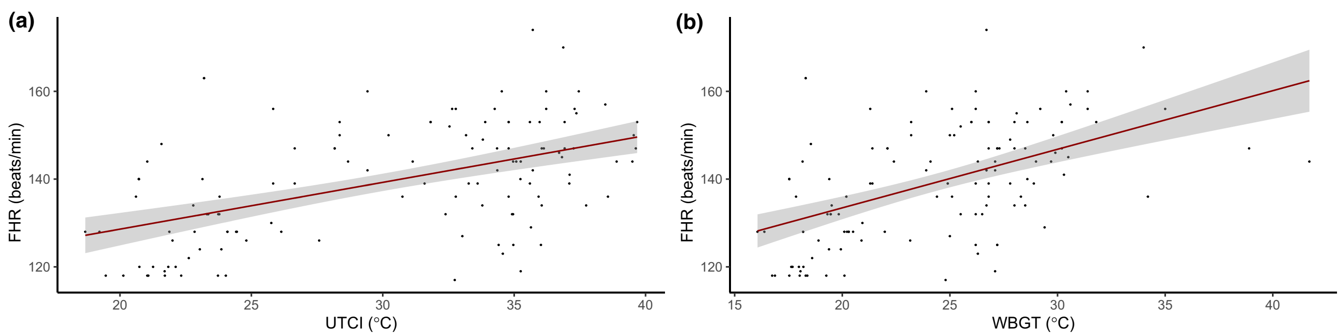

FIGURE 1 Association between fetal heart rate (FHR) and universal climate thermal index (UTCI) (a), and FHR and wet bulb globe temperature (WBGT) (b). Linear model with 95% confidence interval as shading.

the global average, which may impact on the generalizability of the findings globally, although they could be reasonably representative of a rural sub-Saharan Africa population. We found the number of participants with pre-eclampsia was higher in those without an APO, but this is most likely due to chance. This study comes at a time when extreme heat exposure is becoming a reality for much of the

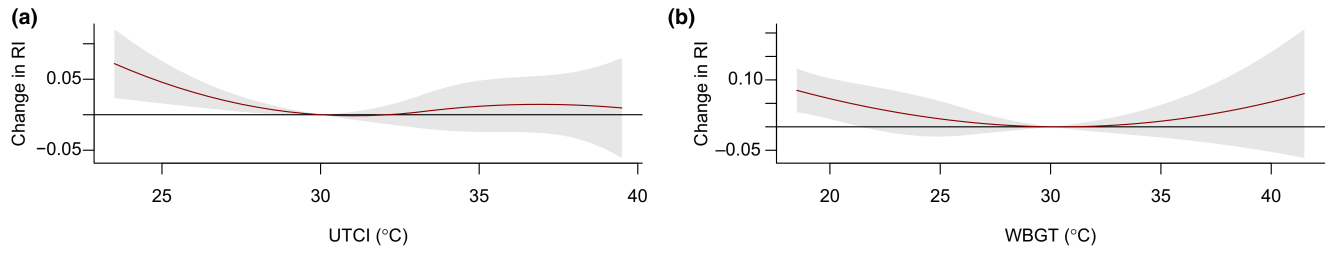

FIGURE 2 Association between change in umbilical artery resistance index (RI) and universal climate thermal index (UTCI) (a), and wet bulb globe temperature (WBGT) (b). Multilevel model output with 95% confidence interval as shading.

global population. Despite this, those most commonly experiencing these extreme conditions are often missing from the medical literature. This study is set in a rural African setting, with a population of women that can be difficult to access but are often exposed to extreme environmental conditions. By exploring ways to improve the understanding of pathophysiologic mechanisms in a real-life setting we highlight the need for future work. The simulation-based sample size calculations (see Supplementary Material, Table S2) give an estimate of the sample size and conditions needed to progress understanding of this using the UmbiFlow™ device. However, without expanding the work to include several key topic areas, the impacts of this research will have little meaning to this population. Identifying at-risk women will not be beneficial without clear management options to reduce the risk of these adverse outcomes. Health system strengthening in both facilities and human capacity in dealing with maternal health are urgently needed, especially in the face of the growing climate crisis and resultant impacts on health care. Additionally, identification of a dangerous heat exposure threshold will not have a real-world impact until evidence-based, effective, realistic, pragmatic, and sustainable interventions for cooling both individuals and their environment are identified and enacted.

AUTHOR CONTRIBUTIONS

AB contributed to conceptualization, methodology, formal analysis, and writing the original draft. VV contributed to the methodology, validation, and editing. BS contributed to software, data curation, and editing. NM contributed to formal analysis and editing. AVC, AH, NM, JH, and AP contributed to conceptualization, methodology, supervision, and editing.

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CONFLICT OF INTEREST

The authors have declared that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

Anonymized data will be made available on reasonable request from the corresponding author.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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Additional discussion

This work relies on the accuracy of the UmbiFlow™ device and therefore some additional details regarding its development, validation and clinical use are described below.

The UmbiFlow™ device was devised by the Medical Research Council Unit for Perinatal Mortality and the Centre for Scientific and Industrial Research (CSIR) in order to provide an accurate and low-cost device that would aid in identifying and managing pregnancies with intra-uterine growth restriction (IUGR).[1] Theron et al tested the UmbiFlow™ device against a commercially available device (Vasoflow) and found that the Resistance Index varied by ≤ 0.03, although there was a non-significant trend in the UmbiFlow™ to under-read the RI. An initial clinical study then evaluated the link between RI values and pregnancy outcomes.[2] Hugo et al classified the RI as >95th, 75-95th and <75th percentile and found that significantly more infants were small-for-gestational-age in both >95th (55.6%) and those between 75-95th (41.2%) compared to those <75th (27.2%). Additionally perinatal mortality rates were 13.2/1000, 39.1/1000 and 41.7/1000 in those with RI <75th, 75-95th and >95th percentiles respectively.

Subsequent studies support these findings. Nkosi et al screened low-risk pregnancies and those with abnormal RI (defined as ≥ 75th percentile) were referred to a high-risk clinic for ongoing management. This significantly reduced the perinatal mortality when compared to the background rate (11.4/1000 vs 21.3/1000 births), risk ratio 0.58 (95% CI 0.42;0.81).[3] A recent multi-country cohort study in Ghana, India, Kenya, Rwanda and South Africa evaluated the use of the UmbiFlow device in low-risk pregnancies.[4] Vannevel et al found a significant increase in low birth weight (15.0% vs 6.8%) in those with abnormal RI (defined as $\geq 75^{th}$ percentile) compared to normal.

Finally, I briefly describe some of the practical and ethical considerations that I faced working with a pregnant population in rural Gambia.

The MRC field station in Keneba supports the research work that occurs in the region and also provides free medical care to anyone resident in the area. This includes the provision of antenatal care. Therefore, inherent in any consenting process in the community is the underlying knowledge of the medical care that MRC provides. Although participation or not in research does not influence the care that is provided there are some benefits to the participants of the study in terms of the care they receive. For example, all women received additional ultrasound scans to assess the fetus as part of the screening process for recruitment into the study. These were performed by clinic staff and so results from the scan were included in ongoing clinical care. Additionally, West Kiang is a rural region with limited travel between villages, therefore although care may be free, it is not accessible to many of those living in more distance villages. By recruiting from villages further than 5km from the Keneba field station, we were able to provide antenatal care at the field station which otherwise would have been difficult for the women to access due to travel. This care included emergency use of an MRC vehicle should it be necessary. These provisions were not overstated in the consenting process, but as MRC has been working in the region for many years, there is an understanding of how these studies are conducted. This leads to broad concerns regarding “valid consent” and lack of coercion, and although not specific to this study, does require acknowledgement and very careful consideration for any research studies being performed in the region.

Further considerations in studies involving pregnant women include balancing risks – i.e. weighing the risks to the mother and the risk to the fetus. In this case, since we were performing an observational study this did not appear relevant immediately, however any ongoing work or interventions need to take this into account.

A particularly challenging aspect of the study was the fact that we were performing additional scans and doppler scans which allowed us to identify conditions that would otherwise not have been identified. The challenge arose due to the lack of provision in the health service to deal with these conditions. Therefore, although our study protocol stated referral to the regular antenatal services in the case of identifying any clinical concerns, the regular antenatal services could not always implement complex management of the case. This was difficult for participants, clinical staff and research staff.

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CHAPTER 5 – Environmental heat stress on maternal physiology and fetal blood flow in pregnant subsistence farmers in The Gambia, west Africa: an observational cohort study

SUMMARY OF CHAPTER

In this chapter I present an accepted manuscript describing the main findings from the observational cohort study. In this study I describe the heat stress exposure experienced by pregnant farmers, the association between heat stress and maternal heat strain, the total effect of heat stress on fetal strain, the direct effect of heat stress on fetal strain and the direct effect of maternal heat strain on fetal strain using multilevel repeated measures logistic and linear regression models.

The full summary of the chapter can be found in the abstract of the paper. Supplementary material for this paper can be found in Appendix 3

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Surname/Family Name	Bonell		
Thesis Title	Climate change, maternal health and birth outcomes: how does environmental heat affect pregnancy and birth outcomes in The Gambia?		
Primary Supervisor	Professor Andrew Prentice		

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Stage of publication	**In press**

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SECTION E

Student Signature	Ana Bonell
Date	18th November 2022

Supervisor Signature	Andrew Prentice
Date	21st November

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Doctopic: Primary Research

Environmental heat stress on maternal physiology and fetal blood flow in pregnant subsistence farmers in The Gambia, west Africa: an observational cohort study

Ana Bonell, Bakary Sonko, Jainaba Badjie, Tida Samateh, Tida Saidy, Fatou Sosseh, Yahya Sallah, Kebba Bajo, Kris A Murray, Jane Hirst, Ana Vicedo-Cabrera, Andrew M Prentice, Neil S Maxwell, Andy Haines

Summary

Background Anthropogenic climate change has caused extreme temperatures worldwide, with data showing that sub-Saharan Africa is especially vulnerable to these changes. In sub-Saharan Africa, women comprise 50% of the agricultural workforce, often working throughout pregnancy despite heat exposure increasing the risk of adverse birth outcomes. In this study, we aimed to improve understanding of the pathophysiological mechanisms responsible for the adverse health outcomes resulting from environmental heat stress in pregnant subsistence farmers. We also aimed to provide data to establish whether environmental heat stress also has physiological effects on the fetus.

Methods We conducted an observational cohort study in West Kiang, The Gambia, at the field station for the Medical Research Council Unit The Gambia at London School of Hygiene & Tropical Medicine (named the MRC Keneba field station). Pregnant women who were aged 16 years or older and who were at <36 weeks' gestation of any gravida or parity were invited to participate in the study. Participants were eligible if they were involved in agricultural or related manual daily tasks of living. Participants were ineligible if they refused to provide consent, had multiple pregnancies (eg, if they had twins), were acutely unwell, or were diagnosed with pre-eclampsia or eclampsia. Heat stress was measured by wet bulb globe temperature (WBGT) and by using the universal thermal climate index (UTCI), and maternal heat strain was directly measured by modified physiological strain index calculated from heart rate and skin temperature. Outcome measures of fetal heart rate (FHR) and fetal strain (defined as a FHR >160 beats per min [bpm] or <115 bpm, or increase in umbilical artery resistance index) were measured at rest and during the working period. Multivariable repeated measure models (linear regression for FHR, and logistic regression for fetal strain) were used to evaluate the association of heat stress and heat strain with acute fetal strain.

Findings Between Aug 26, 2019, and March 27, 2020, 92 eligible participants were recruited to the study. Extreme heat exposure was frequent, with average exposures of WBGT of 27·2°C (SD 3·6°C) and UTCI equivalent temperature of 34·0°C (SD 3·7°C). The total effect of UTCI on fetal strain resulted in an odds ratio (OR) of 1·17 (95% CI 1·09–1·29; p<0·0001), with an adjusted direct effect of OR of 1·12 (1·03–1·21; p=0·010) with each 1°C increase in UTCI. The adjusted OR of maternal heat strain on fetal strain was 1·20 (1·01–1·43; p=0·038), using the UTCI model, with each unit increase.

Interpretation Data from our study show that decreasing maternal exposure to heat stress and heat strain is likely to reduce fetal strain, with the potential to reduce adverse birth outcomes. Further work that explores the association between heat stress and pregnancy outcomes in a variety of settings and populations is urgently needed to develop effective interventions.

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Introduction

Anthropogenic climate change has increased global annual temperatures by approximately 1·2°C compared with pre-industrial temperatures.[1] Without major decreases in greenhouse gas emissions, this trend will continue, with potentially catastrophic impacts on human health.[2] Large epidemiological studies have shown that there is an increased risk of adverse birth outcomes in mothers who are exposed to high ambient temperatures, including premature birth, low birthweight, stillbirth, pre-eclampsia, and gestational diabetes.[3–5]

Although global temperatures are rising, some regions will be affected by the impacts of climate change more than others.[6,7] Populations in west Africa are highly susceptible to the impacts of climate change and will be increasingly exposed to extreme heat.[8] However, data for the impact of heat on pregnancy outcomes in Africa are sparse.[9] The at-risk population is large, with around 200 million women living in

Research in context

Evidence before this study

We searched Embase for articles published between 1947 and Sept 9, 2022, using the following search terms: ("heat" or "heat stress" or "heat wave") AND ("pregnancy" and "pregnancy complication" or "low birth weight" or "prematurity" or "stillbirth") AND ("physiology"). Although there were many studies showing a clear association between maternal exposure to high ambient temperature and poor birth outcomes, the physiological mechanisms have not been defined. Hypothesised mechanisms are based on either animal, fever, or heat chamber studies. To the best of our knowledge, there is no evidence of the pathophysiological pathways between heat stress and maternal and fetal health outcomes from real-world field studies.

Added value of this study

In this study, we directly measured the heat stress exposure of pregnant subsistence farmers, showing that they commonly experience extreme levels of heat during a normal working day. This heat stress was significantly associated with fetal strain even when controlling for maternal heat strain. Maternal heat strain was also associated with fetal strain.

Implications of all the available evidence

Our findings show that in The Gambia, pregnant subsistence farmers are frequently exposed to extreme heat stress, leading to maternal heat strain. This heat strain also has a detectible impact on the fetus. The development and evaluation of interventions to reduce maternal heat strain and the resulting effects on the fetus are therefore urgently needed.

west Africa alone, with this number estimated to reach 400 million by the year 2050.

In The Gambia, as in many similar countries, women make up at least 50% of the agricultural workforce.[10] Outdoor workers, who lack the choice to avoid heat exposure, are at an increased risk of heat strain, although data from Africa are scarce.[11] The growing risk of climate change to both livelihoods and health, particularly for women, is a neglected research topic that needs further work to identify problems and determine actionable solutions.

During pregnancy, the effects of heat stress (defined as the environmental exposure of heat, humidity, solar radiation, and wind speed, while heat strain is defined as the physiological response to that stress) are exacerbated by an increased physiological demand from the fetus and placenta. The physiological mechanisms behind adverse birth outcomes are not clearly defined. Hypotheses from animal and human fever studies speculate that raised core temperature, dehydration, reduced uterine blood flow, inflammatory changes, and heat shock proteins could be involved.[12–14]

Although there is emerging evidence to show that temperature control in pregnancy is conserved,[15] there remain concerns with regard to prolonged ambient exposure and extreme heat.[16] To develop targeted interventions to reduce the risk of adverse birth outcomes, a more complete understanding of the physiological mechanisms involved is required.[5]

See Online for appendix

This observational cohort study of pregnant, subsistence-farming women in The Gambia aimed to assess environmental heat stress on maternal and fetal physiology, in a region and population where high levels of heat stress are often observed. We aimed to assess the effects of working in the heat and to examine whether these populations are at risk of heat strain. In addition, this study also aimed to establish whether there are also physiological effects on the fetus.

Methods

Study design and participants

This observational cohort study was set in West Kiang, a rural area that is approximately 150 km from the capital of The Gambia, where the field station for the Medical Research Council Unit The Gambia at London School of Hygiene & Tropical Medicine is located (named the MRC Keneba field station). West Kiang is populated by 34 villages, with populations ranging from 200 to 2000 people. Antenatal care is provided free of charge at the MRC Keneba field station, where women attend antenatal appointments every month, are routinely supplemented with iron and folic acid, and around 30% of whom attend for delivery.[17] At the time of the study, most villages did not have access to gridded electricity or piped running water.

Pregnant women who were aged 16 years or older and who were at fewer than 36 weeks' gestation of any gravida or parity were invited to participate in the study. Participants were eligible if they were involved in agricultural or related manual daily tasks of living (including water collection, gardening, rice planting, harvesting, and washing clothes). Participants were ineligible if they refused to provide consent, had multiple pregnancies (eg, if they were pregnant with twins), were acutely unwell, or were diagnosed with pre-eclampsia or eclampsia (appendix p 3). All participants gave written informed consent to participate in the study.

The study was approved by the Gambian Government and the Medical Research Council Unit The Gambia joint ethics committee and the London School of Hygiene & Tropical Medicine ethics advisory board in accordance with the Declaration of Helsinki (2013). The published study protocol gives full details of the methods.[18] Figure 1 provides a summary of the physiological pathways investigated and relevant measurements taken.

Procedures and outcomes

Baseline data for previous medical conditions, obstetric history, and current pregnancy were collected for this study. Gestational age was ascertained through last menstrual period (if known) or biparietal diameter, which was measured by ultrasound scan. An ultrasound scan at each visit was conducted to measure fetal growth and to identify anomalies. The study team were scheduled to attend field visits with participants every 2 months until the time of delivery.

During field visits, participants were encouraged to carry out their usual daily tasks. Hourly air temperature, relative humidity, black globe temperature, wet bulb globe temperature (WBGT), and wet bulb and dew point data were measured throughout the participants' outdoor working shift using the HT200: Heat Stress WBGT Meter (Extech, Nashua, NH, USA). Wind speed was measured using a portable anemometer (Extech AN100 thermo-anemometer, Nashua, NH, USA). From these measurements, the universal thermal climate index (UTCI) was calculated using the alfrisci/rBiometeo package.[19] Both average conditions and peak conditions were calculated for WBGT, UTCI, air temperature, and relative humidity for each participant during each visit. WBGT is widely used in both occupational health regulations and in research. Our decision to measure WBGT was to aid the comparability and potential generalisability of our findings. WBGT is a continuous measure but has been divided into five categories, from no risk (0) of heat illness in occupational settings to extreme risk (5) of heat illness in occupational settings. The UTCI, a more recent heat stress index, is based on a physiological model and is potentially better than WBGT at expressing biothermal conditions. The UTCI is divided into ten categories that range from extreme cold stress to extreme heat stress.[20] To the best of our knowledge, there are no modifications that have been specifically developed for pregnancy in any of the heat indexes and therefore both were evaluated.

Participants were fitted with an Equivital LifeMonitor (Cambridge, UK), which is a wearable device with inbuilt fabric sensors. This device continuously recorded maternal heart rate, skin temperature, and triaxis accelerometer data.

Duplicate tympanic temperature measurements from both membranes were taken using a Braun ThermoScan 7 tympanic thermometer (Braun, Kronberg, Germany) and the highest measurement was recorded at each timepoint.[21,22]

The physiological strain index (PSI) has been widely accepted as an accurate measurement of heat strain.[23] This model has been validated for men and women, but there are no data for its use during pregnancy. PSI requires continuous core temperature measurements, but these were unavailable owing to an absence of data for the safety of telemetry pills in pregnancy and therefore we used continuous chest skin temperature measurements to give a modified PSI (PSI_{MOD}), using the following equation:[23,24]

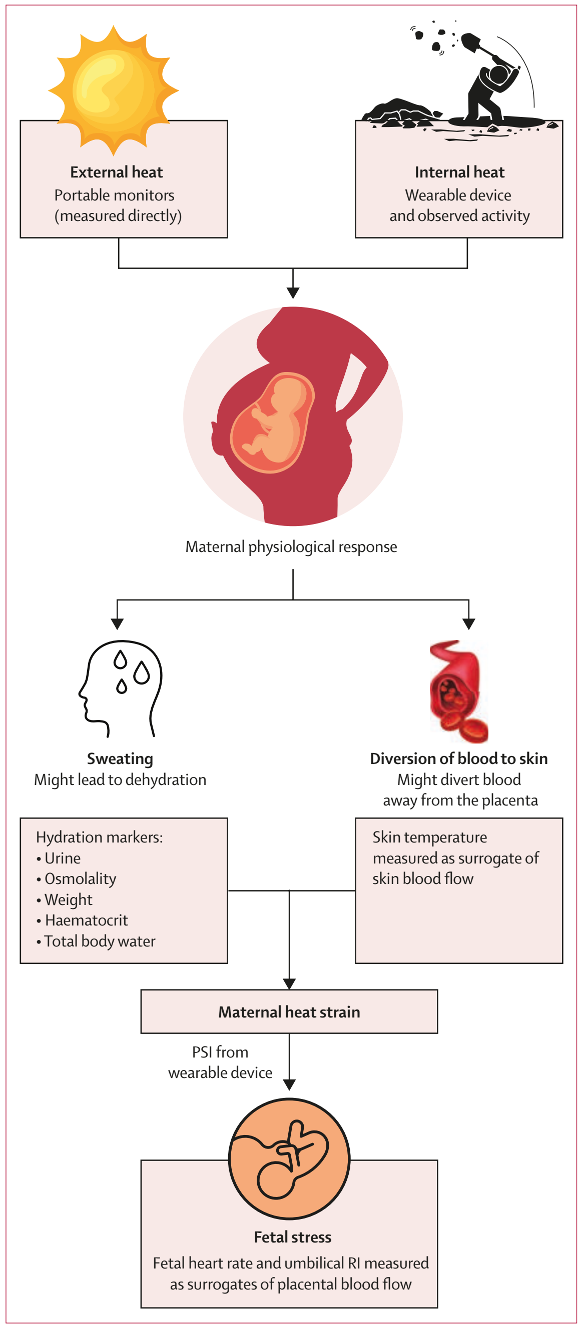

Figure 1: **Maternal physiological responses to thermal heat stress**
Measurements taken at each field visit are shown in grey.
PSI=physiological strain index. RI=resistance index of umbilical artery.

$$PSI_{MOD} = 5*((T_{SKT} - T_{TYMP0})/(39.5 - T_{TYMP0}) + 5*((HR_t - HR_0)/(180 - HR_0)$$

wherein skin temperature at time t (T_{SKT}), tympanic temperature at baseline (T_{TYMP0}), heart rate at time t (HR_t), and heart rate at rest (HR_0) are represented. Use of triaxial accelerometer data in pregnancy to estimate energy expenditure is problematic.[25] We increased the robustness of our estimates by calculating the physical activity energy expenditure (PAEE) with two methods. First, PAEE was calculated from the LifeMonitor data using the following validated equation (method A), with the standard 6 min walk test used to calibrate the device:[26]

$$PAEE=(5*HRaS)+((023*HRaS)*HRaS_{3min})+(22*HRaS_{3min})+9\cdot 2*\log(RMSDD)-(2.6*SHR)-82)$$

wherein heart rate above sleeping or resting heart rate (HRaS), average heart rate above resting heart rate at 3 min into the calibration test ($HRaS_{3min}$), root mean square of successive difference of inter-beat intervals during calibration test (RMSSD), and sleeping or resting heart rate (SHR) are represented.

Second, energy expenditure was determined on the basis of direct activity observations of each participant matched to historic indirect calorimetry data for energy expenditure by task in pregnant women in West Kiang, determined by Lawrence and colleagues (method B),[27] which was given in metabolic equivalents (METs). Where estimates from the LifeMonitor were outside the expected range (2–15 METs), historical data were used.

Measures of hydration, body composition, haematology, and biochemistry were measured at the beginning and end of each field visit. The TANITA BC-418MA segmental body composition analyser uses bioimpedance to measure free fat mass, fat percentage, total body water, and basal metabolic rate.

Maternal symptoms of heat illness were collected at the midpoint and endpoint of field visits. According to Centers for Disease Control and Prevention guidance and other published literature,[11,28] self-reported symptoms included nausea, vomiting, headache, dizziness, weakness, muscle ache, fatigue, and dry mouth.

Ultrasound for biometry, fetal heart rate (FHR), placental position, and assessment of liquor volume was conducted before every field visit by a trained midwife. Umbilical artery doppler is an established non-invasive tool for measuring placental blood flow and gives information on the maternal–fetal circulation.[29] The UmbiFlow device is a portable, low-cost, continuous wave doppler that was developed in South Africa and is validated for use in measuring umbilical artery blood flow. In eligible participants (those at ≥28 weeks' gestation), a baseline recording of the resistance index (defined as [systolic velocity minus diastolic velocity] divided by systolic velocity) was recorded at this time. FHR and resistance index measures that were taken at this time were taken as the baseline measurements.

During field visits, FHR and (if eligible) the umbilical artery resistance index were recorded at the midpoint and the endpoint of the working shift. The umbilical artery resistance index was recorded twice at each timepoint and assessed for quality. An outcome of fetal strain was defined as a FHR greater than or equal to 160 beats per min (bpm), less than or equal to 115 bpm for 5 min, or an increase in umbilical artery risk category from baseline, based on the definition of fetal distress and in keeping with clinical practice and current evidence.[30] These measurements were used as surrogate markers for impact on maternal–fetal circulation.

Data for gestational age, birthweight (within 72 h of delivery), infant sex, mode of delivery, place, level of training of the attendant at delivery, and infant or maternal mortality were collected.

The primary outcome of the study was presence of fetal strain, which was assessed in all participants at each field visit. The theoretical framework of this work has been described previously.[18] As fetal heat strain has never been defined previously and would be extremely challenging to measure, especially in the field, we use surrogate measures (fetal heart rate and umbilical artery resistance index) to determine the effect of heat stress on blood flow to the fetus, defined below as fetal strain. This study was not powered to assess the effect of heat strain on birth outcomes.

Statistical analysis

The initial sample size estimation in our study protocol was based on 35% of workers being exposed to heat stress (WBGT >24·8°C).[11,18] An updated sample size calculation that included an increased exposure level and that assumed an unexposed incidence risk of fetal strain to be 5% estimated that a sample size of 74 would be needed to detect an exposure incidence risk of 30%, with an α of 0·05 and a power of 80%.

All analyses were conducted in R, version 4.1.0. Normally distributed continuous variables are presented as a mean with SD, non-parametric data as median and IQR, and categorical variables as counts. Heat stress exposure variables were analysed as continuous data. Outcome measures of fetal strain were analysed by both FHR as a continuous variable and fetal strain as a binary variable as defined in the Procedures and outcomes section. Initial data exploration assessed changes in mean temperature and heart rate from baseline to working state using Wilcoxon signed-rank tests. The correlation between multiple similar variables (eg, WBGT, UTCI, and air temperature) were evaluated using Pearson's correlation. Univariable analysis of maternal heat strain (PSI_{MOD}), fetal strain by FHR (continuous variable and linear regression), and fetal strain (binary variable and logistic regression) were conducted to explore risk factors. Final datasets in multivariable analyses were complete.

The association between heat stress and maternal heat strain (by PSI_{MOD}) was explored using linear and non-linear models.[31] Non-linear models with natural and logarithmic splines with knots placed at the 50th and 90th centiles were evaluated, in keeping with other studies on the association between temperature and health outcomes. The linear model had the lowest Akaike information criterion and was used in the subsequent repeated measures multivariable models.

To explore the effect of heat stress and maternal heat strain on the fetus, we used two multivariable repeated measures models with FHR (model A, linear regression) and fetal strain (model B, logistic regression) as outcomes. All variables were decided a priori on the basis of biological plausibility and directed acyclic graphs (appendix pp 13–14). Model 1 shows the total effect of heat stress on fetal strain or FHR:

$$Y_{ij} \sim \beta_0 + \beta_1 * \text{Heat stress}_{ij}$$

wherein fetal strain or fetal heart rate for individual *i* at time *j* (Y) and heat stress exposure for individual *i* at time *j* are represented. Model 1 gives the estimate of effect (model A) and the odds ratio (OR; model B) for each 1°C increase in heat stress on fetal strain to give the total effect of heat stress.

Model 2 gives the direct effect of heat stress on fetal strain while controlling for maternal heat strain:

$$Y_{ij} \sim \beta_0 + \beta_1 * \text{Heat stress}_{ij} + \beta_2 * \text{Heat strain}_{ij}$$

wherein FHR or fetal strain for individual *i* at time *j* (Y), UTCI or WBGT for individual *i* at time *j* (heat stress), PSI_{MOD} of individual *i* at time *j* (heat strain), estimation of cardiovascular fitness determined by distance travelled in standardised 6 min walk test for individual *i* at time *j* (fitness), and measurement of body fat (as BMI is not useful in pregnancy) for individual *i* at time *j* (% fat mass) are represented. Model 2 gives the estimate of effect (model A) and the OR (model B) for each 1°C increase in heat stress on fetal strain, controlling for maternal heat strain. This model estimates the effects of heat stress on fetal strain due to other mechanisms outside of maternal heat strain.

Model 3 gives the direct effect of maternal heat strain on fetal strain while controlling for heat stress, cardiac fitness, percentage of fat mass, and gestational age:

$$Y_{ij} \sim \beta_0 + \beta_1 * \text{Heat strain}_{ij} + \beta_2 * \text{Heat stress}_{ij} + \beta_3 * \text{Fitness}_{ij} + \beta_4 * \text{\% fat mass}_{ij} + \beta_5 * \text{Gestational age}_{ij}$$

wherein FHR or fetal strain for individual *i* at time *j* (Y), UTCI or WBGT for individual *i* at time *j* (heat stress), PSI_{MOD} of individual *i* at time *j* (heat strain), estimation of cardiovascular fitness determined by distance travelled in standardised 6 min walk test for individual *i* at time *j* (fitness), and measurement of body fat (as BMI is not useful in pregnancy) for individual *i* at time *j* (% fat mass) are represented. Full details of all models and analysis code can be found in the appendix (pp 19–22). The final models were assessed for violation of model assumptions by assessing the linearity of residuals, homoscedasticity by Levene's Test, and the normal distribution of residuals.

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Study recruitment occurred from Aug 26, 2019, to March 27, 2020, with data collection completed on Dec 17, 2020. All 92 participants attended at least one field visit, with 30 (33%) attending a second field visit (appendix p 3). The demographics, physical characteristics, and birth outcomes of all participants are shown in table 1.

During the study, the COVID-19 pandemic occurred. The Gambia entered lockdown on March 27, 2020, and all study activities stopped, as mandated by the Gambian Government and the MRC Keneba field station. The pandemic affected the study in several ways. First, intending to have a full year of directly measured meteorological exposure, we only have 7 months. Second, our initial sample size calculations required 99 participants. By the end of the study period we had data for 92 participants. Third, we expected to have most participants attend at least two field visits, with some attending up to four field visits. Instead, most participants attended only one field visit, and fewer than half of participants attended two field visits. Last, during the lockdown, retrospective birth outcomes were collected from the antenatal card. However, if data were not recorded they were coded as missing.

Field visits occurred during the rainy season (August to October) and the first half of the dry season (November to March). Throughout the study period, mean air temperature was 33·5°C (SD 3·8°C, range 22·1–45·4°C) and humidity varied substantially (mean 28·1% (SD 23·4%, range 0–87·7%). Mean WBGT was 27·2°C (SD 3·6°C), with a maximum value of 42·0°C. In 38 (31%) of 122 field visits, the WBGT category was four or above. Mean UTCI was 34·0°C (SD 3·7°C), with maximum values reaching 51·3°C. 25 (20%) of 122 field visits showed that pregnant women were exposed to very strong heat stress and above (ie, >46°C; figure 2). Comparisons between measured values and monthly weather station results are presented in the appendix (p 4). However, in this study, 80% of field visits occurred under heat stress conditions. Average METs were not correlated by method or with gestational age, $R^2 < 0 \cdot 01$ (ie, participants worked at similar levels of exertion throughout pregnancy), or with PSI_{MOD}, or with environmental conditions (appendix pp 5–10).

There was a significant increase in both mean tympanic and mean skin temperature from baseline to the working period (p<0·001; figure 3). Maternal heart rate also increased from baseline to the working period (p<0·001). The mean peak PSI_{MOD} was 5·1 (SD 2·4). There was a clear linear association between heat stress and heat strain (PSI_{MOD}, appendix p 11).

	Participants (n=92)
Age, years	27·7 (23·7–35·8)
Schooling, years in education	5 (4–8)
Ethnicity	
Mandinka	85 (92%)
Wolof	6 (7%)
Fula	1 (1%)
Occupation	
Farmer	74 (80%)
Other	18 (20%)
Marital status	
Single	2 (2%)
Married	89 (97%)
Widowed	1 (1%)
Gravida	4 (2–7)
Parity	3 (1–5·25)
Gestational age at visit, weeks	28·5 (23·6–32·9)
Height, cm	162·9 (5·6)
Weight	
Median, kg	61·9 (55·8–97·3)
BMI, kg/m^2	23·0 (21·3–25·9)
MUAC, cm	27·0 (25·1–29·7)
Percentage fat mass, %	28·7% (25·8–33·8)
Birth outcome	
Normal birth	53/91 (58%)*
SGA	24/91 (26%)*
Preterm	12/92 (13%)
Low birthweight	12/91 (13%)*
Stillbirth or intrapartum death	3/92 (3%)

Data are median (IQR), n (%), or mean (SD). MUAC=mid-upper arm circumference. SGA=small for gestational age. *Data are missing for one participant.

Table 1: **Demographics, physical characteristics, and birth outcomes of participants**

Symptoms of heat illness were common in this cohort, with 71 (58%) of 122 participants experiencing at least one symptom during field visits. The most commonly reported symptom was dry mouth (37%), followed by headache (21%) and muscle cramps (17%).

There was a significant increase in FHR from baseline at rest (125 [SD 7·9] bpm) to the working period (147 [SD 11·9] bpm; p<0·0001; appendix p 12). During field visits, a total of 41 (34%) of 122 episodes of fetal strain were measured. 21 participants had a FHR greater than or equal to 160 or less than 115 bpm. In participants who were eligible for UmbiFlow (n=40), resistance index changes by category occurred in 22 (55%) of 40 participants from baseline. All of these participants were monitored for return to baseline measurements after 30 min. All but one participant returned to baseline, and that participant was subsequently referred for urgent antenatal care. Despite close follow-up care, this patient went on to have a stillbirth.

In multivariable analyses, both heat stress indices were similar (with similar Akaike information criterion) and were significantly associated with both fetal heart rate and fetal strain both in model 1 (total effect) and in model 2 (controlling for maternal heat strain; table 2). Figure 4 shows the total effect between FHR and the UTCI or WBGT. When heat stress was defined by the UTCI, total effect on fetal strain resulted in an OR of 1·17 (95% CI 1·09–1·29; p<0·0001), and an adjusted direct effect of OR of 1·12 (1·03–1·21; p=0·010) with each 1°C increase in UTCI. When heat stress was defined by WBGT, total effect of heat stress on fetal strain resulted in an OR of 1·20 (1·12–1·29; p<0·0001), with an adjusted direct effect of OR of 1·12 (1·02–1·24; p=0·018) with each 1°C increase in WBGT. Maternal heat strain was significantly associated with fetal strain when adjusted for heat stress, percentage fat mass, fitness, and gestational age (in the UTCI model, OR 1·20 [1·01–1·43; p=0·038]; in the WBGT model, OR 1·22 [1·03–1·46, p=0·025]), with each unit increase in PSI_{MOD}.

Discussion

To the best of our knowledge, this is the first study to explore the dynamic changes to maternal and fetal physiology in pregnant farmers under extreme environmental heat stress, or indeed pregnant manual workers of any description. We found that exposure to extreme temperatures beyond the recommended outdoor working limits were a common occurrence for pregnant subsistence farmers in our study region (West Kiang) of The Gambia. We found a strong association between maternal heat strain and heat stress exposure. The total and adjusted direct effects of maternal heat stress exposure were significantly associated with fetal strain. Maternal heat strain, controlling for heat stress exposure, was also significantly associated with fetal strain. These findings indicate that, although maternal heat strain is likely to be on the pathway from heat stress to fetal stress, there are possibly other important biological mechanisms occurring that need further exploration.

The existing literature focuses on heat thresholds during early pregnancy, as heat can act as a teratogen, and applies the established threshold of 39·5°C core temperature to the whole pregnancy. However, the mechanisms by which heat can adversely affect outcomes throughout pregnancy and core temperature thresholds in the second and third trimesters have not been established. We provide evidence to show that maternal tympanic membrane temperature increases while doing manual tasks in the heat, even in only moderate intensity activities (metabolic equivalent 3–6), but did not exceed 38·5°C. Despite this modest rise in body temperature, we found evidence of physiological strain in both mother and fetus. We suggest that an important physiological factor to consider in future work is the role of the diversion of blood from the placenta to the skin, which occurs at lower core temperatures than those that have been previously highlighted as teratogenic. This factor has been well recognised in maternal exercise and has been signposted as a potential issue in maternal thermoregulation, but has not been thoroughly investigated.[32,33]

Although this study was not designed to specifically evaluate the applicability of heat stress indices in pregnancy, both UTCI and WBGT models performed similarly, which could aid the accessibility and generalisability of our data for future studies. Few studies have explored the effects of heat on fetal physiology, although the literature is more extensive on the effects of exercise.[16] Heat stress from saunas has been shown to lead to an increase in FHR, although no studies in saunas have led to increases in FHR above 160 bpm and none have shown changes to the umbilical artery resistance index.[34] Our finding that a total of 41 (34%) of 122 episodes of fetal strain were measured was high. However, heat exposure levels in our population were very high and these levels are similar to levels of heat strain in workers in other occupational settings.[11] The dearth of comparable studies highlights the ongoing need to focus on this area.

Heat protection of agricultural workers is of growing concern due to the climate crisis and adaptation strategies are being explored as a matter of urgency.[35] However, subsistence farmers are mostly missing from these strategies. Our findings of self-reported symptoms of heat illness in 58% of participants is similar to the levels found by Frimpong and colleagues[36] in their study of smallholder farmers in Ghana, and Sadiq and colleagues'[37] study of maize farmers in Nigeria, but higher than that found in Flouris and colleagues'[11] systematic review. A study of pregnant farm workers in Florida (USA) reported that there were high rates of heat illness symptoms in these workers and a lack of agency to alter workplace conditions.[38] For subsistence farmers, the pressures are often different, but the inability to avoid the heat is a shared problem, as detailed in our qualitative analysis of heat perception during pregnancy in this population.[39]

There are several limitations to our study. First, as discussed in the Results section, the COVID-19 pandemic had several adverse impacts on our study and reduced our sample size. Second, there were issues with gold standard measurements. In a field-based study in rural sub-Saharan Africa, a rectal thermometer was not acceptable and core telemetry pills do not yet have a safety track record in pregnancy and therefore could not be used. We used tympanic temperature while recognising its flaws, but aimed to minimise these by taking duplicate measurements from each participants' ear at all timepoints. Triaxial accelerometery and heart rate monitoring to estimate energy expenditure in pregnancy is less accurate than in other populations. The PSI is also not validated in pregnancy, where concerns for both mother and fetus must be considered. To aid generalisability and applicability, future studies should aim to establish the accuracy of the PSI during pregnancy. Additionally, this population was exposed to high levels of heat stress throughout the study, which is likely to have resulted in acclimatisation and also prevented comparisons to groups with less heat exposure. Lastly, our population had poorer birth outcomes than the global average, which might have affected the generalisability of our findings.

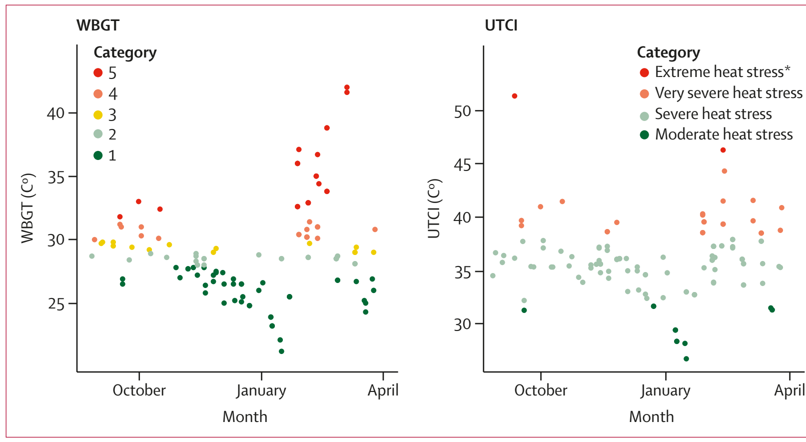

Figure 2: **Maximum measured heat stress exposures of participants during a working shift**
WBGT is coded by risk category for heat illness, whereby 1=no risk, 2=low risk, 3=moderate risk, 4=high risk, and 5=extreme risk. WBGT=wet bulb globe temperature. UTCI=universal thermal climate index. *Extreme heat stress was defined as the scenario in which temperatures exceeded 46°C.

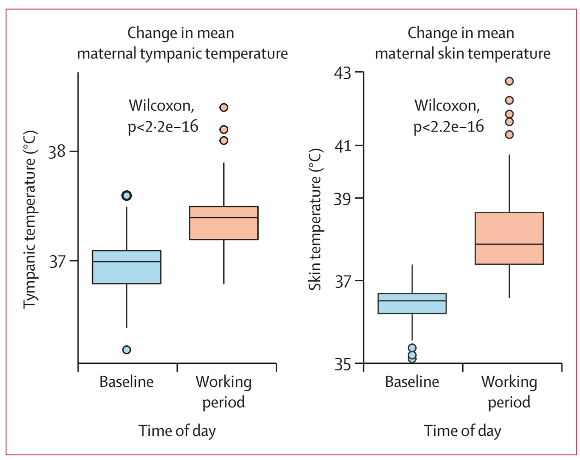

Figure 3: **Mean change in maternal tympanic and skin temperature from baseline to the working period**

Globally, there is a large population at risk to extreme heat, with future predictions being exceedingly concerning. Extreme heat exposure, which poses a risk to health from even moderate physical labour in non-pregnant adults during the hottest month of the year, is predicted to affect 350 million people by the year 2100 if the Paris Agreement of limiting temperature rise to 1·5°C is met, which is increasingly unlikely. Should temperature increases reach 2·5°C above pre-industrial levels, this scenario will mean that approximately 1 billion people will be exposed to dangerous levels of heat stress.[40] There remain large evidence gaps in relation to the pathophysiology of heat in pregnancy, the identification of those most at risk, and the

	Model 1		Model 2		Model 3	
	Estimate (95% CI)	p value	Estimate (95% CI)	p value	Estimate (95% CI)	p value
Model A1—fetal heart rate and UTCI						
UTCI	1·45 (1·26–1·64)	<0·0001	1·18 (0·87–1·49)	<0·0001	1·19 (0·88–1·49)	<0·0001
PSI	1827·2	..	0·77 (0·06–1·47)	0·033	0·82 (0·11–1·52)	0·025
AIC	..	..	1825·0	..	1824·8	..
Model A2—fetal heart rate and WBGT						
WBGT	1·74 (1·50–1·98)	<0·0001	1·26 (0·87–1·65)	<0·0001	1·27 (0·88–1·66)	<0·0001
PSI	1845·2	..	1·11 (0·39–1·82)	0·0024	1·17 (0·45–1·88)	0·0015
AIC	..	..	1838·3	..	1838·1	..
Model B1—fetal strain and UTCI						
UTCI	OR 1·17 (1·09–1·29)	<0·0001	OR 1·12 (1·03–1·21)	0·010	OR 1·13 (1·03–1·23)	0·0090
PSI	..	..	OR 1·18 (1·01–1·37)	0·042	OR 1·20 (1·01–1·43)	0·038
AIC	194·0	..	191·6	..	189·7	..
Model B2—fetal strain and WBGT						
WBGT	OR 1·20 (1·12–1·29)	<0·0001	OR 1·12 (1·02–1·24)	0·018	OR 1·14 (1·02–1·26)	0·016
PSI	..	..	OR 1·19 (1·02–1·40)	0·031	OR 1·22 (1·03–1·46)	0·025
AIC	195·6	..	192·7	..	190·9	..

Model 1 represents the total effect of heat stress on heat strain. Model 2 represents the direct effect of heat stress on fetal strain, controlling for maternal heat strain. Model 3 represents the direct effect of heat strain on fetal strain, controlling for heat stress, percentage fat mass, fitness, and gestational age. UTCI=universal thermal climate index (heat stress). PSI=physiological strain index (heat strain). AIC=Akaike information criterion. WBGT=wet bulb globe temperature (heat stress). OR=odds ratio.

***Table 2:* Multivariable repeated measure models of fetal heart rate and fetal strain**

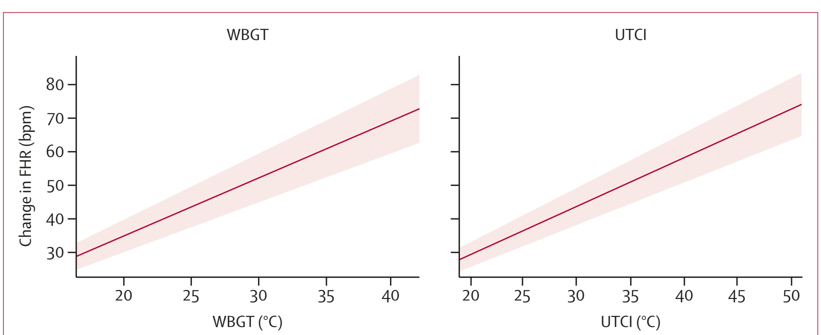

***Figure 4:* Adjusted association between change in FHR and heat stress exposure**
FHR=fetal heart rate. bpm=beats per min. WBGT=wet bulb globe temperature. UTCI=universal thermal climate index.

development of suitable and effective interventions to reduce adverse birth outcomes. Further work in a variety of settings and populations that explore the changes in placental blood flow following heat stress, as well as the association with pregnancy outcomes and heat stress, is urgently needed. In addition, the co-development of trials in pregnant subsistence farmers in sub-Saharan Africa is an urgent imperative.

Contributors

AB was responsible for study conceptualisation, study design, data analysis, and original draft writing. BS was responsible for data curation and database creation, as well as reviewing and editing the manuscript. FS, TSam, TSai, JB, KB, and YS were responsible for data collection, as well as reviewing and editing the manuscript. KAM was responsible for data analysis, as well as reviewing and editing the manuscript. JH was responsible for conceptualisation and study design, as well as reviewing and editing the manuscript. AV-C was responsible for study design, data analysis, and data interpretation, as well as reviewing and editing the manuscript. NSM, AMP, and AH were responsible for study conceptualisation, study design, and data interpretation, as well as reviewing and editing the manuscript. AB and BS accessed and verified the data. All authors had access to the data used in the study.

Declaration of interests

We declare no competing interests.

Data sharing

Anonymised data will be made available by the corresponding author upon reasonable request.

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Additional discussion

In this section I highlight a few additional details regarding accuracy in measurements taken in the field and specific considerations in interpreting these results.

Firstly, as already highlighted, our two energy expenditure estimates were not correlated. Method A was based on an established equation that used changes in heart rate to estimate energy expenditure and method B was based on previously collected indirect calorimetry results from pregnant women performing different manual tasks in West Kiang during the wet and dry season. In the discussion section of the published paper, I emphasise the fact that outputs from wearable devices have been poorly correlated with energy expenditure in pregnancy. A further additional concern regarding estimates of energy expenditure based on heart rate is that heart rate increases under heat stress and therefore the heart rate for a given energy expenditure will be increased due to heat stress, not due to the increased energy demand. Therefore, for this study, Method B should be considered more accurate since this was based on values taken in the field under similar environmental conditions.

The Wet Bulb Globe Temperature (WBGT) presented in Figure 2 of the paper have raised some queries regarding the particularly high values that were measured. The development of WBGT as a heat stress index has been discussed in the introduction, with the equation for WBGT given as: $WBGT = 0.7T_{nwb} + 0.2T_{g} + 0.1T_{db}$

The device used to measure the conditions in the field was the Extech 200 heat stress monitor, of which the general specifications were within the conditions that were experienced during this study. It was due for calibration after one year of use, but due to closure of the study necessitated by the covid-19 pandemic the devices were not used for more than 8 months in the field and therefore never needed to be calibrated. However, due to the extreme nature of the conditions being monitored perhaps they could have undergone this at 6 months.

The device uses capacitance sensors – one black globe sensor and one temperature and humidity sensor. Although this is similar to the original device, which included a 15cm diameter black sphere, it is possible that these results are less accurate. Below are the details of the measurements above 35°C WBGT.

Air velocity m/s	WBGT °C	Air temp °C	Rel humid %	BGT °C	WBT °C	Dew-point °C	UTCI °C	calc WBGT °C
1.1	36	41	1.9	47.9	32	-18.1	40.3	24.1
1.6	38.8	39.1	0.3	45.7	36.8	39	37.9	22.5
1.7	37	42	1.7	47.7	33.2	18.8	41.56	24.7
1.1	38.9	40.8	0.6	46.5	36.5	31.1	39.63	23.7
2.9	41.6	40.9	0	44.6	40.9	40.9	39.54	23.5
1.1	36	41	1.9	47.4	32	-18.1	40.19	24.1
1.2	36.7	45.4	3.4	52.3	31	-8.1	46.28	27.3
0.6	36.1	38.6	0.8	42	34	-29.3	36.06	22.4
0.5	35.3	40.5	1.5	40.9	32.9	-21.2	37.59	23.8
0.4	41.7	41.5	0	42.5	41.5	41.5	38.9	24
1.1	42	41	0	45.9	41	41	39.65	23.7

WBGT = Wet Bulb Globe Temperature, rel humid = relative humidity, BGT = Black Globe Temperature, WBT = Wet Bulb Temperature, UTCI = Universal Thermal Climate Index, calc WBGT = Wet Bulb Globe Temperature calculated using Liljerem method.[1]

Of note on these findings, the air temperature values are in keeping with daily weather station data on maximum temperature (see appendix of Chapter 5), however there were no available directly measured humidity variables from the weather station to allow comparison. Of concern is the strange variation in the dewpoint measurements, where within one hour the value flips from -21.2°C to 41°C. In addition, the dewpoint and relative humidity should be aligned and in some of these very high measurements they are not. Therefore, the Wet Bulb Temperature (derived from the dewpoint) seem highly likely to be inaccurate, possibly due to the extreme desiccating conditions associated with the harmattan (the wind that blows hot, dry and dusty Saharan air across West Africa), drying out the sensor. The calculated WBGT from the relative humidity and air temperature are more in keeping with expected levels. These results highlight some of the challenges around field-based measurements and it would be very useful going forward to test a variety of sensors on the ground to estimate the temperature, solar radiation, black globe temperature and relative humidity to interpret these results with accuracy.

Skin temperature is a useful measurement to indicate skin blood flow and as a surrogate for core temperature. However, there are difficulties in ensuring the measurement of skin temperature is both practical and accurate. The equivital lifemonitor measures skin temperature using an infrared sensor, which is not in direct contact with the skin, and when worn, is positioned on the back. Figure 3 visualises the change in skin temperature that was recorded on the equivital device. Some of the values during the field work were extremely high and likely due to measurement error. On further enquiry to the manufacturers, the device was initially tested with individuals in military fatigues. In this study, all participants were in loose and light-weight clothing. In addition, much of the manual tasks require a bent over position where the back is then exposed to direct sunlight. It is likely that these extreme results are due to localised heating of the device or heating of the air and skin under the device from direct sunlight. It is challenging to disentangle the measurements that were impacted by this, but it is an additional flaw in the data and should be considered when interpreting the results.

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CHAPTER 6 – The challenges of working in the heat whilst pregnant: insights from Gambian women farmers in the face of climate change

SUMMARY OF CHAPTER

In this chapter I present a published manuscript describing the experience of working in the heat from pregnant and recently pregnant farmers in The Gambia. This work details the physical symptoms experienced, the techniques that were used to avoid the heat effects and the ongoing concerns about the impacts of climate change on livelihoods that the women described. This work leads on directly from Chapters 3-5 where quantitative methods were used to explore the current effects of heat in this population.

The full summary of the chapter can be found in the abstract of the paper. Supplementary material for this paper can be found in Appendix 4

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Surname/Family Name	Bonell		
Thesis Title	Climate change, maternal health and birth outcomes: how does environmental heat affect pregnancy and birth outcomes in The Gambia?		
Primary Supervisor	Professor Andrew Prentice		

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SECTION E

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Date	18th November 2022

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The Challenges of Working in the Heat Whilst Pregnant: Insights From Gambian Women Farmers in the Face of Climate Change

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Background: The expected increase in heat in The Gambia is one of the most significant health threats caused by climate change. However, little is known about the gendered dynamics of exposure and response to heat stress, including women's perceived health risks, their adaptation strategies to heat, and their perceptions of climate change. This research project aims to answer the question of whether and how pregnant farmers in The Gambia perceive and act upon occupational heat stress and its health impacts on both themselves and their unborn children, against the backdrop of current and expected climatic changes.

Method: In-depth semi-structured interviews were conducted with 12 women who practice subsistence farming and were either pregnant or had delivered within the past month in West Kiang, The Gambia. Participants were selected using purposive sampling. Translated interview transcripts were coded and qualitative thematic content analysis with an intersectional lens was used to arrive at the results.

Results: All women who participated in the study experience significant heat stress while working outdoors during pregnancy, with symptoms often including headache, dizziness, nausea, and chills. The most common adaptive techniques included resting in the shade while working, completing their work in multiple shorter time increments, taking medicine to reduce symptoms like headache, using water to cool down, and reducing the amount of area they cultivate. Layered identities, experiences, and household power structures related to age, migration, marital situation, socioeconomic status, and supportive social relationships shaped the extent to which women were able to prevent and reduce the effects of heat exposure during their work whilst pregnant. Women who participated in this study demonstrated high awareness of climate change and offered important insights into potential values, priorities, and mechanisms to enable effective adaptation.

Conclusion: Our findings reveal many intersecting social and economic factors that shape the space within which women can make decisions and take adaptive action to reduce the impact of heat during their pregnancy. To improve the health of pregnant working women exposed to heat, these intersectionalities must be considered when supporting women to adapt their working practices and cope with heat stress.

Keywords: climate change, health, women, climate adaptation, The Gambia, occupational heat stress

INTRODUCTION

Climate change is expected to increase the frequency of extreme heat events and change precipitation patterns globally (1). These changes multiply health threats and amplify the health inequities of the most at-risk populations and individuals, and women, and in particular pregnant women, are amongst the groups most directly threatened by climate change (2).

In West Africa, climate change is expected to reduce crop production, compromising the food security of subsistence farmers, and rendering livelihoods based on natural resources more challenging, particularly in the Sahel zone (3). Recent studies in West Africa have shown that differences in age, gender, education, disability as well as livelihood diversification significantly influence levels of vulnerability to the effects of climate change (4). Under the current warming scenarios of 1.5°C to 2°C, about 50 to 100% of the population in most of the Sahel countries are expected to be at risk of the most dangerous effects of heat (5).

The expected increase in heat is one of the most significant health threats caused by climate change. Exposure to both high temperature and humidity can lead to occupational heat stress that can substantially affect people who work outdoors in hot environments (5–7). This will be an important challenge faced by smallholder farmers in The Gambia, where most agriculture is rain-fed, non-mechanized, and the timing of the agricultural seasons requires farmers to work year-round in temperatures exceeding 30°C (8). Strict cultural customs and gender norms limit the land available to and the crops accessible to be cultivated by men and women, reflecting social hierarchies of gender, marital status, and age.

Few studies have laid a particular focus on women or women farmers and their experience of climate change, as well as their agency in climate change adaptation. Women's voices are often missing from climate change mitigation and adaptation discussions and policy decision-making processes (9), a critical gap recognized by the international community (8). Alternatively, women are portrayed as passive victims of climate change processes beyond their awareness or control (10), further exacerbating gender inequalities in the impact of climate change and excluding this group capable of acting as powerful environmental protectors (11). Although the Gambian government has made firm and far-reaching commitments to ensure the country is on track to meet the Paris Climate Accords, a recent interim report evaluating the impact of the UN environment programme project found that there was a general failure to include women into decision making roles, despite this being a stated aim (8). Therefore although women constitute around 50% of the agricultural workforce in The Gambia, their involvement in decision-making and their access to assets are limited, and they have been shown to be more vulnerable to climate change due to their dual productive and reproductive role (12).

Globally, few studies focus on the gendered dynamics of exposure and response to heat stress, including women's perceived health risks and their adaptation strategies to heat (13). Epidemiological datasets on the effects of heat on pregnant women in Africa are scarce, though there is evidence from other settings that there is an increased risk of adverse birth outcomes attributable to heat exposure (14–17). Associations between temperature and birth outcomes are largest among women in lower socioeconomic groups and at age extremes (18), revealing important aspects of identity beyond gender that influence susceptibility to heat stress.

When pregnant, Gambian women generally do not enjoy privileges in their households, with the division of labor in the household requiring women, albeit pregnant, to endure heavy workloads with limited opportunities for sick leave, and often to remain engaged in non-remunerable field work with few economic resources (19). The implications of these factors on the ability of Gambian women subsistence farmers to adapt to increasing temperatures brought on by climate change, during their pregnancy and otherwise, merits further exploration and representation in the climate change discourse. Furthermore, as far as we are aware, no effort has been undertaken to investigate the understanding and experiences of female farmers in The Gambia around the health impacts of heat and their personal adaptation strategies surrounding pregnancy and reproductive health.

This research project is set out to answer the question whether and how women in The Gambia, who depend mainly on subsistence farming and who are either pregnant or have delivered recently, perceive and act upon occupational heat stress and its health impacts on both themselves and their unborn children against the backdrop of current and expected climatic changes. As such, this study was designed to contribute toward the development of a contextualized understanding of how climate change is affecting the health of female subsistence farmers within The Gambia during pregnancy, explore the layered social factors that shape their adaptation strategies, and begin to center the most affected individuals in the design of effective and inclusive climate change adaptation strategies.

This study complements the observational study on heat stress and fetal well-being undertaken in Keneba, The Gambia (20). The aligned outcomes of both projects will help to inform future research as well as inclusive and community-centered health promotion strategies. The knowledge gained will also help to inform future research to understand the nuances of climate change perceptions and adaptive capacity, and inform potential programmatic or policy interventions on adaptation to climate change in West Africa.

METHODS

Theoretical Framework

Much of climate change literature adopts a vulnerability and adaptation framework (21), and often individuals experiencing the effects of climate change are conceptualized as passive victims (22). Similarly, studies that discuss gender in relation to climate change often give disproportionate emphasis on the implications of climate change using a men vs. women dichotomy, with little attention paid to power and social relations among varied identities within these groups (21). This study aims to align with Djoudi's call for an intersectional perspective of climate change that recognizes individual agency and creates spaces for emancipatory change (21).

As such, in this study we situate our approach and analysis within intersectional theory. The concept of intersectionality can address some of the important issues in the debates on vulnerability and adaptive capacity in the face of climate change, as it illuminates how different identities relate to climate change in relation to context specific power structures (9). Grounded in Black feminist theory in the US and first developed as a critical theory by Crenshaw in the early 1990's, intersectional theory recognizes that individuals carry multiple, intersecting identities and privileges associated with these intersections, including ethnicity, race, gender, sexual orientation, social class, and disability (23). Intersectional theory offers an analytical approach to understanding and examining the interconnectedness of numerous socially constructed identities (e.g., race, gender, sexual orientation, class, etc.) as they collectively shape the lived experiences of individuals and groups (24). This theoretical approach requires moving beyond binaries to recognize the complex ways in which power and systems intersect with aspects of identity to shape the lived experience of people, enabling an analysis that reflects the complexity of social issues and outcomes (25). Intersectionality can be used to generate critical and constructive insights, critique existing power relations and institutional practices, and generate alternative knowledge crucial in the formulation of more effective and legitimate climate strategies (9).

In the context of this study, an intersectional theoretical framework allows reflection and analysis on the many intersecting factors that shape women's experience of climate change, heat stress, and reproductive health, and explore how gender norms, class, family structure, displacement, and disability affect levels of exposure to heat, ones' ability to implement adaptive changes during pregnancy, as well as the consequences of adaptive strategies on personal and household wellbeing. To remain true to the critical focus of intersectional theory, a view of intersectionality must also acknowledge the deep need for social transformation, maintain an awareness of privileges and oppressions, and commit to a broad sense of justice (26). Therefore, this study aims to take an initial step toward eliciting the experiences and opinions of Gambian women farmers in order to center them more in the current discourse surrounding the effects of climate change and adaptation processes in The Gambia and globally, and to begin to inform policy approaches to climate change and extreme heat adaptation.

The application of intersectional theory also encourages critical self-reflexivity with regards to the ways in which power imbalances in researcher and participant identities can influence the process of qualitative inquiry (24). To this end, this study has brought together a diverse research team, consisting of Gambian and international researchers with contextual knowledge of The Gambia and lived experience in West Kiang as an attempt to balance potential hierarchies of power between the researchers and research participants during the research process. The research team represents a variety of cultural and academic backgrounds, as well as a range of experience with research in gender, fertility, heat physiology, and climate change adaptation in West Africa.

FIGURE 1 | Binta is a woman residing in Keneba village, working in her rice fields while pregnant.

Study Setting

This study was conducted at Keneba field station, MRCG@LSHTM. This rural field station is 2.5–3 h from the coast and covers the West Kiang region which is an area of 36 villages with ∼15,000 inhabitants where mostly subsistence farming is practiced. The climate in this area has two distinct seasons, a short wet season from June to October and a longer dry season from November to May. Farming of rice and groundnuts occurs during the wet season and farming of vegetables occurs during the dry season. Farming is gender specific, with women cultivating rice on communal plots during the rainy season, see **Figure 1** and vegetables in communal plots during the dry season. Plots for cultivating rice belong to the family and are passed from mother to daughter. The vegetable plots are established communally, but each woman receives a certain number of beds to cultivate each season, from which they can sell or use the harvest for household subsistence. Men in turn cultivate cash crops to be sold or exported, such as groundnut, on plots of land owned by a household. All farming work is done manually, including watering of vegetable crops during the dry season. This requires farmers to carry buckets of water from hand-dug wells or boreholes.

Recruitment was focused on five villages selected due to their proximity (within 10 kms) of the Keneba MRCG@LSHTM Field Station. A list of currently pregnant women residing in these villages was generated from MRC antenatal clinic and DHS records. Women who performed outdoor labor in the form of rice farming or vegetable farming and were either pregnant or had been pregnant in the last six months met the inclusion criteria. Purposive sampling was then used to ensure the sample was diverse in terms of age and came from a range of communities, as well as including women who had had multiple pregnancies and those in their first pregnancy. All women on this list were invited to participate in the study by a fieldworker who resides in the area. Before the interviews, a Gambian researcher familiar to the community held an in-depth conversation with the potential participants to ensure their understanding of the purpose and methodology of the study, and their willingness to participate. All participants gave their written consent to participate in the study. Ethics approval was obtained through the Gambia Government/MRC joint ethics committee, and by the LSHTM ethics committee.

Between two and four interviews were conducted each day, and at the end of each day the interview notes were reviewed to examine emerging themes and plan further recruitment with the aim of reaching data saturation. After seven interviews were conducted, an additional eight women were approached to participate in the study, taking extra care to ensure representation of a range of ages and pregnancy experiences within the sample. Recruitment ended once thematic saturation was suspected, and the sample was reflective of a range of women of different ages and experiences. In all, 15 women were approached to participate in the study. Of these, 12 met the eligibility criteria of being pregnant or recently pregnant and actively engaged in farming during their pregnancy and were included in the study.

In-depth semi-structured interviews were conducted with 12 women who practice subsistence farming and were either pregnant or had delivered within the past month. Interviews sought to examine the ways in which women farmers who work outside during their pregnancies are exposed to heat, the physical effects of working in the heat whilst pregnant, the dynamics that shape how and whether women are exposed to heat, and what mechanisms and resources women draw upon to cope with the heat. The interviews also sought to understand the ways in which women view and are affected by climate change. Interviews were conducted by two researchers, with simultaneous translation from Mandinka to English conducted by one researcher during the interview. Interviewees were encouraged to share their perceptions and allow their ideas to unfold freely, sharing a nuanced account of their opinions and experiences. Drawing on intersectionality theory, follow-up questions and prompts were used to obtain clarity and deepen understanding on the ways in which intersecting identities, and the power and systems that surround them, shape women's experiences, as well as to gather nuanced insights and perspectives on recurring themes and topics. Interviews were conducted near the homes of the participants in a comfortable location that would provide privacy. Given the COVID-19 pandemic, all interviews were conducted outside, physically distanced by 2 m and all people present were provided with face masks. Interviews were recorded using two separate handheld voice recorders. Each interview lasted between 30 and 50 min. Following the interviews, pseudonyms were assigned to all participants to anonymize transcripts and ensure confidentiality. Transcription was completed by a researcher listening to the translation of the recordings. A sample of three interviews were reviewed by a Mandinka-speaking research assistant to verify accuracy of the translation and transcription.

TABLE 1 | Research topics and themes.

Topic	Themes
Experience of heat during pregnancy	Physical symptoms of heat during pregnancy
	Occupational heat stress during pregnancy
	Sources of support
	Personal coping mechanisms
Perceptions and understanding of climate change	Observed changes in weather and/or climate
	Gendered implications of climate change

Data analysis was conducted using thematic analysis, which aims to provide a summary of the regularities and variations within and across individual accounts (27). It is also suitable for exploring participants' worldviews and concepts inductively and iteratively. Starting with two initial themes linked to the objective of the study—experience of heat during pregnancy, and perceptions of climate change—patterns of recurring sub-themes and ideas within the data were noted and a coding scheme developed using NVivo-software.

After coding, common themes and the relationships between them were further grouped into specific themes, as represented in **Table 1**.

RESULTS

Characteristics of Research Participants

The 12 women who participated in this study were residing in one of the five selected villages in West Kiang, were currently or recently pregnant, and their primary occupation was farming. Of the 12, two had delivered their babies in the 10 days prior to the interview, and the remainder were between 4 and 9 months pregnant. The average age of participants was 32 years. Demographic information can be found in **Table 2**.

Heat and Pregnancy

All participants in the study discussed their experience of a range of significant physical changes during pregnancy. Common symptoms included nausea, vomiting, fatigue, and dizziness. Nearly all women interviewed noted changes in their feelings toward their work during their pregnancies due to these physical symptoms. Most women discussed a decreased ability to do

TABLE 2 | Demography of 12 study participants.

No.	Community	Age	Gender	Primary occupation	Number of children
1	Community 1	22	F	Farming	0
2	Community 2	28	F	Farming/ selling food	9
3	Community 2	31	F	Farming	5
4	Community 2	32	F	Farming	7
5	Community 3	41	F	Farming/selling at shop	7
6	Community 3	45	F	Farming/selling ice	4
7	Community 4	40	F	Farming	7
8	Community 4	24	F	Farming/selling food	5
9	Community 4	29	F	Farming	4
10	Community 5	31	F	Farming	6
11	Community 5	30	F	Farming	3
12	Community 5	27	F	Farming	3

the amount of work compared to when not pregnant, due to increased feelings of tiredness or weakness brought on by their pregnancy. Many women noted that these symptoms were made worse when working in the heat. A few shared that there were no changes to how they felt about work at all when pregnant.

> *"When you are not pregnant you can work very easily, very quick. When you are pregnant, even if you want to do it, you feel lazy, and easily tired."—Ajara, age 29*

Some were more tired than usual, which rendered their work more challenging, and others noted some tasks becoming more difficult when pregnant, like bending and watering, especially during the dry season.

> *"The work during the dry season, the work is harder than in the rainy season. During the rainy season only hard work you do in the rainy season is plowing, but in the dry season if you don't have water it will be difficult for you, you must have water for the beds... during the rainy season it is harder [to be pregnant], because you always bend, all the work you do you must bend."—Zainabou, age 40*

Many noted differences in their experience with different pregnancies throughout their lives, indicating that some pregnancies had a more significant impact on their body, with physical symptoms increasing in severity with the number of pregnancies and their increasing age.

> *"Each pregnancy is different, sometimes they are harder than others....All my previous pregnancies, I've felt normal. Sometimes I felt off. But this pregnancy, I don't usually get sick and lie down and do nothing, but I haven't been able to do my work like I usually want to. I heard people saying that when you have many children, more than 6, around 9, some of your last pregnancies you might feel uncomfortable, or encounter a lot of problems"—Isatu, age 32*

Several of the older women interviewed shared that they were hoping that this pregnancy would be their last—this was often due to the physical stress of working while pregnant when older in age, a stress in many cases aggravated by heat. Two women who had recently had tightly spaced pregnancies shared that they were interested in preventing future pregnancies completely, or spacing their pregnancies more to allow their body to rest, as pregnancy and birth was becoming increasingly challenging as they had more children.

> *"Tiredness of work doesn't worry me, I am old now to have more children. Now I don't want to get pregnant unless God wills. The way it was difficult for me to bear this child, I've never experienced that in pregnancy to have a child before."—Fatou, age 28*

Occupational Heat Stress During Pregnancy

Women shared that they completed a range of different types of work throughout the day, with their primary occupation as farmers balanced among many unpaid care responsibilities, including caring for children and elderly family members, cleaning, doing laundry, fetching water, and cooking for the household. The tasks are spread throughout the day, with little time for rest or leisure in between. Gardening is often done in the mid-morning and early evening, after cooking breakfast and cleaning the compound, and before preparing lunch and dinner. Cultivating rice during the rainy season is usually done for the full day.

All women who participated in the study shared their experiences of considerable physical heat stress in their work as farmers and emphasized that their experience of heat stress is significantly more severe during pregnancy. The degree of heat stress varies throughout the year according to workload and exposure to heat. Most women reported their most important exposure to heat as occurring during the dry season, when the sun is most intense, but often exposure to heat was high during the rainy season as well, when humidity is higher and longer days are spent working in the rice fields. One woman shared:

> *"When you work in the garden, you go and come back. When you are working in the rice field, you go, and you are there until evening."—Ajara, age 29*

Women frequently noted a significant difference in their body's reaction to heat when they are pregnant, compared to when they are not pregnant. Many reported feeling the heat more acutely when pregnant, as well as a reduced ability to cool their bodies. Common symptoms were headache, dizziness, nausea, and chills. Interestingly there were no concerns regarding access to drinking water, or maintaining an adequate level of hydration throughout the day, either at the gardens or the rice fields.

> *"When it is very hot, whenever I go out I feel dizzy, headache. When I'm not pregnant I don't feel the heat of the sun very much, but when I am pregnant, whenever I am out, I feel like my body is burning. I don't know for other ladies, but for me, I always feel hot inside my body, I always ask the children to pour water on me so that I can feel a little less warm."—Aminata, age 45*

Sources of Support

Supportive social relationships were frequently mentioned as important factors that enabled women to protect themselves from the heat. In some cases, women who worked with others around them would receive help with particularly challenging tasks during their pregnancy, such as watering or bending. Women with older children capable of helping with farming tasks shared that their children would often help with tasks like watering. However, this was not universal—often children were unable to help as they were going to school or occupied during working hours in the garden or the rice fields, or the woman did not feel comfortable asking those around her for help. Similarly, in some households a strictly gendered division of labor meant that male children would go only to help their father with cultivating cash crops, so a woman without daughters would be left to work alone in the garden or the rice fields.

> *"My daughter is going to school and she is staying there, so my son is the only one who helps me at home but he goes to school as well, so he can only help when the school is closed."—Aisha, age 30*

Having a mother, sister, or co-wife nearby was often stated as an important source of support for women during their pregnancy. Women often referred to their mothers or sisters as being the ones who would help them with their farming and domestic work if they were ill or unable to work. Another woman shared about receiving support from her sister's daughter during her pregnancies:

> *"With my previous pregnancies I was staying with my sister's daughter, and she would help me with my domestic work. But for this one I am alone here."—Aminata, age 45*

Two women shared about being able to divide household tasks between co-wives residing in the same household. They would alternate cooking shifts, allowing each of them a restful afternoon several times a week. Leaving one's village for marriage was often a factor that removed access to these supportive relationships, and often they were not replaced. A woman who had moved to a village for marriage shared that she felt uncomfortable asking people in her village for help with the garden, and experienced limited support from her partner with her work:

> *"These people are not my relatives. My husband doesn't help me at the garden, he only helps me with the domestic work at home."—Fatou, age 28*

Working in group settings was often mentioned as another important source of support. Women's plots are usually located within a larger group garden—each person cultivates their own plots, but their neighbors cultivate plots adjacent to theirs, and they share the same water access point. If sick for a few days, some women mentioned the women cultivating plots next to theirs, or their shift-mates would cover for them. In some cases, doing work collectively was not protective from the heat as it prevented their ability to self-pace their work, and take breaks when needed—one woman reported some social pressures around work from family members who work together, and having more freedom to make autonomous decisions when working individually.

> *"In the rainy season, the work is more difficult than in the dry season, because in the rainy season you can't leave your work because you are working with other people. In the dry season during garden work, you separate from your mom and others. If you have your own work, you can leave your work and do what you can do, and nobody will say it is not fair that you are not working"—Isatu, age 32.*

The socioeconomic status of a household was an important factor that shaped the ability of women to implement coping strategies that involved reducing their workload or minimizing their exposure to heat by not working as intensively during their pregnancy. In some cases, their husband obtained a job, and as their children grew up they were able to help them by working in the field or by sending money from employment they had secured.

> *"For my second pregnancy, when we used to work at the rice fields, and we would go there early in the morning to harvest the rice, we would have to use that rice for the day's lunch, we would pound it there to eat that day. That [amount of work] made me have low blood pressure…Then, our kids were very young, they were all going to school, and our husband wasn't working. Now, my husband is working, and our kids have completed schooling, and some are now working, so they support us. So now, we cultivate rice but it is minimized now, we don't need to harvest and use it that very day to eat, we just harvest and pack it"—Nyima, age 41*

Personal Coping Mechanisms for Heat Stress During Pregnancy

Women shared a range of means that they used to reduce the effects of heat on their body while working outdoors during their pregnancy. Many of these involved taking additional time to rest while working in the field, drinking water, or using water to cool down. Others shared that they used ice to cool themselves down, or bathed before and after working:

> *"Before, I would go with my water to the bush, park my water in the shade, and when it is hot, and I notice I'm tired and hot, I will use that water and drink, and sit under that tree for a while. In that time, I realize that the baby is free and comfortable, that's the time I will go and continue with my work."—Aisha, age 30.*
>
> *"I always take bath, and my sister at the coast, she sends ice from the coast for me to sell. When I have that ice, I take an ice block, and I use it all day. If I don't have that, then there are people who have ice, I will go there to have cool water to drink."—Aminata, age 45*

Some women also shared that they would adapt their domestic work after working in the field, either shifting some tasks to the next day, or doing tasks in smaller batches or with other people to avoid straining.

> *"When I close from work, when it's hot, I normally sit at one place, and ask my children to bring things to me. I also pass things to the next day, and just leave the work."—Fatou, age 28*

One woman shared that she used medicine to help her with her headache, trying both paracetamol and herbal medicine to help with the side-effects of working in the heat.

> *"I usually pour water on my head, when I have medication [tablets] with me I take it for the headache, and I relax for a while. When I take this medicine, and it doesn't help me, I also use herbs, I take them from the bush."—Zainabou, age 40*

Many women shared that they must reduce their workload to be able to carry on working in the heat, even if they want to continue working as usual. When pregnant, some women will reduce the amount of beds they cultivate, leaving the other fields fallow, or offering them to a neighbor to cultivate instead.

> *"When the sun is really hot, it makes you feel tired, and dizzy. The amount of work that you want to do usually you cannot do, your body will be heavy and you will feel dizzy."—Isatu, age 32*
> *"You know, we have these beds, there will be 10 beds, and we cultivate them every year. When you are pregnant you reduce the number of beds to 5."—Bineh, age 27*
> *"Normally I have 16 beds, when I am pregnant I only use 10 beds, and the rest I give to people to use it...for the one [baby] inside, I don't want for it to be disturbed, especially near when I am due, so I make sure to not work as much."—Nyima, age 41*

Women shared a range of techniques for coping with the heat that they would be interested in implementing but were unable to for a variety of reasons. The primary obstacles to implementing alternative adaptive strategies were economic or logistical—all but two communities did not have electricity, limiting access to ice or other cooling devices like a fan or air conditioner. For others, the obstacle was primarily financial—even if available, they would not have funds required to implement the adaptation strategy. Some women shared social norms around dress as an obstacle to using alternative coping strategies—at home, women would often change their clothing to something lighter and looser to cool down, but social norms around dress and modesty prevented them from doing this while in the field.

> *"I have thought of cold water, in my mind I think 'If I had cold water, I would use that one" but I cannot afford it." Aisha, age 30.*

One woman shared that she wasn't interested in trying out new methods of coping with the heat, because it might interfere with her work, and the heat was not bothersome enough to merit the adaptation.

> *". . . . if I had that, I can't say that I wouldn't like it, because it might stop my work – it might be a waste of time."—Mariama, age 31.*

Women who relied on working on the farm as their only livelihood often had less ability to change or reduce the work they did during pregnancy. Some women shared that they were interested in changing the work that they did to protect themselves from heat, but faced constraints to doing so. Most often these constraints were of economic nature, and they lacked start-up capital to begin a new business.

> *"I would like to do business so that I don't need to work under the sun. {what is stopping you from doing this?} I don't have the money."—Bineh, age 27.*
> *"You feel tired. Especially when you are pregnant, we are farmers, and we can't prevent ourselves from working when we are pregnant. Especially me, I am small, and my stomach is big, it is disturbing me."—Aicha, age 30.*

Perceptions and Understanding of Climate Change

During the interviews women were asked about any observed changes in the weather and asked to share their thoughts around the causes of climate change, as well as their perception of its present and future impacts. All women in our study shared that they have observed changes in the weather in the last 5–10 years. The changes most often mentioned were increases in heat, increase in intensity and impact of the sun, and a reduction and shortening of rainfall in the rainy season.

> *"The rain has reduced. Before the water that we would get from the rainfall, we don't get the same amount now. And the sun also usually harms us now, even our crops, it destroys them."—Mariama, age 31.*
> *"When we were young, the amount of rain was more, but now it has minimized."—Nyima, age 41.*

Many women shared that they were aware of climate change as a process, with only a few not familiar with the concept. Some associated their observed changes in weather with global climate change, but others were uncertain of the cause, or associated the changes in weather with the cutting down of trees in their community.

> *"{What is causing the climate to change?} Because of the cutting down of trees. Because of the little rainfall. Because of the heat also. Because when there are not enough trees the heat is too much."—Fatmata, age 22*
> *"The generation has changed now. Because the amount of rain we used to receive was always high, but now the sun is always hot. Maybe a new generation has come now."—Zainabou, age 40.*

Many women associated climate change with a reduction in the amount of production they were able to achieve from their agriculture, and shared that their crops have been significantly affected by the changes in weather observed over recent years.

> *"What we normally farm, in the last three years, we don't gain much....when we sowed the seed, and it started to germinate, the rain stopped coming, and the seedlings dried up, so we didn't store much seed for the next rainy season."—Fatou, age 28*
> *"For the previous three years, the amount of rain we received was not like normal, at the collection points the water will not last until the harvest period, because of shortage of water."—Isatu, age 32*

The social customs and support networks around farming were also influenced negatively by reduced water availability.

"Usually we help each other, we used to help each other, when we finished watering we would help others. But now that the water is less we go in shifts."—Nyima, age 40.

Women also shared a range of insight onto the gendered impact of climate change. In their perspective, everyone is affected by climate change, but those who rely on farming as their primary source of income, and those who bear the social responsibility for providing for the family are the most affected. In most cases men bear the responsibility for providing for the household—they most often cultivate cash crops that are used for income, and if their crops fail it has significant economic and social consequences for the family. However women also bear the effects of climate change given their role as primary caregiver and responsibility for cooking.

"The women, because we are the ones with the children at home… when you are coming to the kitchen, and you don't find anything, when you don't find the ingredients it disturbs you. If what you have [to eat] is going to be finished soon, you think about it all the time."—Fatou, age 28

Feelings of stress around food or income scarcity from the future effects of climate change were common among nearly all women interviewed. In nearly all cases, women discussed the close connection between the environment and their livelihood and explained that any changes in climate would have a direct influence on their ability to provide for their needs and those of their family.

"It really affects me, since at the end of the rainy season I didn't have money up to my expectations, and there are children around me, my husband is also a farmer, and he is not working, and he doesn't know where to get money from. We have children at school, and it really affects us."—Binta, age 31

Many women shared some uncertainty around the impacts of climate change on their future and that of their families and their children. Often a common strategy to adapt to this change was to invest in the education of their child in the hopes that they would secure a job, or of having a family member migrate elsewhere and return remittances as a means of diversifying their income and removing their dependence on farming as a primary livelihood.

"The only hopes I have for my children is that they work hard and become educated and to get a good job in the future. For me, I am not educated, the only thing I depend on is farming, and I don't want my children to go through that."—Nyima, age 40.
"If it continues like this, it might affect me and my family. The only thing we depend on is farming, and if we cultivate crops but there is no rainfall, but don't get anything out of it, it will be very hard. If you don't have any helper or anyone sending money from abroad, it will be very hard."—Aicha, age 30.

One woman spoke of her husband obtaining a job nearby to supplement their income as a factor that allowed her to reduce the most physically strenuous aspects of her agricultural work, and another woman spoke of the positive economic impact of her husband who had migrated to Europe to work, and shared about how much of a struggle it was to return to being reliant only on farming upon his return.

"Before, their father was abroad, and he would take care of us. But now he is back, and we struggle, whatever we get we use to eat." Aisha, age 30.

DISCUSSION

It is clear that all women who participated in the study experienced significant symptoms of heat illness from working outdoors during their pregnancy, with physical effects that have significant implications on their feeling of wellbeing, and reduced their overall productivity. This finding aligns with the few published studies on pregnant farm workers. Flocks et al. study of pregnant farm workers in Florida, USA, found the most common symptom of heat illness was dizziness and fainting (13). A further study among farm workers from Florida by Runkle et al. found high rates of pain or discomfort reported by pregnant farmers, but no impact on birth outcomes (28). While there are differences between these studies and the Gambian context, the women farm workers in Florida are limited by many of the same socioeconomic pressures as Gambian women farmers in that their income is contingent on their productivity on the farm, and workers may push themselves beyond their heat tolerance to avoid compromising their livelihood. Understanding whether and how women are able to cope with heat stress through developing mechanisms to minimize the impact of heat exposure is key to protecting the health of women exposed to heat stress. Our study's intersectionality lens makes an important contribution to furthering this understanding.

Coping Mechanisms Are Shaped by Intersectionalities

A key finding of this study is that layered identities, experiences, and household power structures shaped the extent to which women who participated in the study were able to prevent and reduce the effects of heat exposure during their work whilst pregnant. A predominantly patriarchal society with rigid social norms around gender limited their access to resources, determined the economic activities and opportunities available to them (in turn shaping their economic mobility) and limited their ability to take adaptive action to mitigate their risk of heat stress, including their agency in decision-making surrounding their reproductive health.

The most common adaptive techniques included resting in the shade while working, completing their work in multiple shorter time increments, taking medication or herbal medicine to reduce symptoms like headache, and using water to cool down. A common adaptation was reducing the amount of area they cultivate while pregnant—sometimes this was a choice made to protect themselves and their fetus, and in other situations women were incapable of working to the same extent because the physical effects of pregnancy were so severe. While studies have shown that self-pacing of workload and taking regular breaks from heat exposure during the day can be an important means of reducing the risk of occupational heat stress among outdoor workers (29), income lost was not often replaced by other means, and this often had significant economic implications for the woman and her family. In addition, women's ability to self-pace their work while in the field was limited in some cases by collective work where social norms expect all members to contribute equally, or by an overwhelming workload that left limited time for rest. Given recent evidence on the importance of self-pacing for limiting the negative effects of heat stress and increasing worker productivity (30), further research into these dynamics, as well as into interventions such as education around occupational heat adaptation and productivity for women and their communities, could serve to better inform health promotion strategies surrounding worker-related heat stress in pregnancy.

Several intersecting identities beyond gender had important implications on women's ability to participate to implement coping strategies to mitigate heat stress during their pregnancy. In nearly all cases, the woman's identity as a mother brought on a significant burden of socially obligatory unpaid care work that limited their available time for rest or leisure while pregnant. Roles surrounding motherhood (childcare, cleaning, cooking) are firm, and there is little space to negotiate household care activities with their spouse.

Age was an important factor that often afforded privileges not available to younger women—older women had a higher level of agency in deciding what kind of work to carry out, and more space to negotiate decisions with their husband. Age also often brought more economic stability and social support, and older women often had more social connections to leverage protectively—older children, especially female children, were often able to help them in their work in the field whilst pregnant, or with their domestic responsibilities, though they were unable to when studying, or if they had traveled for schooling or economic activities in the city. Socioeconomic pressures shaped women's ability to adapt their work, which in turn translated directly to increased susceptibility to heat stress by needing to work even whilst suffering the effects of heat, and/or more acute implications on their quality of life if obliged to reduce their workload (and resulting earnings) while pregnant. Marriage status, such as being in a polygamous household, often limited or expanded the resources available to draw upon to adapt work during pregnancy and beyond. Some nuance surrounding this dynamic was outlined in the experience shared by one woman who was able to split household duties with her co-wife, enabling more time for rest during her pregnancy.

Life events such as migration to a new community was also an important factor limiting or enhancing use of coping strategies—having an identity as an "outsider" without blood relatives also shaped the social space within which women felt able to ask for support with their work. Strong familial social support systems nearby were among the most important factors that women rely on to adapt their work and reduce their exposure to heat during their pregnancy. The strongest social supporters were mothers and sisters, and residing in the same community as their mother and sisters often enabled women to take more time to rest during their pregnancy, and reduced their stress around the risk of not working. Women who left their families and community of origin often had fewer social connections to draw upon to support them in their work, and therefore less ability to implement measures to protect themselves from the heat. This raises important questions about the critical role of social networks in climate change adaptation, since social relationships are often fragmented in situations of climate-induced migration and conflict.

Addressing Climate Change Challenges Faced by Women

In our study, climate change was universally recognized as an important challenge for women. Effects of changes in rainfall were most significant as they reduced the amount of crops harvested, with significant implications for their income and livelihood. Effects of climate change were perceived to impact everybody, but particularly those who rely completely on their harvest for food, and those who bear the social and economic responsibility for the primary household income (cash crops, most often men), or for immediately providing for household needs. Women are responsible for cooking and providing food for the household on a daily basis, as well as childbearing and childcare, and often face feelings of stress toward the changes in climate which make their work harder. While income diversification was a common theme that emerged in the data as a means of enhancing resilience to climate change, it was usually limited to children or the male head of households obtaining additional work. Economic opportunities for women are limited by a range of factors, not least of which is a lack of reproductive autonomy that often obligates women to bear the physical burden of bearing and caring for many closely spaced children. Some women recognized this dynamic by emphasizing that with more space between children, they and their families would be healthier and better able to cope with the demands of work.

At the structural level, women are often missing from research, policies, and decision-making surrounding climate change, whilst their bodies, livelihoods, families, and communities are disproportionately affected by it. This is a trend reflected in climate change discourse, academia, and public policy globally, including The Gambia (8, 31). Women who participated in this study demonstrated high awareness of climate change, and offered important insights into potential values, priorities, and mechanisms to enable effective adaptation. There is an important opportunity to make space for women's leadership within climate change discourse, policy-making spaces, and design of development programming in The Gambia to enable better climate adaptation.

Limitations

While the study attempted to recruit pregnant women with a range of intersecting identities, the sample had a smaller than average number of young mothers (between 18 and 25), and the average age of participants in the study was higher than for pregnant women in the communities (32 vs. 28 years). Additionally we did not include pregnant women who were single or from groups that are known to be particularly marginalized, including teenage mothers. Though the sample was reflective of the demography of many women in West Kiang, future studies would benefit from deliberate recruitment of women from marginalized female population groups. If needed the geographic area of the study could be expanded and used as an opportunity for triangulation of findings. Similarly, the time for data collection could be extended to enable women to share more immediate experiences of heat and pregnancy in different seasons throughout the year. While women were asked about the differences in their physical experience when working in the heat while pregnant compared to when not pregnant, in future research, interviewing women who have not been pregnant or who have not recently been pregnant on their experience working during the heat would allow greater attribution of the experiences shared to the effects of pregnancy. In addition, there is currently a disconnect between environmental epidemiological studies that demonstrate the association of heat exposure on increased risk of preterm births, low birth weight and stillbirth and the individual lived experiences of women and their pregnancy outcomes. Future work could focus on perception of worsening birth outcomes in populations exposed to extreme heat/climate shocks.

While the design of the study allowed the research team to gather initial insights into individual experiences in regards to heat and climate change, having a non-local researcher part of the interview process introduced a risk of power hierarchy and potential source of courtesy bias. Though having a non-local researcher with experience in conducting interviews for qualitative research part of the interview process was valuable to make data gathering, processing, and analysis more efficient for the research team, it is possible that women did not feel comfortable sharing openly with someone from outside their community due to a perceived power differential. The research team attempted to balance this risk of courtesy bias by having a researcher who is known to the community introduce the study and describe the identities of the research team in advance of the interviews and during the consent process, allowing women a safe space to raise questions or concerns before committing to participate. At the interview, interviewers took extra time to get acquainted with the women, and used a culturally sensitive, consent-based style of interviewing. For this reason, this study is only an initial, limited, insight into the experiences of Gambian women farmers in regards to climate change and working in the heat whilst pregnant, and further work is needed to more completely understand and center their perspective on these topics. In future, using peer-based interviewing or focus group methods could help to reduce the risk of power imbalances between researcher-participant identities, deepen analysis surrounding the shared experience of working as a farmer in the heat, gather consensus around recurring themes and findings, and create spaces for collective discussion and knowledge-generation surrounding climate adaptation strategies.

CONCLUSION

In the context of the reality that there is a large global female workforce who perform manual labor outdoors during their pregnancy, this study highlights the need to address the potential harms of increasing heat exposure with climate change. Our findings reveal many intersecting social and economic factors that shape the space within which women can make decisions and take adaptive action to reduce the impact of heat during their pregnancy. To improve the health of pregnant working women exposed to heat, these intersectionalities must be taken into account when supporting women to adapt their working practices and cope with heat stress.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The study was approved by MRC/Government of Gambia Joint Ethics Committee and LSHTM Ethics Committee. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

SS: interviewing, data interpretation, analysis, manuscript writing, and revision. TS: community liaison, interviewing, data interpretation, and manuscript edit. KW and SM: research design, protocol development, and manuscript edit. AB: research conceptualization, research design, protocol development, manuscript writing, and edit. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2022.785254/full#supplementary-material

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CHAPTER 7 – Assessing the impact of heat stress on growth faltering in the first 1000 days of life in rural Gambia

SUMMARY OF CHAPTER

In this chapter I present a research paper exploring the effect of heat stress exposure on growth metrics. I used data from a randomised controlled trial and linked this to global gridded climate data to give hourly exposures to heat stress for each individual. Using repeated measures multilevel linear regression I demonstrated a significant reduction in weight-for-age and weight-for-height z-score in those aged 0-2 years with increasing heat stress exposure. The converse was found for height-for-age z-scores.

A full summary of the chapter can be found in the abstract.

The paper is due to be submitted and I present it here with the text and figures ready for submission, but in the format of the rest of the thesis. Supplementary material for this paper can be found in Appendix 5.

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Surname/Family Name	Bonell		
Thesis Title	Climate change, maternal health and birth outcomes: how does environmental heat effect pregnancy and birth outcomes in The Gambia?		
Primary Supervisor	Professor Andrew Prentice		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

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Stage of publication	**Not yet submitted**

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	I conceptualized, designed the study, completed the analysis and wrote the complete first draft of the paper. Ana Vivedo-Cabrera, Kris Murray and Giovenale Moirano advised on data analysis, and edited the manuscript. Bakary Sonko was responsible for data curation in the original study and edited the manuscript. Sophie Moore, Andy Haines and Andrew Prentice advised on study design, data analysis plan, and edited the manuscript

SECTION E

Student Signature	Ana Bonell
Date	18th November 2022

Supervisor Signature	Andrew Prentice
Date	21st November 2022

Assessing the impact of heat stress on growth faltering in the first 1000 days of life in rural Gambia.

Ana Bonell, Ana M Vicedo-Cabrera, Kris A Murray, Giovenale Moirano, Bakary Sonko, Sophie E Moore, Andy Haines, Andrew M Prentice

Abstract

The intersecting crises of climate change, crop failure, food security and malnutrition are disproportionately impacting children living in the Global South. Understanding the relationship between heat stress exposure and child growth is needed considering current and projected increasing temperatures. We used multilevel, multivariate linear regression models of 60-day heat stress exposures on metrics of child growth; prenatal weight-for-age (WAZ); and 0-2 years WAZ, weight-for-height (WHZ) and height-for-age (HAZ) z-scores, using data from a randomised control trial of nutritional interventions in pregnancy in The Gambia. Heat stress was defined by the Universal Thermal Climate Index (UTCI), summarised from hourly gridded data.

Postnatally WAZ and WHZ reduced with increasing heat stress exposure. In contrast HAZ increased with increasing UTCI, to a threshold of 29°C mean UTCI, beyond which HAZ plateaued/decreased. Our results suggest that rising global temperatures may impact child growth in at risk areas with long-term implications for morbidity and mortality.

Introduction

Undernutrition is estimated to be associated with 3 million child deaths per year worldwide.[1] West Africa experiences one of the highest rates of child undernutrition in the world with pooled rates in children under 5 years of age estimated at 31.8% stunted, 20.1% underweight and 10% wasted,[2] defined as less than 2 standard deviations of the international standard (stunting < 2 SD in height-for-age; underweight < 2 SD in weight-for-age; wasted < 2 SD in weight-for-height). Additional impacts include a life course increased risk of chronic health conditions such as type 2 diabetes (associated with poor fetal growth), delays in neurocognitive development and reduced economic productivity in adulthood.[3] Repeated anthropometric measurements – most commonly weight and length/height - are used to measure a child's nutritional status and to identify failure to thrive; "growth faltering". Growth faltering is known to be multifactorial and is influenced by genetic and epigenetic variants, food insecurity, poverty, poor sanitation, repeated infectious episodes, emotional and physical neglect, and environmental exposures.[4-6] However, recent studies have shown limited benefits for growth faltering from nutrition interventions and disappointingly no impact from sanitation interventions.[7,8]

With anthropogenic climate change having already heated the planet by an average 1.2°C above pre-industrial levels, with even greater increases over the populated land masses, there is a growing interest in the impact of ambient temperature on both fetal and infant health.[9] The increasing exposure to extreme heat, which is disproportionately affecting those in extreme poverty,[10] and the current intersecting crises of climate change, crop failure, drought, and globally rising food costs, results in an urgent need to understand the impact of heat in more detail.

A recent systematic review found the median effect of maternal exposure to high temperatures (variable temperature threshold depending on location) on the odds of LBW was 1.09 (IQR 1.04-1.47),[11] and a cross-sectional study of growth faltering in African children found increased prevalence of wasted and underweight children in those exposed to temperatures above 35°C, but a reduction on the prevalence of stunted children.[12]

There are several postulated mechanisms for the *in utero* heat stress effects on birth weight: variation in DNA methylation *in utero* leading to changes in gene expression;[13] change in placental blood flow due to shunting of blood to the skin for thermoregulation resulting in acute and/or chronic fetal stress;[14] and reduction in maternoplacental nutrient delivery.[15,16] The possible biological mechanisms of environmental heat stress affecting growth faltering in childhood are hypothesised to include: reduction in food intake to reduce metabolic heat production and so aid thermoregulation (acute alteration); increased risk of acute episodes of diarrhoea;[17] and alteration in surface area to mass ratio to improve heat loss – which would increase wasting but have little or no impact on stunting.[18] Despite the biological plausibility of the impact of heat stress on growth faltering, and the evidence from animal studies, there remains a paucity of evidence of the effect.

In this study we utilise longitudinal data from the first 1000 days of life, where multiple repeated measures of individual pregnant women and their children have been taken to examine the relationship between ambient heat stress exposure and growth faltering.

Methods

Ethics approval was granted by the Gambia Government/MRC Laboratories joint ethics committee in August 2008 (ref SCC 1126v2) for the original study and further ethical approval from the Gambia Government/MRC joint ethics committee and the London School of Hygiene and Tropical Medicine Ethics Advisory Board (ref 25171) for this analysis in April 2021.

Birth cohort data

The Early Nutrition and Immunity Development (ENID) randomised trial was based in the West Kiang region of The Gambia. This rural area has a resident population of approximately 15,000 individuals spread over 750 km^2. It is a resource-poor region with seasonal variations in climate, nutritional exposures and birth outcomes.[19,20] The ENID trial recruited pregnant participants prior to 20 weeks gestation and used obstetric ultrasound to determine gestational age (GA) at entry into the trial (mean GA at enrolment 13.3 weeks). Pregnancy dating was done using the crown-rump-length or bi-parietal diameter, depending on the GA at enrolment. Full details of the trial can be found in the published protocol.[21]

Briefly, pregnant women were allocated into four arms where they received different nutritional supplementation from enrolment until delivery: iron & folate; multiple micronutrients; protein-energy; and multiple micronutrients & protein-energy. In addition, infants were randomised to two further nutritional supplement arms, from six to 18 months of age: lipid-based supplement with micronutrients and lipid-based supplement alone. During their pregnancy detailed maternal anthropometry including weight, height, mid-upper arm circumference and skin fold thickness were taken. Repeated fetal ultrasound scans were done at weeks 20 and 30 gestation of the following parameters: head circumference, biparietal diameter, abdominal circumference, femur length, and tibia length. All measurements were taken in triplicate by trained sonographers and averaged for analysis. Estimated fetal weight was calculated using the Intergrowth-21 calculator based on head and abdominal circumference and from this the gestational age specific z-score.[22] Date of delivery, child sex and mode of delivery were collected, and all mother-infant pairs were visited by a study midwife within 72 hours of delivery for a health assessment and collection of newborn anthropometry.[23] Weight and length measurements were collected on the infants and children up to 2 years of life at the following weeks post birth: 1, 8, 12, 24, 40, 52, 78 and 104.[24] After birth z-scores for weight-for-age (WAZ), height-for-age (HAZ) and weight-for-height (WHZ) from 2 months to 2 years were calculated using the World Health Organization Multicentre Growth Reference Study.[25] Weekly screening visits up to 2 years identified any acute illness, including fever, diarrhoea, vomiting, cough, difficulty in breathing or any other infection. These were aggregated as any diarrheal illness in the 4 weeks prior to the anthropometric measurement visit.

Environmental exposure data

The ERA5-HEAT (Human thermal comfort) dataset from the Copernicus Climate Change Service (C3S) was used to determine location specific heat stress (Universal Thermal Climate Index – UTCI).[26] ERA5 uses quality-controlled historical meteorological station observations to give global grided estimates by advanced modelling and data assimilation. Data is grided at 0.25 by 0.25 degrees, equivalent to approximately 27km^2 at the equator, and available hourly.[27] Use of the UTCI (a composite measure of heat, humidity, wind speed and solar radiation) was considered of importance due to the wide variation in humidity in The Gambia from the wet to the dry season and because the UTCI more effectively captures the physiological response to heat stress exposure compared to air temperature alone.[28,29] Hourly data were first summarised to daily mean UTCI and then further averaged over 30, 60 and 90 days. The village of residence for each mother-infant pair was matched by geolocation to the UTCI grid from the ERA5-HEAT. The date of each anthropometric measurement (*in utero* and in infancy) was taken as the end point of 30, 60 or 90 days UTCI exposure. Therefore, individual measurement of each participant was linked to average heat stress exposures during the previous 30/60/90 days. This allowed long-term exposures to be explored, which in the case of growth faltering was considered important.

Statistical analysis:

Four outcomes, namely WAZ *in utero* and WAZ 0-2 years; HAZ 0-2 years; and WHZ 0-2 years, were evaluated with regards to heat stress exposures, performing longitudinal multilevel, multivariate linear regression models. Multilevel modelling was adopted given the hierarchical nature of the data, with repeated measurements within individuals, who were furthered clustered by village and study arm.

Thus, we included three random effects, at individual, village and study arm level, aiming to take into account unmeasured but likely existing heterogeneity, between individual, villages and study arms.

The first step in modelling involved determining the relationship between UTCI and each outcome (WAZ *in utero*, WAZ 0-2, WHZ 0-2, and HAZ 0-2) using linear and non-linear models. Non-linear models were tested by natural and cubic splines with different knot placement and 3 degrees of freedom. The lowest AIC was used to determine the best model fit for describing exposure-outcome relationship. The second step in modelling involved the evaluation of the presence of seasonality in outcome measurements. Seasonal decomposition did not give a clear seasonal pattern, however due to extensive previous work giving a strong a priori supposition of seasonality,[20,30] we used natural spline and two degrees of freedom on day of the year to model seasonality.[31,32]

Third, we included in the models a priori determined covariates, including both time varying and time constant covariates. The covariates are presented in Table 1 and included maternal, child and environmental exposures that have been linked to growth faltering.

Finally the dlnm package was used to synthetize the exposure response curve for UTCI and WAZ, HAZ and WHZ, centred at the median value of UTCI exposure over the study period, for each final model.[33] All models were assessed for compliance with model assumptions. All analyses were performed in R version 4.1.0 and R code for all models can be found in the supplement.

Table 1: Model parameters included in both the *in utero* and 0-2 years multilevel model of heat stress on WAZ, WHZ and HAZ.

***In utero* model variables**	**0-2 years model variables**
Maternal factors	***Maternal factors***
Maternal age	Maternal age
Enrolment BMI	Enrolment BMI
Maternal MUAC*	Parity
Parity	
Child-level factors	***Child-level factors***
Age*	GA at birth
Sex	Age*
	Sex
	Acute diarrheal illness in last 4 weeks*
Environmental factors	***Environmental factors***
Heat stress (UTCI)*	Heat stress (UTCI)*
Season of conception	Season of conception
Season of exposure*	Season of exposure*
	Year*

* = time varying covariates. BMI = body mass index; MUAC = mid-upper arm circumference; GA = gestational age

Results

The clinical trial was performed from 2010-2015. The *in utero* to birth dataset included 776 individuals with 2186 measurements (an average of 2.8 measurements per participant – including newborn anthropometry). Final numbers for the 0-2 years dataset included 754 individuals with 5415 measurements (an average of 7.2 measurements per participant). Complete live birth outcome data was available for 670 participants, 329 females and 341 males, with a mean birth weight of 3.00kg ($\pm$ 0.40) and 66 (9.9%) with LBW by definition of < 2.5kg. There were 220 (32.8%) infants born small for gestational age (defined as less than 10th percentile for standardised gestational age weight).[34,35] Complete data at 2 years of age was available for 645 participants, with 153 (23.7%) underweight, 80 (12.4%) wasted, 166 (25.7%) stunted and 35 (5.4%) with concurrent wasting and stunting. See Figure 1 for flow-chart of numbers of participants at each stage of analysis. See supplement for individual weight trajectories from 0-2 years and individual WAZ from 0-2 years.

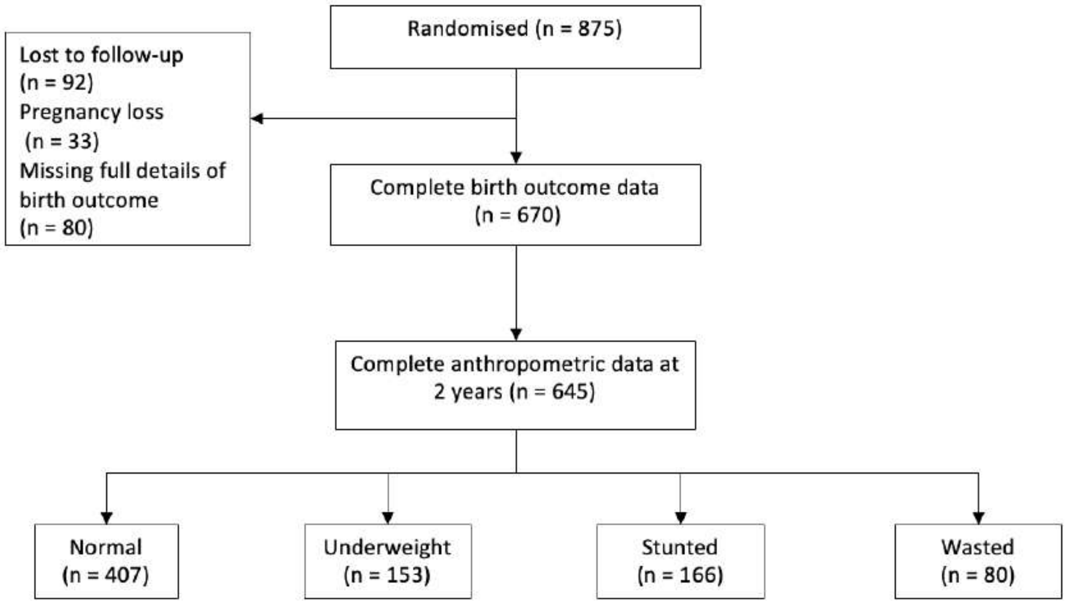

Figure 1: Flow chart of numbers of participants in analysis

Monthly average heat stress exposure over the study period ranged from 20.4°C to 31.5°C UTCI, with a mean and median value of 27.0°C and 28.0°C UTCI respectively.

Figure 2 demonstrates the seasonal nature of the heat stress exposure for the region (further detail can be visualised in the supplemental video.)

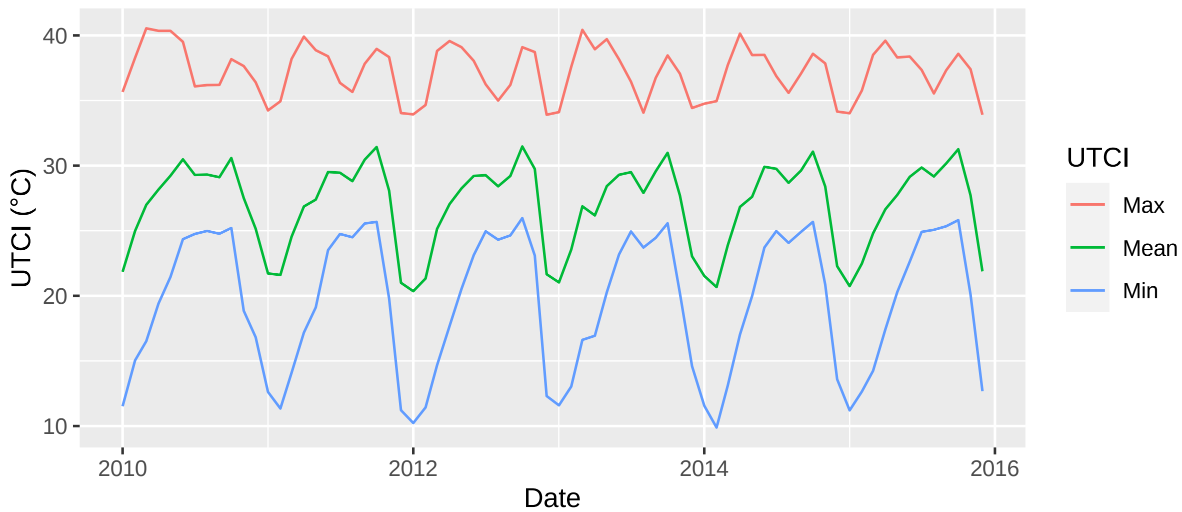

Figure 2: Monthly maximum, mean and minimum UTCI values for the study area covering the years of recruitment

Multilevel models:

The *in utero* multilevel model demonstrated no clear association between WAZ and UTCI exposure at 30-, 60- or 90-day exposures (Figure 3), where the 95% confidence intervals include zero at all points. Full outputs from the models can be found in the supplement (Table 2, page 4).

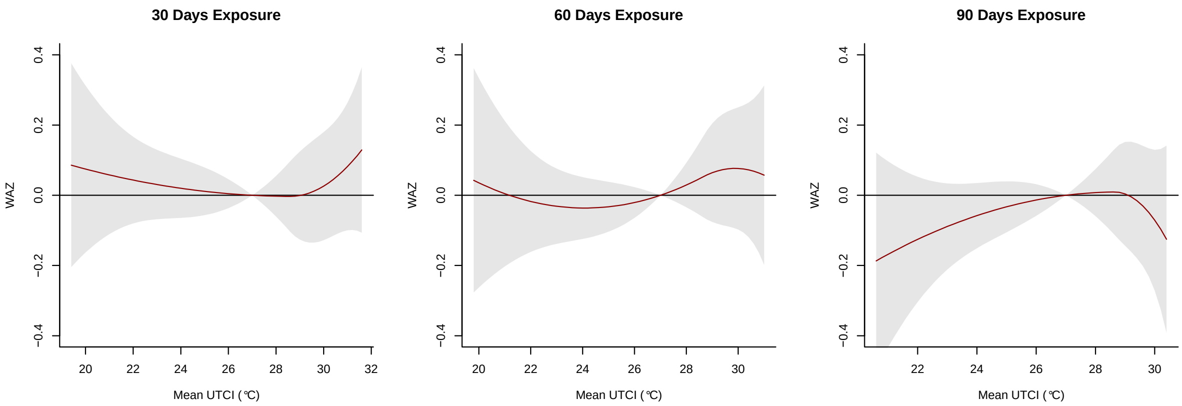

Figure 3: Association between weight-for-age z-scores and mean UTCI over 30-, 60- and 90-day summaries *in utero*.

Estimates of the association between WAZ and the 95th percentile (31.0°C) UTCI exposure summarised over 30/60/90 days exposures are presented in Table 2.

Table 2: Model estimates for *in utero* heat stress exposure on weight-for-age z-score and 0-2 years heat stress exposure on weight-for-age, weight-for-height and height-for-age z-scores. Heat stress defined as 95th percentile mean UTCI at 30-, 60- and 90-day exposure compared to median.

30 days exposure	60 days exposure	90 days exposure
***in Utero* WAZ**		
0.08 (-0.10;0.26)	0.06 (-0.20;0.31)	-0.13 (-0.39; 0.14)
0-2 years WAZ		
-0.06 (-0.13;0.005)	-0.10 (-0.16;-0.03)	-0.14 (-0.22;-0.07)

0-2 years WHZ		
-0.11 (-0.19;-0.02)	-0.15 (-0.23;-0.08)	-0.16 (-0.26; -0.07)
0-2 years HAZ		
-0.03 (-0.09;0.04)	-0.03 (-0.09;0.03)	-0.11 (-0.18; -0.03)

In the infant model we explored WAZ, WHZ and HAZ as outcomes. There were significant associations between all outcomes and 60-day heat stress exposure (Figure 4 and Supplement Table 2). There was a bimodal distribution of WAZ and UTCI, with a clear reduction in WAZ associated with increasing mean UTCI exposure over all time periods. The estimates of effect at the 95th percentile compared to median value for all outcomes are presented in Table 2. When 0-2 year olds were exposed to average heat stress temperatures of 31°C UTCI versus 28°C UTCI, WAZ reduced by 0.10 (95% CI -0.16;-0.03), WHZ reduced by 0.15 (95% CI -0.23;-0.08) and HAZ reduced by -0.03 (95% CI -0.09;0.03).

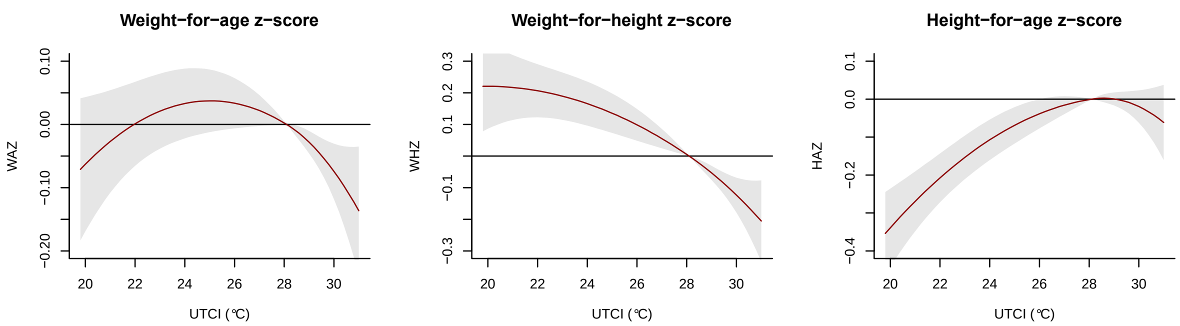

Figure 4: Association between weight-for-age z-scores, weight-for-height z-score and height-for-age z-score and mean UTCI over 60-day summaries in 0-2 year olds.

Of the growth faltering metrics, WHZ reduced the most with increasing UTCI, including across all time summary values (see supplement for 30- & 90-day model outputs).

HAZ and heat stress demonstrated a very different association compared with WAZ and WHZ. Increasing UTCI was associated with increasing HAZ up to a threshold of around 29°C UTCI, above which there is uncertainty in the relationship with confidence intervals crossing zero in 30- and 60-day summary exposures, but significantly decreasing when summarised by 90-day exposures (see supplement).

Discussion

In this study we found increasing heat stress exposure associated with a reduction in WAZ and WHZ in infants, but no significant effect *in utero.* This may indicate that the *in utero* environment can protect against the effects of heat on growth, or that we were not powered to detect the effect *in utero*, which would be in keeping with the literature on the association between heat and birth weight.[11,36,37] It is also possible that behavioural changes during pregnancy, including increasing rest and shade, may reduce the risks of exposure during pregnancy and that the documented effects of high temperatures on the risks of premature labour and stillbirth may be mediated through short term exposure and acute stressors that have no measurable impact on growth.[11] In the infant models, the relationship with WAZ seemed to demonstrate a bimodal distribution with both low and high temperatures increasing the risk of a reduced WAZ (although at lower temperatures this failed to meet statistical significance as demonstrated by the wide confidence intervals). The ideal heat stress range fell between 23-26°C UTCI, with heat stress above this resulting in a reduction in WAZ. This upper value is consistent with the UTCI established categories of no thermal stress between 9-26.0°C UTCI and various degrees of heat stress occurring above 26.0°C. WHZ was the most negatively impacted measurement of growth faltering by heat stress. Conversely, we found an increase in HAZ with increasing UTCI to a threshold of around 29°C mean UTCI. There have been many studies exploring the ecogeographical phenomenon described as Allen's rule where individuals from the same species have shorter limbs in cooler climates compared to those living closer to the equator.[38] Austin's early modelling study of human thermoregulation found that there was a consistent positive correlation between surface area to volume ratio and heat tolerance, i.e. taller individuals are better adapted to hotter climates, however at extreme hot humid conditions this relationship becomes negative.[39] To corroborate this, on direct measurements, Tilkens et al. demonstrated that longer limbed individuals loose heat faster than shorter limbed individuals.[40] This study adds further evidence to this effect.

A further consideration is that growth velocity may not be constant throughout the year. Marshall found that growth velocity in 7-10 year olds in the UK varied across the year, and when measured every 3 months there were peak velocities from March-June, with slowest velocities from September to February.[41] However Cliffer et al. performed a highly detailed study on 5039 children aged 6 to 28 months with 108,802 repeated anthropometric measures in Burkina Faso.[42] Although they found seasonal variations in growth and weight gain velocities, there was no variation in length-for-age z-scores across the year, contrary to studies from The Gambia.[7,32]

The Medical Research Council Unit in The Gambia has performed extensive work in West Kiang where this study was set. An early study from Rowland et al established the clear link between growth faltering in children aged 3 months to 3 years and gastrointestinal infections.[43] They found both height and weight significantly negatively correlated with diarrheal disease, which impeded any catch-up growth that was seen when diarrhea was not present. Since this work in the 1970s there has been a wealth of nutritional interventions as well as improvements in clinical care, vaccinations, access to water and sanitation and general infrastructure. During this time infant anthropometry has been routinely collected and allows an unprecedented analysis of changes in growth metrics over time. Nabwera et al analysed this extensive longitudinal cohort and found that the proportion of children with stunting or underweight halved from 1970s to 2000s, but remained disturbingly high at 30.0% and 22.1% respectively.[7] There was almost no change in the percentage of children with wasting. Interestingly there was a significant decrease in the seasonal effect on growth faltering, where in 1970, the wet season was associated with faltering across all metrics, and by the 2000s this had greatly reduced. This detailed and extensive analysis concluded that despite intensive nutrition interventions there are missing factors in the established understanding of contributors to growth faltering. We suggest that increasing environmental heat stress may be one of those factors.

Furthermore, this study supports the scarce published literature on this topic. Two previous studies utilised the demographic and health surveillance data[44] to explore the relationship between heat stress and growth faltering.[12,45] Both these cross-sectional studies were based in Sub-Saharan Africa, with Tusting et al including 656,107 children across 29 countries and Baker including 192,000 across 30 countries. Both studies found an increase in wasting with increasing temperature exposure, as we have shown. Neither study found lower rates of wasting at lower temperatures as hinted by our results suggesting that our non-significant trend in this respect is a chance finding. Additionally, Tusting et al[12] found a decreased odds of stunting in those exposed to temperatures above 35°C compared to below 30°C and Baker et al[45] found a similar shaped curve of the relationship between HAZ and heat as our study – with an increase in HAZ up to a threshold and then a plateau/reduction. Although our findings are similar, the methodology is very different, and as far as we are aware this is the first study to utilise longitudinal data to assess the impact of heat on growth faltering in the first 1000 days of life. Although smaller than the cross-sectional studies cited above, it is methodologically rigorous because of the multiple measurements on individuals over time which reduce the likelihood of both bias and confounding. Very few other studies have exploring heat and growth faltering; however studies from both Mexico and Kyrgystan found cold shocks increased the risk of stunting.[46,47]

This study is based on robust trial data and therefore gives a longitudinal exposure to temperature which has previously been lacking, though there are several limitations. The data come from only one area in rural Gambia and generalisability, especially in relationship to potential thresholds, may be limited. We also used mothers' residences to geolocate mother-infant pairs, but this did not take into account relocation or potential movement within the region. Nevertheless this is likely to have a minimal effect as daily temperature variation across the region was small. The strength of this study lies in the exploration of the relationship between heat stress and growth faltering, taking into account seasonality and acute diarrhoeal episodes which we know impacts on growth faltering and as far as we are aware has not previously been done.

Future studies that explore the interaction between heat stress and growth faltering in different populations would be helpful in determining at risk thresholds for different populations which would be useful to inform public health measures. Future studies that explore interventions to reduce heat load (through personal or structural building interventions) and the impact that has on appetite, food intake, food availability and growth would help determine effective, evidence-based solutions to adapt to global heating.

In conclusion, our study suggests that increasing heat stress is associated with decreasing WAZ and WHZ. With global heat records being broken yearly and currently no reduction in greenhouse gas emissions, our findings could have major implications for child health and development in future.

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CHAPTER 8 – Grassroots and youth-led climate solutions from The Gambia

SUMMARY OF CHAPTER

In this chapter I present a published paper describing the methodology and outcomes of a public engagement activity with school-aged children in The Gambia. The paper is written as a community case study and details the climate and environmental solutions determined by Gambian youth.

A full summary of the chapter can be found in the abstract.

Supplementary material for this paper can be found in Appendix 6. Appendix 7 is a commentary (in press at Lancet Planetary Health) on the engagement activity and potential ways to improve these interactions going forward.

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SECTION E

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Grassroots and Youth-Led Climate Solutions From The Gambia

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Climate change and environmental degradation are among the greatest threats to human health. Youth campaigners have very effectively focused global attention on the crisis, however children from the Global South are often under-represented (sometimes deliberately) in the dialogue. In The Gambia, West Africa, the impacts of climate change are already being directly experienced by the population, and this will worsen in coming years. There is strong government and community commitment to adapt to these challenges, as evidenced by The Gambia currently being the only country on target to meet the Paris agreement according to the Nationally Determined Contributions, but again children's voices are often missing—while their views could yield valuable additional insights. Here, we describe a "Climate Change Solutions Festival" that targeted and engaged school children from 13 to 18 years, and is to our knowledge, the first peer-to-peer (and student-to-professional) learning festival on climate change solutions for students in The Gambia. The event gave a unique insight into perceived climate change problems and scalable, affordable and sometimes very creative solutions that could be implemented in the local area. Logistical and practical methods for running the festival are shared, as well as details on all solutions demonstrated in enough detail to be duplicated. We also performed a narrative review of the most popular stalls to explore the scientific basis of these solutions and discuss these in a global context. Overall, we find extremely strong, grass-roots and student engagement in the Gambia and clear evidence of learning about climate change and the impacts of environmental degradation more broadly. Nevertheless, we reflect that in order to enact these proposed local solutions further steps to evaluate acceptability of adoption, feasibility within the communities, cost-benefit analyses and ability to scale solutions are needed. This could be the focus of future experiential learning activities with students and partnering stakeholders.

Keywords: climate change, solutions, youth, West Africa, public engagement

INTRODUCTION

Humanity's impact on the environment including the climate has been acknowledged as one of the greatest threats to human health (1, 2). In their latest report IPCC state that it is "*unequivocal that human influence has warmed the atmosphere, ocean and land,*" with further evidence that this has led to increased frequency of weather and climate extremes, including heatwaves, heavy precipitation, droughts, and tropical cyclones (3). This, in turn, has already had a devastating effect on biodiversity, food security, and livelihoods in various parts of the world (4, 5).

Children, now and in the future, will be the ones to bear the burden of humanity's environmental impacts, both in terms of direct impacts on their health but also in a multitude of indirect effects ranging from food security to economic impacts (6). Youth representatives from around the world have forced climate change into the global agenda where they have campaigned to highlight the need for immediate action (7). The passion and power of this group is inspirational but also demonstrates the need to engage with the youth in finding solutions and shaping the future in line with their visions (8). Nonetheless, children's voices are often not acknowledged or considered important in environmental policy settings (9).

Additionally, accessing school children in many areas of the world, including The Gambia has its own challenges. The global population has become increasingly connected, however, social media, email and internet access to connect and communicate remains uncommon in many areas and/or among certain societal groups, especially in rural Sub-Saharan Africa, adding to logistical difficulties in this endeavor (10, 11).

In order to encourage youth civic engagement, it has been shown that influences from both home and the school environment are important (12, 13). By exposing students to the ideas, problems and solutions to climate change, focus and awareness can be garnered around the issues, empowering discussions and allowing students to drive the conversation. Interactive and peer-to-peer learning methods have been shown to be effective at delivery of an educational message and to be both engaging and motivating (14, 15).

Here, we present an interactive, peer-to-peer (and student-to-professional) learning "Climate Change Solutions Festival," targeting school children aged 13-18 years old nationwide. This work was informed by a previous public engagement activity in January 2020 at Bakau Newtown Primary School, Fajara, The Gambia, which gave insights into the perceptions of climate change and students' ideas of how to mitigate/adapt to climate change. During this preliminary work, there was a keen interest in the subject, and a wish to share knowledge. We therefore built on this experience with a larger, nationwide festival. The aim of the festival was to learn with, and from, school aged children, non-government organisations (NGOs) and other actors across The Gambia about existing climate change impacts and adaptation/mitigation solutions, to encourage young people to engage in climate and health science, and stimulate discussion among young people and other delegates to consider priorities related to climate change.

Below we provide an overview of this experiential learning event, with details on its inception, design and our approach to channeling these ideas into practical demonstrations run by students and NGOs for students. We also comment on the feasibility or feasibility gaps in scaling up locally proposed solutions to help solve local environmental challenges as gleaned from solution-specific literature review (which is for the most part inaccessible to students prior to designing their solutions), and where they lie in the global perspective.

CONTEXT

West Africa is considered a particularly vulnerable region to the past and projected impacts of climate change (16, 17). The population in this region is already exposed to the impacts of climate change (increased drought, reduced growing season, extreme heat and increase in flooding) and are addressing this by strong government commitments in conjunction with community measures (18). However, the disconnect between resource availability for individuals to adapt to exposures such as extreme heat (e.g., construction materials, digital technology, sustainable, and affordable energy resources) and the increasing impact of climate change on everyday life is nowhere more evident than in The Gambia, the smallest and one of the least developed countries in Sub-Saharan Africa (19). This is recognized by the Gambian government, which is showing global leadership in its climate commitments that align emissions to within a 1.5°C global warming target (18). However, while climate change is currently taught in Gambian Schools, the Ministry of Education are looking to expand the curriculum (20). Accessing schools throughout the country (despite challenges) was important for equity of opportunity, since there are 137 government run schools in the six regions, of which 68% are in region 1 and 2. In addition, the standard teacher-led approach to education means school children learn predominantly only theory which has been shown to lack engagement compared to child-centered approaches (21).

PROGRAMMATIC DETAIL

Conceptualization and Planning

Conceptualization and initial planning for the Climate Solutions Festival built upon prior public engagement activities in The Gambia, the UK and India. **Figure 1** gives the detailed timeline leading up to the festival. In brief, we received confirmation of funding in July 2020. In November 2020, in collaboration with the Ministry of Education (MoE) in The Gambia, we determined target year groups from Gambian schools across the country as well as local grass-roots NGOs that were active within The Gambia to invite to the festival to attend as students or demonstrators. We also determined which regions to approach based on logistical, time and cost constraints, received approval to visit the schools and discussed future work on expanding the coverage of climate change in the school curriculum. The festival's objectives were determined at this meeting with the MoE.

Objectives

1. To enrich the debate around local climate change adaptation and mitigation by giving youth a voice/platform and encourage the dialogue between youth and decision-makers, NGOs and other stakeholders
2. To stimulate peer-to-peer teaching and learning among school-aged children
3. To develop open-source "*Climate change mitigation and adaptation options in the local environment*" resources—based on the science festival displays—with technical details

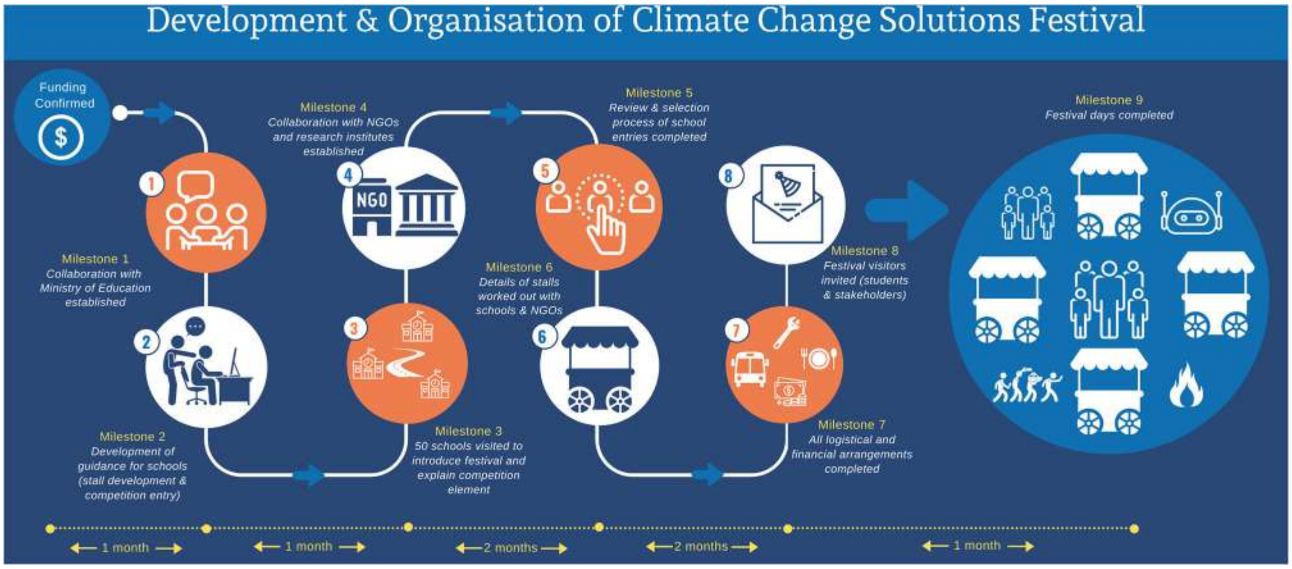

FIGURE 1 | Timeline of organisational events leading up to the festival.

for climate change projects suitable for use in schools and local communities.

We aimed to meet the above objectives by:

- Engaging 50 secondary schools to participate in a nationwide competition for grade 10-12 students (and their teachers)—aged 16-18 years and inviting them to submit ideas to interactively demonstrate climate or environmental change solutions.
- Selecting the most promising ideas for an interactive stall and offer demonstrators assistance (both financial and logistical) to develop their ideas.
- Inviting environmental, conservation and climate action groups active within The Gambia to develop and run interactive stalls on climate or environmental change solutions targeted to 13-16-year olds.

Selection of Schools and Other Demonstrators

We included all regions in The Gambia except region three, which was logistically too challenging to visit (due to poor transport infrastructure). All eligible schools (for participation in the festival) required an in-person visit to explain in detail the festival aims: therefore, the maximum number of invitees was set to 50 to stay within time and budgetary constraints. Based on the total numbers of schools per region, we estimated the proportional number of schools to invite by region (out of 50) to observe diversity and regional representation. We communicated the total number of invitees per region to the regional education directors (members of the Ministry of Education overseeing schools in their region) and asked them to select specific schools for our invitational visits. Upon visiting the schools, the team explained the aims of the festival and delivered an invitation to participate in the competition as well as application forms.

A panel of five reviewers (AB, JB, ZA, KM, and PS) doubly assessed and scored all submissions based on three criteria: feasibility, level of interaction and visualization. To reduce regional bias and to allow voices from across the country to be included, schools were scored within each region and the number invited to participate was again proportional to the number of schools in the region. The top 11 schools were invited to demonstrate their ideas in a stall at the festival. Selected schools were supported financially and logistically and encouraged to make their stall highly interactive.

All environmental, conservation and climate action groups, known to the extended organizing team, and active within The Gambia were also invited to run interactive stalls at the festival and supported in the development of their ideas.

The final content areas (reflecting layout on the day) of the festival were divided into four main categories: trees and forests, food and agriculture, plastic and waste, and oceans and waterways.

Winning Schools

On the days of the festival, the school stalls were judged by an expert panel [comprising two senior scientists and the head of communications for the Medical Research Council Gambia (MRCG)] as well as student peers. Expert judges scored the stalls on: effectiveness of solution; visualization of the stall; and communication of the message. Peers voted on their favorite overall stall (**Figure 2**). The scores from peers and experts were combined to determine the overall "winners" of the festival (**Figure 3**).

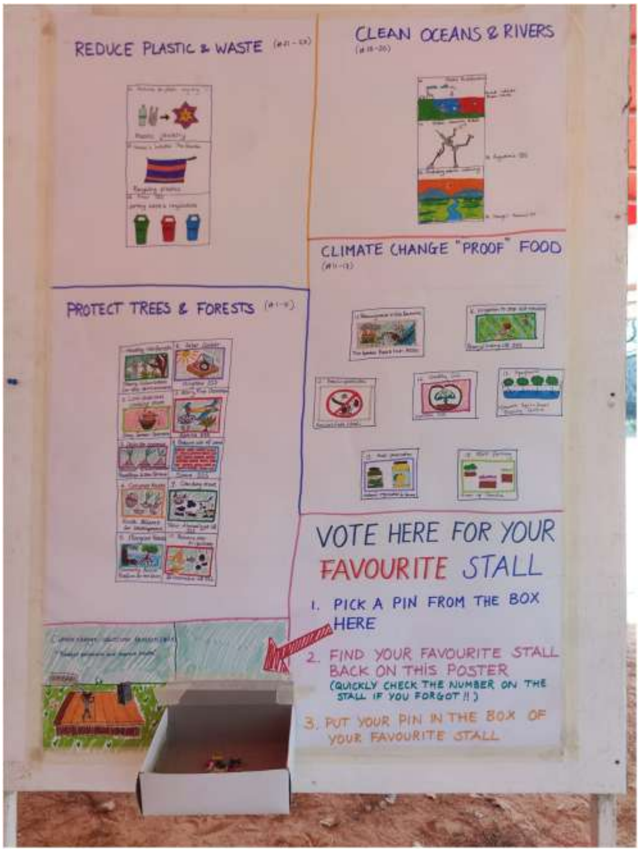

FIGURE 2 | Student's voting board. Each student placed a pin in their favourite stall.

FIGURE 3 | Demonstrators from the winning stall (banana charcoal) receiving prize from Mr Faal, Ministry of Education.

Observer Schools and Other Festival Participants

The primary audience of the festival were students in upper basic schools (aged 13-16 years). Six schools were invited from region one and transported to and from the festival grounds by the organizing committee. Key stakeholders from different governmental departments, NGOs and civil society organizations were also invited to observe and interact with presenting schools.

FIGURE 4 | Festival attendees watching the theatrical performance on dangers of burning car tyres and benifits of alternative options.

Environmental and COVID-19 Considerations

To reduce environmental harm from the festival itself, we used compostable food trays, mainly vegetarian catering, water dispensers and plant-based biodegradable drinking cups. To protect against COVID-19 transmission, the event was held entirely outside with open-sided markees; all demonstrators and visitors were provided with surgical masks and encouraged to wear them throughout; hand-washing stations were positioned at regular intervals; and local transmission rates were deemed very low at the time.

Ethics

Ethical approval was not sought for this initiative due to the nature of the festival and lack of data collection. Written informed consent was granted by legal guardians or individuals over 18 for display of any identifiable images.

The Festival

The festival ran on 26th-27th May 2021 and involved 600 school children visiting and participating, with 200 in attendance at any given time (**Figure 4**). There were 21 stalls active during the festival (see **Table 1** for the summary). Full details of all stalls can be found in the supplement—*Climate change mitigation and adaptation options in the local environment*—a toolkit for teachers, educators and students to recreate the experiments.

We present below a selection of the most popular stalls, highlighting the health and environmental benefits of these proposed solutions, as well as a narrative review of the global context for each topic.

TABLE 1 | List of all festival stalls.

Name of NGO or school	Stall theme	Number
Trees and forests		
Young Volunteers for The Environment	Solar cooker (protecting forests)	1
Gunjur Environmental Protection and Development Group	Reforestation and its many benefits	2
Youth Alliance for Development	Coconut husks as mulch and other nature-based solutions	3
Stay Green Gambia	Improved cook stove (mud stove)	4
Community Action Platform for the Environment	Importance of mangrove forests	5
Mingdaw Senior Secondary School	Solar Cooker	6
Somita Upper Basic and Senior Secondary School	Smoke detector for bush fires	7
Soma Upper Basic and Senior Secondary School	Air pollution and health/Alternative construction material	8
Tahir Ahmadiyya Upper Basic and Senior Secondary School	Cow dung oven	9
Brikamaba Upper Basic and Senior Secondary School	Banana charcoal briquettes	10
Kalagi Upper Basic and Senior Secondary School	Theatre—harmful practice of burning tires	21
Food and Agriculture		
Farmers Field School (Department of Agriculture)	Botanic pesticide/insecticide.	11
National coordinating organization for farmers association The Gambia	Food preservation	12
Kairaba Senior Secondary School	Cover cropping and organic manure	13
Banjulnding Upper Basic and Senior Secondary School	Salt intrusion	14
Oceans and waterways		
Great Institute (Ocean Heroes)	Ocean and estuary acidification	15
St. Augustine's Senior Secondary School	Plastic cleaning robot for the ocean	16
St. George's Technical Senior Secondary School	Protection of freshwater ponds	17
Plastic and Waste		
Plastic Recyclers Gunjur	Recycle plastic to make building tiles/bricks	18
The Women initiative The Gambia	Recycle plastic and tyres	19
Kaur Senior Secondary School	Importance of waste management	20

Alternative Fuel for Cooking

The most popular topic overall included solutions aimed at providing alternative fuels for cooking—5/21 of stalls focused on this. The demonstrators explained that these solutions address the combined impacts of air pollution on human health and biomass harvesting (e.g., firewood) from the environment. The benefits advocated included reduced respiratory diseases, reduced greenhouse gas (GHG) emissions and protection of forests (22–24). The following alternative fuel options were presented: (1) banana charcoal made of chopped banana peeling mixed with powdered grass/leaf charcoal and sand to from round briquettes; (2) clay cow dung oven made from clay collected at the river, shaped, dried and fired over 3 days and then dried animal dung used as fuel; (3) mud oven made from clay and sand, designed to improve cooking efficiency and so reduce fuel consumption; (4) two different solar cookers made from locally available materials in which the demonstrators cooked rice to indicate efficiency. Full details of how demonstrators made each of these alternatives are available in the supplement.

Global Context

There are ∼3 billion people globally that use biomass for cooking (25). The health effects of this results in an estimated 3.5 million deaths annually due to household air pollution (26), and there is a significant environmental cost to biodiversity due to deforestation driven by fuelwood production (27). In The Gambia, as in other SSA countries, firewood, charcoal and other biomass make up approximately 85% of local energy consumption (28). Burning biomass for cooking results in individuals exposed to harmful air pollutants, release of GHG emissions, deforestation and habitat degradation related to firewood collection (29).

Utilizing existing biomass waste (e.g., banana charcoal) have been minimally explored. A study by Mopoung and Udeye (30) found that banana peel briquettes were smokeless when burnt; however, combustion efficiency—a measure of how effectively the heat content of the fuel is transferred into usable heat—is low (9.1% compared to 80% for firewood) and therefore end-users may find it slow to cook food or heat water (36 vs. 18 min to reach maximum temperatures/boil water) (30, 31). However, overall, banana charcoal or utilizing biomass waste, with its simple and practical methodology should make it a priority to explore in future work as a potential locally realistic solution.

Despite the many benefits of alternative fuels, solar cookers and ICS, none of them have had extensive uptake globally (32, 33). A recent review of barriers to uptake of ICS identified 31 significant factors that determined whether an intervention to introduce ICS would be successful or not. Solar cooker uptake also suffers with similar problems (33). Identified barriers to use relate to issues such as perception of only targeting the poor, space and position limitations and cost, as well as the necessity to co-develop the end product with the end-users and ensure low or easy maintenance (34). Solar cookers should not be considered a purely low-income country alternative, as a study from Spain demonstrates potential annual life-cycle cost reduction of 40%, energy savings of 65% and electricity use reduced by 67 GWh/yr for solar cooker use compared to microwave use (35).

The clear message from our festival is that alternative fuel options are a priority for those living in The Gambia, highlighting a clear need to engage with communities on the issues around uptake of alternatives and to help identify effective solutions to reduce the amount of firewood and charcoal use.

Solutions to Address the Impacts on Food Systems of Climate Change

Solutions for Saline Water Intrusion

Protecting food and agriculture from climate change impacts featured highly in the various types of solutions that were proposed by participating students. Where students from rural areas—further inland—were mainly focusing on alternative fuel and deforestation, students from schools closer to the coast aimed to address another climate change related impact on the food system: saline water intrusion and its negative impacts on crops.

The solution presented by the students aimed at building embankments around coastal agricultural land, diverting encroaching sea water into canals that were dug just outside the embankments. The students explained that they would use a fresh-water pond in the middle of the agricultural plot (inside the embankments) for irrigation with fresh water.

In addition, students explored the possibility of creating co-benefits of salt-intrusion by harvesting salt from salt evaporation ponds for later sale. The technique of raking salt from the bottom of salt evaporation ponds has existed for centuries and is a very effective, low-cost, traditional technique that could contribute to income diversification for farmers.

Global Context

Due to a number of gradual changes and shocks in climatic and environmental conditions, the frequency and intensity of saline water intrusion due to floods—especially in deltaic areas around the world—have been increasing (36). Weather events such as cyclones, tsunamis, extreme rainfall, extreme tides and sea level—all related to climate change—are important contributors to flood risks (37, 38). Saline water intrusion has been described in detail in South and South East Asia, including in the Ganges-Brahmaputra Delta (39), where it has an impact on drinking water quality and human health (40–42). However, inland encroachment of saline water is also experienced along the African coast (43) and can lead to substantial declines in crop yields if no appropriate adaptation measures are in place (44). The high salt concentration makes water uptake more difficult for the majority of crops, leading to reduced growth (45). Furthermore, excess sodium is toxic to several crops and crop plants, in particular, vegetables are highly salt-sensitive and salt-tolerant varieties are not as abundant as for the majority of staple crops (46, 47).

Worldwide, in the year 2000, ∼620 million people lived in low-elevation coastal zones, of which ∼93 million in low-income settings with often more limited possibilities to switch to salinity-tolerant varieties or diversification to other crops, livestock and/or alternative income sources (48). At the same time salinity problems are increasing, with salinity causing an estimated 50% reduction in global rice production (49). With still 6.7% (47 million) of children under five in the world severely underweight, many of them living in low-lying deltaic areas, it will be crucial to prevent a further decrease in food availability to ensure additional progress to SGD2: eradicate hunger. While the longer-term solutions are embedded in climate change mitigation strategies, in the immediate term, low-input solutions for saline water intrusion, that—preferably—can be developed and managed locally, are pivotal to successful adaptation and ensure food system resilience. Whilst the "diversion" of seawater is not widely practiced and would be technically challenging given the subterranean flows of saline water into soils and ponds (50), barriers to keep saline water at a distance from crop land are already widely used and show great potential as an adaptation strategy, provided numerous conceivable costs could be circumvented (51). Canal-type barriers filled with fresh water are used to create a "push-back" to the encroaching sea water, whilst various types of vegetation, including mangroves, salt marshes and seasonal grasses are often used as infiltration zone, before the seawater reaches agricultural land. A study from Khulna showed rice yield increased up to 41% in areas with mangrove planting vs. no flood protection (52). Salt mining would be an added co-benefit of managing saline water and help rural communities to diversify their income sources.

Solutions for Food Preservation in Hotter Climates

A second food related topic covered at the festival addressed food preservation. The National Coordinating Organisation of Farmers Association (NACOFA) from Brikama demonstrated a number of food preservation techniques for a variety of foods. The organization explained that due to the increasing peak temperatures during the day preservation was pivotal in avoiding substantial amounts of food waste. In addition, given the increasing risk of yield failures, food preservation could be an effective solution to ensure food supply during the "hungry season" (wet season, July-Sep). Preservation techniques presented varied widely and included: (1) sugar-preservation techniques, such as preparing kabaa jam (*Saba senegalensis*) by boiling and jarring kabaa fruit with sugar and lime; (2) salting techniques, also applied to fruits like the *Saba senegalensis*, with added pepper, salt and flavor enhancers; (3) drying/dehydration techniques, for example applied to "*mbahal*" (rice, dried fish *(kobo)* and flavor enhancers) or *"findi"* (also called *Fonio*—a type of millet).

Global Context

Food preservation techniques date back to as far as centuries ago—with use of salt as preservation technique known to have been used in Egypt as early as 2000BC (53). However, with increasing discovery and use of preservatives in food and introduction of (affordable) refrigerators for domestic use, the need for preservation at household level changed drastically. Nonetheless, climate change has posed a renewed necessity for preservation in some areas, especially in areas experiencing prolonged periods of extreme heat. It started to be mentioned as a climate change adaptation strategy in the food and agricultural sector 10-15 years ago [e.g., (54)], and has been slowly coming back into mainstream practices, especially in the Global South. Parajuli et al. (55) highlight that supply of (especially perishable) produce is highly dependent on logistical management, transportation and refrigeration and/or preservation requirements. As a consequence, food waste is directly linked to the application of food preservation and refrigeration. Several case studies from small island states also illustrate that (traditional) food preservation techniques could increase food security in the aftermath of natural disasters (56).

Solutions to Reduce Plastic Pollution in the Environment

While the link between climate change and plastic pollution might not be well known (see global context below), there was high interest in the issue of environmental plastic pollution among students: 2/11 of all solutions presented by the participating schools focused on plastic. Two schools—focusing on plastic pollution in oceans and in the urban environment, respectively, were shortlisted for demonstration at the festival.

The school aiming to reduce plastic in oceans designed, engineered and demonstrated a floating solar powered plastic cleaning "robot," made primarily from waste materials, complete with a moving conveyer belt to transport floating plastic from the surface of water bodies into a container with a capacity of around 20 L, as well as rudders to passively guide flotation. The robot was demonstrated to effectively capture polystyrene pieces floating on the surface of a paddling pool.

Global Context

While the link is often not well-known to the wider public, plastic in the environment certainly contributes considerably to climate change. Plastics in the environment slowly release greenhouse gases (mostly methane and ethylene) throughout their lifetime (57), especially when exposed to substantial amounts of heat and sunlight (58). Furthermore, presence of (micro)plastics in the ocean will substantially interfere with carbon fixation (57). Shen et al. estimated that greenhouse gas emissions from all plastics (cradle to grave) will reach 1.34 Gigatonnes per year by 2030, seriously affecting carbon budgets and the ability to stay below +1.5°C above pre-industrial levels (57). Ocean plastics contribute to this problem: annual methane production of the standing stock of ocean pollution is 76Mt of methane, which translates into ∼2.1 Megatons of CO_2 (59). The robot design demonstrated was not unlike commercially available plastic traps in current use or trials (60), for examples the Seabin and FRED (Floating Robot for Eliminating Debris) (61, 62). The makers of Seabin estimated that each 20 L bin is able to capture 1.4 tons of debris per year, while the current network of 860 bins worldwide captures more than 3.5 tons per day (∼1,200 tons per year) and more than 2,000 tons have been collected since their deployment (61, 62). However, capacity needs to be substantially increased to meet current rates of plastic pollution, which have been estimated to average 8 million tons per year with a standing stock of >200 million tons, and is increasing at an alarming rate (63). Given the rapid increase in use of plastics, and the fact it also hinders the carbon sequestering capacity of oceans, its future impact on climate change is projected to become more dominant.

DISCUSSION

Substantial negative impacts of climate change on the lives of many residing in West Africa is a daily reality and is of particular concern for the youth residing in the region. As "experts by experience," there are often many practical ideas and solutions among members of the public on how to adapt to or mitigate these impacts, but not all voices have a platform.

The Climate Change Solutions Festival allowed students to demonstrate their ideas, interact with educators, researchers, NGO workers, decision-makers, funders and other stakeholders and engage in peer-to-peer teaching and learning related to practical knowledge and skills on climate change mitigation and adaptation options in their local environments.

Student engagement and stakeholder-student interaction give a platform for young people to share their concerns and ideas on climate change. As future leaders on climate change action their early engagement in research and decision-making in climate change is crucial in two ways: their concerns—and also possible solutions to overcome them—may give better insight in climate change impact at the grass-roots level, while their engagement in the topic at a younger age will make them (and their generational peers) more aware, knowledgeable, enthusiastic and equipped to work toward climate change mitigation targets in the future.

Peer Learning

Peer-to-peer teaching and learning has been used for decades to increase student motivation, responsibility, commitment, and sense of purpose while using various learning styles that appeal to their peers (64). In a global climate crisis that will affect many generations to come such elements are crucial for effective future leadership in climate change action. In addition, the group work element of the presenting teams at the festival allowed them to negotiate what problems to tackle, what solutions to present and what mode to use for their communication to ensure comprehension for their peers (65). Hence, there were many opportunities to strengthen transferrable skill, such as listening, explaining, questioning, summarizing, speculating, and hypothesizing (66). In the predominantly teacher-oriented pedagogic styles adhered to in many low-income settings (67), including the Gambia, the trusting relationship between peers (whereby no one holds a position of authority), may facilitate self-disclosure of ignorance and misconception, which will likely accelerate learning (66). Students appeared to appreciate the often enthusiastic, competent and sometimes humorous presentations of the stall-members. However, we did not directly evaluate this or ask for feedback from the students on the format of the festival, rather we asked more generic questions regarding learning on the day and overall enjoyment. In future endeavors it would be helpful to thoroughly evaluate this style of learning.

Co-creation of Research and Policy by Citizens and Practice Communities

The student-stakeholder interaction created a platform for practice communities with young people at its center, to voice their experiences and ideas for improvement and therewith potentially influence decision-making in practice and policy. The crucial importance of practice communities and citizens in climate change action and decision-making is increasingly acknowledged by national and international governing and advisory bodies. The Danish government, for instance, co-created their national climate strategy with members of the public (Climate Consortium Denmark), while the UK Government organized a citizen's Assembly on Climate Change to explore: *"How should the UK meet its target of net zero greenhouse gas emissions by 2050?"* (68). With several government officials and other-decision makers present during our festival, mainly due to the support from the Ministry of Education but also through long ties with our Institution and many key decision makers reflecting a long history of public health research and collaboration, this could accelerate the process of citizen's involvement in The Gambia, or other West African contexts. Despite this, we did not evaluate communications between students, stakeholders and NGOs to assess whether our objective of encouraging dialogue was met. Moreover, in order to foster transformative change there needs to be ongoing projects, communications and interactions which the festival organizers did not actively seek out and set up.

All proposed solutions have their highly context-specific benefits, some more than others, backed up with scientific evidence. Their presentation feeds back into research in two ways: (1) the problems addressed shed light on perceived problems and local priorities and hence could direct research focus in the local area, and (2) the solutions posed could be further refined and tested and their benefit for health and the environment could be calculated for use in cost-benefit analyses. Additionally, to act upon these proposed solutions in the community would require close collaboration with local authorities and communities to assess feasibility to the wider population of The Gambia.

A Positive Note in the Climate Crisis

The applied nature of the solutions posed by students and NGOs and the interactive components that allowed participants to explore local solutions to climate change adaptation and mitigation in great depth would likely have contributed community building and knowledge sharing. Some of the problems addressed at the festival, such as deforestation, increased heat and water salinization are well documented, but community members often feel powerless or out-of-depth in their personal attempts to take action. The practical solutions aiming to reduce or prevent climate change impacts may have formed a positive message and a start for finding scalable solutions that resonate with the users/implementers. The data captured during the festival in personal conversations, feedback forms, photos, notes from the festival stalls, and in-person evaluations with organizers are shared and presented in this manuscript as well as in a practical booklet describing the climate change mitigation and adaptation options. (*Climate change mitigation and adaptation options in the local environment—Climate Change Solutions Festival Banjul—May 2021.)* This could be used as a "handbook" for education on local climate change action, as well as a starting point for community involvement in developing future climate change strategies.

METHODOLOGICAL CONSTRAINTS

While we intended to get wide-spread representation of students and NGOs from various areas in The Gambia, logistical constraints prevented all schools from being able to participate, further highlighting the widespread problem of underservice in remote communities (25). In addition to this the six schools that attended the festival were all from region 1—the region where the capital is situated and therefore the area with many existing opportunities. Future programs or festivals must consider equity of access, inclusivity and fairness going forward.

In future we would also have defined evaluations of the designated objectives to allow a thorough assessment of successes and areas in need of improvement.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

Written informed consent was obtained from the minor(s)' legal guardian/next of kin for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

AB and PS conceived, organized, enacted project and wrote first draft. JB coordinated festival and edited manuscript. SJ, ZA, AA, KM, and AP were on the organizing committee and edited manuscript. MH, AD, MF, and WH involved in organizing festival, demonstrated on the day, and edited manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2022.784915/full#supplementary-material

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CHAPTER 9 – DISCUSSION

SUMMARY OF CHAPTER

In this chapter I discuss the findings related to each of the thesis objectives and how they fit together to contribute to the thesis and wider research area. I also discuss the limitations of the work and implication of the findings, and building on these consider future research areas.

9. 1 PhD Summary

There is rising consensus that the climate crisis is a health crisis.[1] In the field of maternal health the growing body of evidence on the adverse effects of heat on pregnant women and pregnancy outcomes[2] however only very minimally explores the potential pathophysiological pathways involved or the effects on early infant growth.[3] In this thesis, I conducted a prospective observational cohort study of environmental heat stress exposure and its effects on maternal and fetal physiology, exploring two main pathways – maternal heat strain and placental blood flow. This work highlights the high levels of heat stress exposure already being experienced by outdoor workers in The Gambia and contributes to understanding the mechanistic pathways by being the first field-based study to show an acute change in placental function under heat stress. My study on the relationship between heat stress exposure and growth faltering metrics uses longitudinal data to describe the impact of heat stress on weight-for-age, weight-for-height and height-for-weight z-scores. This study adds to the evidence from cross-sectional survey studies[4,5] and brings into focus the health impacts of a warming climate on child health. Finally, my ongoing public engagement work brings the knowledge and perspectives of Gambian youth on local climate solutions to researchers, policy makers and the wider public. Listening to and implementing solutions proposed by those most affected by the climate crisis seems like an essential step in solving this crisis. Below, I discuss the PhD findings under each objective.

Objective 1: Determine the heat stress exposure of pregnant agricultural workers in The Gambia.

This objective was achieved in Chapter 5, with Chapter 3 detailing the methodology. This objective was a necessary first step in describing the physiological effects of heat in pregnancy. My field team and I used small, light-weight portable devices to directly measure the air temperature, relative humidity, dew point, black globe temperature, wet bulb temperature and wind speed (Figure 1).

Figure 1: Tida Samateh using the Extech 200 heat stress meter to measure heat stress in a rice field.

From these measurements the device calculated the wet bulb globe temperature (WBGT) and I calculated the universal thermal climate index (UTCI) using the rBiometeo package in R.[6] Based on either of these heat stress indices, the heat stress exposure was high. Using the UTCI categories of thermal stress, there was not a single day of work that occurred during thermal neutral conditions, despite field work being forced to stop (due to the COVID-19 pandemic) prior to the intense heat just before the start of the rainy season when conditions would have been worse.

This objective has wider implications, both in terms of documenting the existing and worsening problem of heat stress exposure, and in understanding physiological limits. There were several field visit days where the measured WBGT exceeded 32.2°C (category 5 in the WBGT heat stress risk index), where even minimal workloads put an individual at risk.[7] Despite this, we found women in their third trimester of pregnancy still able and willing to work on their farms or fields. Clear questions remain regarding acclimatisation, longer-term health impacts and behaviour change options in this setting which I will expand on in the later sections.

Objective 2: Determine the maternal physiological response to heat stress exposure

This objective was achieved in Chapter 5 with Chapter 3 detailing the methodology. We found a significant increase in both maternal tympanic temperature and heart rate during a working shift in the heat. The modified physiological strain index was used to determine maternal heat strain, based on heart rate and skin temperature and although a modified physiological strain index (mPSI) has been used previously, I found no evidence of it being validated for use in pregnancy.[8] This may be relevant as resting heart rate increases throughout pregnancy, and so mPSI may underestimate the physiological strain. As demonstrated in the supplementary material for Chapter 5, mPSI and heat stress were correlated, but not strongly in our cohort.

The wider implications of these findings are related to characterising the pathophysiological pathways in more detail and so inform ongoing and future work. These pathways are visualised in the Directed Acyclic Graph (DAG) in Figure 2.

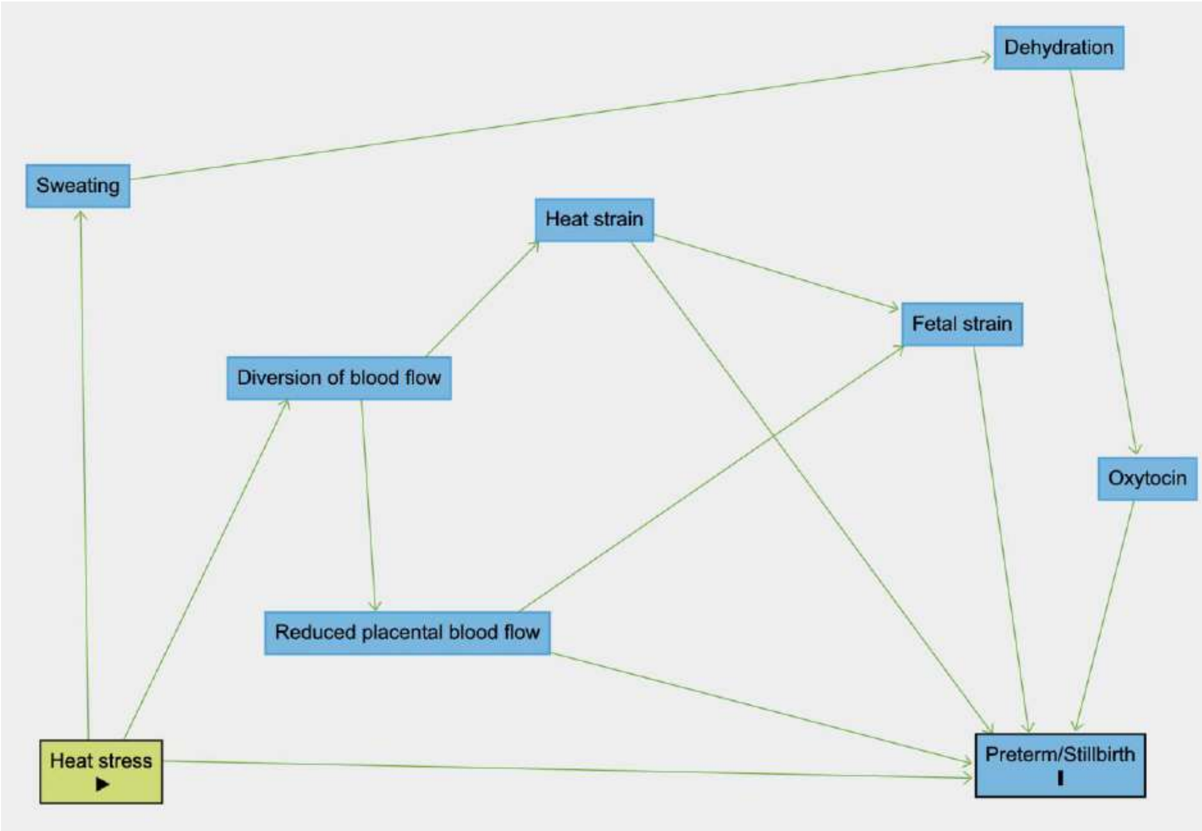

Figure 2: Directed Acyclic Graph of maternal heat stress exposure and preterm birth/stillbirth. HSP = Heat Shock Proteins

In this visualisation I have used the overall findings from the thesis to inform potential pathways that may be causing adverse birth outcomes. By demonstrating the role of maternal heat strain there is potential to develop pregnancy-specific tools and evidence-based metrics which I will expand on below.

Objective 3: Determine the acute effect of heat stress on the fetus.

This objective was achieved in Chapters 4 and 5. Chapter 4 gives detail on the 40 participants that I was able to collect dynamic umbilical artery doppler results on (Figure 3).

Figure 3: Measuring the umbilical artery resistance index using UmbiFlow™ on Dallo Njai, a subsistence farmer.

Chapter 5 includes all participants and evaluated the relationship between heat stress on both fetal heart rate and fetal strain. In both these chapters, heat stress has a significant impact on the fetus. Using the detailed data from the doppler study I show a potential threshold of effect at 30°C WBGT and 32°C UTCI. In Chapter 5, the total and direct effect of heat stress on fetal strain is demonstrated, showing that although maternal heat strain is important, heat stress also has a direct effect even when controlling for heat strain.

Beyond this thesis, these research findings are the first, to my knowledge, to demonstrate acute alterations in fetal physiology attributed to maternal heat stress exposure. These results can be used as a building block to begin unravelling the pathophysiological pathways involved in the association between maternal heat stress and adverse birth outcomes.

Objective 4: Determine the perception of heat risk in pregnancy amongst pregnant subsistence farmers in The Gambia and what adaptation options are available.

This objective was achieved in Chapter 6. Pregnant or recently pregnant farmers discussed their perception of the climate and their heat exposure, how this affected them physically, how they tried to minimise their symptoms and what strategies they would be interested in exploring to adapt to the heat. All women interviewed recognised that they were exposed to high levels of heat stress and that this had worsened over the last 5-10 years. The most concerning aspects of climate change to this population was the ability to survive in the current and worsening environmental conditions due to difficulties in growing crops and in raising money to educate and provide for their families.

Wider implications of this work relate to centring the dialogue and action on climate change around those who are most affected by it. Listening to and learning from populations that are struggling with the interconnected impacts of climate change is a necessary first step to allow subsequent co-production of action and interventions that are based on the lived experience of those facing this crisis in their everyday lives.

Objective 5: Determine the chronic effect of heat stress on growth faltering in the first 1000 days of life in The Gambia.

This objective was achieved in Chapter 7. Using robust data from a randomised control trial of nutritional interventions, I found that in children aged 0-2 years, both weight-for-age z-score (WAZ) and weight-for-height z-score (WHZ) were reduced at high heat stress exposures. Conversely height-for-age z-score (HAZ) increased with increasing heat stress exposure up to a threshold. The repeated measures, multilevel linear regression model allowed important covariables to be taken into account (maternal age, maternal body mass index, parity, gestational age at birth, age, sex, diarrhoeal illness, season of conception and season of exposure). Despite the results giving a complicated picture of the relationship between heat stress and growth metrics, these findings were similar to published cross-sectional analyses by Baker et al (Figure 4).

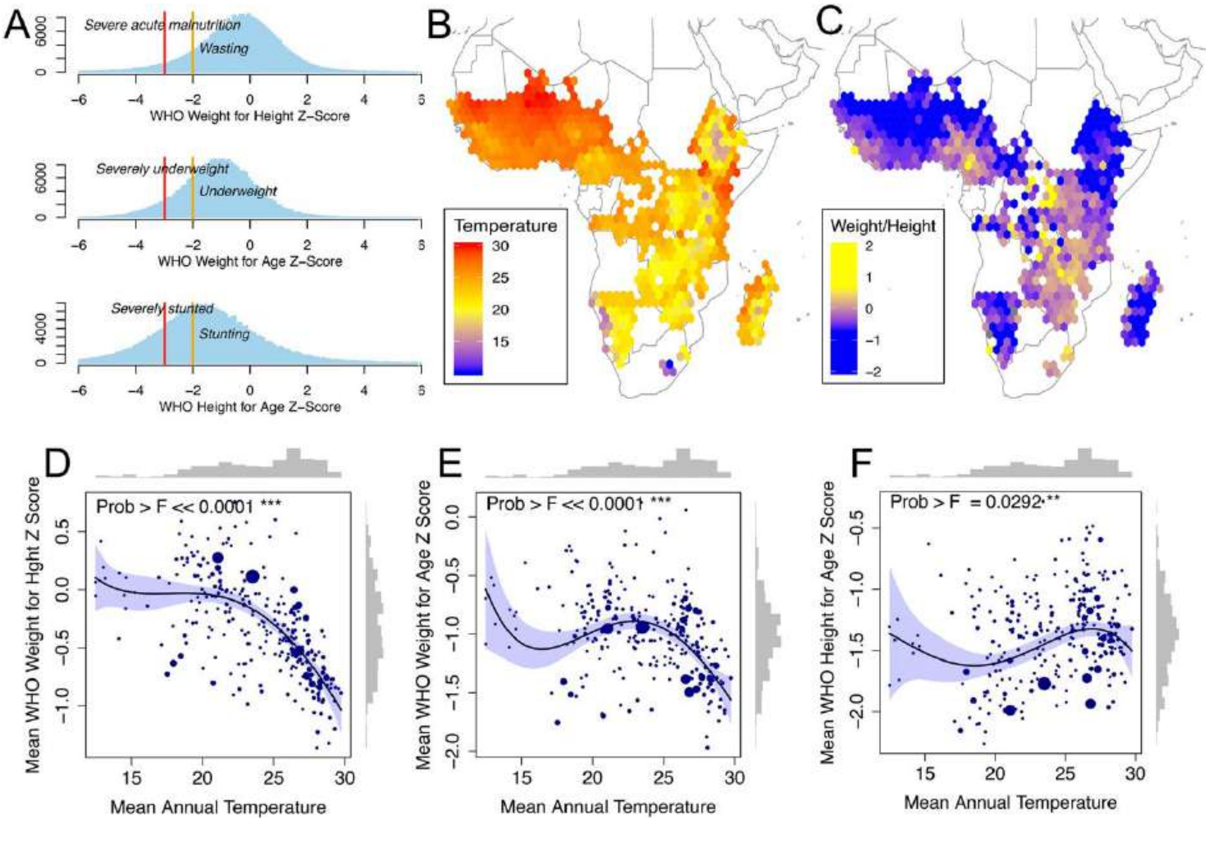

Figure 4: Average temperature and child anthropometric outcomes. (**A**) Distribution of child WHO weight and height measures in sample, weighted using DHS sample weights to be representative at region-by-survey level.

WHO wasting, underweight, and stunting thresholds shown for moderate (yellow, − 2σσ) and severe (red, − 3σσ) cases. (**B**) Spatial variation in 50-year average temperature and (**C**) average child weight-for-height for gridded 1.5 * 1.5∘∘ bins of latitude and longitude. (**D**–**F**) Sub-national regional (admin level 1) correlation between average (50 years) regional temperature and average anthropometric measures for children surveyed in that region. A fourth-order polynomial is fitted to the data, weighted by number of observations (proportional to dot size). The F-statistic for the polynomial fit is shown along with histograms of the distribution of the data.[4]

The wider implications of these findings relate to the current gap in the literature on the health impacts of heat in children. From previous studies,[4,5] West Africa was already identified as an a- risk area for the impact of heat on growth faltering, which this study corroborates. The combined risks of heat stress and change in rainfall put Sustainable Development Goals (SDG) 1 & 2 (at risk.

Objective 6: Engage and listen to the Gambian youth on their views on the problems posed by and solutions to environmental degradation and climate change.

This objective was achieved in Chapter 8. The climate change solutions festival and toolkit (Appendix 6) is described in enough detail to allow duplication. The majority of the actions suggested by the students related to reduction in the use of firewood or charcoal for cooking in order to stop deforestation and protect trees and forests. Other identified problems included sand mining, salt intrusion, waste management, freshwater protection and ocean waste pollution. The students demonstrating the problems and solutions at the stalls and those attending the festival were engaged, passionate and committed to environmental protection and reversal of climate change.

This work gave voice to youth solutions to climate change and environmental degradation and allowed an opportunity for the students to meet and discuss with key actors in this field. Moving forward this model of engagement could be used in other areas to identify youth-led problems and solutions which, with appropriate evaluation could then be embedded into development, adaptation and mitigation action.

9.2 Limitations

Specific limitations of individual research papers are described in the relevant chapters 3 to 8. In summary limitations relating to the prospective cohort study are mainly related to challenges due to 1) lack of established metrics in maternal and fetal heat strain; 2) difficulties in taking gold-standard measurements due to this being a field-based study rather than a laboratory-based study; 3) lack of cool work exposure due to the unseasonal heat in January/February of 2020; 4) reduction in sample size and repeated measures due to lockdown necessitated by COVID-19.

The limitations identified related to the qualitative work include 1) geographical limitations; 2) limited number of participants in the younger age range; 3) limited scope of the study, with no capacity to explore the perceived impacts of heat on well-being, feelings of stress, or on quality or quality of sleep.

The limitations identified related to the growth faltering study include 1) similar heat stress exposure across the cohort (due to limited geographical spread of residency); 2) geolocation was based on mother's residency which therefore would miss any relocations that may have occurred; 3) difficult to apply these findings globally, but potentially generalisable locally.

The limitations of the public engagement work relate to sustainability and impact. This work was funded by an LSHTM continued development grant for public engagement and therefore at the end of the festival there was a lack of funds to take any of the solutions further.

Additionally to these individual study limitations there are broader challenges related to research on the health impacts of climate change. Firstly, climate change occurs over decades.[9] Therefore, studying acute health effects has its own challenges and when this is combined with the difficulties in maternal health research in this setting (with no government register of antenatal care or birth register and no accurate routine gestational age assessment),[10] exploring long-term impacts or outcomes of interventions can be especially challenging.

An important and urgent area to highlight is the power imbalance that exists in current research funding structures. With the Global North mostly setting the research agenda and making the funding decisions, but the Global South being the regions most effected in the case of climate change.[11,12] Although this leads to collaborations, there is still a long way to go to ensure equal partnerships. As a result , research institutions are beginning to acknowledge their colonial history and how that may have shaped their research agenda, but recent reports on racism within both LSHTM (where this thesis is based) and Wellcome Trust (the funders of this work) indicate that significant barriers remain in place preventing progress on addressing structural racism.[13,14] This seems particularly important in relation to climate justice and the ongoing global discussions concerning loss and damages.[15]

9.3 Future research

9.3.1 Expanding understanding of the physiological pathways

There remains a need to determine basic metrics against which future interventions and assessments can be measured. These include a consensus on a definition of both maternal heat strain and fetal heat strain. Although results in Chapter 5 clearly show an acute impact on fetal heart rate and placental blood flow, evaluation of how these acute changes effect birth outcomes are needed. In addition, improved knowledge of the role of the maternal fetoplacental unit and other potential biochemical pathways would improve understanding of the exact mechanisms by which heat leads to adverse birth outcomes. With an expansion of this work, there should be a focus on development of safety targets for activity levels at different heat stress exposures during pregnancy to inform policy makers.

Other areas which have been touched on in this work but would be interesting to explore in more detail include understanding acclimatisation in this setting; what physiological phenotypic changes are particularly relevant in pregnancy and whether any of these can be induced. Additionally, understanding the biological, genetic, epigenetic, social and economic risk factors that increase susceptibility to poor birth outcomes in women exposed to high temperatures would help in targeting public health measures.

9.3.2 Co-development of interventions

A first step in co-production of interventions includes stakeholder consultation and evidence review.[16] Chapter 6 gives an indication of what effects climate change is having on the lives of communities living in rural Gambia. Moving forward it is vital that any interventions are co-produced with communities and remain centred around community priorities. It would be interesting to explore bundles of interventions that consider the individual, community and structural interventions. Individual action could include education campaigns on the risk to health of extreme heat, personal cooling mechanisms, alterations in behaviour to reduce exposure and targeting of at-risk groups. Community interventions could include communal cooling spaces, commitment to plant and protect trees and other green spaces and easy access to water for vulnerable groups during extreme heat events. Structural interventions could include exploring construction material that keeps houses cool, use of natural ventilation mechanisms, addition of plants and trees surrounding buildings, green or white roofs and solar powered mechanical cooling.[17]

9.3.3 Expanding on impacts of heat in early infancy

Expanding on the work presented in Chapter 7 it would be interesting to study the effect of a combination of heat stress exposure with drought or reduced rainfall on growth faltering or malnutrition. Evidence from Burkina Faso would indicate that child growth depends on the preceding season's rainfall and harvest.[18] Further work taking into account all these factors would help to develop the evidence required to target feeding campaigns to at-risk areas going forward.

Although further evidence of the effect of heat on mortality in African children was recently published by Chapman et al.,[19] there remain significant geographical areas where data are sparse. Additionally, the morbidity impacts could be expanded to include changes in neurocognition. It is known that high temperatures are very detrimental to the developing brain[20] and a recent multi-country study found heat exposure in schools reduced learning capabilities and attainment.[21] Characterising this relationship would help guide future action to allow all children to reach their full capabilities.

9.3.4 From public engagement to action

Although the climate change solutions festival delivered on engaging and listening to students and the Gambian youth on their solutions to identified local problems related to climate change and environmental issues, there is a need to take this work further to enact some of these solutions in the community. I have attempted to do this with one of the suggested solutions - solar cookers, and am in the process of building, evaluating and disseminating to the communities several solar cooker models. However, to make significant impact in this area it would be helpful to connect the students themselves directly to policy makers or funding bodies to allow locally-led action going forward.

9.3.5 Attribution

Lastly there has been extensive work in recent years to attribute specific extreme weather events to climate change.[22] For example, the extreme heatwave experienced in March-May 2022 in India and Pakistan was made about 30 times more likely to occur due to anthropogenic climate change.[23] Future evaluation of the measured heat exposure in the prospective cohort study linked to either fetal heart rate or fetal strain could be used to attribute exposure in this region to climate change. Attribution is a vital step in quantifying loss and damage which then can be acted upon to minimise ongoing potential harms including by influencing funding.[24]

9.4 Conclusion

This thesis has assessed the relationship between acute heat exposure and maternal and fetal physiology, the chronic impacts of heat on growth in the first 1000 days of life and presented climate change solutions from Gambian youth. For The Gambia, this thesis shows that climate change is already having an impact on health and that there is strong youth engagement in both climate adaptation and mitigation. Currently, there are high levels of heat stress being experienced by farmers in rural West Kiang and models predict that this will worsen in the near future.[25] This exposure puts pregnant women at risk of developing heat strain and acute fetal strain in their unborn child. Chronic effects of heat on early life showed increased risk of wasting in those exposed to high heat stress. By demonstrating the current health impacts, future work can focus on developing local and sustainable interventions with vulnerable communities at their centre.

9.5 References

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APPENDIX

1	Ethical approval for all studies	173
2	Supplementary material for “A feasibility study of the use of UmbiFlow™ to assess the impact of heat stress on fetoplacental blood flow in field studies”.	185
3	Supplementary material for “Environmental heat stress on maternal physiology and fetal blood flow in pregnant subsistence farmers in The Gambia, West Africa: an observational cohort study”.	194
4	Supplementary material for “The Challenges of Working in the Heat Whilst Pregnant: Insights From Gambian Women Farmers in the Face of Climate Change”.	217
5	Supplementary material for “Assessing the impact of heat stress on growth faltering in the first 1000 days of life in rural Gambia”.	219
6	Supplementary material for “Grassroots and youth-led climate solutions from The Gambia”.	232
7	Accepted commentary in Lancet Planetary Health on the public engagement work: “Towards equity and impact in planetary health education initiatives”	261
8	Published paper in Frontiers in Public Health “Impact of personal cooling on performance, comfort and heat strain in healthcare workers in PPE, a study from West Africa”.	265

APPENDIX 1

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The Gambia Government/MRC Joint
ETHICS COMMITTEE

Dr Ana Bonell

London School of Hygiene & Tropical Medicine, UK

19 June 2019

Dear Dr Bonell,

MRCG ethics ref: 16405: An observational cohort study of heat strain and fetal wellbeing in pregnant farmers in The Gambia

Thank you for submitting your response to the queries raised by the Gambia gGvernment/MRCG Joint Ethics Committee.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation.

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document Type	File Name	Date	Version
Investigator CV	Andrew Prentice CV	16/03/2019	1
Protocol / Proposal	protocol HS pregnancy for SCC	17/03/2019	1
Investigator CV	Haines CV Mar 2019docx	17/03/2019	1
Investigator CV	Neil Maxwell CV_2019_short version	17/03/2019	1
Investigator CV	Ana Bonell CV 2019	17/03/2019	1
Information Sheet	ICD heat strain pregnancy SCC	17/03/2019	1
Covering Letter	Cover Letter	10/04/2019	1
Protocol / Proposal	protocol HS pregnancy V2	10/04/2019	2.0
Protocol / Proposal	technical manual on temperature pills and monitoring system	10/04/2019	1.0
Information Sheet	ICD heat strain pregnancy V2	10/04/2019	2.0
Covering Letter	Cover letter V2.0	28/05/2019	2.0
Protocol / Proposal	protocol HS pregnancy V3	28/05/2019	3.0
Protocol / Proposal	ICD heat strain pregnancy V3	28/05/2019	3.0

After ethical review

The Chief Investigator (CI) or delegate is responsible for informing the ethics committee of any subsequent changes to the application. These must be submitted to the Committee for review using an Amendment form. Amendments must not be initiated before receipt of written favourable opinion from the committee.

An annual report should be submitted to the committee using an Annual Report form on the anniversary of the approval of the study during the lifetime of the study. At the end of the study, the CI or delegate must notify the committee using an End of Study form.

All aforementioned forms are available on the ethics online applications website and can only be submitted to the committee via the website at: http://leo.lshtm.ac.uk

Additional information is available at: www.lshtm.ac.uk/ethics.

With best wishes,

Yours sincerely,

[redacted]

Dr. Mohammadou Kabir Cham
Chair, Gambia Government/ MRCG Joint Ethics Committee

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Observational / Interventions Research Ethics Committee

Dr Ana Bonell
LSHTM

23 July 2019

Dear Ana,

Submission Title: An observational cohort study of heat strain and fetal wellbeing in pregnant farmers in The Gambia

LSHTM Ethics Ref: 16405

Thank you for responding to the Observational Committee Chair's request for further information on the above research and submitting revised documentation.

The further information has been considered on behalf of the Committee by the Chair.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation as revised, subject to the conditions specified below.

Conditions of the favourable opinion

Approval is dependent on local ethical approval having been received, where relevant.

Approved documents

The final list of documents reviewed and approved is as follows:

Document Type	File Name	Date	Version
Investigator CV	Andrew Prentice CV	16/03/2019	1
Protocol / Proposal	protocol HS pregnancy for SCC	17/03/2019	1
Investigator CV	Haines CV Mar 2019docx	17/03/2019	1
Investigator CV	Neil Maxwell CV_2019_short version	17/03/2019	1
Investigator CV	Ana Bonell CV 2019	17/03/2019	1
Information Sheet	ICD heat strain pregnancy SCC	17/03/2019	1
Covering Letter	Cover Letter	10/04/2019	1
Protocol / Proposal	protocol HS pregnancy V2	10/04/2019	2.0
Protocol / Proposal	technical manual on temperature pills and monitoring system	10/04/2019	1.0
Information Sheet	ICD heat strain pregnancy V2	10/04/2019	2.0
Local Approval	SCC decision	16/04/2019	1
Covering Letter	Cover letter V2.0	28/05/2019	2.0
Protocol / Proposal	protocol HS pregnancy V3	28/05/2019	3.0
Protocol / Proposal	ICD heat strain pregnancy V3	28/05/2019	3.0
Covering Letter	Cover Letter V3	08/07/2019	3

After ethical review

The Chief Investigator (CI) or delegate is responsible for informing the ethics committee of any subsequent changes to the application. These must be submitted to the committee for review using an Amendment form. Amendments must not be initiated before receipt of written favourable opinion from the committee.

The CI or delegate is also required to notify the ethics committee of any protocol violations and/or Suspected Unexpected Serious Adverse Reactions (SUSARs) which occur during the project by submitting a Serious Adverse Event form.

An annual report should be submitted to the committee using an Annual Report form on the anniversary of the approval of the study during the lifetime of the study

At the end of the study, the CI or delegate must notify the committee using the End of Study form.

All aforementioned forms are available on the ethics online applications website and can only be submitted to the committee via the website at: http://leo.lshtm.ac.uk.

Further information is available at: www.lshtm.ac.uk/ethics.

Yours sincerely,

[redacted]

Professor Jimmy Whitworth
Chair

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The Gambia Government/MRC Joint
ETHICS COMMITTEE

Dr Ana Bonell
LSHTM

18 October 2020

Dear Dr Bonell

Study Title: Climate change and its health impacts on rural Gambian female farmers; a qualitative study of local understanding and adaptations focused on pregnancy

Project ID/ethics ref: 22545

Thank you for your application for the above research, which was considered by the Gambia Government/MRCG Joint Ethics Committee at its meeting held on 24 September 2020.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation.

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document Type	File Name	Date	Version
Other	Research_Ethics_online_training_certificate	19/07/2020	1.0
Investigator CV	Ana Bonell CV 2020	19/07/2020	1.0
Investigator CV	CV_english_SCC_Gambia	19/07/2020	1.0
Protocol / Proposal	Topic guide	20/07/2020	1.0
Information Sheet	ICD	20/07/2020	1.0
Protocol / Proposal	study protocol	20/07/2020	1.0
Protocol / Proposal	study protocol	10/08/2020	1.1
Protocol / Proposal	Topic guide	10/08/2020	1.1
Covering Letter	Cover Letter (1)	11/08/2020	1.0

After ethical review

The Chief Investigator (CI) or delegate is responsible for informing the Ethics Committee of any subsequent changes to the application. These must be submitted to the Committee for review using an Amendment form. Amendments must not be initiated before receipt of written favourable opinion from the Committee.

The CI or delegate is also required to notify the ethics committee of any protocol violations and/or Suspected Unexpected Serious Adverse Reactions (SUSARs) which occur during the project by submitting a Serious Adverse Event form. An annual report should be submitted to the Committee using an Annual Report form on the anniversary of the approval of the study during the lifetime of the study. At the end of the study, the CI or delegate must notify the committee using an End of Study form.

All aforementioned forms are available on the ethics online applications website and can only be submitted to the committee via the website at: http://leo.lshtm.ac.uk. Additional information is available at: www.lshtm.ac.uk/ethics

Best wishes

Yours sincerely

[redacted]

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Observational / Interventions Research Ethics Committee

Dr Ana Bonell

LSHTM

21 October 2020

Dear Dr Bonell

Study Title: Climate change and its health impacts on rural Gambian female farmers; a qualitative study of local understanding and adaptations focused on pregnancy

LSHTM Ethics Ref: 22545

Thank you for your application for the above research project which has now been considered by the Observational Committee via Chair's Action.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation, subject to the conditions specified below.

Conditions of the favourable opinion

Approval is dependent on local ethical approval having been received, where relevant.

Approved documents

The final list of documents reviewed and approved is as follows:

Document Type	File Name	Date	Version
Other	Research_Ethics_online_training_certificate	19/07/2020	1
Investigator CV	Ana Bonell CV 2020	19/07/2020	1
Investigator CV	CV_english_SCC_Gambia	19/07/2020	1
Protocol / Proposal	Topic guide	20/07/2020	1
Information Sheet	ICD	20/07/2020	1
Protocol / Proposal	study protocol	20/07/2020	1
Protocol / Proposal	study protocol_V2	10/08/2020	2
Protocol / Proposal	Topic guide_V2	10/08/2020	2
Covering Letter	Cover Letter (1)	11/08/2020	1

After ethical review

The Chief Investigator (CI) or delegate is responsible for informing the ethics committee of any subsequent changes to the application. These must be submitted to the committee for review using an Amendment form. Amendments must not be initiated before receipt of written favourable opinion from the committee.

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An annual report should be submitted to the committee using an Annual Report form on the anniversary of the approval of the study during the lifetime of the study.

At the end of the study, the CI or delegate must notify the committee using the End of Study form.

All aforementioned forms are available on the ethics online applications website and can only be submitted to the committee via the website at: http://leo.lshtm.ac.uk.

Further information is available at: www.lshtm.ac.uk/ethics.

Yours sincerely,

[redacted]

Professor Jimmy Whitworth
Chair

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Dr Ana Bonell

MRCG at LSHTM, Fajara

20 April 2021

Dear Dr Bonell

Study Title: Association of extreme maternal heat exposure on foetal and early childhood growth

Project ID/ethics ref: 25171

Thank you for submitting your application which was considered by the Gambia government/MRCG Joint Ethics Committee at its meeting held on 25 March 2021.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form and supporting documentation.

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document Type	File Name	Date	Version
Local Approval	SCC 1126v2 21Jul08 Moore final approval 20Aug08	21/07/2008	2
Consent form	ENID_InfoSheet&ConsentForm_v3	06/05/2010	3.0
Other	Research_Ethics_online_training_certificate	17/07/2020	1
Investigator CV	Ana Bonell CV Dec2020	09/12/2020	1
Protocol / Proposal	Study ProtocolAMBER_final	15/02/2021	1

After ethical review

The Chief Investigator (CI) or delegate is responsible for informing the Ethics Committee of any subsequent changes to the application. These must be submitted to the Committee for review using an Amendment form. Amendments must not be initiated before receipt of written favourable opinion from the Committee.

The CI or delegate is also required to notify the ethics committee of any protocol violations and/or Suspected Unexpected Serious Adverse Reactions (SUSARs) which occur during the project by submitting a Serious Adverse Event form. An annual report should be submitted to the Committee using an Annual Report form on the anniversary of the approval of the study during the lifetime of the study. At the end of the study, the CI or delegate must notify the committee using an End of Study form.

All aforementioned forms are available on the ethics online applications website and can only be submitted to the committee via the website at: http://leo.lshtm.ac.uk. Additional information is available at: www.lshtm.ac.uk/ethics.

With best wishes

Yours sincerely

[redacted]

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LONDON SCHOOL of HYGIENE &TROPICAL MEDICINE

Observational / Interventions Research Ethics Committee

Dr Ana Bonell
LSHTM

22 April 2021

Dear Dr Ana Bonell

Study Title: Association of extreme maternal heat exposure on fetal and early childhood growth

LSHTM Ethics Ref: 25171

Thank you for your application for the above research project which has now been considered by the Observational Committee via Chair's Action.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation, subject to the conditions specified below.

Conditions of the favourable opinion

Approval is dependent on local ethical approval having been received, where relevant.

Approved documents

The final list of documents reviewed and approved is as follows:

Document Type	File Name	Date	Version
Local Approval	SCC 1126v2 21Jul08 Moore final approval 20Aug08	21/07/2008	2
Consent form	ENID_InfoSheet&ConsentForm_v3	06/05/2010	3.0
Other	Research_Ethics_online_training_certificate	17/07/2020	1
Investigator CV	Ana Bonell CV Dec2020	09/12/2020	1
Protocol / Proposal	Study ProtocolAMBER_final	15/02/2021	1

After ethical review

The Chief Investigator (CI) or delegate is responsible for informing the ethics committee of any subsequent changes to the application. These must be submitted to the committee for review using an Amendment form. Amendments must not be initiated before receipt of written favourable opinion from the committee.

The CI or delegate is also required to notify the ethics committee of any protocol violations and/or Suspected Unexpected Serious Adverse Reactions (SUSARs) which occur during the project by submitting a Serious Adverse Event form.

An annual report should be submitted to the committee using an Annual Report form on the anniversary of the approval of the study during the lifetime of the study.

At the end of the study, the CI or delegate must notify the committee using the End of Study form.

All aforementioned forms are available on the ethics online applications website and can only be submitted to the committee via the website at: http://leo.lshtm.ac.uk.

Further information is available at: www.lshtm.ac.uk/ethics.

Yours sincerely,

[redacted]

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Chair

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The Gambia Government/MRC Joint
ETHICS COMMITTEE

Dr Ana Bonell
LSHTM, UK

16 September 2020

Dear Dr Bonell

Study Title: Evaluation of heat alleviation strategies in healthcare workers wearing Personal Protective Equipment

Project ID/ethics ref: 22590

Thank you for your application for the above research, which was considered by the Gambia Government/MRCG Joint Ethics Committee at its meeting held on 27 August 2020.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation.

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document Type	File Name	Date	Version
Other	GCP Certificate (R2)	29/01/2019	1
Investigator CV	Neil Maxwell CV_2019_short version	04/02/2019	1
Sponsor Letter	A Bonell Award Letter final	11/03/2019	1
Protocol / Proposal	Study Protocol Evaluation of Heat Alleviation strategies Gambia	19/07/2020	1
Other	Research_Ethics_online_training_certificate	19/07/2020	1
Investigator CV	Ana Bonell CV 2020	19/07/2020	1
Information Sheet	ICD heat alleviation	19/07/2020	1

After ethical review

The Chief Investigator (CI) or delegate is responsible for informing the Ethics Committee of any subsequent changes to the application. These must be submitted to the Committee for review using an Amendment form. Amendments must not be initiated before receipt of written favourable opinion from the Committee. The CI or delegate is also required to notify the Ethics Committee of any protocol violations and/or Suspected Unexpected Serious Adverse Reactions (SUSARs) which occur during the project by submitting a Serious Adverse Event form. An annual report should be submitted to the cCmmittee using an Annual Report form on the anniversary of the approval of the study during the lifetime of the study. At the end of the study, the CI or delegate must notify the committee using an End of Study form. All aforementioned forms are available on the ethics online applications website and can only be submitted to the committee via the website at: http://leo.lshtm.ac.uk. Additional information is available at: www.lshtm.ac.uk/ethics.

With best wishes

Yours sincerely

[redacted]

Dr Mohammadou Kabir Cham
Chairperson, Gambia Government/MRCG Joint Ethics Committee

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Observational / Interventions Research Ethics Committee

Dr Ana Bonell
LSHTM

17 September 2020

Dear Dr Bonell

Study Title: Evaluation of heat alleviation strategies in healthcare workers wearing Personal Protective Equipement

LSHTM Ethics Ref: 22590

Thank you for your application for the above research project which has now been considered by the Interventions Committee via Chair's Action.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation, subject to the conditions specified below.

Conditions of the favourable opinion

Approval is dependent on local ethical approval having been received, where relevant.

Approved documents

The final list of documents reviewed and approved is as follows:

Document Type	File Name	Date	Version
Other	GCP Certificate (R2)	29/01/2019	1
Investigator CV	Neil Maxwell CV_2019_short version	04/02/2019	1
Sponsor Letter	A Bonell Award Letter final	11/03/2019	1
Protocol / Proposal	Study Protocol Evaluation of Heat Alleviation strategies Gambia	19/07/2020	1
Other	Research_Ethics_online_training_certificate	19/07/2020	1
Investigator CV	Ana Bonell CV 2020	19/07/2020	1
Information Sheet	ICD heat alleviation	19/07/2020	1

After ethical review

The Chief Investigator (CI) or delegate is responsible for informing the ethics committee of any subsequent changes to the application. These must be submitted to the committee for review using an Amendment form. Amendments must not be initiated before receipt of written favourable opinion from the committee.

The CI or delegate is also required to notify the ethics committee of any protocol violations and/or Suspected Unexpected Serious Adverse Reactions (SUSARs) which occur during the project by submitting a Serious Adverse Event form.

An annual report should be submitted to the committee using an Annual Report form on the anniversary of the approval of the study during the lifetime of the study.

At the end of the study, the CI or delegate must notify the committee using the End of Study form.

All aforementioned forms are available on the ethics online applications website and can only be submitted to the committee via the website at: http://leo.lshtm.ac.uk.

Further information is available at: www.lshtm.ac.uk/ethics.

Yours sincerely,

[redacted]

Professor Jimmy Whitworth
Chair

ethics@lshtm.ac.uk
http://www.lshtm.ac.uk/ethics/

SUPPLEMENT

A feasibility study of the use of UmbiFlow™ to assess the impact of heat stress on fetoplacental blood flow in field studies.

Ana Bonell, Valerie Vannevel, Bakary Sonko, Nuredin Mohammed, Ana M. Vicedo-Cabrera, Andy Haines, Neil S Maxwell, Jane Hirst, Andrew M Prentice

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STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No.	Recommendation	Page No.	Relevant text from manuscript
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1	Feasibility study in title
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	2	See abstract
Introduction				
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	3	With the ongoing climate crisis, global extreme heat exposure is progressively increasing……
Objectives	3	State specific objectives, including any prespecified hypotheses	5	determine if UmbiFlow™ identifies a change in umbilical artery resistance index under heat stress; and determine the practical considerations needed to use UmbiFlow™ in the field
Methods				
Study design	4	Present key elements of study design early in the paper	6	Briefly, pregnant women living in West Kiang, The Gambia, participated in an observational cohort study
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	6	…from August 2019 to March 2020, with follow-up until December 2020.
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	6	Participants were identified through the antenatal clinic or the health and demographic surveillance system in place in West Kiang and were eligible if they were pregnant with a singleton, undertook farming or manual tasks during pregnancy and did not suffer with pre-eclampsia or eclampsia at the time of recruitment.
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case		
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	6-7	External environmental conditions (air temperature, relative humidity, solar radiation, wind speed) were measured hourly using the HT200: Heat Stress WBGT Meter, Extech® …..

Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	6-7	UmbiFlow™ measures the blood flow velocity in the umbilical cord and calculates the RI = (systolic velocity – diastolic velocity)/systolic velocity
Bias	9	Describe any efforts to address potential sources of bias	7	Duplicate measurements of RI taken to reduce bias and measurement error
Study size	10	Explain how the study size was arrived at	NA	Study to determine needed sample size. Sample size of cohort study based on expected rates of heat stress and heat strain – see protocol paper

Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	7-8	Exposure variables continuous and not grouped. Outcome variable defined
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	8	Multilevel model used
		(*b*) Describe any methods used to examine subgroups and interactions		
		(*c*) Explain how missing data were addressed		
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	NA	
		(*e*) Describe any sensitivity analyses		
Results				
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	8-9	Table 1
		(b) Give reasons for non-participation at each stage		
		© Consider use of a flow diagram		
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	Table 1	Table 1
		(b) Indicate number of participants with missing data for each variable of interest		
		© *Cohort study*—Summarise follow-up time (eg, average and total amount)	7	All participants followed up after delivery….
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	Table 1	Table 1
		Case-control study—Report numbers in each exposure category, or summary measures of exposure		
		Cross-sectional study—Report numbers of outcome events or summary measures		
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	9	
		(*b*) Report category boundaries when continuous variables were categorized	NA	
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period		

Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	Supplement	Fig 2
Discussion				
Key results	18	Summarise key results with reference to study objectives	11	We show that the UmbiFlow™ device is highly suited to field work, being light and compact and that
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	12	Several limitations…..
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	13	Additionally, identification of a dangerous heat exposure threshold…..
Generalisability	21	Discuss the generalisability (external validity) of the study results	12	Additionally, pregnancy and neonatal outcomes in the general population of The Gambia are worse than the global average which may impact on generalisability of the findings globally but could be reasonably representative of a rural SSA population
Other information				
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	14	

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

Table 2: Power calculation predictor for determining association between umbilical artery resistance index z-scores under heat stress.

Outcome	Highest UTCI exposure (°C)	Power to detect effect size (%)	95% CI	Sample size
Association between RI and heat stress undifferentiated	34.79	83%	80.53;85.28	500
Association between RI and heat stress in those with APO	34.92	91.1	89.2;92.8	997

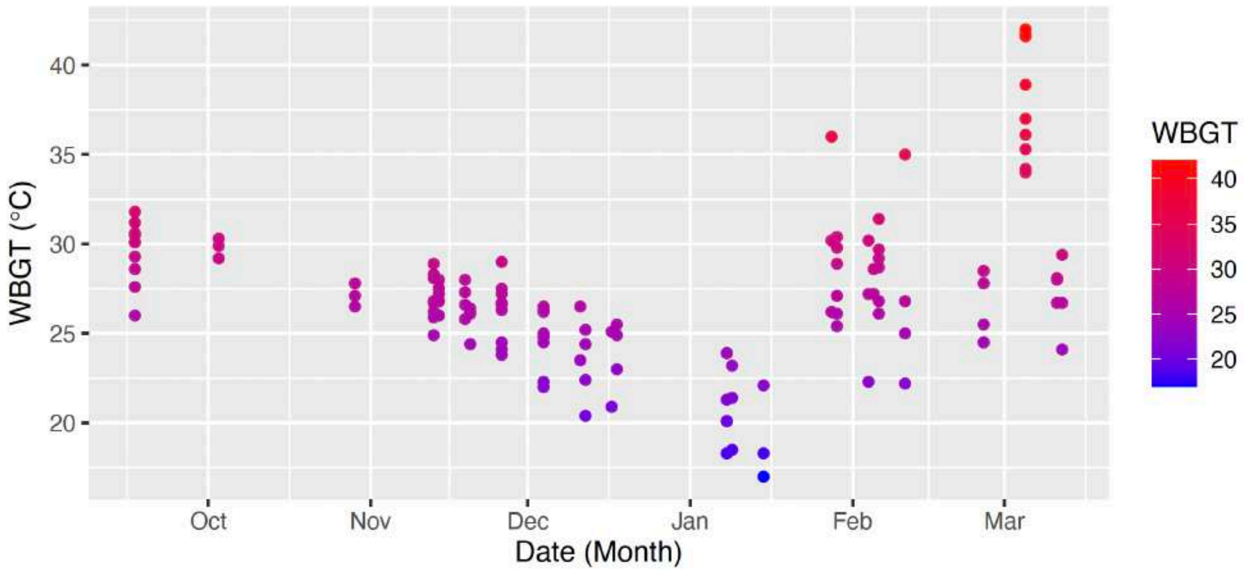

Figure 1a: Time series of heat stress (Wet Bulb Globe Temperature - WBGT) exposure. Each point corresponds to a directly observed measurement during the field study.

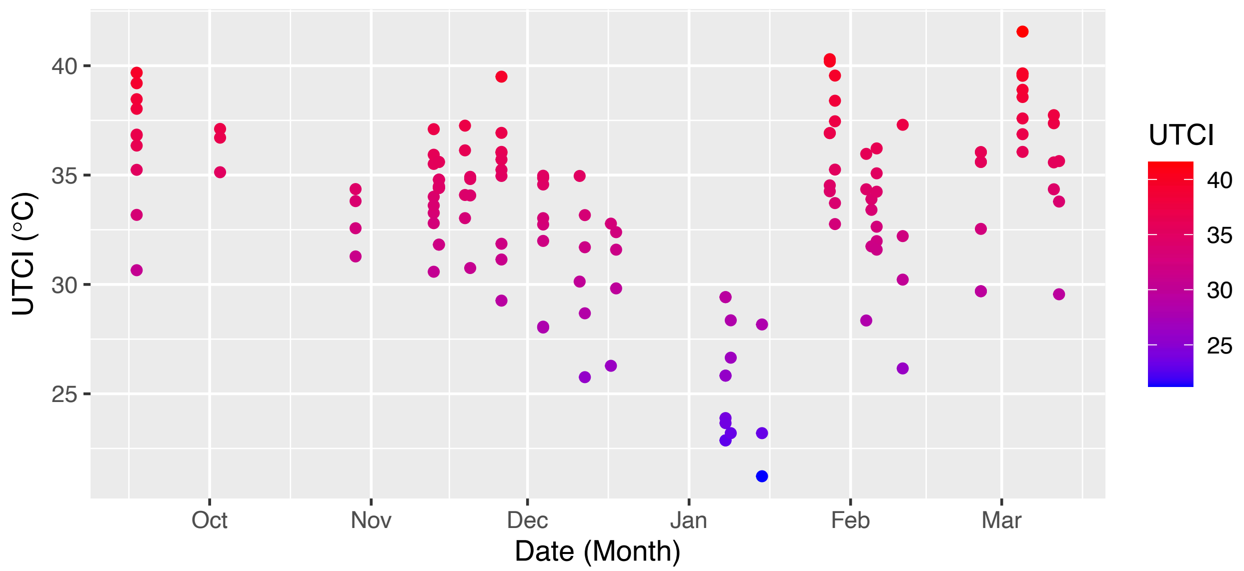

Figure 1b: Time series of heat stress (Universal Thermal Climate Index - UTCI) exposure. Each point corresponds to a directly observed measurement during the field study.

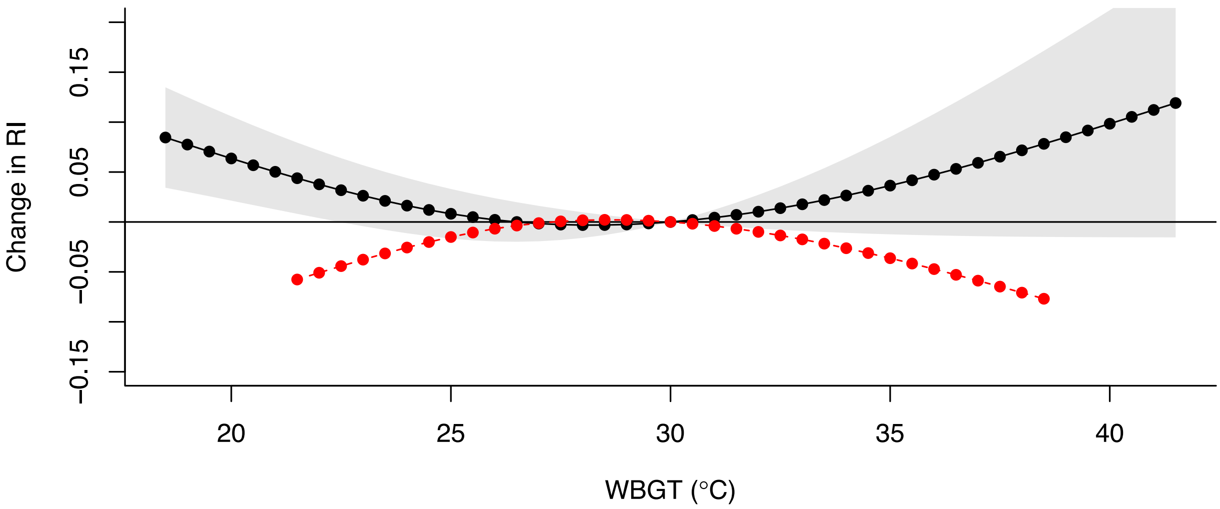

Figure 2a: Change in umbilical artery RI under heat stress (WBGT) in those with and without APO. Black = no APO; red = APO. Shading = 95% CI.

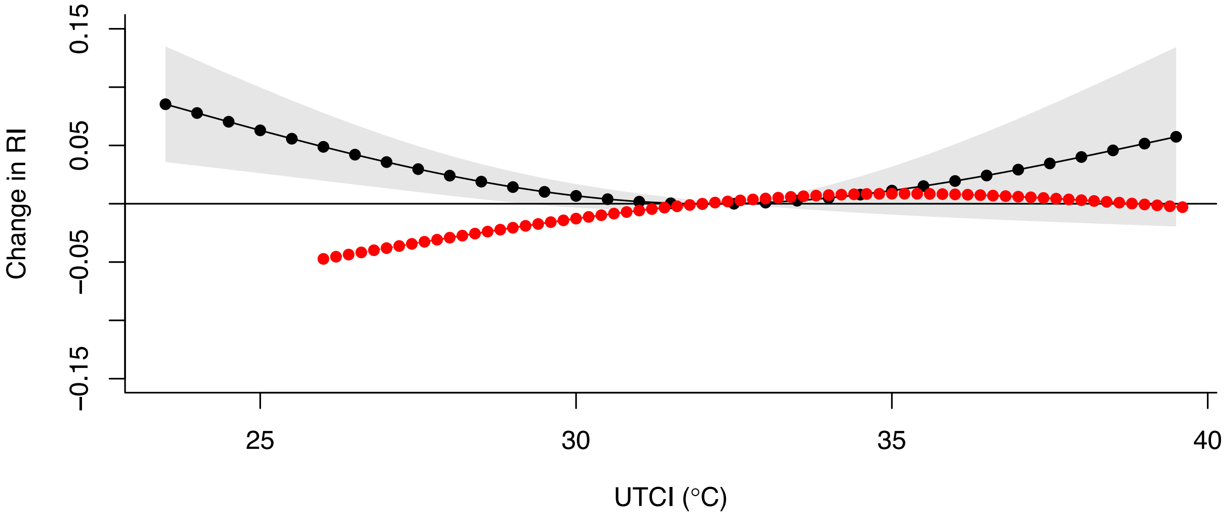

Figure 2b: Change in umbilical artery RI under heat stress (UTCI) in those with and without APO. Black = no APO; red = APO. Shading = 95% CI.

SUPPLEMENT

Environmental heat stress on maternal physiology and fetal blood flow in pregnant subsistence farmers in The Gambia, West Africa: an observational cohort study

Authors: Ana Bonell, Bakary Sonko, Jainaba Badjie, Tida Samateh, Tida Saidy, Fatou Sosseh, Yahya Sallah, Kebba Bajo, Kris A Murray, Jane Hirst, Ana Vicedo-Cabrera, Andrew M Prentice, Neil S Maxwell, Andy Haines

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Table 1: univariate analyses of PSI_{MOD}, fetal heart rate and fetal stress

	Peak PSI_{MOD}		Fetal heart rate (bpm)		Fetal Stress (Y/N)	
	Estimate (CI)	p-value	Estimate (CI)	p-value	Odds Ratio (CI)	p-value
UTCI	0·35 (0·31;0·38)	<0·001	1·45 (1·27;1·64)	<0·001	1·17 (1·09;1·26)	<0·001
WBGT	0·43 (0·39;0·47)	<0·001	1·74 (1·50;1·98)	<0·001	1·20 (1·12;1·29)	<0·001
Air temp	0·25 (0·21;0·29)	<0·001	1·11 (0·92;1·31)	<0·001	1·11 (1·05;1·17)	<0·001
Relative humidity	-0·04 (-0·02;-0·06)	<0·001	-0·18 (-0·28;-0·08)	<0·001	0·97 (0·96;0·99)	0·01
Duration in field	0·003 (-0·003;0·01)	0·32	0·02 (-0·01;0·05)	0·18	1·00(1·00;1·01)	0·41
MET	-0·21 (-0·70;0·28)	0·41	0·63 (-1·71;2·97)	0·60	1·08 (0·72;1·64)	0·71
Tymp temp	5·48 (4·53;6·43)	<0·001	20·93 (15·99;25·86)	<0·001	7·71 (2·63;22·59)	<0·001
Skin temp	-	-	6·44 (5·24;7·63)	<0·001	1·85 (1·42;2·40)	<0·001
Heart rate	-	-	0·34 (0·29;0·38)	<0·001	1·05 (1·03;1·07)	<0·001
PSI_{MOD}	-	-	2·93 (2·46;3·40)	<0·001	1·36 (1·22;1·53)	<0·001
Osmolality	0·004 (0·002;0·006)	<0·001	0·02 (0·00;0·02)	<0·001	1·00 (1·00;1·00)	0·20
Haematocrit	-0·04 (-0·12;0·04)	0·35	-0·20 (-0·58;0·19)	0·32	0·96 (0·89;1·04)	0·37
TBW	0·04 (-0·05;0·13)	0·39	0·35 (-0·07;0·77)	0·10	1·02 (0·95;1·10)	0·58
Weight	-0·02 (-0·05;0·01)	0·24	0·03 (-0·13;0·20)	0·68	1·00 (0·95;1·10)	0·80
Maternal age	0·00 (-0·05;0·05)	0·98	0·03 (-0·22;0·28)	0·80	1·00 (0·96; 1·05)	0·75
CVS reserve	0·00 (-0·005;0·01)	0·83	6·70 (-0·02;0·03)	0·60	1·00 (1·00;1·01)	0·79
Hb	-0·11 (-0·36;0·14)	0·41	-0·46 (-1·66;0·74)	0·45	0·98 (0·93;1·03)	0·43
Fat mass	-0·06 (-0·11;-0·01)	0·02	-0·10 (-0·35;0·15)	0·43	0·98 (0·93;1·03)	0·35
GA at field visit	-0·01 (-0·06;0·05)	0·81	-0·01 (-0·29;0·26)	0·93	1·06 (1·00;1·11)	0·05
Comp in pregnancy	0·20 (-0·59;0·99)	0·62	0·74 (-3·05;4·53)	0·70	0·86 (0·45;1·71)	0·68
Adverse pregnancy outcome	0·07 (-0·73;0·86)	0·87	-1·16 (-4·96;2·64)	0·55	1·08 (0·55;2·12)	0·82

CVS reserve = cardiopulmonary reserve (measured by standard 6-minute walk test); Hb = Haemoglobin concentration; Fat mass = % fat mass as measured on bioimpedance; GA = gestational age in weeks; Comp = any complication in pregnancy except anaemia; Adverse pregnancy outcome = LBW, preterm birth, SGA, stillbirth, peripartum death.

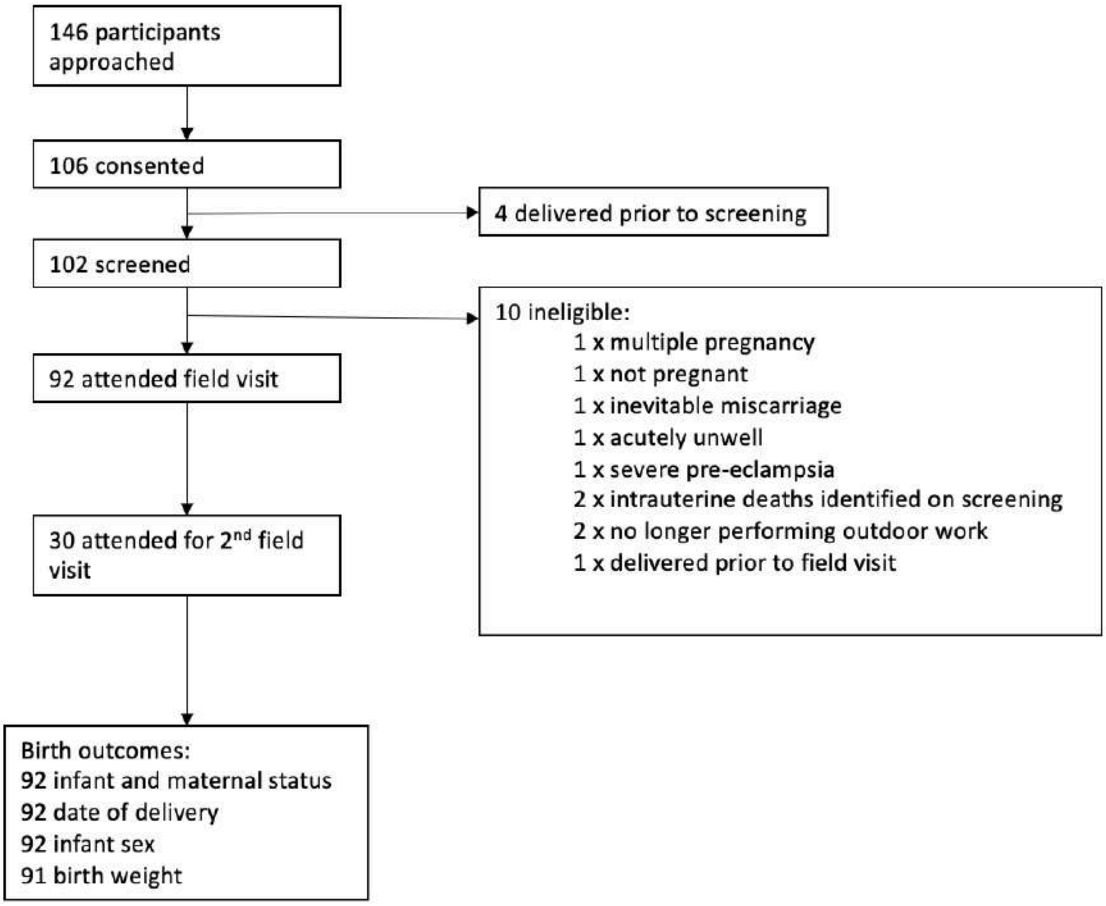

Figure 1: Flow-chart of study recruitment

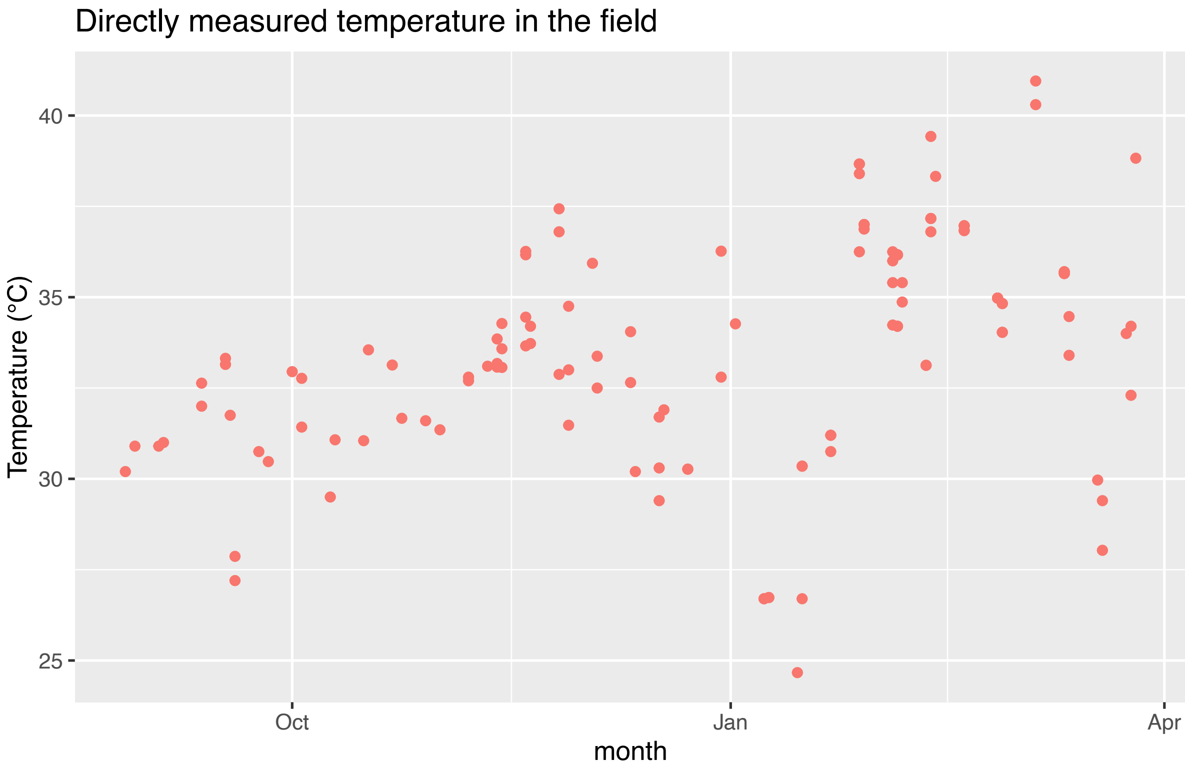

Figure 2: Directly measured temperature from each field visit (August 2019 – March 2020)

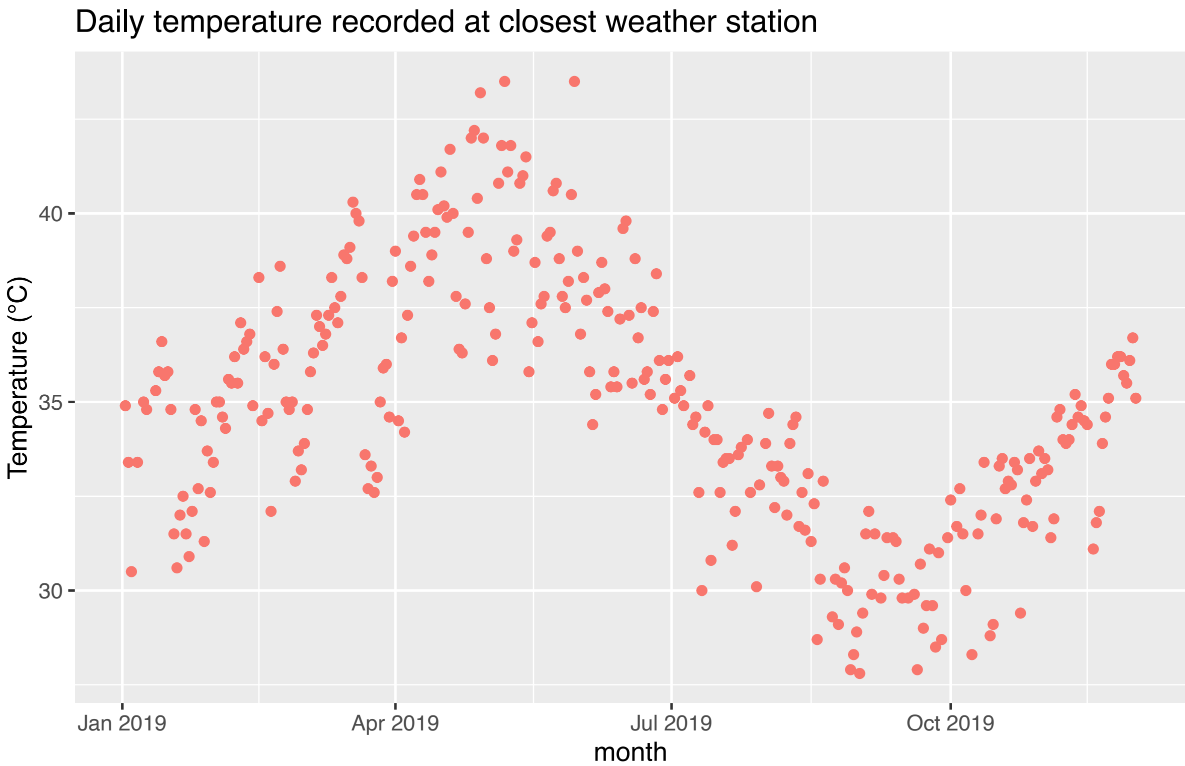

Figure 3: Daily temperature recorded at the closest weather station (Kerewan station)

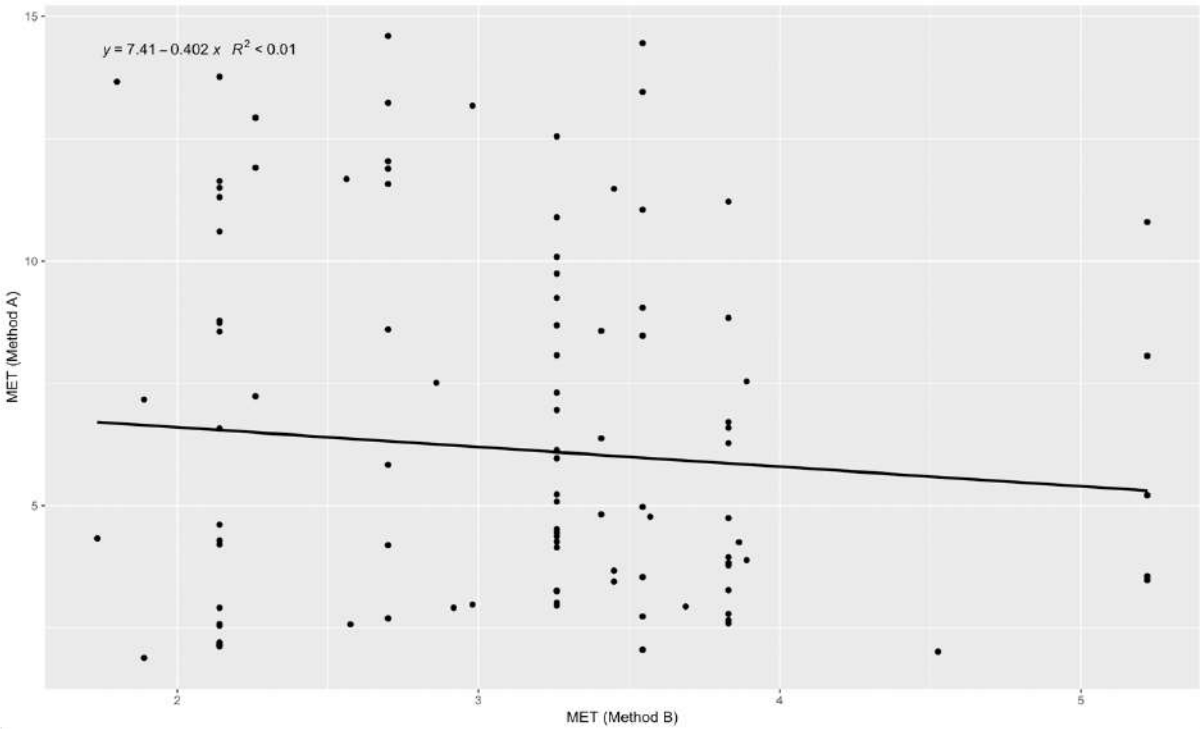

Figure 4: Metabolic equivalent (MET) comparison: method A against method B

This highlights the difficulty in estimating energy expenditure in pregnancy. Method A (calculated from continuous heart rate recorded by wearable device) and Method B (calculated from observed action in the field linked to historical measurements) are poorly correlated. Additional work on developing gestational age specific algorithms to estimate energy expenditure from wearable devices would be useful.

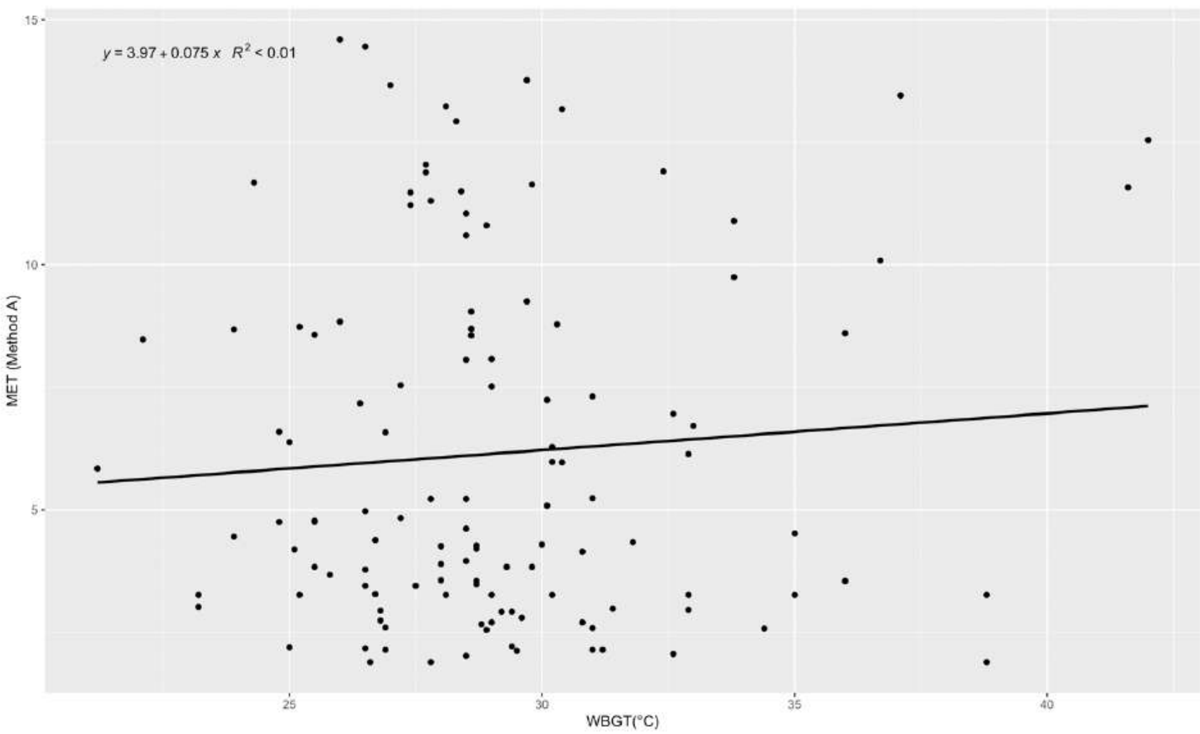

Figure 5a: MET (method A) against WBGT exposure. MET = Metabolic equivalent; WBGT = Wet Bulb Globe Temperature

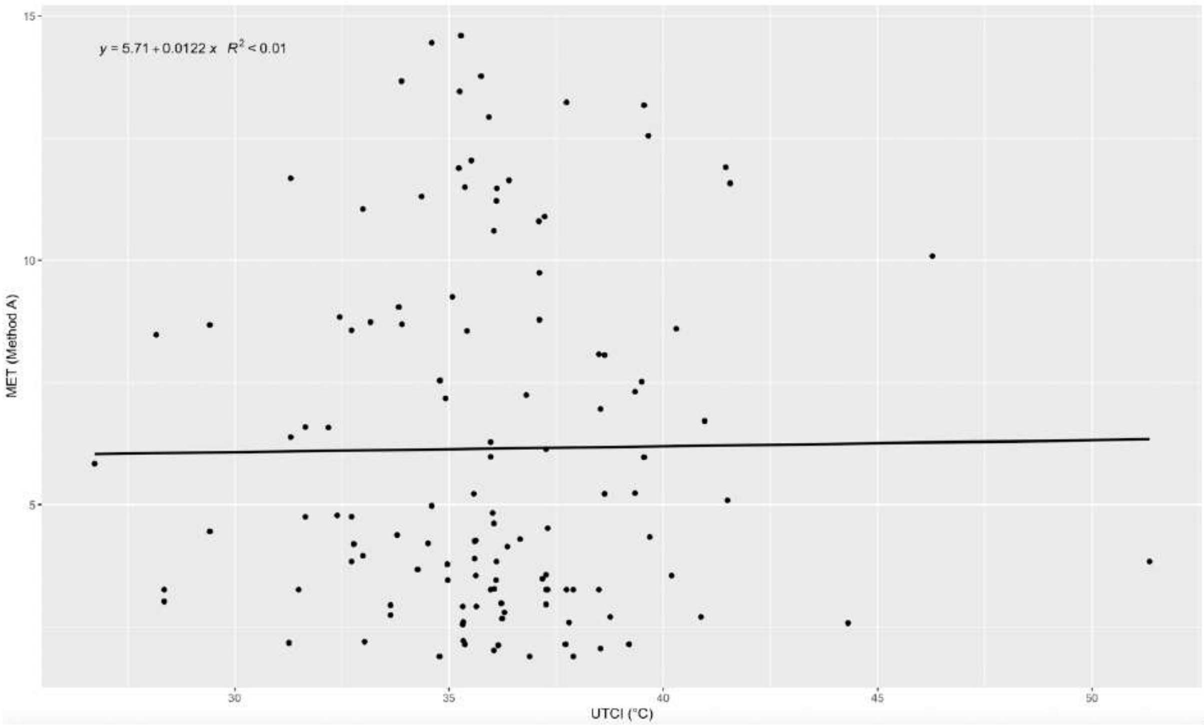

Figure 5b: MET (method A) against UTCI exposure. MET = Metabolic equivalent; UTCI = Universal Thermal Climate Index

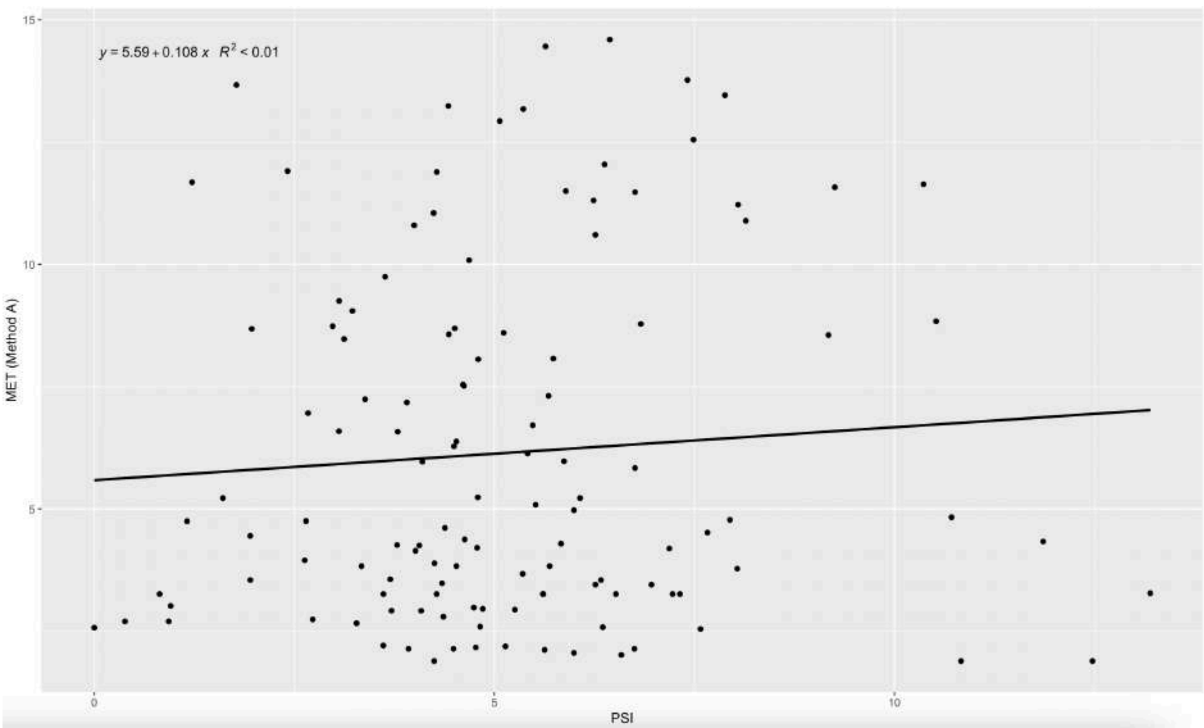

Figure 5c: MET (method A) against maternal heat strain by PSI_{MOD}. MET = Metabolic equivalent. PSI_{MOD} = modified physiological strain index

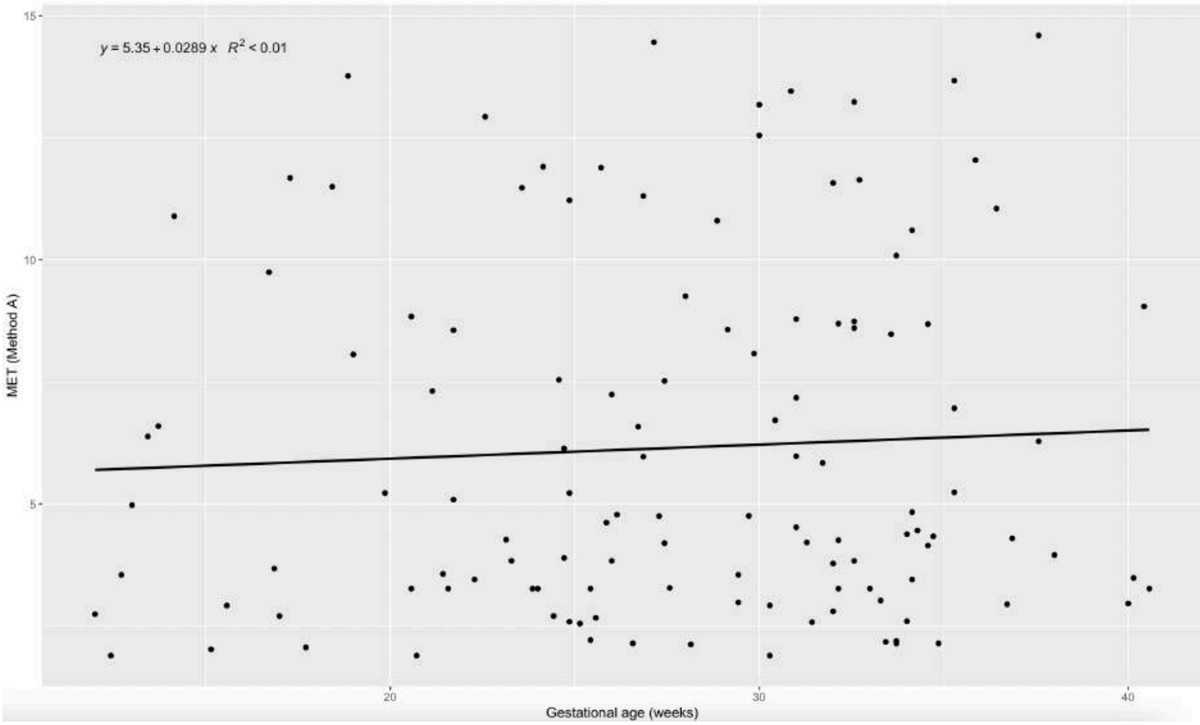

Figure 5d: MET (method A) against gestational age at field visit in weeks. MET = Metabolic equivalent

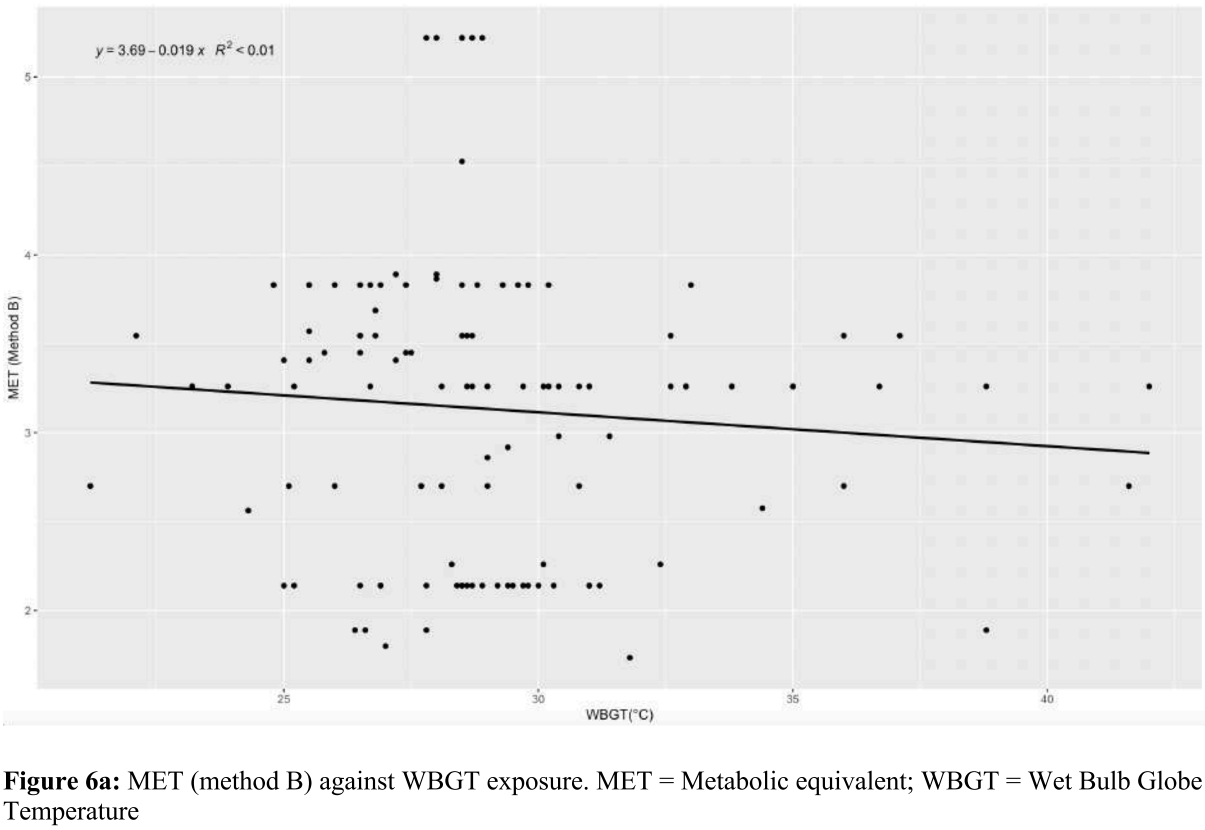

Figure 6a: MET (method B) against WBGT exposure. MET = Metabolic equivalent; WBGT = Wet Bulb Globe Temperature

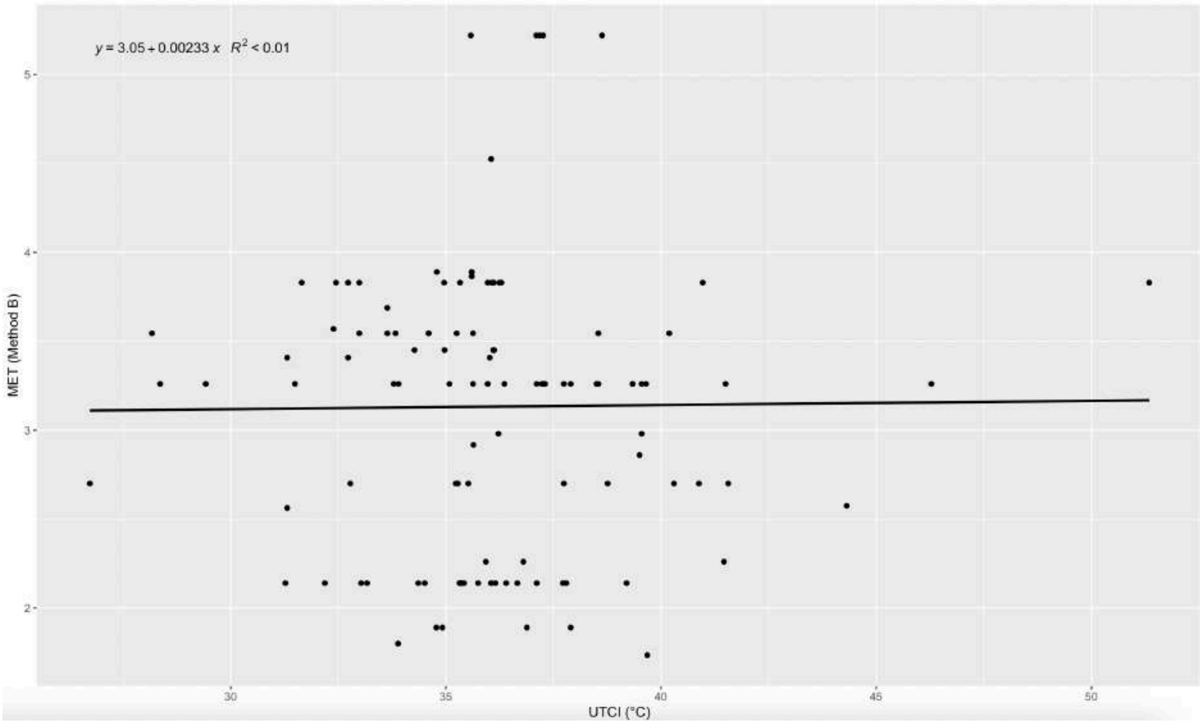

Figure 6b: MET (method B) against UTCI exposure. MET = Metabolic equivalent. UTCI = Universal Thermal Climate Index

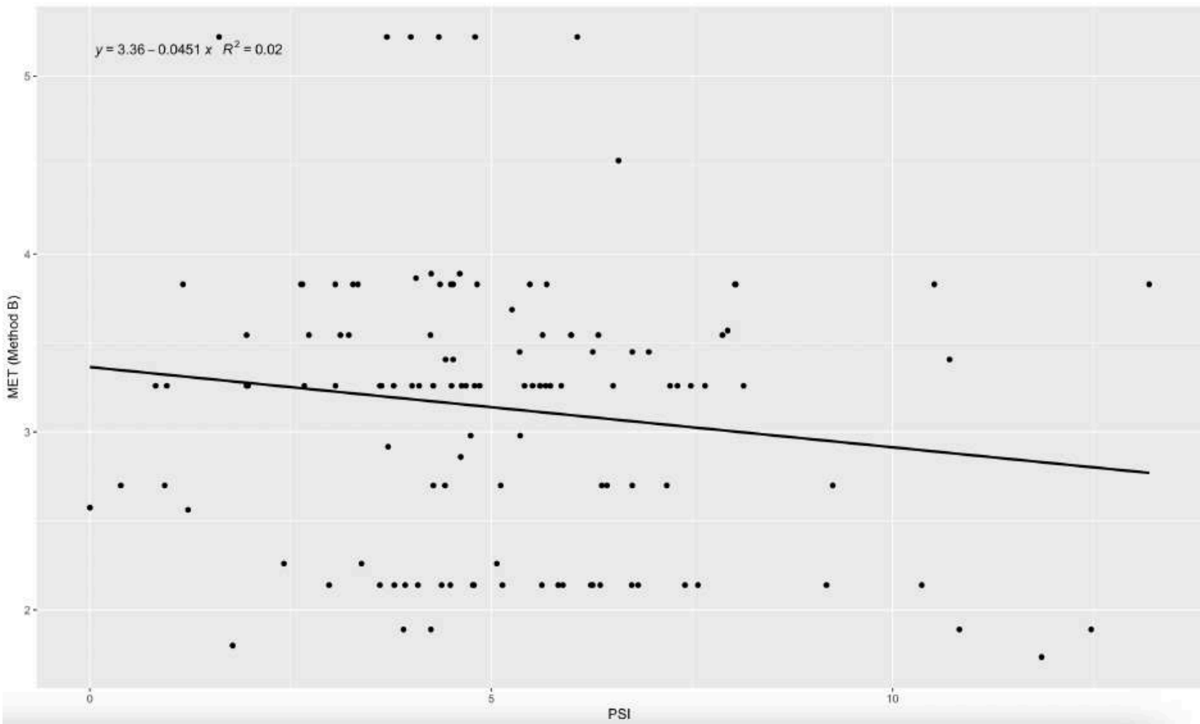

Figure 6c: MET (method B) against maternal heat strain by PSI_{MOD}. MET = Metabolic equivalent; PSI_{MOD} = modified physiological strain index

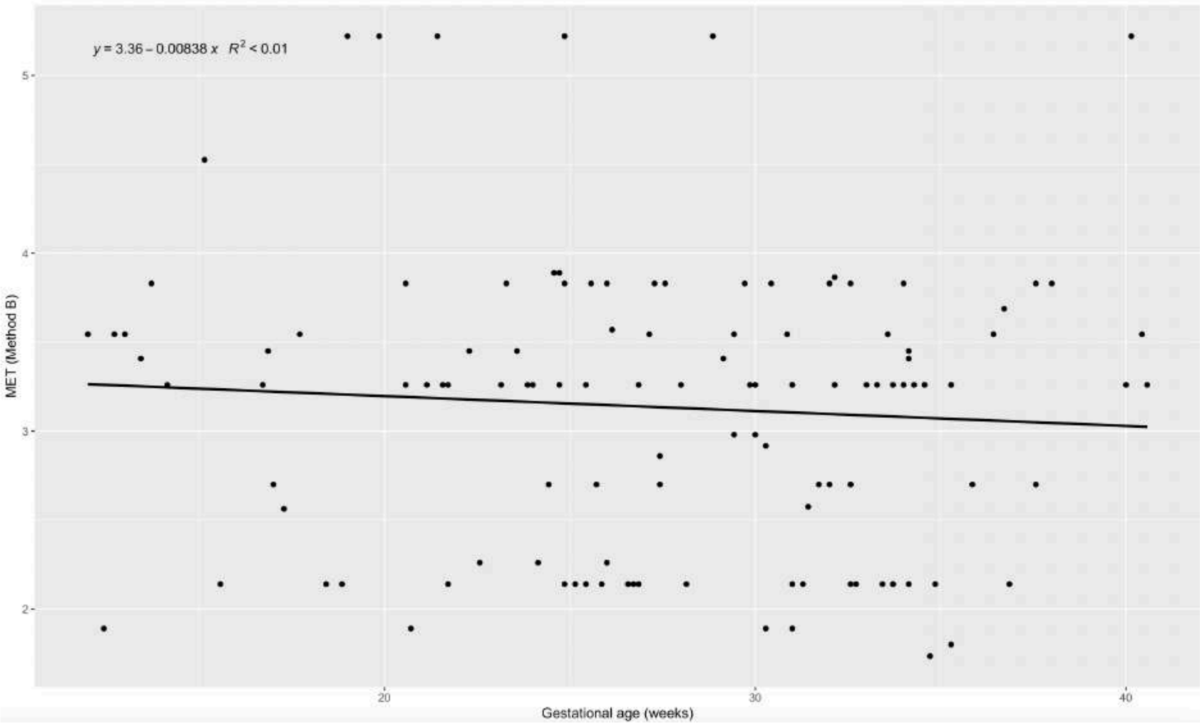

Figure 6d: MET (method B) against gestational age at field visit in weeks. MET = Metabolic equivalent

Figures 5 and 6 demonstrate the poor correlation of both our estimations of energy expenditure with environmental conditions, maternal heat strain or any changes during pregnancy. Again this highlights the need for pregnancy specific algorithms to improve accuracy of wearable technology to aid with detailed physiological understanding.

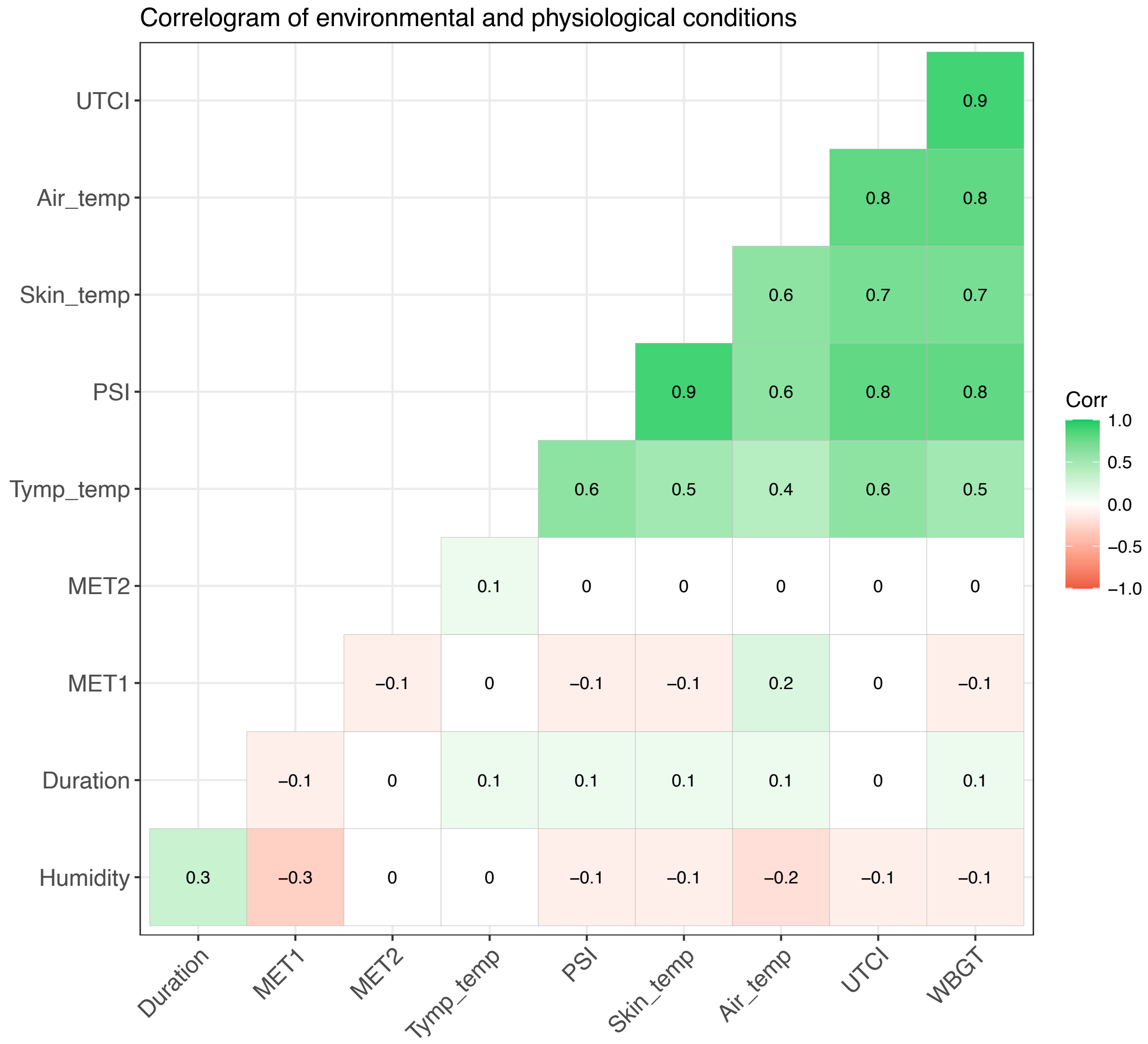

Figure 7: Pearson's correlation coefficient for environmental and physiological variables. UTCI = Universal Thermal Climate Index; WBGT = Wet Bulb Globe Temperature; air_temp = Air temperature (°C); Skin_temp = chest skin temperature (°C); PSI = modified physiological strain index; Tymp_temp = tympanic temperature (°C); MET2 = Metabolic equivalent using observation and historic measurements; MET1 = Metabolic equivalent calculated from the wearable device; Duration = time spent working outdoors; Humidity = relative humidity (%)

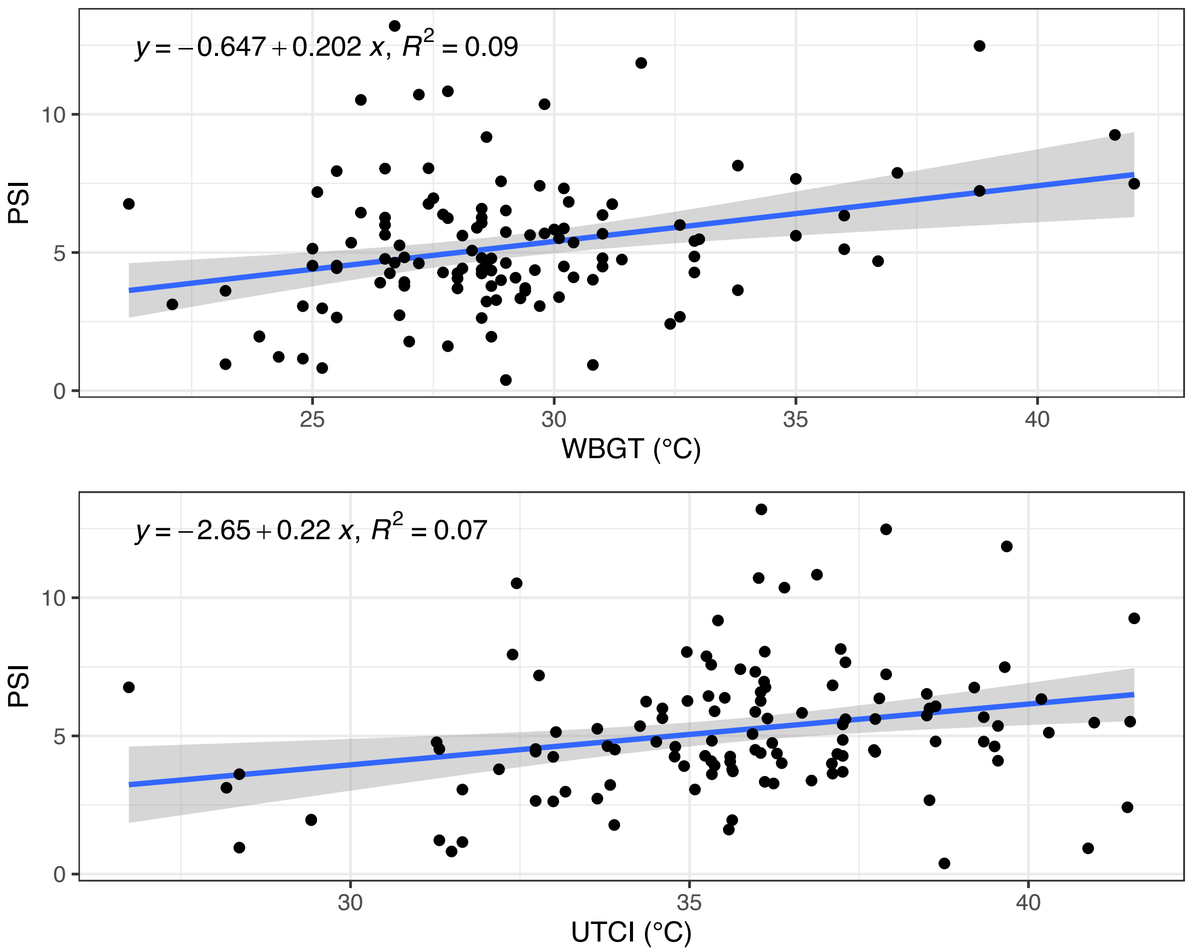

Figure 8: Association between heat stress (by WBGT and UTCI) and heat strain (by PSI_{MOD}). WBGT = Wet Bulb Globe Temperature; UTCI = Universal Thermal Climate Index; PSI_{MOD} = modified physiological strain index

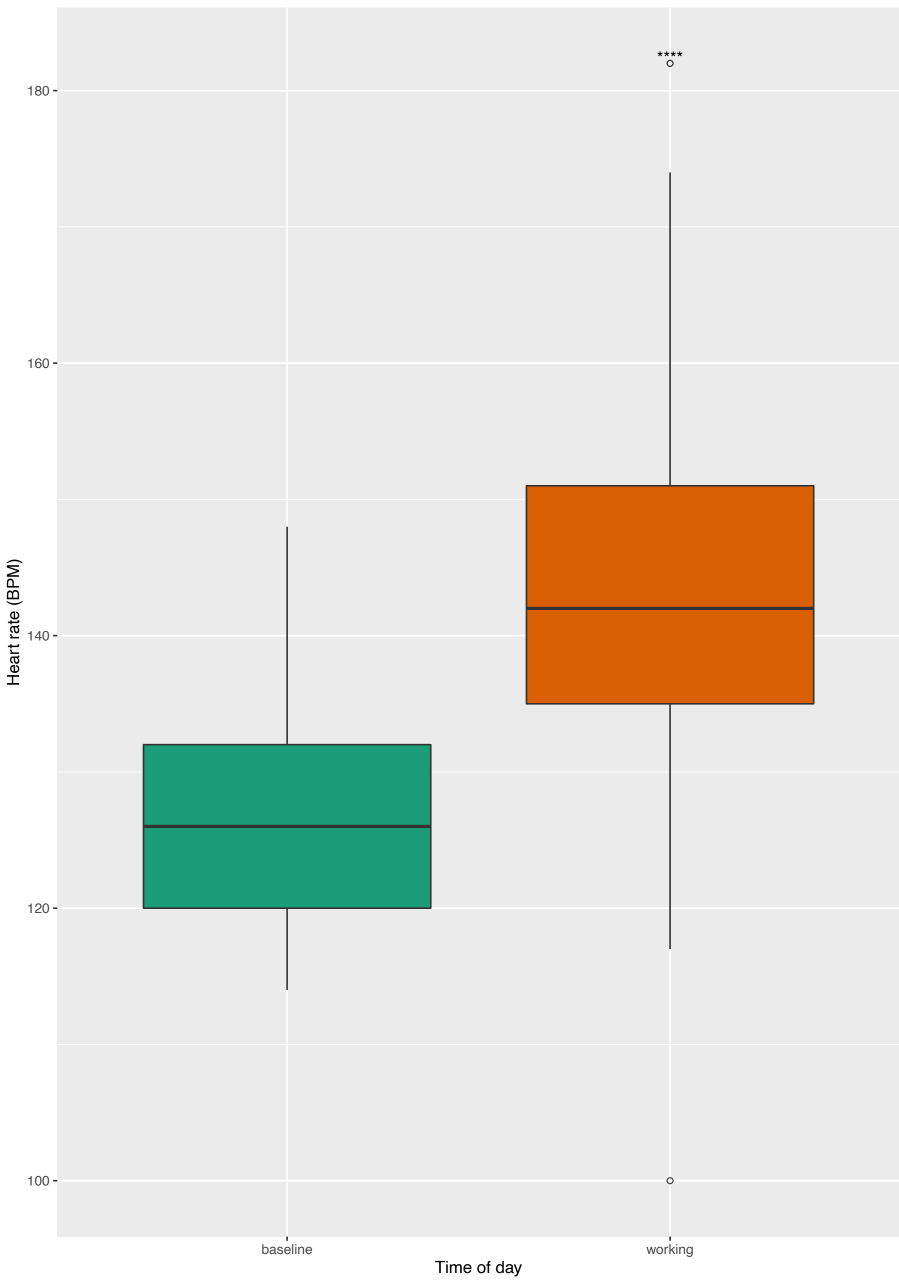

Figure 9: Change in fetal heart rate (BPM = beats per minute) from baseline to during the working shift

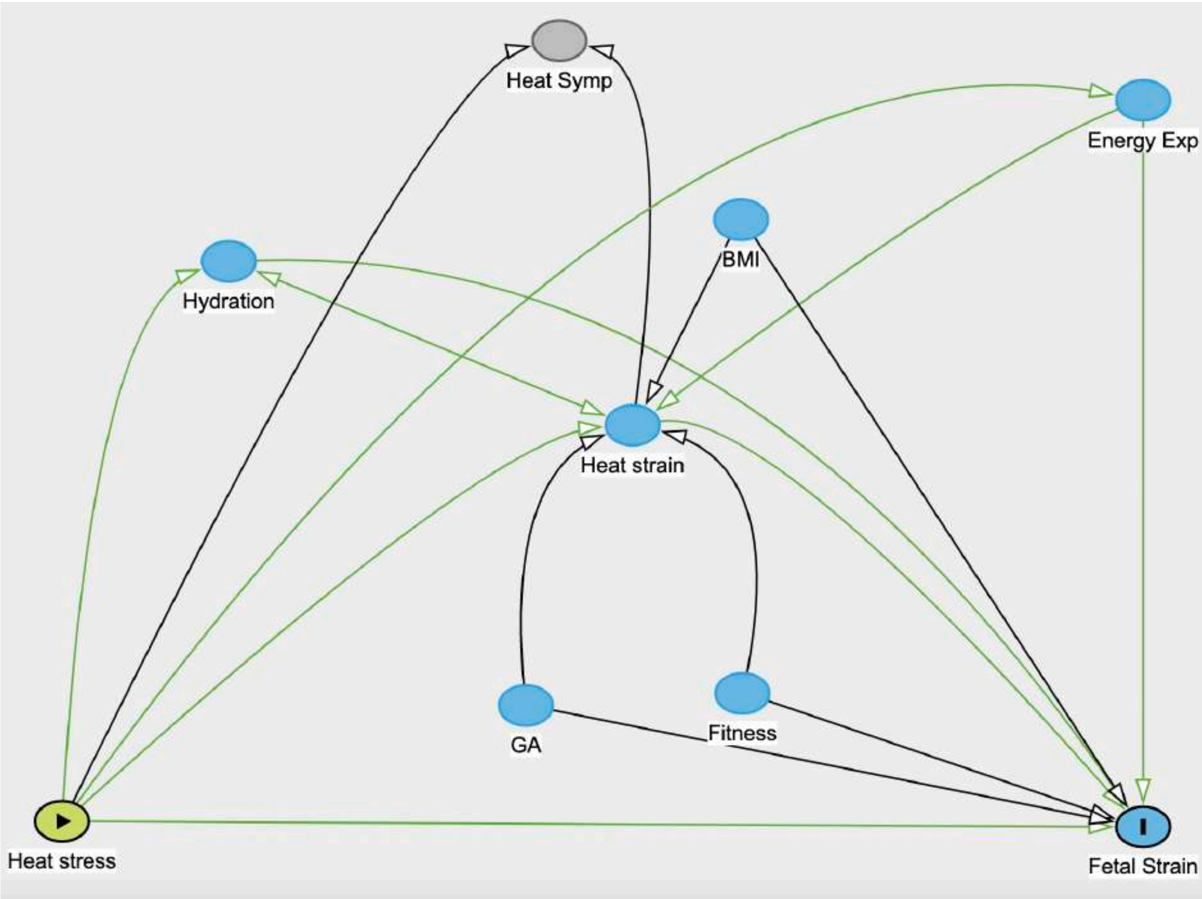

Figure 10: Directed Acyclic Graph (DAG) of heat stress and fetal strain

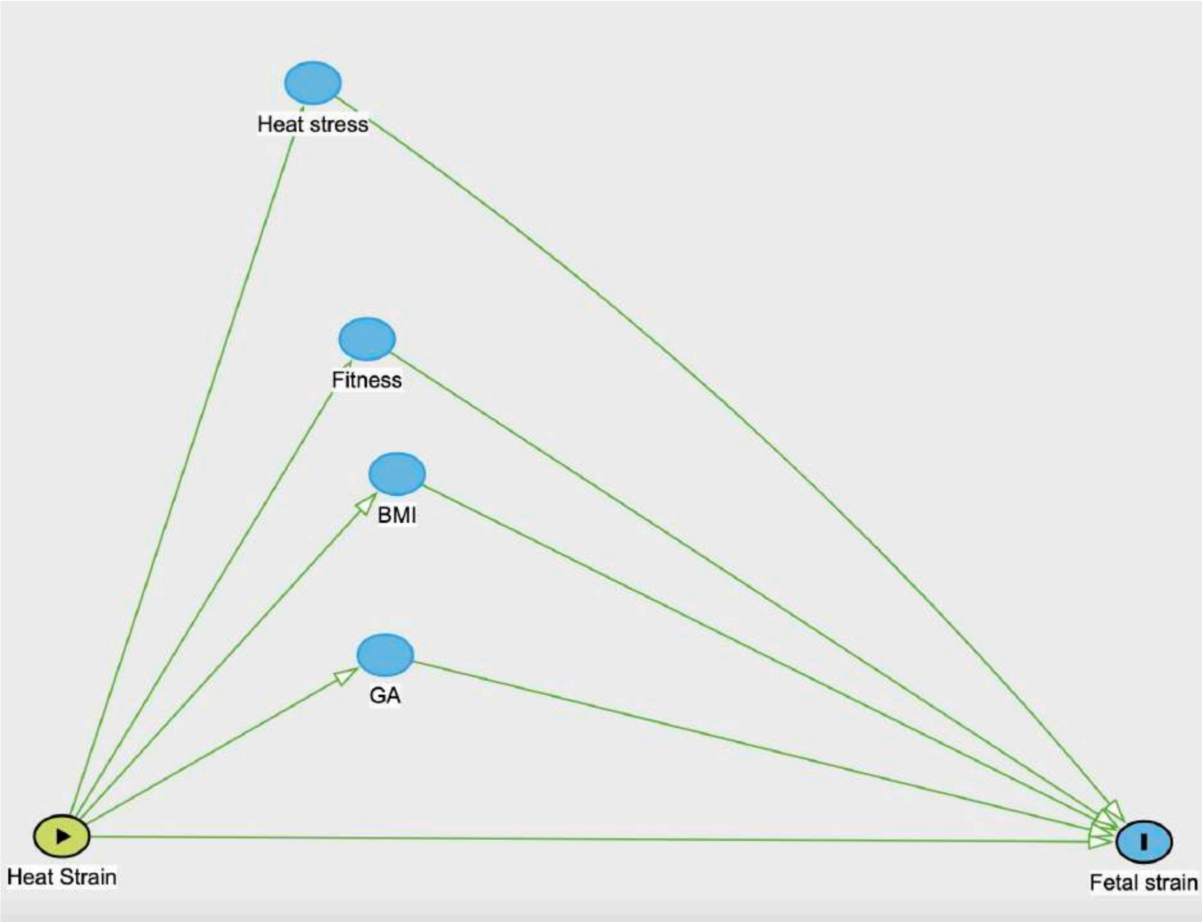

Figure 11: Directed Acyclic Graph of maternal heat strain and fetal strain

R code:
The # on a line indicates notes in the code. Other lines can be run directly in RStudio.

```
#packages
library(dplyr)
library(magrittr)
library(rstatix)
library(ggplot2)
library(ggcorrplot)
library(ggpmisc)
library(ggpubr)
library(RColorBrewer)
library(gridExtra)

#data: t = wide_df gives results for each participant per field visit. a = long_df gives baseline and working
#changes in physiology, environment etc for each participant at each visit.
t <- readRDS("wide_df.rds")
a <- readRDS("long_df.rds")
#table 1 results:

#categorical variables:
dem_soc <- t %>% filter(visit==1)
dem_soc %>% select(dem_ethnicity, soc_occupation, dem_married) %>% summary()


#age - check distribution
```

```
dem_soc %>% shapiro_test(dem_age)
# not normally distributed - present median and IQR

#years in education - check distribution
dem_soc %>% shapiro_test(dem_eduyrs)
# not normally distributed - present median and IQR

dem_soc %>% select(dem_eduyrs) %>% summary()

# obstetric parameter:
gp <- t %>%
  select(dem_screenno, obs_gravida, obs_parity) %>%
  na.omit() %>%
  unique()

gp %>% shapiro_test(obs_gravida)
gp %>% shapiro_test(obs_parity)
#both non parametric - present median and IQR
gp %>% summary()

t %>% shapiro_test(GA_atvisit)
# non parametric - present median and IQR

summary(t$GA_atvisit)

#anthropometric/physical characteristics

t %>% shapiro_test(ant_height)
# normally distributed
summary(t$ant_height)
sd(t$ant_height)

t %>% shapiro_test(ant_weight)
#non-parametric
summary(t$ant_weight)

t %<>% mutate(BMI = (ant_weight/((ant_height/100)^2)))
t %>% shapiro_test(BMI)
summary(t$BMI)

t %<>% mutate(ant_muacave = ((ant_muac1 + ant_muac2)/2))
t %>% shapiro_test(ant_muacave)
#non-parametric

summary(t$ant_muacave)

t %>% shapiro_test(ant_fatpercent)
#non-parametric
summary(t$ant_fatpercent)

# birthoutcomes

table(dem_soc$APO)
table(dem_soc$prem)
table(dem_soc$LBW)
table(dem_soc$sga)
table(dem_soc$alivedead)

#heat illness symptoms
t %<>%
```

```
  mutate(headache = pmax(per_headache_1, per_headache_2, na.rm=T),
         nausea = pmax(per_nausea_1, per_nausea_2, na.rm = T),
         vomiting = pmax(per_vomitting_1, per_vomitting_2, na.rm = T),
         dizziness = pmax(per_dizziness_1, per_dizziness_2, na.rm = T),
         weakness = pmax(per_weakness_1, per_weakness_2, na.rm = T),
         irritability = pmax(per_irritability_1, per_irritability_2, na.rm = T),
         dry_mouth = pmax(per_drymouth_1, per_drymouth_2, na.rm = T),
         muscle_cramp = pmax(per_musclecramps_1, per_musclecramps_2, na.rm = T))

heat_ill <- t %>% select(dem_screenno, visit, headache,
                    nausea, vomiting, dizziness, weakness,
                    irritability, dry_mouth, muscle_cramp)


heat_ill %<>% convert_as_factor(headache,
                         nausea, vomiting, dizziness, weakness,
                         irritability, dry_mouth, muscle_cramp)

# melt data frame to long format
h_melt <- data.table::melt(heat_ill[, c(1, 3:10)], id.vars = "dem_screenno")

h_melt %<>% na.omit()

# add ggplot
Fig5 <- ggplot(data = h_melt) +
  geom_bar(aes(x = variable, fill = value, colour = value), color="black", position=position_dodge()) +
  scale_fill_manual(values=c( "#FFFFFF", "#d8b365")) +
  theme_minimal() +
  ylab("count") +
  xlab("heat illness symptoms") +
  theme(legend.title = element_blank())


table(t$heat_symp)



#### univariable models for supplement table one ####

library(lme4)

a1 <- lmer(psimax ~ fbc_hgb + (1|dem_screenno), data = a)
a2 <- lmer(psimax ~ osmo + (1|dem_screenno), data = a)
a3 <- lmer(psimax ~ fbc_hct + (1|dem_screenno), data = a)
a4 <- lmer(psimax ~ GA_atvisit + (1|dem_screenno), data = a)
a5 <- lmer(psimax ~ tymptem + (1|dem_screenno), data = a)
a6 <- lmer(psimax ~ duration  + (1|dem_screenno), data = a)
a7 <- lmer(psimax ~ MET1_ave + (1|dem_screenno), data = a)
a9 <- lmer(psimax ~ wlk_distance + (1|dem_screenno), data = a)
a10 <- lmer(psimax ~ obs_APO + (1|dem_screenno), data = a)
a11 <- lmer(psimax ~ ant_weight + (1|dem_screenno), data = a)
a12 <- lmer(psimax ~ ant_tbw  + (1|dem_screenno), data = a)
a13 <- lmer(psimax ~ ant_fatmass  + (1|dem_screenno), data = a)
a14 <- lmer(psimax ~ del_sex +  (1|dem_screenno), data = a)
a15 <- lmer(psimax ~ del_weight  + (1|dem_screenno), data = a)
a16 <- lmer(psimax ~ WeightCentile  + (1|dem_screenno), data = a)
a17 <- lmer(psimax ~ GA_days + (1|dem_screenno), data = a)
a18 <- lmer(psimax ~ preg_bp  + (1|dem_screenno), data = a)
a19 <- lmer(psimax ~ dem_age + (1|dem_screenno), data = a)
a20 <- lmer(psimax ~ APO + (1|dem_screenno), data = a)
```

```
a21 <- lmer(psimax ~ preg_inf  + (1|dem_screenno), data = a)
a22 <- lmer(psimax ~ MET1_ave*duration + (1|dem_screenno), data = a)
a23 <- lmer(psimax ~ (1|dem_screenno), data = a)
a24 <- lmer(psimax ~ AE_all + (1|dem_screenno), data = a)
a26 <- lmer(psimax ~ max_wbgt + (1|dem_screenno) , data = a)
a27 <- lmer(psimax ~ ave_wbgt + (1|dem_screenno), data = a)
a28 <- lmer(psimax ~ max_UTCI + (1|dem_screenno), data = a)
a29 <- lmer(psimax ~ ave_UTCI + (1|dem_screenno), data = a)
a30 <- lmer(psimax ~ max_TA + (1|dem_screenno), data = a)
a31 <- lmer(psimax ~ ave_TA + (1|dem_screenno), data = a)
a32 <- lmer(psimax ~ max_RH + (1|dem_screenno), data = a)
a33 <- lmer(psimax ~ ave_RH + (1|dem_screenno), data = a)


#use car::Confint(model) to get estimate and confidence intervals
#use car::Anova(model) to get p values

# univariate analysis of fetal heart rate:

b2 <- lmer(fhr ~ max_UTCI + (1|dem_screenno), data = a)
b3 <- lmer(fhr ~ ave_UTCI + (1|dem_screenno), data = a)
b5 <- lmer(fhr ~ max_wbgt + (1|dem_screenno), data = a)
b6 <- lmer(fhr ~ ave_wbgt + (1|dem_screenno), data = a)
b7 <- lmer(fhr ~ max_TA + (1|dem_screenno), data = a)
b8 <- lmer(fhr ~ ave_TA + (1|dem_screenno), data = a)
b9 <- lmer(fhr ~ max_RH + (1|dem_screenno), data = a)
b10 <- lmer(fhr ~ ave_RH + (1|dem_screenno), data = a)
b11 <- lmer(fhr ~ duration + (1|dem_screenno), data = a)
b12 <- lmer(fhr ~ MET1_ave + (1|dem_screenno), data = a)
b13 <- lmer(fhr ~ AE_all + (1|dem_screenno), data = a)
b14 <- lmer(fhr ~ tymptem + (1|dem_screenno), data = a)
b15 <- lmer(fhr ~ osmo + (1|dem_screenno), data = a)
b16 <- lmer(fhr ~ fbc_hct + (1|dem_screenno), data = a)
b17 <- lmer(fhr ~ ant_tbw + (1|dem_screenno), data = a)
b18 <- lmer(fhr ~ ant_weight + (1|dem_screenno), data = a)
b19 <- lmer(fhr ~ dem_age + (1|dem_screenno), data = a)
b20 <- lmer(fhr ~ wlk_distance + (1|dem_screenno), data = a)
b21 <- lmer(fhr ~ fbc_hgb + (1|dem_screenno), data = a)
b22 <- lmer(fhr ~ ant_fatmass + (1|dem_screenno), data = a)
b23 <- lmer(fhr ~ GA_atvisit + (1|dem_screenno), data = a)
b24 <- lmer(fhr ~ obs_APO + (1|dem_screenno), data = a)
b25 <- lmer(fhr ~ APO + (1|dem_screenno), data = a)
b26 <- lmer(fhr ~ skin_temp + (1|dem_screenno), data = a)
b27 <- lmer(fhr ~ heartrate + (1|dem_screenno), data = a)
b28 <- lmer(fhr ~ psimax + (1|dem_screenno), data = a)

#use car::Confint(model) to get estimate and confidence intervals
#use car::Anova(model) to get p values


# fetal stress as a categorical outcome

a$fetal_stress <- as.factor(a$fetal_stress)

c2 <- glmer(fetal_stress ~ max_UTCI + (1|dem_screenno), data = a, family = binomial)
c3 <- glmer(fetal_stress ~ ave_UTCI + (1|dem_screenno), data = a, family = binomial)
c5 <- glmer(fetal_stress ~ max_wbgt + (1|dem_screenno), data = a, family = binomial)
c6 <- glmer(fetal_stress ~ ave_wbgt + (1|dem_screenno), data = a, family = binomial)
c7 <- glmer(fetal_stress ~ max_TA + (1|dem_screenno), data = a, family = binomial)
c8 <- glmer(fetal_stress ~ ave_TA + (1|dem_screenno), data = a, family = binomial)
```

```
c9 <- glmer(fetal_stress ~ max_RH + (1|dem_screenno), data = a, family = binomial)
c10 <- glmer(fetal_stress ~ ave_RH + (1|dem_screenno), data = a, family = binomial)
c11 <- glmer(fetal_stress ~ duration + (1|dem_screenno), data = a, family = binomial)
c12 <- glmer(fetal_stress ~ MET1_ave + (1|dem_screenno), data = a, family = binomial)
c13 <- glmer(fetal_stress ~ AE_all + (1|dem_screenno), data = a, family = binomial)
c14 <- glmer(fetal_stress ~ tymptem + (1|dem_screenno), data = a, family = binomial)
c15 <- glmer(fetal_stress ~ osmo + (1|dem_screenno), data = a, family = binomial)
c16 <- glmer(fetal_stress ~ fbc_hct + (1|dem_screenno), data = a, family = binomial)
c17 <- glmer(fetal_stress ~ ant_tbw + (1|dem_screenno), data = a, family = binomial)
c18 <- glmer(fetal_stress ~ ant_weight + (1|dem_screenno), data = a, family = binomial)
c19 <- glmer(fetal_stress ~ dem_age + (1|dem_screenno), data = a, family = binomial)
c20 <- glmer(fetal_stress ~ wlk_distance + (1|dem_screenno), data = a, family = binomial)
c21 <- glmer(fetal_stress ~ fbc_hgb + (1|dem_screenno), data = a, family = binomial)
c22 <- glmer(fetal_stress ~ ant_fatmass + (1|dem_screenno), data = a, family = binomial)
c23 <- glmer(fetal_stress ~ GA_atvisit + (1|dem_screenno), data = a, family = binomial)
c24 <- glmer(fetal_stress ~ obs_APO + (1|dem_screenno), data = a, family = binomial)
c25 <- glmer(fetal_stress ~ APO + (1|dem_screenno), data = a, family = binomial)
c26 <- glmer(fetal_stress ~ skin_temp + (1|dem_screenno), data = a, family = binomial)
c27 <- glmer(fetal_stress ~ heartrate + (1|dem_screenno), data = a, family = binomial)
c28 <- glmer(fetal_stress ~ psimax + (1|dem_screenno), data = a, family = binomial)


## to get odds ratios

fs_list <- list(c2,c3,c5,c6,c7,c8,c9,c10,c11,c12,c13,
c14,c15,c16,c17,c18,c19,c20,c21,c22,c23,c24,
c25, c26,c27, c28)

### write functions
get_se <- function(x){sqrt(diag(vcov(x)))}
get_tab <- function(x,y){
  cbind(Est = fixef(x), LL = fixef(x) - 1.96 * y, UL = fixef(x) + 1.96 *y)
}

get_or <- function(x){exp(x)}

### list of OR with CI.

se_list <- map(fs_list, get_se)
tab_list <- map2(fs_list, se_list, get_tab)
or_list <- map(tab_list, get_or)
or_list


## to get p value
pv_list <- map(fs_list, car::Anova)


#### heat stress and heat strain ####

#remove resting state
ab <- a %>% filter(psi > 0)

locknots <- quantile(ab$max_wbgt,c(0.25, 0.9), na.rm=T) # location of the knots of the spline (in the median
and 90th percentile of the tmean distribution)
locknot2 <- quantile(ab$max_wbgt, c(0.5), na.rm = T)
locknot3 <- quantile(ab$max_wbgt, c(0.5, 0.9), na.rm=T)

wbgtmaxb1 <- onebasis(ab$max_wbgt, fun="lin")
wbgtmaxb2 <- onebasis(ab$max_wbgt, fun="ns", knots = locknot2)
```

```
wbgtmaxb3 <- onebasis(ab$max_wbgt, fun="bs", degree=2, knots=locknots)
wbgtmaxb4 <- onebasis(ab$max_wbgt, fun="bs", degree=2, knots=locknot2)
wbgtmaxb5 <- onebasis(ab$max_wbgt, fun="bs", degree=2, knots=locknot3)

# RUN MODELS
psi1 <- lm(psimax ~ wbgtmaxb1, ab)  # LINEAR
psi2 <- lm(psimax ~ wbgtmaxb2, ab)  # NON-LINEAR WITH NS
psi3 <- lm(psimax ~ wbgtmaxb3, ab)  # NON-LINEAR WITH BS
psi4 <- lm(psimax ~ wbgtmaxb4, ab)
psi5 <- lm(psimax ~ wbgtmaxb5, ab)

AIC(psi1)
AIC(psi2)
AIC(psi3)
AIC(psi4)
AIC(psi5)

# PREDICT
predpsi1 <- crosspred(wbgtmaxb1,psi1)
plot(predpsi1)

# UTCI
ac <- ab %>% filter(max_UTCI <45)

nots <- quantile(ac$max_UTCI,c(0.25, 0.9), na.rm=T) # location of the knots of the spline (in the median and
90th percentile of the tmean distribution)
not2 <- quantile(ac$max_UTCI, c(0.5), na.rm = T)
not3 <- quantile(ac$max_UTCI, c(0.5, 0.9), na.rm=T)


utcimaxb1 <- onebasis(ac$max_UTCI, fun="lin")
utcimaxb2 <- onebasis(ac$max_UTCI, fun="ns", knots = not2)
utcimaxb3 <- onebasis(ac$max_UTCI, fun="bs", degree=2, knots=nots)
utcimaxb4 <- onebasis(ac$max_UTCI, fun="bs", degree=2, knots=not2)
utcimaxb5 <- onebasis(ac$max_UTCI, fun="bs", degree=2, knots=not3)


# RUN MODELS
psia <- lm(psimax ~ utcimaxb1, ac)  # LINEAR
psib <- lm(psimax ~ utcimaxb2, ac)  # NON-LINEAR WITH NS
psic <- lm(psimax ~ utcimaxb3, ac)  # NON-LINEAR WITH BS
psid <- lm(psimax ~ utcimaxb4, ac)
psie <- lm(psimax ~ utcimaxb5, ac)

AIC(psia)
AIC(psib)
AIC(psic)
AIC(psid)
AIC(psie)

predpsia <- crosspred(utcimaxb1, psia)
plot(predpsia)



#### Multivariable models ####

# functions
get_se <- function(x){sqrt(diag(vcov(x)))}
get_tab <- function(x,y){
```

```
  cbind(Est = fixef(x), LL = fixef(x) - 1.96 * y, UL = fixef(x) + 1.96 *y)
}

get_or <- function(x){exp(x)}

#### fetal strain ###
## Model 1

mod_1 <- glmer(fetal_stress ~ wbgtmaxb1 + (1|dem_screenno), data = a, family = binomial)
mod_2 <- glmer(fetal_stress ~ utcimaxb1 + (1|dem_screenno), data = a, family = binomial)

se_mod1 <- get_se(mod_1)
tab_mod1 <- get_tab(mod_1, se_mod1)
or_tab_mod1 <- get_or(tab_mod1)
or_tab_mod1

se_mod2 <- get_se(mod_2)
tab_mod2 <- get_tab(mod_2, se_mod2)
or_tab_mod2 <- get_or(tab_mod2)
or_tab_mod2


## model 2 ## heat stress and heat strain to get adjusted direct effects based
# on a priori assumptions and DAG

mod_3 <- glmer(fetal_stress ~ wbgtmaxb1 + psimax + (1|dem_screenno), data = a, family = binomial)

mod_4 <- glmer(fetal_stress ~ utcimaxb1 + psimax + (1|dem_screenno), data = a, family = binomial)

summary(mod_3)
summary(mod_4)

se_mod3 <- get_se(mod_3)
tab_mod3 <- get_tab(mod_3, se_mod3)
or_tab_mod3 <- get_or(tab_mod3)
or_tab_mod3

se_mod4 <- get_se(mod_4)
tab_mod4 <- get_tab(mod_4, se_mod4)
or_tab_mod4 <- get_or(tab_mod4)
or_tab_mod4

## determine heat strain and fetal strain adjusted for confounders

mod_5 <- glmer(fetal_stress ~ wbgtmaxb1 + psimax + GA_atvisit + wlk_distance
            + ant_fatmass + (1|dem_screenno), data = a, family = binomial)

mod_6 <- glmer(fetal_stress ~ utcimaxb1 + psimax + GA_atvisit + wlk_distance
            + ant_fatmass + (1|dem_screenno), data = a, family = binomial)

summary(mod_5)
summary(mod_6)

se_mod5 <- get_se(mod_5)
tab_mod5 <- get_tab(mod_5, se_mod5)
or_tab_mod5 <- get_or(tab_mod5)
or_tab_mod5

se_mod6 <- get_se(mod_6)
tab_mod6 <- get_tab(mod_6, se_mod6)
```

```
or_tab_mod6 <- get_or(tab_mod6)
or_tab_mod6


#### same but for fetal heart rate

## model 1 ## total effect of heat stress of FHR

mod_7 <- lmer(fhr ~ utcimaxb1 + (1|dem_screenno), data = a)

summary(mod_7)
AIC(mod_7)
car::Anova(mod_7)
confint(mod_7)


mod_8 <- lmer(fhr ~ wbgtmaxb1 + (1|dem_screenno), data = a)

summary(mod_8)
AIC(mod_8)
car::Anova(mod_8)
confint(mod_8)

pred_8 <- crosspred(wbgtmaxb1, mod_8)
pred_7 <- crosspred(utcimaxb1, mod_7)

## model 2

mod_9 <- lmer(fhr ~ utcimaxb1 + psimax + (1|dem_screenno), data = a)

summary(mod_9)
AIC(mod_9)
car::Anova(mod_9)
confint(mod_9)

mod_10 <- lmer(fhr ~ wbgtmaxb1 + psimax + (1|dem_screenno), data = a)

summary(mod_10)
AIC(mod_10)
car::Anova(mod_10)
confint(mod_10)

## model 3

mod_11 <- lmer(fhr ~ utcimaxb1 + psimax+ ant_fatmass + GA_atvisit
          + wlk_distance + (1|dem_screenno), data = a)

summary(mod_11)
AIC(mod_11)
car::Anova(mod_11)
confint(mod_11)

mod_12 <- lmer(fhr ~ wbgtmaxb1 + psimax+ ant_fatmass + GA_atvisit
           + wlk_distance + (1|dem_screenno), data = a)

summary(mod_12)
AIC(mod_12)
car::Anova(mod_12)
confint(mod_12)
```

```
#test model assumptions:
ab <- a %>% select(dem_screenno, wlk_distance, GA_atvisit, ant_fatmass, psimax, max_wbgt)
Plot.Model <-plot(resid(mod_12),ab$fhr)

#test homogeneity of variance using Levene test:

ab$Model.fhr.Res<- residuals(mod_12) #extracts the residuals and places them in a new column in our original data table
ab$Abs.fhr.Res <-abs(ab$Model.fhr.Res) #creates a new column with the absolute value of the residuals
ab$Model.fhr.Res2 <- ab$Abs.fhr.Res^2 #squares the absolute values of the residuals to provide the more robust estimate
Levene.Model.fhr <- lm(Model.fhr.Res2 ~ dem_screenno, data=ab) #ANOVA of the squared residuals
anova(Levene.Model.fhr) #displays the results


#### visualisations ####

##Fig 2

t$wbgt_cat2 <- factor(t$wbgt_cat, levels = rev(levels(t$wbgt_cat)))
t$UTCI_cat2 <- factor(t$UTCI_cat, levels = rev(levels(t$UTCI_cat)))
t1 <- t %>% select(wlk_date, max_UTCI, UTCI_cat2)
t1 %<>% na.omit()

b4 <- ggplot(t,aes(wlk_date, max_wbgt)) +
  geom_point(aes(colour = factor(wbgt_cat2)), size =2)+
   labs(title = "Wet Bulb Globe Temperature", x = "month", y = "WBGT(\u00B0C)") +
   scale_colour_brewer(palette = "RdYlGn", name = "WBGT category") +
   theme_bw()
 b4
>b5 <- ggplot(t1,aes(wlk_date, max_UTCI)) +
 geom_point(aes(colour = factor(UTCI_cat2)), size =2) +
  labs(title = "Universal Thermal Comfort Index", x = "month", y = "UTCI(\u00B0C)") +
   scale_color_brewer(palette = "RdYlGn", name = "UTCI category", labels = c("EH", "VSH", "SH", "MH")) +
   theme_bw()
 b5

 Fig2 <- grid.arrange(b4, b5, ncol=2)

## Fig 3

#gather for change in temp

mat_temp <- t %>% select(dem_screenno, TBS, Tmax)

mat <- mat_temp %>% tidyr::pivot_longer(c(TBS, Tmax), names_to = "temperature", values_to = "degree")

#change in skin temperature:

skt_temp <- t %>% select(dem_screenno, cam_chesttemp_1, SKT.Max.)
skt_temp %<>% na.omit()

skt <- skt_temp %>% tidyr::pivot_longer(c(cam_chesttemp_1, SKT.Max.), names_to = "temperature", values_to = "degree")

b11 <- ggplot(mat, aes(x = temperature, y = degree, group = temperature, fill = temperature)) +
 geom_boxplot(outlier.shape = 1) +
 labs(title = "Change in mean maternal temperature", x = "Time of day", y = "Tympanic temperature (\u00B0C)") +
```

```
 scale_fill_brewer(palette = "Dark2", name = "Time of day", labels = c("Baseline", "Working")) +
 theme_bw() +
   theme(axis.text.x = element_blank()) +
 stat_compare_means(paired = T, label.x = 1, label.y = 38.6)

 b11

 b11b <- ggplot(skt, aes(x = temperature, y = degree, group = temperature, fill = temperature)) +
   geom_boxplot(outlier.shape = 1) +
   labs(title = "Change in mean maternal skin temperature", x = "Time of day", y = "Skin temperature
(\u00B0C)") +
   scale_fill_brewer(palette = "Dark2", name = "Time of day", labels = c("Baseline", "Working")) +
   theme_bw() +
   theme(axis.text.x = element_blank()) +
   stat_compare_means(paired = T, label.x = 1, label.y = 41.1)

 b11b

Fig3 <- grid.arrange(b11, b11b, ncol=2)


## fig4 – output from multilevel model

par(mfrow=c(1,2))
plot(pred_8, xlab = expression(paste("WBGT (",degree,"C)")),
     ylab = "Change in FHR",
     col = "dark red")
title(main = "Wet Bulb Globe Temperature")
plot(pred_7, xlab = expression(paste("UTCI (",degree,"C)")),
     ylab = "Change in FHR",
     col = "dark red")
title(main = "Universal Thermal Climate Index")
```

Topic guide: Climate change and its health impacts on rural Gambian female farmers; a qualitative study of local understanding and adaptations focused on pregnancy (CHIQ)

Version 3.0
25/03/2021

I want to thank you for taking the time to meet with me today. My name is____________________ and I would like to talk to you about your experiences as a farmer and (becoming) mother, especially with regard to heat.

The interview should take about an hour and a half. I would like to record the session because I don't want to miss any of your comments. Are you happy for this to happen? No-one outside the project team will have access to the recording and after the data have been transcribed and analysed the recordings will be destroyed. I will also be taking some notes during the session to remind myself of important thoughts and ideas.

All responses will be kept confidential. This means that your interview responses will only be shared with my supervisors and we will ensure that any information we include in our report does not identify you as the respondent. You don't have to talk about anything you don't want to share and you may end the interview at any time.

Are there any questions about what I have just explained? Are you willing to participate in this interview?

<u>Warm-up questions:</u>
How old are you? / When were you born?

Have you always lived in this place?

Tell me about your family.

{depending on whether she's pregnant or has just delivered}: How many children do you have? Is this the first time you are pregnant? How are you feeling with this pregnancy?

Working habits & pregnancy

1. Please describe your "workplace" ["farm/garden"] and the type of work that you do.
   [probe] Can you tell me about any other people you work with? Who helps you with your work?
2. When did you start working outside regularly?
3. Please describe if and how your working habits changed when you became pregnant.
4. What is the weather usually like when you are working?
   - Are there changes over the year?
   - Can you describe the weather over the course of a working day from morning to evening?
   - Can you describe what working outside is like usually when it is hot?
   - Can you describe what working outside is like when it is very hot, and you are pregnant versus when you are not pregnant?
5. {depending on whether she already has had children or not}: How was working outside when it was hot during your other pregnancies?
6. Can you describe if the heat impacts you and the baby?

- [probe, if speaking in hypothetical] Can you tell me about a time that you experienced the impacts that you described yourself?

What do you currently do to protect yourself and the baby against the heat during work?

7. According to you, what could be important things to do when it is very hot to protect yourself (and the baby)?
    - Probe: Can you please describe how could you adapt your work to reduce the impact of the heat?
8. Do you feel you are able to take these measures?
    - Probe: What is stopping you from taking these measures?
    - Probe: What would you need in order to use these measures?
9. What would happen if you could not go to work?

Perceptions of climate change:

10. From your experience, has the weather changed over the last years?
    - {if yes}: How? Why do you think this is happening?
    - {if yes}: In your opinion, have these changes affected everyone equally?
    - {if yes}: What impacts does the changing weather have on you as a farmer?
    - **{if no}:** What does climate change mean to you? Do you think it will have any impacts? Please describe from your understanding of which impacts, where, and on whom.
11. According to you how will the weather continue to change in the future?
12. Describe how you think your life and that of your children will be affected by these changes in future years.
13. Can you describe any hopes you might have for your children's future?
14. Can you describe any worries you might have for your children's future?

Reproductive decision-making:

15. Can you describe how you usually decide to become pregnant?
    - What factors influence whether you decide to become pregnant?
16. How do you feel about having this pregnancy/baby?
    - Why did you want to have another baby at this time?
17. How do you feel about family planning/contraception?
    - What factors would make you want to use family planning or contraception?
    - Could you get access to contraception if you wanted to use it? Please describe how and where.
    - Can you describe any barriers you feel you would face to accessing family planning?

Non-leading prompts for interviewer:

That sounds very interesting, can you tell me more about this?
Could you expand more on …
You mentioned before ... can you explain that in more detail?
How did you feel when … happened?
What were you thinking about … ?

Supplementary material

Assessing the impact of heat stress on growth faltering in the first 1000 days of life in rural Gambia.

Ana Bonell, Ana Vicedo-Cabrera, Kris Murray, Giovenale Moirano, Bakary Sonko, Sophie Moore, Andy Haines, Andrew Prentice

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Exploration of seasonality:

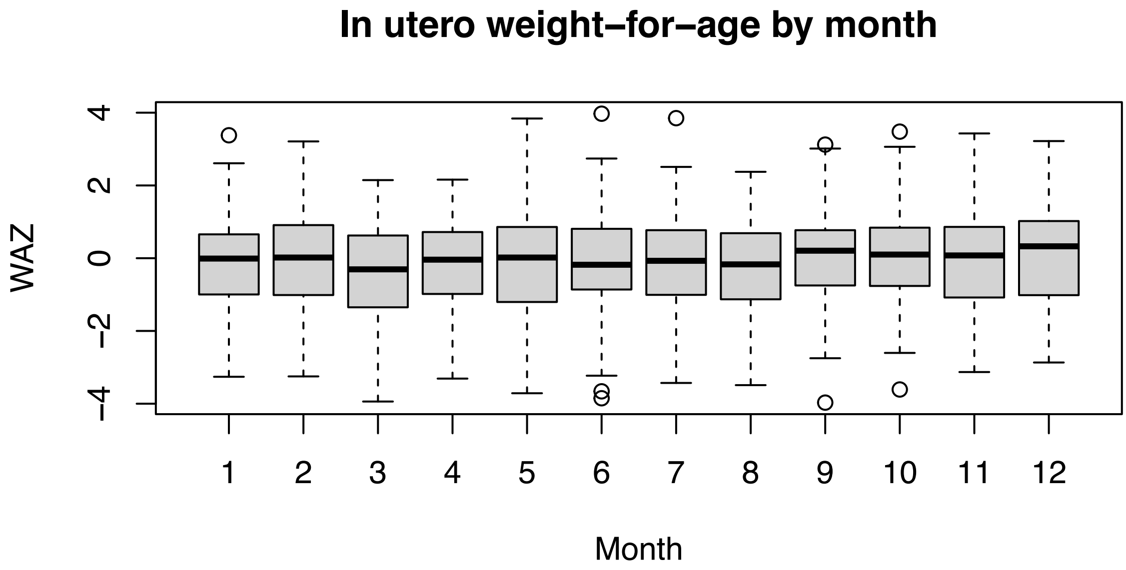

Figure 1: Plot of mean weight-for-age z-score in utero by month.

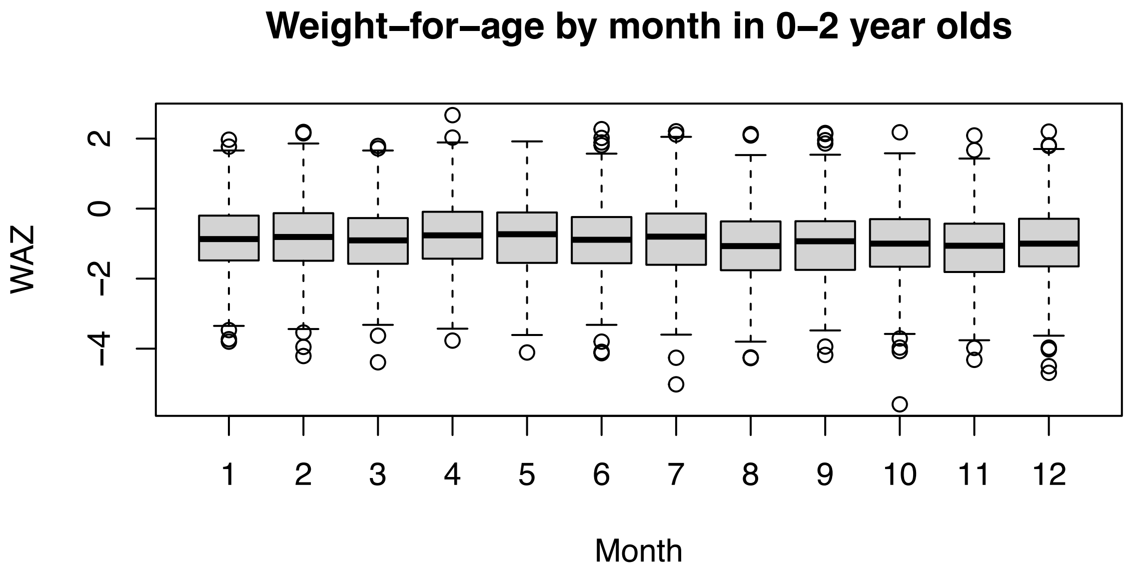

Figure 2: Plot of mean weight-for-age z-score from 0-2 years by month.

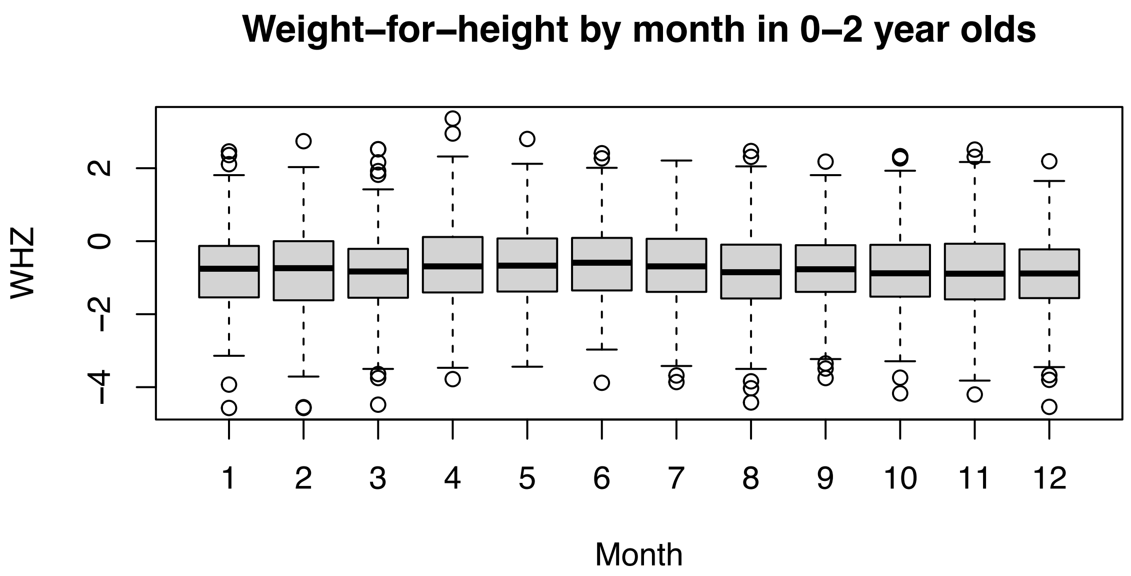

Figure 3: Plot of mean weight-for-height z-score from 0-2 years by month.

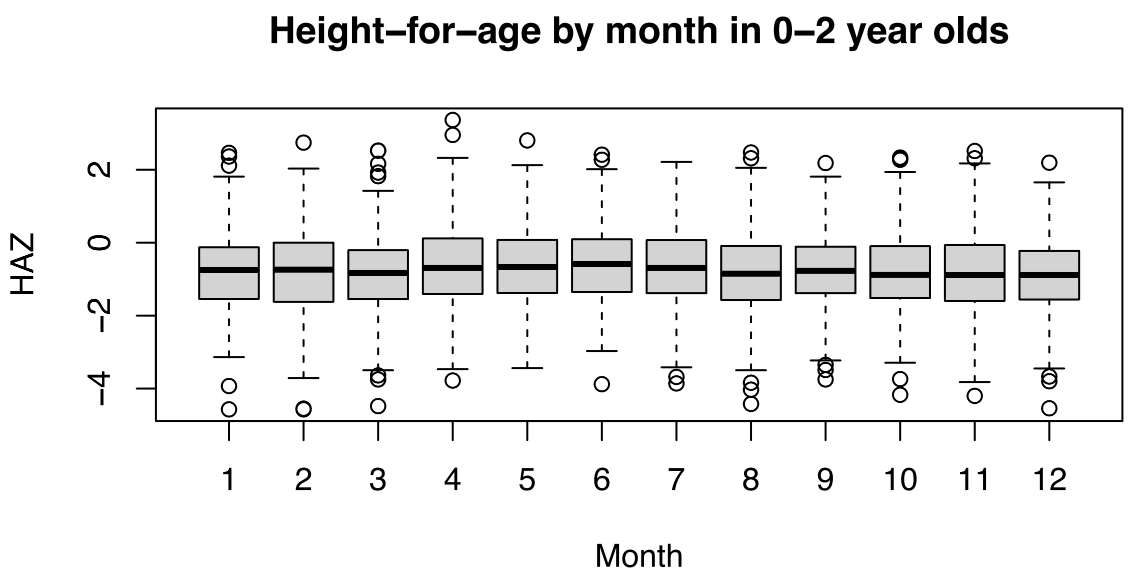

Figure 4: Plot of mean height-for-age z-score from 0-2 years by month.

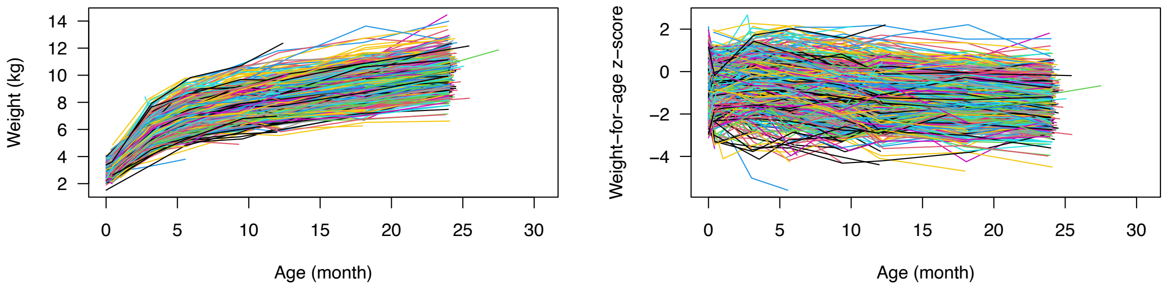

Figure 5: plots of individual weight trajectories 0-2 years and individual waz 0-2 years over time

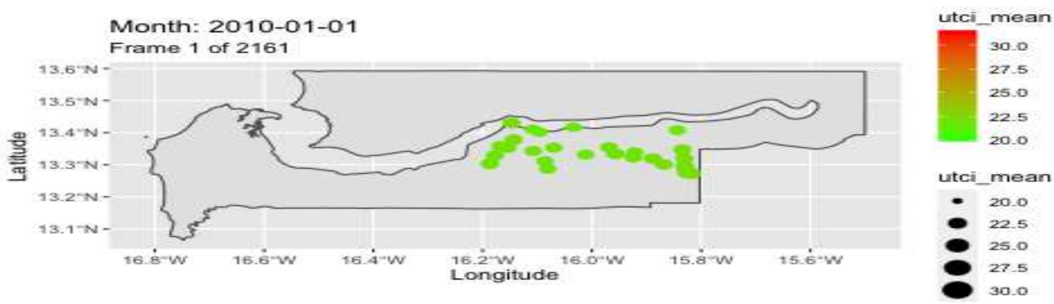

Figure 6 – GIF of heat by village over time (2010-2015)

Table 1: In utero multivariate multilevel model of WAZ with heat stress exposure defined as average UTCI exposure for the 60 days prior to each visit.

Variables	Estimate (95% CI)	p-value on LRT
Maternal factors		
Maternal age	3.74×10^{-7} (-4.1×10^{-5};4.2×10^{-5})	0.99
Enrolment BMI	5.99×10^{-2} (2.7×10^{-2}; 9.3×10^{-2})	<0.001
MUAC	-4.10×10^{-2} (-7.7×10^{-2};-5.4×10^{-3})	0.02
Parity	-3.83×10^{-4} (-3.6×10^{-2};3.5×10^{-2}	0.98
Child-level factors		
Age	-4.27×10^{-3} (-5.2×10^{-3};-3.4×10^{-3})	<0.001
Sex	6.21×10^{-2} (-4.4×10^{-2};0.17)	0.26
Environmental factors		
Cubic spline UTCI	-0.17 (-0.70;0.37)	0.83
	5.65×10^{-2} (-0.22;0.33)	
	8.15×10^{-3} (-0.38;0.39)	
Season of conception	0.12 (-1.0×10^{-2};0.25)	0.07
Season of exposure	-9.27×10^{-3} (-0.18;0.16)	0.92

Table 2: Multilevel model of weight-for-age, height-for-age and weight-for-height and heat stress defined as mean UTCI exposure 60 days prior to each measurement

	WAZ 0-2 years		HAZ 0-2 years		WHZ 0-2 years	
Variables	**Estimate (95% CI)**	**p-value**	**Estimate (95% CI)**	**p-value**	**Estimate (95% CI)**	**p-value**
Maternal factors						
Maternal age	-0.00 (-0.00;-0.00)	0.512	-0.00 (-0.00;0.00)	0.236	-0.00 (-0.00;-0.00)	0.015
Enrolment BMI	0.04 (0.02;0.06)	<0.001	0.00 (-0.02;0.02)	0.690	0.05 (0.03;0.07)	<0.001
Parity	-0.01 (-0.05;0.02)	0.465	-0.03 (-0.07;0.01)	0.124	-0.00 (-0.04;0.04)	0.880
Child-level factors						
GA at birth	0.01 (0.00;0.01)	0.011	0.02 (0.01; 0.02)	<0.001	-0.00 (-0.00;0.00)	0.996
Age	-0.04 (-0.04; -0.03)	<0.001	-0.04 (-0.05;-0.03)	<0.001	-0.03 (-0.04;-0.03)	<0.001
Sex	-0.18 (-0.29;-0.05)	0.005	-0.20 (-0.32;-0.07)	0.003	-0.10 (-0.22;0.02)	0.114
Acute diarroheal illness in last 4 weeks	-0.07 (-0.11;-0.02)	0.002	0.05 (0.01;0.09)	0.007	-0.10 (-0.16;-0.05)	<0.001
Environmental factors						
Cubic spline UTCI	0.18 (0.00;0.35)	0.004	0.32 (0.15;0.49)	<0.001	0.00 (-0.22;0.22)	<0.001
	0.04 (-0.08;0.15)		0.37 (0.26;0.48)		-0.30 (-0.45;-0.16)	
	-0.07 (-0.24;0.10)		0.29 (0.12;0.45)		-0.44 (-0.65;-0.22)	
Season of conception	-0.02 (-0.14;0.14)	0.858	-0.05 (-0.19;0.08)	0.435	0.06 (-0.06;0.20)	0.318
Season of exposure	-0.76 (-1.47;-0.05)	0.036	-0.17 (-2.39;-0.93)	<0.001	0.81 (-0.06;1.68)	0.127
	-0.38 (-0.85; 0.08)		-0.93 (-1.39;-0.46		0.43 (-0.14;0.99)	
Year	0.19 (0.07;0.30)	0.002	0.26 (0.15;0.37)	<0.001	-0.00 (-0.15;0.15)	0.991
Model parameters						
VPC(treatment)	0.00		0.00		0.00	
VPC(village)	0.01		0.02		0.01	
VPC(individual)	0.60		0.67		0.50	
VPC(residual)	0.39		0.31		0.49	
AIC	11027		9211		10997	

Scaled residuals	Median 0.02 (range -4.00;3.94)		Median 0.02 (range -5.44;6.17)		Median 0.04 (range -4.29;4.17)	

WAZ = weight-for-age z-score; HAZ = height-for-age z-score; WHZ = weight-for-height z-score; GA = gestational age; UTCI = universal thermal climate index; VPC = variance partition coefficient; AIC = Akaike Information Criterion

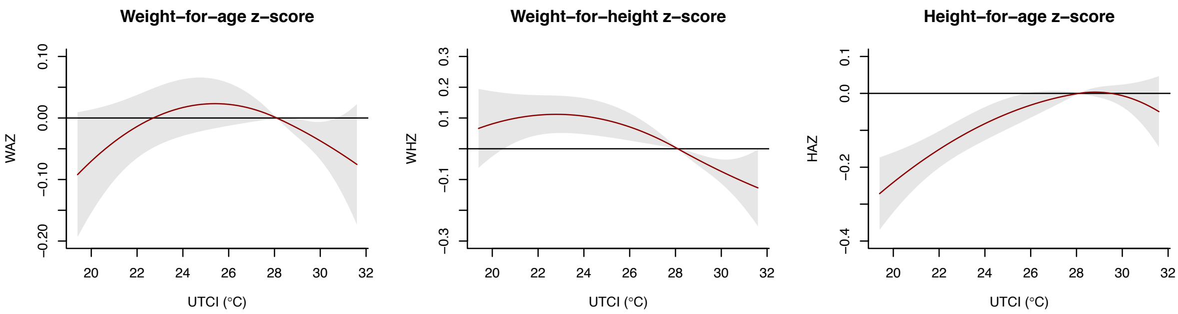

Figure 7: Association between weight-for-age z-scores, weight-for-height z-score and height-for-age z-score and mean UTCI over 30-day summaries in 0-2 year-olds.

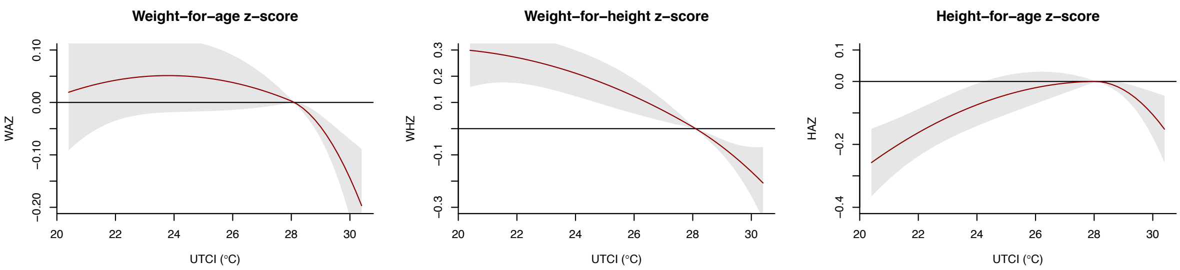

Figure 8: Association between weight-for-age z-scores, weight-for-height z-score and height-for-age z-score and mean UTCI over 90-day summaries in 0-2 year-olds.

R code:

code is presented – first for the in utero model and then for the infant model. Lines of code can be run directly in R. ## indicates annotation to code.

```
#### packages ####

library(tidyverse)
library(magrittr)
library(sitar)
library(lme4)
library(dlnm)
library(rstatix)
library(splines)

#### data #####
utero_formodel <- readRDS("~/utero_formodel.rds")
utero_formodel %<>% convert_as_factor(ID, SUPPLEMENTGROUP, InfantSex, VillageName)


#### set the splines ####

get_utknots <- function(x){
  quantile(x, c(0.5), na.rm=T)
}

knot30mean <- get_utknots(utero_formodel$utci_mean_30)
knot60mean <- get_utknots(utero_formodel$utci_mean_60)
knot90mean <- get_utknots(utero_formodel$utci_mean_90)


#### get one basis object ####

ob_30mean <- onebasis(utero_formodel$utci_mean_30, fun="bs", degree=2, knots =
knot30mean)
ob_60mean <- onebasis(utero_formodel$utci_mean_60, fun="bs", degree=2, knots =
knot60mean)
ob_90mean <- onebasis(utero_formodel$utci_mean_90, fun="bs", degree=2, knots =
knot90mean)


#### run the models ####


mod_30mean <- lmer(zscore ~ age + ob_30mean + Maternal_age + season_15 + InfantSex +
            season_conc + muac + BMI + parity + (1|SUPPLEMENTGROUP) +
```

```
               (1|VillageName) + (1|ID), data = utero_formodel)

mod_60mean <- lmer(zscore ~ age + ob_60mean + Maternal_age + season_30 + InfantSex +
               season_conc + muac + BMI + parity + (1|SUPPLEMENTGROUP) +
               (1|VillageName) + (1|ID), data = utero_formodel)

mod_90mean <- lmer(zscore ~ age + ob_90mean + Maternal_age + season_45 + InfantSex +
               season_conc + muac + BMI + parity + (1|SUPPLEMENTGROUP) +
               (1|VillageName) + (1|ID), data = utero_formodel)


#### crosspred ####
vis_30mean <- crosspred(ob_30mean, mod_30mean, cen = 28.1)
vis_60mean <- crosspred(ob_60mean, mod_60mean, cen = 28.1)
vis_90mean <- crosspred(ob_90mean, mod_90mean, cen = 28.1)


#### plots ####
plot(vis_30mean)
plot(vis_60mean)
plot(vis_90mean)


get_meanplots <- function(x){
  plot(x, ylim=c(-0.4, 0.4) ,xlab = expression(paste("Mean UTCI (",degree,"C)")),
     ylab = "WAZ",
     col = "dark red")
}


# plots for fig 2 #
par(mfrow=c(1,3))

get_meanplots(vis_30mean)
title(main= "30 Days Exposure")
get_meanplots(vis_60mean)
title(main= "60 Days Exposure")
get_meanplots(vis_90mean)
title(main= "90 Days Exposure")


## code below runs the models for the 0-2 years ##


#### data #####

joined <- readRDS("~/joined.rds")
```

```
joined %<>% convert_as_factor(ID, SUPPLEMENTGROUP, InfantSex, VillageName)


#### set the splines ####
# already tested in other scripts - just need 0.5 knot and BS spline

get_knots <- function(x){
  quantile(x, c(0.5), na.rm=T)
}


knot30mean <- get_knots(joined$utci_mean_30)
knot60mean <- get_knots(joined$utci_mean_60)
knot90mean <- get_knots(joined$utci_mean_90)

#### get onebasis objects for all ####

ob_30mean <- onebasis(joined$utci_mean_30, fun="bs", degree=2, knots = knot30mean)
ob_60mean <- onebasis(joined$utci_mean_60, fun="bs", degree=2, knots = knot60mean)
ob_90mean <- onebasis(joined$utci_mean_90, fun="bs", degree=2, knots = knot90mean)

#### WAZ models ####
## any illness in last 4 weeks ##
joined$year <- year(joined$visdate.x)

mod_waz30mean <- lmer(waz ~ age_mth + ob_30mean + Maternal_age + ns(visdate.x, 2) +
InfantSex
                + sickany4week + year + GA_atbirth + season_conc + BMI + parity +
(1|SUPPLEMENTGROUP)
                + (1|ID) + (1|VillageName), data = joined)

mod_waz60mean <- lmer(waz ~ age_mth + ob_60mean + Maternal_age + ns(visdate.x, 2) +
InfantSex
                 + sickany4week + year + GA_atbirth + season_conc + BMI + parity +
(1|SUPPLEMENTGROUP)
                 + (1|ID) + (1|VillageName), data = joined)

mod_waz90mean <- lmer(waz ~ age_mth + ob_90mean + Maternal_age + ns(visdate.x, 2) +
InfantSex
                 + sickany4week + year + GA_atbirth + season_conc + BMI + parity +
(1|SUPPLEMENTGROUP)
                 + (1|ID) + (1|VillageName), data = joined)


vis_waz30mean <- crosspred(ob_30mean, mod_waz30mean, cen = 28.1)
vis_waz60mean <- crosspred(ob_60mean, mod_waz60mean, cen = 28.1)
vis_waz90mean <- crosspred(ob_90mean, mod_waz90mean, cen = 28.1)
```

```
plot(vis_waz30mean)
plot(vis_waz60mean)
plot(vis_waz90mean)

#### WHZ models ####


mod_whz30mean <- lmer(whz ~ age_mth + ob_30mean + Maternal_age + ns(visdate.x, 2) +
InfantSex
               + year + sickany4week + GA_atbirth + season_conc + BMI + parity +
(1|SUPPLEMENTGROUP)
               + (1|ID) + (1|VillageName), data = joined)

mod_whz60mean <- lmer(whz ~ age_mth + ob_60mean + Maternal_age + ns(visdate.x, 2) +
InfantSex
               + year + sickany4week + GA_atbirth + season_conc + BMI + parity +
(1|SUPPLEMENTGROUP)
               + (1|ID) + (1|VillageName), data = joined)

mod_whz90mean <- lmer(whz ~ age_mth + ob_90mean + Maternal_age + ns(visdate.x, 2) +
InfantSex
               + year + sickany4week + GA_atbirth + season_conc + BMI + parity +
(1|SUPPLEMENTGROUP)
               + (1|ID) + (1|VillageName), data = joined)

vis_whz30mean <- crosspred(ob_30mean, mod_whz30mean, cen = 28.1)
vis_whz60mean <- crosspred(ob_60mean, mod_whz60mean, cen = 28.1)
vis_whz90mean <- crosspred(ob_90mean, mod_whz90mean, cen = 28.1)

plot(vis_whz30mean)
plot(vis_whz60mean)
plot(vis_whz90mean)


#### HAZ models ####

mod_haz30mean <- lmer(haz ~ age_mth + ob_30mean + Maternal_age + ns(visdate.x, 2) +
InfantSex
               + year + sickany4week + GA_atbirth + season_conc + BMI + parity +
(1|SUPPLEMENTGROUP)
               + (1|ID) + (1|VillageName), data = joined)


mod_haz60mean <- lmer(haz ~ age_mth + ob_60mean + Maternal_age + ns(visdate.x, 2) +
InfantSex
```

```
                + year + sickany4week + GA_atbirth + season_conc + BMI + parity +
(1|SUPPLEMENTGROUP)
                + (1|ID) + (1|VillageName), data = joined)

mod_haz90mean <- lmer(haz ~ age_mth + ob_90mean + Maternal_age + ns(visdate.x, 2) +
InfantSex
                + year + sickany4week + GA_atbirth + season_conc + BMI + parity +
(1|SUPPLEMENTGROUP)
                + (1|ID) + (1|VillageName), data = joined)


vis_haz30mean <- crosspred(ob_30mean, mod_haz30mean, cen = 28.1)
vis_haz60mean <- crosspred(ob_60mean, mod_haz60mean, cen = 28.1)
vis_haz90mean <- crosspred(ob_90mean, mod_haz90mean, cen = 28.1)

plot(vis_haz30mean)
plot(vis_haz60mean)
plot(vis_haz90mean)

get_hazplots <- function(x){
  plot(x, ylim=c(-0.4, 0.1) ,xlab = expression(paste("UTCI (",degree,"C)")),
       ylab = "HAZ",
       col = "dark red")
}

get_whzplots <- function(x){
  plot(x, ylim=c(-0.3, 0.3) ,xlab = expression(paste("UTCI (",degree,"C)")),
       ylab = "WHZ",
       col = "dark red")
}

get_wazplots <- function(x){
  plot(x, ylim=c(-0.2, 0.1) ,xlab = expression(paste("UTCI (",degree,"C)")),
       ylab = "WAZ",
       col = "dark red")
}


par(mfrow=c(1,3))

get_wazplots(vis_waz30mean)
get_whzplots(vis_whz30mean)
get_hazplots(vis_haz30mean)

get_wazplots(vis_waz60mean)
title(main= "Weight-for-age z-score")
get_whzplots(vis_whz60mean)
```

```
title(main= "Weight-for-height z-score")
get_hazplots(vis_haz60mean)
title(main= "Height-for-age z-score")
```

Climate change mitigation and adaptation options in the local environment

Climate Change Solutions Festival

May 2021

This learning and action pack details the stalls presented at the Climate Change Solutions Festival in Fajara, The Gambia, West Africa, May 2021.

We would like to take this opportunity to acknowledge all the schools that participated in both the competition, demonstrating and attending. Both the teachers and students were fantastically engaged in developing the stalls and in the peer-to-peer learning that occurred during the festival.

Additional thanks goes to all the other stall demonstrators who dedicated their time to improving the understanding and discussions around climate change solutions and helped inspire the attendees.

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Trees and forests
Climate Change Solutions
CLIMATE CHANGE
SOLUTIONS FESTIVAL

1. Solar cooker

Basic principles: Reduce use of firewood for cooking

Interaction: build your own solar cooker using recycled items.

Equipment required:
Carboard
Inner tube of tire
Cooking pot
Glass

Cook with solar to reduce firewood and charcoal use

- Place a flat piece of cardboard or wood on the ground.
- Inflate the inner tube of a large car tire.
- Place your item to cook in the middle of the tire as shown in the picture.
- Place a large sheet of glass over the top and leave in the sun.

Experiment with boiling water and cooking rice – timing each to see how long they take to cook.
Explore solar cooker recipes: https://solarcooking.fandom.com/wiki/Recipes

2. Reforestation and its many benefits

Basic principles: reforestation to improve the health of humans and the planet

Interaction: Explore different growing potential of different soil types

Equipment required:
Seeds
Soil
Plant containers
Bucket

Plant trees to protect the planet

Experiment: test which soils results in healthy seedlings

- Discuss benefit of trees generally (e.g. clean the air we breathe, clean the water we drink, provide shade, improve soil, reduce rainwater run-off, improve biodiversity and social/psychological benefits).
- Discuss specific considerations of coastal regions (e.g. sand encroachment, storm and flood protection etc).
- Experiment with growth of different trees in different soil types.
- Take a selection of seeds (moringa, oranges and mangoes) and take three different soil types: sandy, loamy and clay.
- Plant each seed in the three different soils and watch to see which one germinates and thrives.
- Will take several weeks.

3. Coconut husks as mulch/growing medium and other nature-based solutions

Basic principles: the importance of plants for a healthy planet & healthy humans

Interaction: making coconut mulch and biodegradable pots

Equipment required:
Pestle and mortar Scissors
Coconut husks (dried) Paper tape
Newspapers Glass jar

More plants = cleaner air

- Discuss the benefits of using coconut husk as mulch/growing medium (e.g., water retention ability, aeration capacity, sustainable, naturally pH balanced, nutrient density, beneficial bacteria and cost free) and
- Allow students to pound coconut husk to powder.
- Discussed on the benefits of houseplants (e.g. cleaner indoor air).
- Explain benefit of biodegradable pot versus plastic for planting
- Made paper pots:
- Take one sheet of newspaper
- Place glass jar one third from the top and at the horizontal edge and then roll with the newspaper.
- Tape the cylinder then remove the glass jar.
- Fold the bottom and tape closed to give a paper pot.
- Add soil and coconut mulch and seed/seedling. Can be planted straight into the ground.

4. improved cook stove (mud stove)

Basic principles: improve efficiency of stoves to reduce firewood/charcoal use

Interaction: Build your own mud stove.

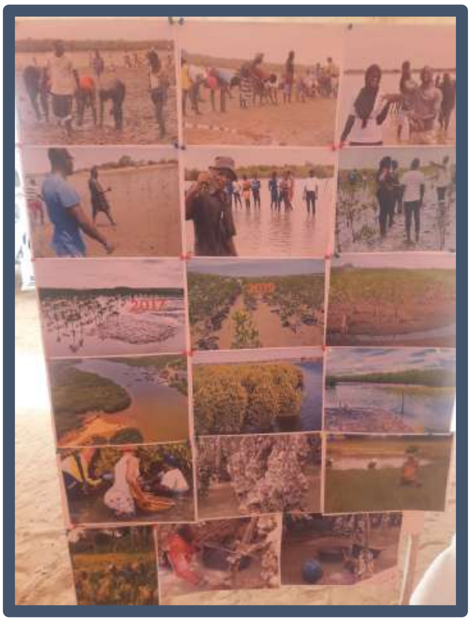
Equipment required:
Bucket
Straw
Clay soil
Firewood
Cooking pot

Efficient cook stoves save trees

Experiment: test efficiency of mud stove

- Collect large bucket of clay soil.
- Collect one bucket of straw.
- Use the outer edge of your cooking pot to measure out an arc and place the straw in this position on the ground.
- Add water to the clay soil slowly and mix until it becomes muddy.
- Shape the mud into rectangular blocks and place on top of the straw, three blocks high.
- Leave to dry for one day.
- Use firewood in the mud stove and place the cooking pot on top. Test length of time to heat water compared to conventional stove.

5. Importance of mangrove forests



Basic principles: costal protection & costal ecosystems need healthy mangroves

Interaction: discuss importance of mangroves & practice planting mangrove seedlings

Equipment required (for in class presentation):
Clear photos of planting mangrove forest
Clear photos of the protective effect of mangrove forests
Mangrove shoots & seedlings

Planting mangrove forests protects the environment

Experiment: demonstrate the multiple benefits from mangrove forest planting

- Develop a clear presentation board indicating 1) every step of mangrove forest planting in the community; 2) several examples of the protective effect of mangrove forests.
- Explain the main steps of mangrove forest planting, including the direction (in rows) and the way how seedlings are planted
- Show seedlings and show how they are planted: this can be practiced by the participants
- Explain benefits of mangrove forests, including 1) possibilities to harvest oysters that grow on mangrove roots; 2) their positive impact on biodiversity, by creating favourable habitats for birds and bees; 3)highly salt absorbing: lowering salinity in ground and surface water that is used for irrigation; 4)

Solar cooker

Basic principles: Reduce use of firewood for cooking

Interaction: make your own solar cooker

Equipment required:
Carboard box
Polystyrene
Black paint
Aluminium foil
Cooking pot
Glass sheet

Solar cookers are great for The Gambia

Discuss important factors for a solar cooker: time of day for cooking, need to reflect and focus sunlight, need to insulate – give the students time to come up with ideas on how to maximise each of these components.

To make the solar cooker:

- Take one carboard box. Paint the outside of the box with black paint.
- Line the inside of the box with polystyrene and cover with aluminium foil as shown in the picture. Cover the inside of the lid with aluminium foil or a mirror if available.
- Paint the cooking pot with black paint and allow to dry
- Experiment with cooking different food and drink.

7. Smoke detector for bush fires

Basic principles: Reduce the damage of bushfires

Interaction: early recognition of bushfires to reduce damage

Equipment required:

Smoke detector
String
Model aeroplane
Wood/dry grass
Fire blanket/extinguisher
Matches

Bushfires harm life

Discuss the damage of bushfires and impact on human health (air pollution). Demonstrate the use of a smoke detector with smart phone connection for early recognition and intervention.

Set-up: make a fire pit in a safe place. Put wood, kindling and dry grass ready for ignition. Use string to suspend the smoke detector attached to the model aeroplane (as a surrogate for a drone) over the area of the fire pit. Ensure the smartphone app is installed to allow communication between the smoke detector and the phone.

- Divide students into 3 groups and separate where they cannot see each other.
- Group 1 starts the fire and ensures it does not spread.
- Group 2 has the smartphone and receives the signal to indicate there is a fire and informs group 3.
- Group 3 run to extinguish the fire (with fire blanket/extinguisher).
- Can be timed and run as a competition to see who can extinguish the fire the quickest.

8. Health impacts of air pollution from cars & alternatives to sand for construction

Basic principles: Solutions to reduce air pollution

Interaction: Health impacts of air pollution and potential solutions

Equipment required:
Paper
Paint
Pens

We want clean air

Experiment:

- Discuss health impacts of air pollution (asthma/respiratory disease, cardiovascular disease etc).
- Give the students an opportunity to discuss causes of air pollution and potential ways to reduce this (including clean cars/legislation regarding fuel type/use of trees and plants to clean the air etc).
- Allow students to draw their own posters to spread awareness.

Basic principles: To provide a clean alternative for housing construction

Interaction: Experiment with alternative construction material for sustainable living

Equipment required:
Tyres
Stones, Quarry Dust
Sand and Mud

No to erosion

Experiment:

- Discuss problems with sand mining (erosion/loss of biodiversity etc.) and discuss impact on livelihoods & environment
- Allow students to consider alternative options and share experiences with alternative building materials
- Encourage students to experiment and build model houses out of their proposed material and test for strength of building blocks.

9. Clay cow dung oven

Basic principles: Reduce use of firewood for cooking

Interaction: build your own clay oven

Equipment required:
Clay
Sticks
Dry grass
Cow dung

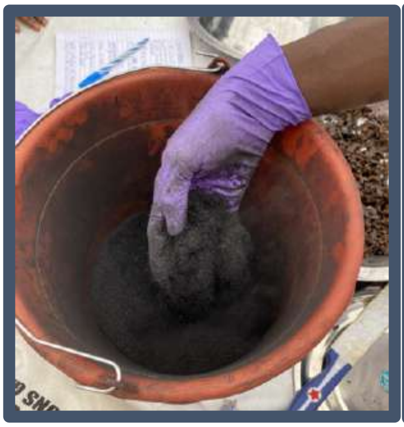
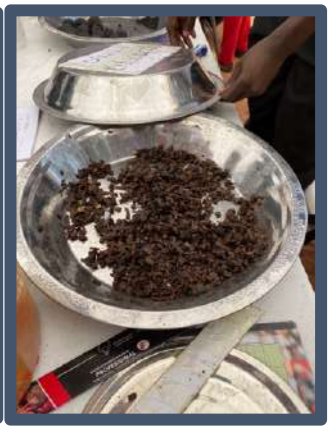
Don't plant back trees – just don't cut them!

Experiment

- Collect clay from the river.
- Leave to dry in the sun. Alternative option is to recycle old clay objects – pound and sieve and mix together.
- Allow students to design their own ovens similar to the pictures shown.
- Leave to dry for 3 days.
- Fire with cow dung and dry grass for 6-7 hours.

Once cooled experiment with cooking different foods. Fuel = cow dung.

10. Topic: Banana charcoal briquettes


Basic principles: Reduce use of firewood for cooking

Interaction: make banana charcoal briquettes.

Equipment required:
Grass
Leave fall
Banana peelings
Sand
Sieve
Knife

Burns as well as other charcoal but produces no smoke and doesn't chop down a single tree.

- Collect dried grass/leaves and slow burn under a mound of earth with minimal oxygen to produce charcoal.
- Collect, pound and sieve the charcoal to give charcoal dust (see picture).
- Collect fresh banana peelings and cut into small pieces (see picture).
- Mix banana peelings (50%), charcoal dust (25%) and sand (25%) together and mould into small briquettes.
- Leave to dry (from 2-4 days depending on season). Burns with minimal smoke.

Test against other charcoal for time to boil a set volume of water.
Additional experiment: make charcoal briquette from other household organic waste and test heat efficiencies as above.

Food and farming

Climate Change Solutions

CLIMATE CHANGE SOLUTIONS FESTIVAL THE GAMBIA

11. Botanical pesticide/insecticide

Basic principles: An environmentally friendly alternative to chemical pesticides

Interaction: Seeing and touching the plants, Wearing protective equipment for chemical insecticide application

Equipment required:
Plants to make botanical pesticides/insecticide
Spraying cans
10 litre barrel/bucket with water
Sieve
Mashing pestle

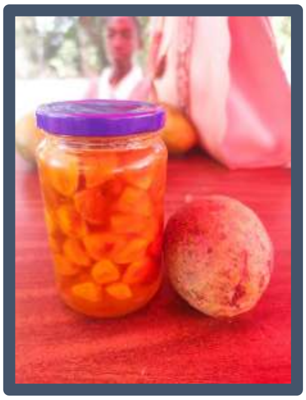
Botanical pesticides
are good for you,
the environment
& our crops

Experiment:

- Brief explanation of the various plants that can be used as botanic pesticide and insecticide, including leaves of eucalypt, African mahogany and neem trees
- Use a pestle to crush the plant leaves (and in some cases seeds)
- When using leaves: add half of a bucket of leave to a full (10 litre) bucket of water. Add lid and leave to brew for a few days. For attendees on the day, take a mixture that has already brewed for a few days.
- Sieve the mixture and fill spraying cans
- Show pictures of experiments with crops/trees (e.g mango & orange) with and without botanical pesticides/insecticides and show the difference in yields

Furthermore, participants can try on the protective equipment for the application of chemical fertilizer (full body suit, boots, google) to show the challenges of use of such equipment in hot climates.

12. Food preservation



Basic principles: Prolong the shelf life of perishable products through various preservation techniques

Interaction: Tasting foods, trying out preservation technologies

Equipment required:
Bottles and jars
Plastic sealable bags
Stove
Pot
Sugar, lime, salt, pepper, other preservation ingredients

No food waste with these preservation techniques

Experiment:

- Explain that due to the increasing peak temperatures during the day preservation is important to reduce food waste.
- Explain that food preservation could be an effective solution to ensure food supply during the hunger season.
- Demonstrate the preparation of kabaa jam (Saba senegalensis) by boiling kabaa fruit with sugar and lime
- Demonstrate salting technique of the Saba senegalensis, with added pepper, salt and flavour enhancers
- Demonstrate drying/dehydration techniques of "*mbahal*" (rice, dried fish *(kobo)* and flavour enhancers) or *"findi"*.
- Show participants the finished products that have been prepared before the demonstration
- Participants can practice the techniques with small amounts of food
- Participants can taste the different foods by providing small samples

Cover cropping and organic manure


Basic principles: importance of healthy soil structure

Interaction: Demonstrate different growing potentials in different conditions

Equipment required:
Small plot of land
Soil
Animal dung
Seeds

Healthy soil = healthy plants

- Prepare 3 beds for planting
- All beds will grow corn and be watered with the same amount of water.
- Bed 1: plant corn and grow in soil with only watering.
- Bed 2: prepare soil with dried groundnut shells. Plant corn. Water as needed.
- Bed 3: prepare soil with manure. Plant corn. Water as needed
- Students are responsible for watering and weeding as needed.
- Around 3 months assess height of plants, width of stem, size and number of corn, and most importantly the taste of the corn.

14. Reducing salt intrusion

Basic principles: protection of land from salt intrusion

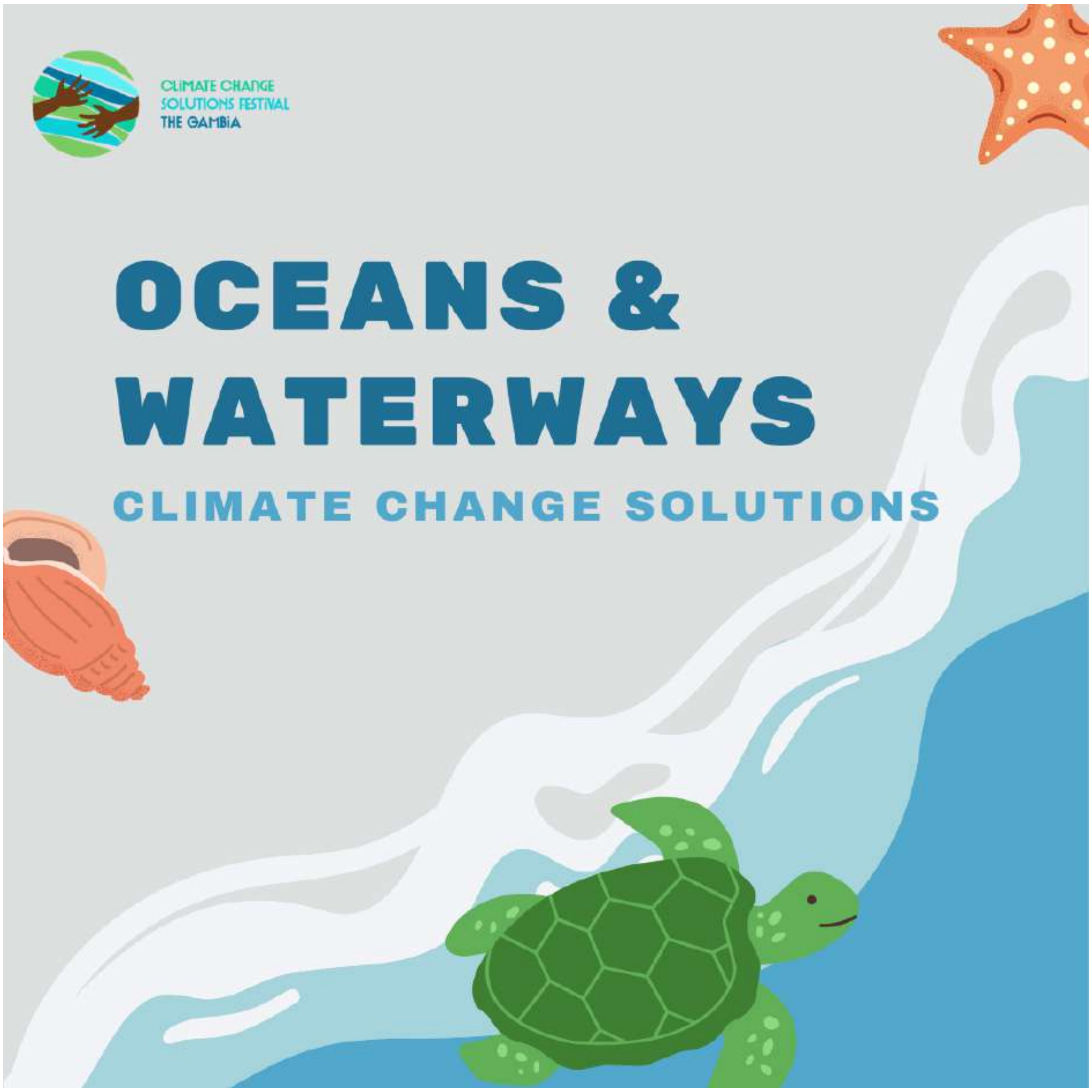
Interaction: build your own channels to divert salt water and create an artificial salt pan

Equipment required:
Land
Salt
Water
Spade
Bucket
Board (plastic/wood)

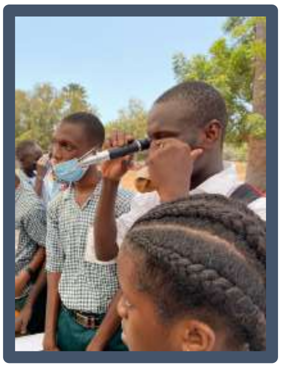
Saltwater intrusion will reduce our crops – let's find a solution

Discuss saltwater intrusion: principles of salt entering the ground and impact of climate change on this. Discuss impacts of salt water on soil fertility, crops growing potential and on human/animal health. Discuss ways in which this may be addressed and options – allow the students to generate their own thoughts and ideas.

- Dig channels as indicated in the picture on the left
- Dig a smooth flat area to make the artificial salt pan (picture on right)
- Use a large amount of salt water to fill the channels
- Open the board/barrier to the salt pan to allow the water in and then close off
- Leave the salt water to evaporate or stay in the channels


CLIMATE CHANGE
SOLUTIONS FESTIVAL
THE GAMBIA
OCEANS &
WATERWAYS
CLIMATE CHANGE SOLUTIONS

15. Understanding ocean and estuary acidification




Basic principles: How climate change affects estuaries and causes ocean's acidification

Interaction: understanding marine ecosystems

Equipment Required:
pH meter
Dissolved oxygen meter (DO)
Refractometer
2 - 500 mL beakers
3 reusable plastic tanks
3 bamboo or paper straws
Materials to resemble a marine environment (coral, fish, shells, etc).

Ocean acidification harms our estuaries

Explain to the students what an estuary is. Discuss how carbon dioxide is released into the atmosphere then dissolves into the ocean causing an increase in the acidity of the water. Discuss the threat of climate change in the marine ecosystems.

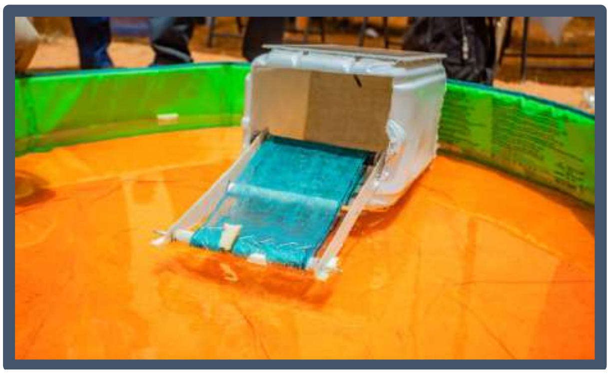
To demonstrate an estuary:

- Collect or make freshwater, brackish water or saltwater and place each one of the reusable plastic tanks.
- Divide students into three groups. Each group will represent a fresh aquatic system, salt aquatic system, and a brackish aquatic system.
- Using the map of the River Gambia, demonstrate the areas of saltwater, brackish water, and freshwater.
- Using a refractometer, ask the students to determine which reusable plastic tank represents fresh, brackish or saltwater.
- Then use the dissolved oxygen meter to measure the DO of each aquatic system. Explain to the student why DO is important in an aquatic system.

To demonstrate ocean acidification:

- Collect or make 800 mL of saltwater and divide the sample into the two (2) 500 mL beakers.
- Ask students to blow air through the straw into each beaker containing the saltwater for three minutes.
- Using the pH meter, ask the students to measure the pH levels for both samples.
- Repeat steps 2 and 3 but ask the students to blow for six (6) minutes to measure the pH levels.
- Using the DO meter, repeat steps 2 and 4 to measure DO.

16. Plastic cleaning robot for the ocean



Basic principles: remove harmful floating plastic items from waterways

Interaction: highlight the impact of plastic use and build your own plastic cleaning robot

Equipment required:
Polystyrene box
Solar panel
Net
Small pieces of plastic rubbish
Dynamo
Small pool

Keep the ocean clean

Discuss ways in which we use plastic in our lives. Ask students to count the number of plastic items they use in one day. Ask students to think about what happens to plastic once it has been thrown away (e.g. length of time for degradation of 1 plastic bag = 1000 years). Most plastic ends up in landfill or water. The ocean now has 5.25 trillion pieces of plastic in it and that number is increasing daily.
What does the plastic in the ocean do?
What ways can the students suggest to clean plastic from the ocean?
Use equipment above to build their own robot similar to what is seen in the pictures.

Protection of freshwater ponds

Basic principles: Importance of the water cycle and healthy freshwater ecosystems

Interaction:
Interaction: Use role play/theatrics to explore the stressors on the water cycle

Equipment required:
Paper
Pens
Art supplies

Plan for the future and care for our ponds. Don't drain them as once they are gone, they are gone

This may take several sessions.

1. Discuss the water cycle with the students and ask them to produce drawings to illustrate it.
2. Form small study groups and give each student the opportunity to present their drawing to the members of their group.
3. In the study groups discuss the water cycle, how humans may affect it and what impact that can have.
4. As a group, choose one impact that is the most important to them and develop a play to demonstrate/discuss this with potential solutions.
5. Each group performs their play to the whole group.
6. Finish with any final take home messages or questions from the groups.


CLIMATE CHANGE
SOLUTIONS FESTIVAL
THE GAMBIA
Plastics and waste
Climate change solutions

18. Recycle plastic to make building tiles/bricks

Basic principles: recycle low-density polyethelyne (LDPE) plastic to create tiles and bricks

Interaction: discuss plastic waste in The Gambia. Ask students if they think plastic is a problem and what can be done about it.
Explain the options for recycling plastics into other useful items – e.g. bricks.
Ask each student to collect any stretchy type of plastic they use over the next 2 weeks.
If feasible arrange a visit to Gunjur plastic initiative to give the plastic waste for recycling and see the whole process in action.

Details of the process of making plastic tiles:

- Collect plastic
- Clean and sort
- Use LDPE plastic
- Weigh total
- Melt plastic at 185°C
- Add sand
- Mix
- Pour into mould
- Leave for 15 mins then remove and ready for use

Build your home with recycled plastic

Recycling plastic and tyres


Basic principles: recycle plastic bags and tyres to make bags, purses and bowels

Interaction: make your own recycled purse/bag

Equipment required:
Bucket and cleaning product
Discarded plastic bags
Scissors
Crochet needle

There's too much plastic, so let's recycle

Discuss plastic waste globally and in The Gambia. Ask the students if they think recycling is important and why.
Ask students to collect discarded plastic bags.

- Clean the bags
- Dry them
- Cut into strips
- Crochet into bag or other item they prefer as seen in the pictures

20. Importance of waste management

Basic principles: REDUCE | REUSE | RECYCLE

Interaction: waste sorting and reusing

Equipment required:
Household waste
Glue
Paint
Paintbrushes
Bins to sort rubbish into

Reduce
Reuse
Recycle

This will take place over 3 sessions.

1. discuss the principles of reduce, reuse and recycle. Consider waste management in their local area and identify if there is a problem – do the students know of any local actions to reduce waste?
2. Each student collects household waste (non-food waste only) for 1 week and then brings to school. Hold a competition for fastest and most accurate sorting of waste (e.g. cans/paper/plastic/glass).
3. Spend time using the household waste to create either something of use, or of artistic value.


THE CLIMATE
CHANGE SOLUTIONS
THEATER CLUB

21. Climate change solutions theatre

Basic principles: show a detrimental impact to health of climate change or environmental degradation

Interaction: Put on a play to the school

Learn through theatre

Equipment required:
Costumes
Other props as needed
Microphones

- Spend some time discussing different aspects of climate change and how it can impact human health
- Allow the students to form small groups and work on their ideas for a play
- Give them the opportunity to practice together
- Put a show on for the school to spread awareness

Towards Equity and Impact in Planetary Health Education Initiatives

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Climate change impacts are being experienced around the world and should urgently be addressed. Learning from and with young people is crucial for the co-development of suitable and effective interventions and to equip the next generations with the necessary skills to achieve environmental sustainability and increase climate change resilience.(1) Whilst teaching the science and skills needed for a healthy future are important, there is growing recognition that the complexity and interconnectedness of climate change, health, sustainability and resilience as well as socio-economic drivers require transformative educational methods.(2) In addition, equity, justice, ethical and human rights issues related to climate change likely benefit from interactive educational methodology and co-developed solutions.(3)

We present here an example of youth involvement, co-learning and co-creation of educational material, using as a case study our "Climate Change Solutions Festival" that took place in May 2021 in The Gambia, West Africa. The festival used and applied innovative educational methods, with co-learning, equity and respect as core values.

The project was run by the Medical Research Council Unit The Gambia at London School of Hygiene & Tropical Medicine in collaboration with the Gambian Ministry of Education (MoE). The team jointly decided on key objectives, scope, student ages to involve, and the logistical support available. We approached students aged 16-18 years in 50 schools across The Gambia to participate in a competition to develop an interactive stall to demonstrate their local solutions to adapt to and/or mitigate the impacts of climate change or environmental degradation more broadly. Eleven schools were selected to demonstrate at the festival based on relevance, innovation and engagement of their proposed solutions. Ten non-governmental organisations (NGOs) in the area of conservation and environmental protection were also invited to participate to demonstrate their (professional) solutions and promote co-learning with students. Over two days, 600 school children attended the festival. The days involved peer-to-peer learning with interactive experiments, action sketches and a theatre play covering a variety of climate change solutions. An example of a stall is given in Figure 1 (full stall details: https://doi.org/10.17037/PUBS.00002767(4)). Below we highlight successes and pitfalls of the festival.

The importance of equal partnerships

From the outset, we aimed to form equal partnerships between government departments, academia and NGOs. In practice, the project was predominantly led by the academic partners. There were several reasons why this occurred: 1) the relatively short time frame for festival organisation placed a time constraint on collaborator contributions; 2) a limited budget impacted accessibility and scope; and 3) the budget holder being the academic institution introduced an imbalance in power. We have identified three key leverage points on how partnerships could be strengthened in future editions of the festival or similar co-learning activities through this experience and the literature.(5)

1. Improved planning with longer lead-in time, communication, and transparency between all partners with a commitment of investing time to build relationships and trust.
2. Discuss and agree on shared goals for any future programs.
3. Evaluation (and potential adjustments) of the partnership during the collaboration.

From festival to impact

Students who demonstrated and attended the festival showed strong enthusiasm for further roll-out of local solutions to tackle specific environmental and climate change related problems. The festival structure and layout allowed networking between students, academics, NGOs and government stakeholders, however no specific strategy was in place to encourage professionals to enact upon students' solutions. .

Although long-term impacts at this stage are impossible to gage, the passion, enthusiasm and ingenuity of the students give hope that the climate leaders of the future are ready. Despite this we felt there was an unequal balance between climate change adaptation solutions and climate justice, with the latter being underrepresented at the festival. While a focus on adaptation is imperative (given the climate change impacts already experienced in this setting) (6) failing to represent climate justice may have disabled an important avenue to enact change.(7) Without addressing the global inequality in those responsible for climate change versus those impacted by it reduces the likelihood of leveraging global action.(8) To overcome this in future editions a more proactive approach could be taken; for instance, by inviting NGOs with a climate justice focus; running workshops in schools on different aspects of climate adaptation and justice; or by encouraging student projects which address climate equity or justice.

Education and co-learning are pivotal in addressing the climate crisis. Young people are strong supporters of action to change our current global trajectory on climate change and it is time their voices are heeded by those in power.

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frontiers in Public Health

ORIGINAL RESEARCH
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Check for updates

Impact of Personal Cooling on Performance, Comfort and Heat Strain of Healthcare Workers in PPE, a Study From West Africa

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Background: Personal protective equipment (PPE) is an essential component of safely treating suspected or confirmed SARS-CoV-2 patients. PPE acts as a barrier to heat loss, therefore increasing the risk of thermal strain which may impact on cognitive function. Healthcare workers (HCWs) need to be able to prioritize and execute complex tasks effectively to ensure patient safety. This study evaluated pre-cooling and per-cooling methods on thermal strain, thermal comfort and cognitive function during simulated emergency management of an acutely unwell patient.

Methods: This randomized controlled crossover trial was run at the Clinical Services Department of the Medical Research Unit The Gambia. Each participant attended two sessions (Cool and Control) in standard PPE. Cool involved pre-cooling with an ice slurry ingestion and per-cooling by wearing an ice-vest external to PPE.

Results: Twelve participants completed both sessions. There was a significant increase in tympanic temperature in Control sessions at both 1 and 2 h in PPE ($p = 0.01$). No significant increase was seen during Cool. Effect estimate of Cool was −0.2°C (95% CI −0.43; 0.01, $p = 0.06$) post 1 h and −0.28°C (95% CI −0.57; 0.02, $p = 0.06$) post 2 h on tympanic temperature. Cool improved thermal comfort ($p < 0.001$), thermal sensation ($p < 0.001$), and thirst ($p = 0.04$). No difference on cognitive function was demonstrated using multilevel modeling.

Discussion: Thermal strain in HCWs wearing PPE can be safely reduced using pre- and per-cooling methods external to PPE.

Keywords: personal protective equipment, heat strain, cooling, cognitive function, healthcare workers, occupational heat strain

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INTRODUCTION

SARS-CoV-2 continues to cause significant mortality and morbidity worldwide (1). Healthcare systems and healthcare workers (HCW) must ensure effective and timely treatment of cases without compromising safety (2). For HCWs this involves use of personal protective equipment (PPE) when treating suspected or confirmed cases, following international guidelines (3, 4).

PPE is a physical barrier preventing viral contamination, however it also reduces evaporative and radiative heat loss leading to potential uncompensable heat load, thermal strain and discomfort (5). Acknowledging this, the Center for Disease Control and Prevention (CDC), the American Conference of Governmental Industrial Hygienists (ACGIH) and the International Organization for Standardization (ISO) have all produced guidelines to ensure workers' safety in thermal extremes (6–8). However even if these guidelines are known about and adhered to, recent studies have questioned whether the measures are sufficient in tropical climates (9, 10).

In tropical regions there are several factors that increase the risk of thermal strain. Ambient environmental conditions are likely to be high. For example in The Gambia, West Africa, average daily temperatures range from 29 to 34°C with annual average levels of relative humidity at 68%, significantly higher than recommended temperature and humidity for indoor surgical operating theaters (25°C and 60%) (11). Additionally, in most healthcare facilities in resource-limited tropical settings, natural ventilation systems alone are often relied upon, with limited availability of air-conditioning (12). Wall-mounted air-conditioning units, where available, recirculate air without a HEPA filter and are advised against by the WHO (13). Ceiling or standing fans are not recommended in any but single occupancy rooms. Therefore, there is a high environmental heat load that is difficult to mitigate. Concerns regarding shortages of PPE mean that healthcare workers often wear PPE for prolonged periods. The length of time in PPE increases the risk of dehydration, thermal strain, physical exhaustion and may compromise decision making (14–16). During this current pandemic, many HCW are wearing PPE for 4 or more hours (17).

The most appropriate personal cooling mechanism for healthcare workers in PPE likely differs depending on work load, environmental stressors and resources (5). Comparative evidence from industry and athletes have shown internal, external and mixed-method cooling to reduce thermal strain (18–25).

Pre-cooling (reducing body temperature prior to heat exposure) with ice slurry ingestion (ISE) lowers core temperature and increases heat storage capacity, delaying the onset of sweating and risk of dehydration, reducing thermal discomfort and improving endurance capabilities (26, 27). ISE is more effective than water ingestion at absorbing heat and can therefore have a greater impact on reducing body temperature (28). It also improves perception of effort, cognitive function and fatigue (29). However, the effects of ISE are time-limited (30). Ice-vests have been shown to improve endurance performance and thermal comfort via changes in skin temperature, although they do not lower core temperature as ISE does (18, 21). Mixed methods of cooling, including pre and per (during)-cooling methods have been found to be the most effective (18). Studies of ice-vests with PPE to date have placed the ice-vests under PPE (18, 21), however after several hours the ice packs will melt and will then add to physical discomfort and energy cost. A simple effective cooling mechanism for HCW in PPE has not been established.

Despite conflicting evidence of the impact of heat strain on simple mental tasks, there is growing consensus that above 38.2°C core temperature, dual-task performance and complex-task sharing are negatively impacted by heat strain (31–34). This is particularly relevant to HCWs who are often caring for multiple patients, need to be able to prioritize tasks effectively and perform accurate calculations, all under stress. There is little literature on the impact of heat stress on HCWs' ability to perform routine tasks in tropical conditions (11). Studies from temperature-controlled settings give conflicting evidence of the effect of PPE on HCW emergency tasks performance, where clinical tasks performed by specialists appear to be preserved from the impact of the physical effects of PPE (i.e., anesthetists vs. clinicians on intubation) (35, 36). One study on surgeons' ability to perform laparoscopic operative tasks at 26 vs. 19°C found a significant increase in both physical demand and distractibility at higher temperatures (37). Another study evaluating different PPE suits at 22 and 28°C did not show any impact on simulated HCW tasks (38).

We hypothesize that PPE-induced thermal strain impairs complex task performance by HCWs and this effect will be mitigated by personal cooling methods. This study aimed to be directly transferable to clinical practice and therefore was simple and pragmatic, assessed the risk of compromising PPE and assessed the ability to perform life-saving procedures. We evaluated the use of a combination of pre-cooling with ISE ingestion and per-cooling via ice-vests external to PPE on thermal strain, thermal comfort and cognitive function during simulated emergency management of an acutely unwell patient.

MATERIALS AND METHODS

Participants

We enrolled 16 HCWs from the pool of staff working on the COVID wards in the Clinical Services Department of the Medical Research Unit The Gambia (MRCG). We used convenience sampling of non-pregnant, non-shielding staff. Written informed consent was given by all participants. Baseline characteristics are presented in **Table 1**. All participants were long-term residents of The Gambia. All experiments described below took place around the usual staff shifts.

TABLE 1 | Mean (SD) demographic and anthropometric measurements of participants.

	Males	Females	*p*-value
N (%)	7 (58%)	5 (42%)	
Ethnicity: Gambian	6	2	
Other West African country	1	3	
Occupation: Qualified nurse	4	4	
Auxiliary nurse (HCA)	3	1	
Chronic medical conditions	0	0	
Age (years) Mean (SD)	29.4 (2.6)	36.5 (12.2)	0.28
Weight (kg) Mean (SD)	68.0 (15.6)	80.2 (24.4)	0.31
Height (cm) Mean (SD)	184.2 (11.6)	171.4 (7.5)	0.06
BMI* (kg/m^2) Mean (SD)	19.8 (2.67)	26.9 (6.38)	**0.02**

Body mass index. Bold indicates p value < 0.05.

Ethics approval was granted by the Gambia Government/MRC joint ethics committee and the London School of Hygiene and Tropical Medicine Ethics Advisory Board (Ref. 22590). The study was conducted in accordance with the Institution's ethics and governance committee, and Declaration of Helsinki (39).

Experimental Design

This was a randomized controlled crossover, repeated measures experiment of ISE and ice-vests (Cool) on thermal strain, thermal comfort, and cognitive function in HCW in PPE. Each participant was invited to attend two sessions (Cool vs. Control) at least 4 days apart to minimize any further acclimation effect from repeated heat exposures, at the same time of day to avoid the effect of diurnal rhythms on core temperature.

Sample Size

Sample size calculation was based on results from Quinn et al.'s study of cooling methods in PPE in environmental conditions designed to reproduce conditions in West Africa (40). In this study core temperature in control (38.86C) and ice-vest intervention (37.94C) gave an effect size of 0.92. Taking an alpha of 0.05 and a power of 0.8, a minimum sample size requirement of 12 would detect a similar difference.

Session Protocol and Simulation Training

Sessions occurred in an unoccupied hospital ward. Environmental conditions were measured using the HT200: Heat Stress WBGT (Wet Bulb Globe Temperature) Meter (Extech®, NH, USA). The first hour mimicked a teaching ward round covering the WHO Basic Emergency Care course and the Advanced Life Support Algorithm from the UK Resuscitation Council (41, 42). This hour was spent standing or sitting taking notes with an estimated metabolic equivalent task (MET) of 1.8. There followed a revision quiz and simulation training. During the simulation all participants had to deliver effective cardiopulmonary resuscitation (CPR) and bag-mask ventilation to a mannequin. The estimated METs of CPR were 5.7 (43). Sessions were delivered by an Advanced Life Support Instructor and medical doctor and were tailored to locally available equipment. Sessions lasted ∼2 h, with some extension to allow completion of the cognitive function tests.

PPE

All participants wore standard PPE for treating suspected or confirmed covid-19 patients, as specified by MRCG@LSHTM. This consisted of scrubs under category III type 5B/6B protection coveralls with hood, shoe covers, gloves, an FFP2 mask, and face shield.

Measurements

Tympanic temperature measurements were taken using a Braun ThermoScan® 7 tympanic thermometer (Braun GmbH, Kronberg, Germany). Duplicate measurements were taken from both left and right tympanic. The highest measurement was taken from the four readings at each time point (44–46).

Heart rate and blood pressure were measured whilst sitting from the right arm using an OMRON M3 automatic device (Omron, Kyoto, Japan). These were measured hourly throughout the sessions.

Urine specific gravity was measured by urine dipstick and urine osmolality with a portable refractometer, calibrated daily (Osmocheck™, TECIL, Barcelona, Spain).

Thermal comfort was measured on a six-point scale from very comfortable (1) to very uncomfortable (6). Thermal sensation was measured on an eight-point scale from very cold (1) to unbearably hot (8). Thirst was measured on a five-point scale from not thirsty (1) to very, very thirsty (5).

Cognitive Function Test

A cognitive battery test was used to assess overall cognitive function. CogniFit General Cognitive Assesment® is a computer-based series of exercises which test multiple cognitive domains and is widely used (47, 48)[1]. The program gives an overall score and specific scores for 26 cognitive areas. All participants completed a familiarization visit with the program prior to attending the study sessions.

Cooling Intervention

For the Cool session, participants were given 7.5 ml/kg of ice slurry to drink over 15 min immediately prior to donning PPE (26). Once full PPE was applied, a commercially available outdoor cooling vest to protect against heat stroke was put on (Sports Cooling Vest, Desertcart.com©). The cooling vest was a sleeveless, zipped vest with 6 pockets for ice packs, two at the front and four at the back. Ice packs were placed in the vest at the start of the session and replaced hourly (**Figure 1**).

Statistical Analyses

Data are reported as mean ± SD, all continuous variables were assessed for normality by distribution and Shapiro-Wilk normality test. Baseline physiology and environmental conditions between control and intervention sessions were assessed using paired *t*-test for normally distributed variables and Wilcox Signed-Rank test for non-parametric variables.

One-way ANOVA was used to determine the change in temperature or heart rate over time in Cool and Control. However, due to violation of model assumptions for repeated measures ANOVA, a multilevel model was used to assess change in tympanic temperature (model 1), heart rate (model 1), and cognitive function (model 2) with intervention as a fixed effect and individuals as random effects. The overall cognitive score and four pre-determined outputs from the cognitive battery test: divided attention, focused attention, and shifting and working memory, were analyzed (model 2). These four outputs were chosen to correlate with the need to multi-task whilst remaining focused as a healthcare worker.

Model 1:

$$Y \sim \beta_0 + \beta_1 * intervention + (1|ind)$$

[1] Available online at: https://www.cognifit.com/cognitive-research-tool.

FIGURE 1 | A participant in full PPE with ice vest.

Model 2:

$$\begin{aligned} \textit{Cognitive score} \sim \beta_0 \; &+ \; \beta_1 * \textit{intervention} + \beta_2 * \textit{session} + \beta_3 * \textit{order} \\ &+ \; \beta_4 * \textit{sex} + \beta_5 * \textit{age} + \beta_6 * T_{\text{tymp}} + \; (1|\textit{ind}) \\ \textit{Session} &= \textit{session 1 or 2} \\ \textit{Order} &= \textit{order of intervention by session} \\ \textit{Sex} &= \textit{male or female} \\ \textit{Age} &= \textit{age of participant in years at recruitment} \\ T_{\text{tymp}} &= \textit{maximum tympanic temperature} \\ (1|\textit{ind}) &= \textit{participant as a random effect} \end{aligned}$$

The difference between thermal comfort, sensation and thirst for control and intervention at the end of the session were assessed by proportions and chi-squared. Thermal comfort was redefined as comfortable (very comfortable to just comfortable) and uncomfortable (just uncomfortable to very uncomfortable). Thermal sensation was redefined as not hot (very cold to warm) and hot (hot to unbearably hot). Thirst was redefined as minimal thirst (not thirsty to slightly thirsty) and thirsty (thirsty to very, very thirsty).

RESULTS

Sixteen participants were recruited and participated in the first session. Three participants (2 male and 1 female) were unable to attend the second session. One participant (female) was acutely unwell during session two, was subsequently diagnosed with an acute viral infection and removed from the study.

Twelve registered and auxiliary nurses, 7 males and 5 females, completed both Control and Cool sessions. Of these, one participant terminated the simulation early during the Control session due to light-headedness and pre-syncope. All participants completed the Cool session.

Mean air temperature, relative humidity and wet bulb globe temperature (WBGT) at baseline were 29.3°C, 69.3% and 26.1°C, respectively. Average temperature, humidity and WBGT throughout the sessions were 30.2°C (range 28.8–32.0°C), 68.2% (range 53.8–75.3%), and 27.2°C (range 25.0–29.3°C), respectively. There was no statistically significant difference in climate exposure between Cool and Control sessions ($p = 0.42$).

Baseline

Baseline physiology of participants at the start of each session were similar: heart rate (Control = 79.1; Cool = 80.8 bpm), $t_{(11)} = -0.2$, $p = 0.82$ and urine osmolality (Control = 695; Cool = 628 mOsm/kg), $t_{(11)} = 0.6$, $p = 0.54$ and Wilcox Signed-Rank test for tympanic temperature (Control = 36.8; Cool 37.0°C), $Z = 10.5$, $p = 0.17$ and urine specific gravity (Control = 1.03; Cool = 1.03), $Z = 16$, $p = 0.79$.

Physiology

Mean tympanic temperature change are presented in **Figure 2**. There was a significant increase in tympanic temperature in the Control group from baseline to 1 h in PPE ($p = 0.01$) and 2 h in PPE ($p = 0.01$), but no significant increase in Cool ($p = 0.06$, $p = 0.21$ at hour 1 & 2, respectively). Heart rate did not change in either Control or Cool sessions (see supplement).

Multilevel modeling gave an effect estimate of Cool as −0.2°C, 95% CI −0.43; 0.01, $p = 0.06$ post 1 h and as −0.28°C, 95% CI −0.57; 0.02, $p = 0.06$ post 2 h on tympanic temperature.

Perception

Thermal sensation, comfort and thirst all differed significantly between control and intervention (**Figure 3**). For thermal comfort 92% (11/12) were uncomfortable in the control vs. 8% (1/12) in the intervention ($p < 0.001$). For thermal sensation 100% (12/12) of those in the control arm felt hot or above at the end of the session vs. 0% (0/12) in the intervention arm ($p < 0.001$). For thirst, 83% (10/12) felt thirsty or very thirsty in the control vs. 17% (2/12) in the intervention ($p = 0.04$).

Cognitive Function

Mean cognitive function scores per session are presented in **Table 2**.

The first test was the familiarization test and each subsequent test was run after completion of the sessions whilst participants remained in PPE. The standard error of measurement (SEM) indicated there was a learning element to the test where the test completed at the end of session 2 scored higher than the session 1 test (familiarization: session 1 SEM = 19.0%, session 1: session 2 SEM = 17.2%.

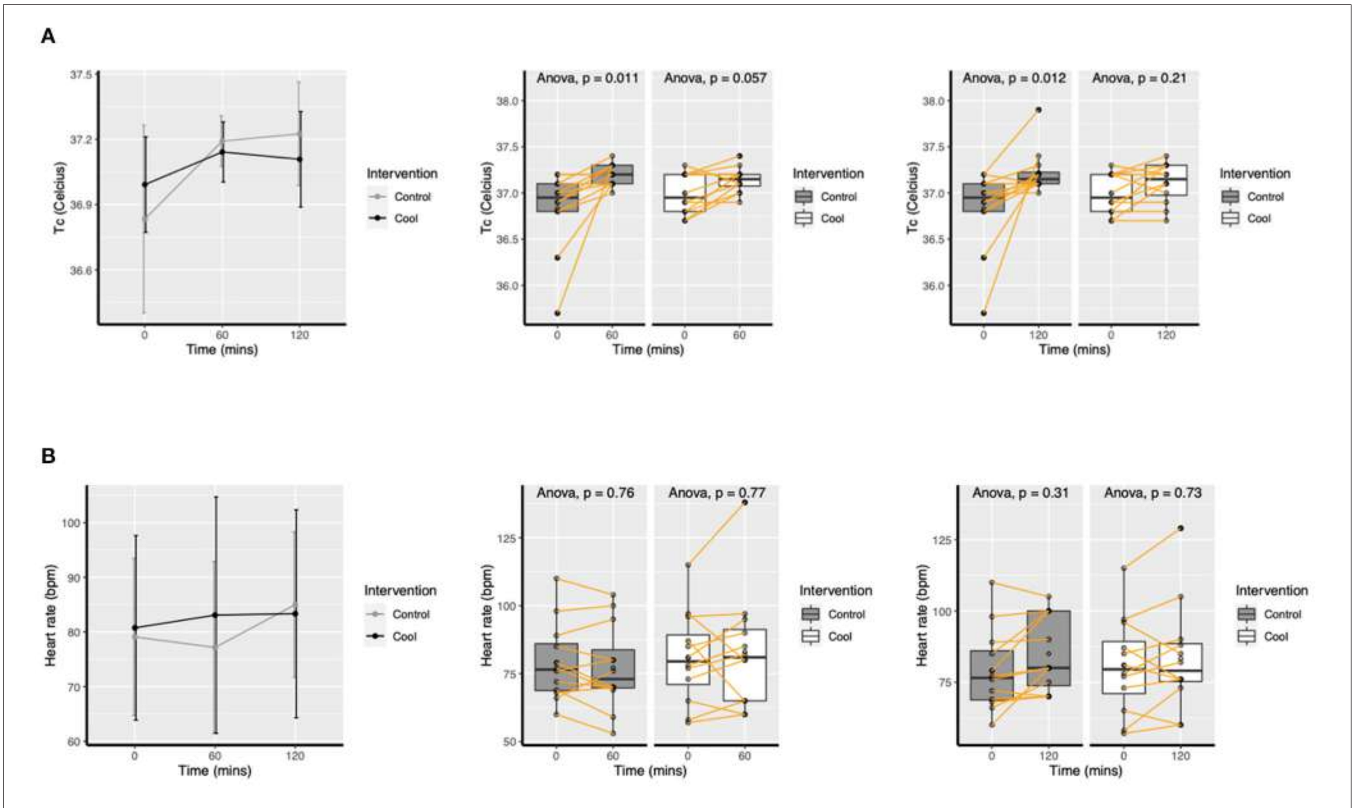

FIGURE 2 | Mean (SD) change in tympanic temperature **(A)** and heart rate **(B)** over time for Cool and Control.

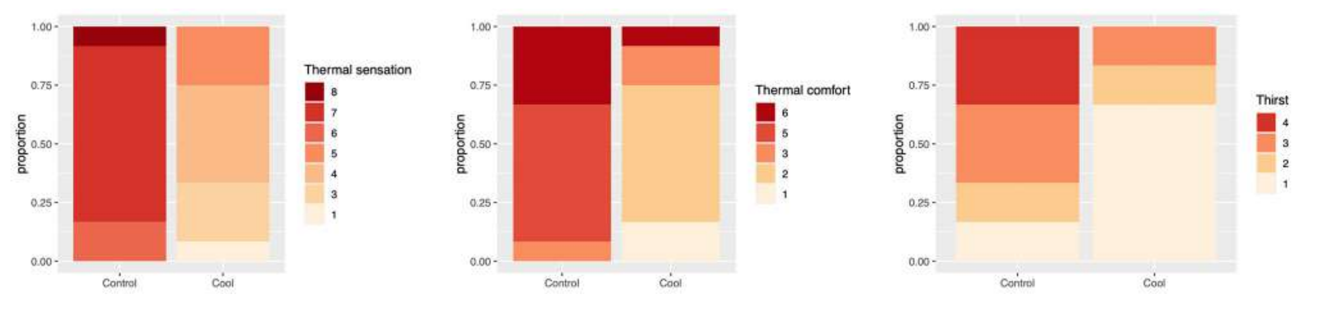

FIGURE 3 | Thermal sensation, comfort and thirst by Control and Cool.

TABLE 2 | Mean (SD) Cognitive function results by order of test performed and Control vs. Cool.

Cognitive function test	Familiarization test	Session 1 test	Session 2 test
Mean (SD)	150 (66.5)	208 (87.1)	224 (101.9)
Range	46–273	106–366	79–380
	Control	**Cool**	
Mean (SD)	222 (102.5)	210 (86.8)	
Range	94–380	79–366	

Multilevel modeling did not demonstrate any difference in overall cognitive function by Control vs. Cool. **Table 3** gives details of the models for all pre-specified cognitive domains tested. Intervention had no impact on any domains.

Model Validity

Plots of all multilevel model residuals were examined for deviation from linear form by Pearson correlation. Constance of variance of residuals was also examined and normality of residuals. All model assumptions in all models were met according to these tests.

DISCUSSION

This study demonstrated that a combination of pre- and per-cooling reduced thermal strain in HCW wearing PPE, and

TABLE 3 | Linear multilevel model estimates for different cognitive parameters.

	Estimate [95% CI]	*P*-value for LRT	Estimate [95% CI]	*P*-value for LRT
	Total cognitive function score		*Divided attention*	
Session 1	63.2 [24.6, 102.6]	**<0.001**	103.6 [−48.1, 255.1]	0.43
Session 2	76.2 [42.7, 109.1]		19.3 [−110.3, 149.0]	
Order	54.8 [−25.2,134.7]	0.24	193.0 [57.6, 328.7]	**0.01**
Intervention	−7.6 [−40.5, 25.6]	0.67	−83.6 [−212.8, 54.5]	0.25
Tc	1.3 [−130.5, 146.1]	0.99	458.8 [−9.7, 923.6]	0.08
Age	−4.2 [−9.2, 0.7]	0.14	10.3 [2.0, 18.7]	**0.03**
Sex	24.1 [−44.4, 92.4]	0.54	−23.1 [−142.0, 95.6]	0.73
	Focused attention		*Shifting*	
Session 1	60.5 [−73.7, 192.7]	0.40	76.3 [−81.9, 228.2]	0.41
Session 2	82.4 [−31.0, 196.8]		92.7 [−38.0, 226.6]	
Order	46.1 [−87.5, 179.9]	0.56	247.9 [59.3, 437.1]	**0.02**
Intervention	13.6 [−100.1, 126.7]	0.82	40.2 [−92.4, 170.9]	0.57
Tc	−37.0 [−463.9, 368.5]	0.87	534.3 [−22.7, 1015.6]	0.06
Age	−5.3 [−13.6, 2.9]	0.27	6.5 [−5.1, 18.2]	0.34
Sex	−40.4 [−156.6, 76.0]	0.55	107.1 [−55.8, 270.9]	0.26
	Working memory			
Session 1	79.9 [17.4, 144.2]	**<0.001**		
Session 2	135.9 [81.5, 189.4]			
Order	18.3 [−120.6, 157.0]	0.82		
Intervention	−15.0 [−68.4, 38.9]	0.60		
Tc	−193.5 [−407.3, 47.3]	0.11		
Age	−5.7 [−14.3, 2.9]	0.25		
Sex	−31.1 [−150.0, 87.4]	0.65		

Bold indicates p value < 0.05.

can improve discomfort from thermal sensation, comfort and thirst. We did not show any impact on cognitive function.

Several recent studies have explored personal cooling options whilst wearing PPE and although our findings are similar to these, this study is novel in that it evaluated a mixed-method cooling approach (using both internal and external, and pre and per-cooling) and the effect of external cooling was prolonged by replacing ice-packs. The study by De Korte et al. explored 21°C phase change vests under PPE and significantly improved thermal comfort and sensation, although it had no impact on thermal strain (49). However, the transferability of this vest for cooling in the tropics is questionable due to differences in ambient conditions and potential resource limitation. Another study of PPE used for Ebola treatment, based in a heat-chamber, found a reduction in heat strain with several different types of cooling vest (40). Although this study was performed in similar ambient conditions, the PPE requirements for Ebola are different to COVID and the exposure was only for 1 h and so not directly transferrable to current practice in treating COVID.

Focusing on the physiological changes in the study, we did not see the rise in temperatures described in two other studies of PPE use in West Africa (50, 51). These studies were performed during the Ebola outbreak and found HCW in PPE had an average core temperature rise to 38°C and in 4/25 individuals exceeded 38.5°C after 1 h in PPE (50). This may in part be due to the characteristics of the PPE requirements for Ebola vs. COVID, since external conditions were similar, but may in part be due to heat acclimation. Our study's participants were West African nationals, who had been residing in the region for at least 6 months prior to the study and therefore had likely acclimated (a series of phenotypic changes resulting in physiological alterations that act to protect against heat stress) and the other studies participants were French and American nationals. Notably, mean resting tympanic temperature was lower in the participants of the present study.

This may also help to explain why there was no impact of wearing PPE on cognitive function amongst HCW. The literature on the impact of heat stress on cognitive function suggests a critical threshold of thermal strain on cognitive function, below which there is no impact (31). The HCW in our study did not cross this critical threshold, potentially explaining the lack of impact on cognitive function. This is reassuring for patient care, although our data was measured on a single day and it is unclear whether cumulative thermal strain over successive days wearing PPE would result in a diminished cognitive function.

All participants in the study were able to perform emergency medical procedures with no evidence of compromise to the PPE, condensation or droplet spread caused by the per-cooling vest. The practicalities of enacting this intervention will depend on the facilities available. In the MRCG hospital, we have completed staff sensitization and awareness sessions, provided access to cold/iced drinks in the hospital staff common room and located a chest freezer, the ice-packs and ice-vests in the COVID-zone. This will enable staff to use the ice-vests in a contaminated space and keep them in that space, avoiding the risk and inconvenience of repeated decontamination.

There are several limitations to the study. There were four participants who were unable to complete both sessions, reducing the sample size. The sample size calculation was based on previous studies of heat alleviation in PPE, and so although we did not meet the target of sixteen, twelve was within our minimal sample required. At baseline, the tympanic temperature of the Cool group was 0.2C higher than the Control and although this is likely due to chance and was not a statistically significant difference, it may have impacted on the findings. Additionally, although the temperature and humidity remained relatively constant during the session, it did vary more than if the study had been run in a heat-chamber, but there was no significant difference between Cool and Control sessions. The advantage of the study being run on a hospital ward was that although the ambient conditions were not controlled, they were exactly what HCWs experience and so directly generalizable. The gold standard for core temperature is rectal or esophageal temperature. These were not practical whilst in PPE and cost constraints prevented the use of a telemetry pill. Core temperature may thus have under-recorded, however we monitored both the change in temperature as well as the absolute temperature to reduce the impact of this limitation on data interpretation. Additionally, most physiological studies use continuous heart rate monitoring, which was not available in this study. The cognitive battery test used was designed and validated in America and assumes a degree of computer or tablet literacy resulting in certain language and technological aptitude barriers. Finally, the study used simulation to model real-life ward experience, to ensure standardization, but in reality, clinical work can be highly variable, and this may not have been captured. Additionally, shift durations vary dramatically depending on staffing, clinical workload and availability of PPE and therefore the applicability of these solutions will be locally dependent. However, direct comparison of Control and Cool would have been very challenging in a real-world setting.

CONCLUSION

Pre- and per- cooling using internal and external cooling modalities reduced thermal strain in HCW in PPE for a prolonged duration, dramatically improved thermal sensation, comfort and thirst and is safe to implement, with no detriment on ability to perform medical tasks or contamination risk by condensation.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Gambia Government/MRC joint ethics committee and the London School of Hygiene and Tropical Medicine Ethics Advisory Board. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

AB conceived, designed, implemented, and completed first draft of the manuscript. BN advised on design, facilitated implementation, and edited manuscript. TS and JB facilitated implementation and edited manuscript. RP-T, KF, and AP advised on design and edited manuscript. NM advised on conception and design and edited manuscript. All authors contributed to the article and approved the submitted version.

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