Climate Change and Maternal Health: Modelling the Impact of Heat Stress on Pregnant Subsistence Farmers in The Gambia

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handed in by

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Preface

Human-induced climate chance and its impacts on mortality and morbidity set increasing pressure on health systems around the world [1]. Population subgroups in developing countries, such as pregnant women working in subsistence agriculture in The Gambia, are particularly at risk of climate change-related adverse health outcomes, whereby the respective risk is influenced by increased exposure and vulnerability to more frequent and extreme weather conditions as well as by the underlying environmental hazards. Therefore, it is crucial to advance the understanding of the mechanisms through which extreme heat stress affects the physiology of pregnant women. In this Master thesis, we analysed observational data from a previous cohort study of Bonell et al. [2] and modelled data on solar radiation from ERA5 climate reanalysis. While applying Pearson product moment correlation analysis, mixed-effect models with random intercepts, and confirmatory composite analysis, we gained a more detailed understanding of the associations between environmental and physiological variables. With our results we aimed to contribute to the development of climate change adaptation strategies.

At the nexus between Climate Sciences, Environmental Epidemiology, and Physiology, the results of this study offer interdisciplinary evidence on increased effects of heat stress on maternal physiology under conditions of humid heat and after a gestational age above 27 weeks. The analysis on the associations between environmental and physiological variables can support the selection of heat stress indices for potential heat-health warning systems and support the risk assessment of pregnant women.

This Master thesis has been written in the format of a research article. In addition to the submitted manuscript, the present document aims to provide further perspectives on the results of the study. It serves as a research commentary and is divided into five chapters. Chapter 1 introduces the study context and the most important concepts of this thesis. Chapter 2 contains the manuscript "Integrating Observational and Modelled Data to Advance the Understanding of Heat Stress Effects on Pregnant Subsistence Farmers in The Gambia" in its format submitted to *Scientific Reports*. Chapter 3 provides conclusions on the implications of the findings and suggests an outlook on future lines of research. Chapter 4 contains references of both the manuscript and the present research commentary. Chapter 5 includes additional analyses that have been made in the context of this Master thesis and did not enter the manuscript.

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Abbreviations

°C	Degrees Celsius
AT	Apparent Temperature
bpm	Beats per minute
CI	Confidence interval
ERA5	Climate reanalysis produced by the European Centre for Medium-Range Weather Forecasts
HI	Heat Index
IPCC	Intergovernmental Panel on Climate Change
m/s	Meters per second
Max	Maximum
Min	Minimum
N	Number of participants
NA	Not announced
p-value	Probability value
Ptl.	Percentile
r	Correlation coefficient
Std. Dev.	Standard deviation
UTCI	Universal Thermal Climate Index
W/m2	Watts per square meter
WBGT	Wet Bulb Globe Temperature

1. Introduction

1.1. Research context

Most recent regional assessments of the Intergovernmental Panel on Climate Change (IPCC) [3] have reported an increase in mean annual temperatures as well as in the frequency and intensity of heat waves and droughts through climate change. The annual number of days above lethal heat thresholds is projected to increase in West Africa from under 50 days between 1995 and 2005 to 50-150 days under a global warming scenario of 1.6 °C, respectively to 250-350 days under a global warming scenario of 4.4 °C by the end of the century [4]. In The Gambia, historical country-level linear trends show that the mean annual temperature has increased by 1.0 °C, the wet season has shortened and the wet season precipitation has decreased by 8.8 mm per month since 1960 [5]. Regional climate models project an additional increase in mean annual surface temperature between 0.9 °C to 4.8 °C in The Gambia by 2100, depending on the shared socio-economic pathway [6].

The impacts of climate change are multi-dimensional, affecting ecosystems, livelihoods, food security, infrastructure, and the economy. Climate change impacts on human health are already observable and projected to further increase [3]. On a global level, heat-related mortality increased by 37.0 % due to human-induced climate change [7]. Population subgroups such as pregnant women are particularly vulnerable to the health impacts of climate change and face an elevated risk of adverse pregnancy outcomes under continued exposure to extreme heat. A previous study from Ghana has found that the odds ratio of having stillbirth or miscarriage increases by 12.0 - 15.0 % with each additional degree increase in Wet Bulb Globe Temperature (WBGT) [8].

1.2. Research setting

This Master thesis is based on a previous observational cohort study of Bonell et al. [2], which collected data from 92 pregnant women who work in the agricultural sector in West Kiang, a district in the Lower River Division of The Gambia. Located within the Sahelian climate zone, the climate in West Kiang is characterized by an annual mean temperature of 28.7 °C and annual rainfall of 836.0 mm [9, 10], which is ideal for the cultivation of rice, groundnuts, and vegetables [10]. The average age of study participants was 27.7 years, and the average gestational age was 28.6 weeks. Despite pregnancy, women performed physically demanding tasks with an average duration of work shifts between 4.5 - 7.5 hours per day. A previous qualitative study in the same research setting has shown that women self-reported heat stress at their workplace in agriculture, with symptoms being more severe during pregnancy [10].

It is important to note that all study participants provided informed consent and the data collection 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". For this Master thesis, we applied for additional ethical review to the "Ethics Committee of University of Bern", but our application was not assessed, given that it fell under the same ethical assessment of the previous cohort study of Bonell et al [2].

1.3. Research questions

The following three research questions were formulated with this Master thesis:

i. What are the separate and independent effects of air temperature, relative humidity, air velocity, black globe temperature and modelled solar radiation on heart rate, skin temperature, tympanic temperature, and core temperature estimates of pregnant women working in subsistence agriculture in West Kiang, The Gambia?
ii. What are the compound effects of environmental heat stress on maternal heat strain of pregnant women working in subsistence agriculture in West Kiang, The Gambia?
iii. How do heat stress indices, namely the Heat Index, Apparent Temperature, Wet Bulb Globe Temperature (WBGT), and the Universal Thermal Climate Index (UTCI) apply to our study setting?

We assessed the first and third research questions (i + iii) through Pearson product moment correlation analysis and mixed-effect models with random intercepts per study participants. The second research question (ii) was addressed through confirmatory composite analysis, whereby we considered environmental variables as indicators for heat stress and physiological variables as indicators for maternal heat strain.

1.4. Research process

The research process involved multiple phases, namely the data preparation and analysis, and the writing and review of the manuscript. Throughout the entire research process, bi-weekly meetings were held with both Supervisors. Furthermore, weekly meetings with the research group "Climate Change and Health" at University of Bern were led by Prof. Dr. Ana Maria Vicedo Cabrera. The meetings provided a platform to present and interpret findings, resolve questions, and determine subsequent research steps.

During the phase of data preparation, multiple datasets with observational data from the cohort study of Bonell et al. [2] were merged with modelled solar radiation data in the statistics software R-studio. The observational data included a total of twenty datasets with physiological variables, a dataset with environmental variables, a dataset with the geolocation of study participants, and a dataset with modifying variables. Additionally, 80 datasets with location-specific modelled solar radiation data were extracted from ERA5 climate reanalysis of the Copernicus Climate Change Service [11], based on tutorials recommended by Dr. Coral Salvador Gimeno. We decided to model solar radiation, given that we could not disentangle solar radiation from black globe temperature measurements. For the merging of datasets, we assigned hourly means of physiological variables for each of the multiple measurements of study participants to environmental variables, given differences in temporal resolutions between datasets.

During the phase of data analysis, we used the R-package lme4 [12] for the mixed-effect modelling with random intercepts, cSEM [13] and lavaan [14] for the confirmatory composite analysis, and the cor() command to perform Pearson product moment correlation coefficient analysis. The R script of the Master thesis comprises 8500 lines of code and was made available to the Supervisors in case future Master studies will address similar research questions.

Ultimately, during the phase of writing and review of the manuscript, multiple drafts were created and edited. Submission guidelines from the journal *Scientific Reports* on the format and content were taken into consideration. The review process with inputs from Supervisors and co-authors allowed to improve the coherence of the manuscript. Overall, the writing and review process provided learnings on how to visualize and communicate scientific findings more effectively and gave an insight into the work of researchers.

2. Manuscript Submission

The manuscript "Integrating Observational and Modelled Data to Advance the Understanding of Heat Stress Effects on Pregnant Subsistence Farmers in The Gambia" entered the submission of the special edition "Heat and Human Health" of Springer Nature's Scientific Reports on February 5th, 2023. In terms of the topic, our analysis covers three elements mentioned in the call for submissions:

i. **Research on the impact of extreme heat**: Our methodology has enabled us to disentangle the effects of heat stress on multiple physiological indicators of maternal heat strain.
ii. **Focus on a population subgroup at high risk**: The study covers on-site measurements of 92 agricultural workers, whose risk to the impact of climate change is influenced by increased exposure to extreme heat given their outdoor work location, increased vulnerability to extreme heat during pregnancy as well as increased hazard of extreme heat reported by climate change projections for Western Africa.
iii. **Evidence for early warning systems and risk management**: Our findings provide a foundation for the risk assessment of pregnant women and suggest pathways to include heat stress indices in future weather warning systems as an adaptation strategy to climate change.

The following pages contain the version of the manuscript which was submitted to Scientific Reports.

Integrating Observational and Modelled Data to Advance the Understanding of Heat Stress Effects on Pregnant Subsistence Farmers in The Gambia

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Abstract

Studies on the effect of heat stress on pregnant women are scarce, particularly in highly vulnerable populations. To support the risk assessment of pregnant subsistence farmers in The Gambia, we conducted a study on the pathophysiological effects of extreme heat stress and assessed the applicability of heat stress indices. We added location-specific modelled solar radiation from ERA5 climate reanalysis to datasets from a previous observational cohort study involving on-site measurements of 92 women working in the heat. Associations between physiological and environmental variables were assessed through Pearson correlation coefficient analysis, mixed effect linear models with random intercepts per participant and confirmatory composite analysis. We found low to moderate associations $(0<r<0.54)$ and robust estimates for independent effects of environmental variables on skin- and tympanic temperature, but not on heart rate and core temperature. Skin temperature increased more significantly in conditions above a 50% relative humidity threshold, demonstrating interactive effects between air temperature and relative humidity. Pregnant women experienced stronger pathophysiological effects of heat stress in their third than in their second trimester. In conclusion, environmental heat stress significantly altered maternal heat strain, particularly under humid conditions. Based on our results, we recommend including UTCI or WBGT in local heat-health warning systems.

2.1. Introduction

Pregnant women who work outdoors are particularly vulnerable to heat stress and face an elevated risk of heat-related adverse health outcomes [15, 16, 17]. Heat stress indices offer a way for stakeholders to interpret, communicate, and potentially prevent the health impacts of climate change in the workplace [18]. However, more than 100 indices have been developed to model heat stress (defined by air temperature and its interplay with humidity, solar radiation and air velocity) and defining their appropriateness for a given study setting is key to producing robust and reliable predictions [19]. In addition, heat strain (the physiological response to heat stress) is defined by changes in certain physiological parameters (heart rate, core temperature, etc.) known to be related to exposure to above-optimal temperatures. It is unclear which environmental factors act singularly or in combination to affect maternal physiology leading to heat strain as this area has been under-researched to date [20, 21]. Therefore, a more thorough understanding of the effects of heat stress on maternal physiology, particularly in highly vulnerable populations, could support the adoption of specific heat stress indices that would allow accurate public health messaging and so reduce the health risks of working in the heat.

In West Africa, rapid and widespread changes in climate exacerbate the frequency, duration, and severity of extreme heat [22], whereby the resulting health inequalities are projected to become even more pronounced in the future [3]. Additionally, adverse pregnancy outcomes are disproportionally frequent in low-income countries [23] with 42% of stillbirths and 66% of maternal deaths worldwide occurring in sub-Saharan Africa [24]. This burden is attributable not only to healthcare system deficiencies or limited access to resources but also to environmental factors including heat stress [25].

The mechanisms by which heat stress affects human physiology are well documented in the literature [26]. To reduce excess heat storage, thermoregulatory responses are activated and cool the body through convection, radiation, or evaporation [27, 28]. When thermoregulation is unable to compensate for heat stress, negative health effects can arise, ranging from dizziness, dehydration, thermal fatigue, heat syncope, muscle cramps, and rashes to organ damage and heat stroke [25, 29]. A growing body of scientific evidence suggests that pregnancy represents a vulnerable time to the effects of extreme heat because foetal development is sensitive to alterations in the internal environment and because of the added heat burden of foetal growth, due to increased metabolism [25, 20]. Various studies indicate that exposure to heat during pregnancy affects placental and endocrine functions, and increases the probability of adverse pregnancy outcomes, including pre-eclampsia, premature birth, stillbirth, and prolonged labour [17, 16]. Nonetheless, the effect of environmental factors, both separately and jointly, on the physiological parameters of pregnant women and the applicability of heat stress indices in pregnancy are unclear.

To address these gaps, we used data previously collected by Bonell et al. [15] from 92 pregnant farmers in West Kiang, The Gambia in West Africa. First, we aimed to identify the separate and independent effects of air temperature, air velocity, relative humidity, black globe temperature, and modelled solar radiation on the physiological parameters of agricultural workers during pregnancy, while considering the potential confounding influence of general fitness status, gestational age, and metabolic rate. The physiological parameters (heart rate, skin temperature, tympanic temperature and core temperature) indicate the level of heat strain observed in study participants and thus the internal response of the human body when exposed to extreme heat [26]. We also compared the applicability of a range of heat indices (the Heat Index, Apparent Temperature, Wet-bulb Globe Temperature (WBGT), and Universal Thermal Climate Index (UTCI)) in our study context, to determine the potential added value of integrating these heat stress indices in local heat-health warning systems. The second aim was to investigate through confirmatory composite analysis the compound effects of exposure to heat stress (as an indicator for simultaneous changes in environmental variables) on heat strain (as an indicator for simultaneous changes in physiological variables). This study incorporated two types of data, namely (i) observational data, which contain both physiological and environmental on-site measurements of 92 pregnant women working in the heat in West Kiang, The Gambia, collected by the observational cohort study of Bonell et al. [1], and (ii) modelled solar radiation data which was extracted from the ERA5 climate reanalysis [11].

2.2. Results

2.2.1. Associations between environmental and physiological variables

Overall, Pearson product moment correlation coefficient analysis revealed interlinkages both within and between the pools of physiological and environmental variables. Visualized through the dendrogram lines at the left side of the heatmap *(Figure 1)*, we observed that, in terms of similarity in correlation pattern, the variables were not clustered in the initial two pools of environmental and physiological variables

(Table 1). Instead, skin temperature and tympanic temperature were nested within the cluster of environmental variables, indicating that their associations followed patterns that were more similar to those of environmental variables than to those of other physiological variables. Other physiological variables, such as core temperature estimate, the Physiological Strain Index, and heart rate, together with air velocity, formed the second cluster of variables.

Within the pool of environmental variables, Pearson correlation coefficients ranged from negligible to very high strength ($-0.08 < r < 0.80$) *(Figure 1, Supplementary Table 2)* [30]. Specifically, negative correlations were observed between relative humidity and air temperature ($r=-0.44$), black globe temperature ($r=-0.46$), and air velocity ($r=-0.35$), while positive correlations were found between solar radiation and air temperature ($r=0.42$), and between black globe temperature and air temperature ($r=0.80$). The heat stress indices, namely the UTCI, WBGT, the Heat Index, and Apparent Temperature, correlated with moderate to very strong strength ($0.65 < r < 0.94$), indicating their convergent validity *(Supplementary Table 2)*. Convergent validity measures how closely an index is related to another index that measures the same concept [31].

Within the pool of physiological variables, Pearson correlation coefficients ranged from negligible to very high strength ($-0.01 < r < 0.99$) *(Figure 1, Supplementary Table 2)*. The tympanic temperature of pregnant women was positively associated with skin temperature ($r=0.50$). Very high positive correlations were found between core temperature estimates and heart rate ($r=0.97$), between the Physiological Strain Index and heart rate ($r=0.99$), and between the Physiological Strain Index and the core temperature estimate ($r=0.99$). This high correlation is related to the calculation methods used for the Physiological Strain Index and the core temperature estimate based on other physiological variables.

Between the pools of environmental and health variables, Pearson correlation coefficients of low to moderate strength were calculated ($0.00 < r < 0.54$) *(Figure 1, Supplementary Table 2)*. Relative humidity was negatively associated with heart rate ($r=-0.30$), while positive correlations were found between skin temperature and air temperature ($r=0.37$), between skin temperature and solar radiation ($r=0.34$), and between tympanic temperature and relative humidity ($r=0.30$). The heat stress indices showed similar positive associations with skin temperature ($0.43 < r < 0.54$) and tympanic temperature ($0.26 < r < 0.33$) supporting the construct validity of the heat stress indices *(Supplementary Table 2)*. Construct validity refers to how well an index measures an intended concept [31]. Nevertheless, the construct validity of heat stress indices was only partial, given that the negative associations of heat stress indices with heart rate $(-0.22 < r < -0.35)$, core temperature estimate $(-0.14 < r < -0.30)$, and the Physiological Strain Index $(-0.18 < r < -0.32)$ were found. Overall, heat stress indices, as well as air temperature, black globe temperature, and solar radiation correlated most strongly with skin temperature.

Variable pool	Variable type	Variable	Unit	N	Mean	Std. Dev.	Min	Pctl. 25	Pctl. 75	Max
Environmental variables	Observed	Air velocity	m/s	407	1.3	0.83	0.1	0.7	1.7	5.2
		Air temperature	°C	407	33	3.8	22	31	36	45
		Relative humidity	%	407	28	23	0	9.9	41	88
		Black globe temperature	°C	407	38	4.9	15	34	41	52
	Modelled	Solar radiation	W/m^2	407	$6e^6$	$4.37e^6$	$3.29e^5$	$2.27e^6$	$8.33e^6$	$2e^7$
	Calculated	Universal thermal climate index	°C	407	33	3.9	20	31	35	51
		Apparent temperature	°C	407	33	4.4	19	31	36	51
		Heat index	°C	407	33	4.5	21	30	36	71
		Wet bulb globe temperature	°C	407	24	3.4	15	22	27	35
Physiological variables	Observed	Heart rate	bpm	353	106	13	65	97	115	147
		Skin temperature	°C	353	37	1.1	32	36	38	40
	Calculated	Core temperature	°C	299	38	0.31	37	37	38	39
		Tympanic temperature	°C	89	37	0.35	36	37	37	38
		Physiological strain index	NA	299	3.8	1	1.4	3.1	4.5	7.1
	Observed	Gestational age	weeks	407	27	6.9	12	23	33	41
		Fitness status, 6 min walking test	m	407	498	74	135	461	544	687
	Estimated	Metabolic rate	kcal/kg/hr	357	3.2	0.85	1.9	2.3	3.8	5.2

Table 1. Descriptive statistics table of merged datasets with two main pools of variables.

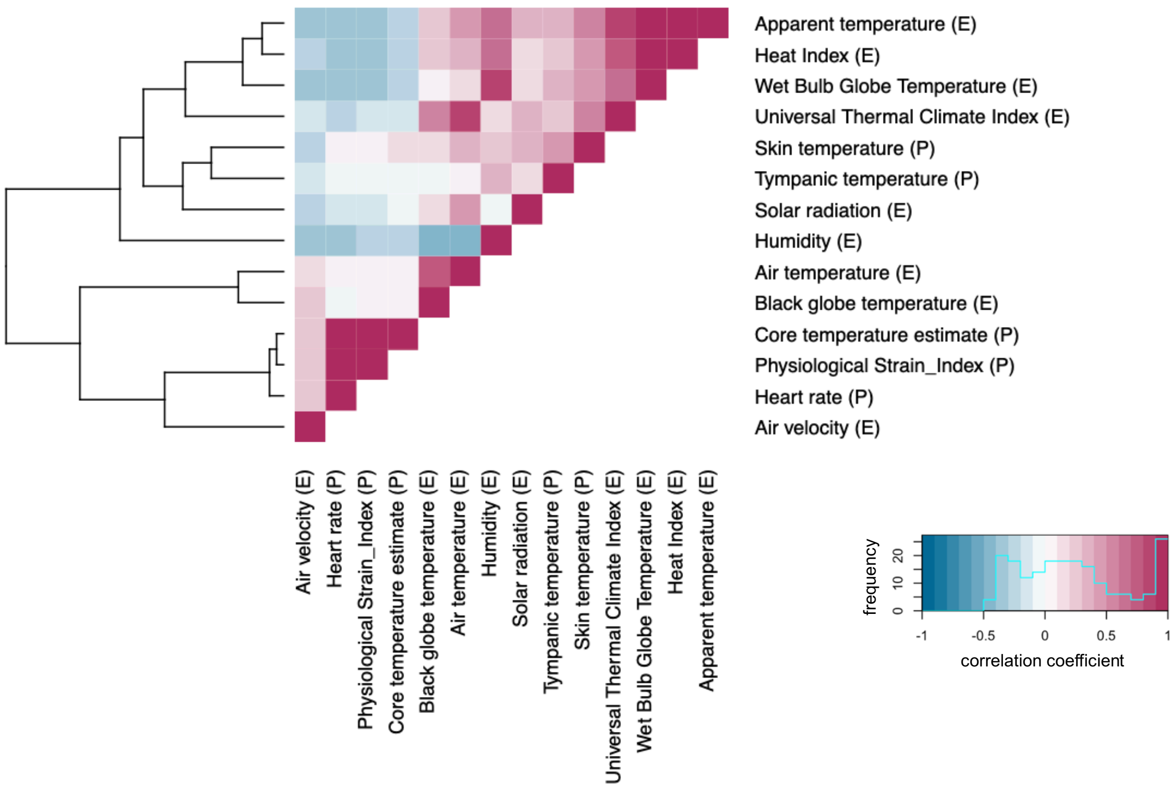

Figure 1. Heatmap indicating the strength of the Pearson correlation coefficients between variables as colour gradients. Denoted with (E) for environmental variables and (P) for physiological variables. P-values are contained in Supplementary Table 3. The dendrogram at the left side orders variables according to the similarity of their correlation with other variables.

2.2.2. Independent and compound effects of heat stress on heat strain

The abovementioned relatively strong correlation of environmental variables with skin temperature also became apparent when assessing the independent effect of single environmental variables and the compound effects of multiple environmental variables. First, we assessed the independent association of each environmental factor, adjusted one by the other, on the physiological variables, using mixed effect linear models with random intercepts by each study participant. Here, increases in air temperature, relative humidity, and solar radiation led to highly robust increases in skin temperature, *ceteris paribus*, but not in air velocity, black globe temperature or metabolic rate *(Table 2 - Model 2A)*. Further, air temperature and relative humidity were associated with tympanic temperature *(Table 2 - Model 4A)*, and with core temperature and the Physiological Strain Index as output variables, but the estimates were more imprecise *(Table 2 - Model 3A, 5A)*. However, we found no robust estimates for the joint association of environmental variables with heart rate *(Table 2 - Model 1A)*. We found a robust estimate for solar radiation in association with heart rate through sensitivity analysis, whereby we rematched the highest

5-minute average heart rate within the 1-hour interval prior to each environmental datapoint *(Supplementary Table 5)*. Further interactive effects were found between air temperature and relative humidity in association with skin temperature *(Table 2 - Model 2B)*. Increases in skin temperature were more rapid when the air temperature rose under conditions of relative humidity above the 50% threshold *(Figure 2)*. No robust evidence for this interaction was found for the association with heart rate, core temperature estimates, or tympanic temperature *(Table 2 - Model 1B, 3B, 4B, 5B)*.

Sensitivity analysis showed that the inclusion of fitness status as an additional model parameter did not considerably change the estimates *(Supplementary Table 6)*. Nor did gestational age behave as a confounder *(Supplementary Table 7)*. However, we found an interaction effect of gestational age with air temperature on all models *(Table 2 - Model 1C, 2C, 3C, 4C)*. With increasing temperature, women in their third trimester of pregnancy experienced greater increases in heart rate, skin temperature, core temperature, and tympanic temperature than women in the second trimester of pregnancy did. This interaction effect of gestational age also became evident in the model in which the Physiological Strain Index served as an output variable *(Table 2 - Model 5D)*.

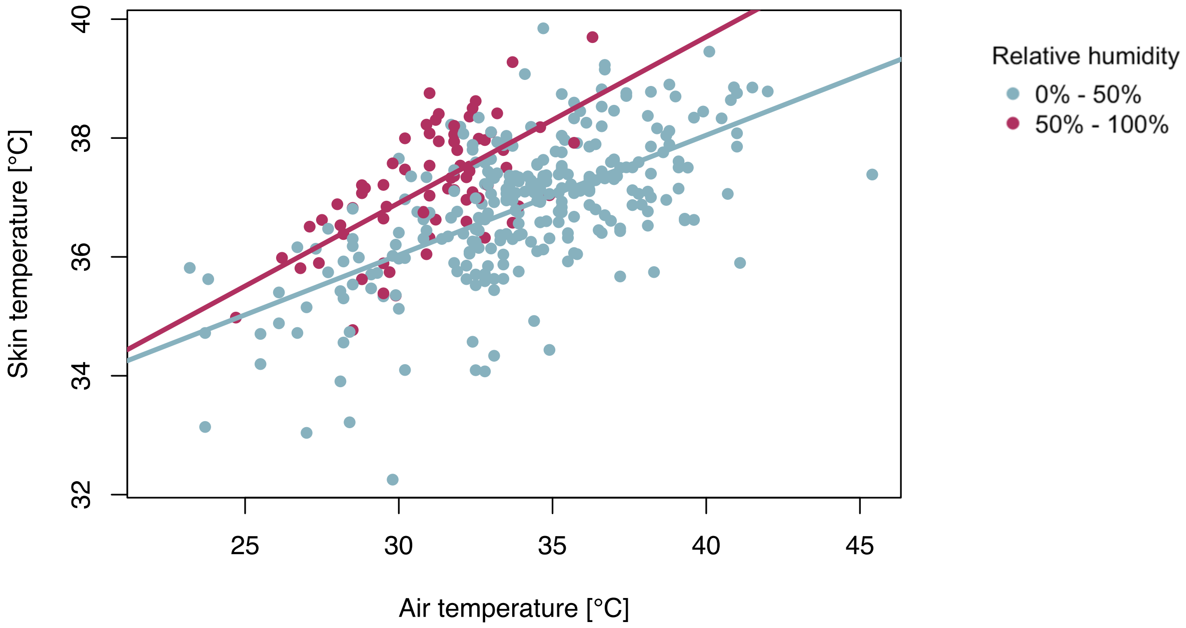

Figure 2. Interaction between air temperature and relative humidity in association with skin temperature at a threshold of 50% relative humidity. The skin temperature increases more rapidly with increasing temperature under conditions in which the relative humidity is above the 50% threshold.

	Model 1: Heart rate	Model 2: Skin temperature	Model 3: Core temperature	Model 4: Tympanic temperature	Model 5: Physiological Strain Index
	Estimate (98% CI)	Estimate (98% CI)	Estimate (98% CI)	Estimate (98% CI)	Estimate (98% CI)
Model A – environmental parameters and physiological parameters					
Air temperature	0.59 (-0.33 ; 1.50)	0.20 (0.14 ; 0.27)	$1.91e^{-2}$ ($-4.92e^{-3}$; $4.28e^{-2}$)	0.05 (-0.01 ; 0.11)	0.05 (-0.03 ; 0.13)
Relative humidity	-0.08 (-0.20 ; 0.04)	0.02 (0.01 ; 0.03)	$-2.21e^{-3}$ ($-5.19e^{-3}$; $7.69e^{-4}$)	0.01 ($2.36e^{-3}$; 0.01)	-0.01 (-0.02 ; $1.91e^{-3}$)
Air velocity	-0.60 (-2.26 ; 1.37)	-0.05 (-0.19 ; 0.09)	$-2.66e^{-2}$ (-0.07 ; $2.20e^{-2}$)	0.01 (-0.08 ; 0.11)	-0.08 (-0.24 ; 0.08)
Black globe temperature	0.20 (-0.39 ; 0.78)	-0.01 (-0.05 ; 0.03)	$2.38e^{-3}$ (-0.01 ; $1.75e^{-2}$)	-0.02 (-0.07 ; 0.02)	0.01 (-0.04 ; 0.06)
Solar radiation / 100.000	-0.02 (-0.07 ; 0.02)	0.01 ($2.78e^{-3}$; 0.01)	$-5.28e^{-5}$ ($-1.22e^{-3}$; $1.12e^{-3}$)	$7.02e^{-4}$ ($-1.48e^{-3}$; $2.92e^{-3}$)	$-1.27e^{-3}$ (-0.01 ; $2.59e^{-3}$)
Metabolic rate	-0.03 (-2.52 ; 2.45)	-0.05 (-0.22 ; 0.12)	$1.38e^{-2}$ (-0.06 ; $8.30e^{-2}$)	0.02 (-0.09 ; 0.13)	0.06 (-0.17 ; 0.28)
Model B – interaction between air temperature and relative humidity					
Air temperature	0.81 (0.35 ; 1.28)	0.20 (0.17 ; 0.23)	0.02 (0.01 ; 0.04)	0.02 (-0.01 ; 0.05)	0.06 (0.02 ; 0.10)
Relative humidity	-9.75 (-60.49 ; 41.05)	-2.59 (-6.39 ; 1.24)	-0.39 (-1.62 ; 0.85)	3.46 (-0.96 ; 7.91)	-1.64 (-5.71 ; 2.45)
Air temperature · relative humidity	0.29 (-1.32 ; 1.89)	0.11 (0.01 ; 0.23)	0.01 (-0.03 ; 0.05)	-0.10 (-0.24 ; 0.04)	0.05 (-0.08 ; 0.18)
Model C – interaction between air temperature and gestational age					
Air temperature	0.55 (-0.09 ; 1.20)	0.19 (0.14 ; 0.24)	0.02 ($4.80e^{-4}$; 0.03)	-0.03 (-0.07 ; 0.01)	0.04 (-0.02 ; 0.10)
Gestational age	-16.36 (-45.38 ; 13.05)	-0.69 (-2.97 ; 1.60)	-0.52 (-1.29 ; 0.26)	-2.22 (-4.22 ; -0.30)	-1.84 (-4.39 ; 0.73)
Air temperature · gestational age	0.53 (-0.34 ; 1.39)	0.01 (-0.06 ; 0.07)	0.02 ($-6.88e^{-3}$; 0.04)	0.06 ($3.12e^{-3}$; 0.12)	0.06 (-0.02 ; 0.13)

Table 2. Mixed effect linear models with random intercepts per participant. Model A assessed the independent effect of each environmental variable on physiological variables (i.e. single models with environmental variables against each physiological variable). Model B assessed the interactive effect of air temperature and relative humidity on physiological variables, with air temperature as a continuous variable and relative humidity as a dummy variable at a 50% relative humidity threshold. Model C assessed the interactive effect of air temperature and gestational age on physiological variables, with air temperature as a continuous variable and gestational age as a dummy variable at a threshold of 27 gestational weeks, separating the second from the third trimester of pregnancy. P-values are in the Supplementary Table 4.

Through composite confirmatory analysis [32], we assessed the simultaneous influence of environmental parameters on the conjunction of observed physiological parameters. We constructed a model with air temperature, relative humidity, black globe temperature, solar radiation, air velocity, and metabolic rate as observable indicators of the composite artefact of heat stress, and with heart rate and skin temperature as observable indicators of the composite artefact of maternal heat strain. We found a factor loading of *0.71* between heat stress and maternal heat strain *(Figure 3)*. Model estimations showed that the highest indirect effects of environmental variables were from changes in air temperature, relative humidity, and solar radiation, with loadings equal to *0.45*, *0.46*, and *0.55* respectively. Black globe temperature yielded a loading of 0.17, and negative loadings were observed for air velocity *(-0.45)* and metabolic rate *(-0.45)*. This negative value of metabolic rate is in line with a behavioural response to reduce the level of physical activity at rising temperature. The indirect effects on maternal heat strain were positive for skin temperature *(0.87)* and negative for heart rate *(-0.50),* whereby the heart rate was also influenced by behavioural change when working in the heat, which might not sufficiently be covered by estimations of metabolic rate. Even though the fit indices of our model lie within the optimal ranges *(Table 3)*, the p-values indicate only robust estimates for the loadings of air temperature, solar radiation, and skin temperature *(Supplementary Table 7)*.

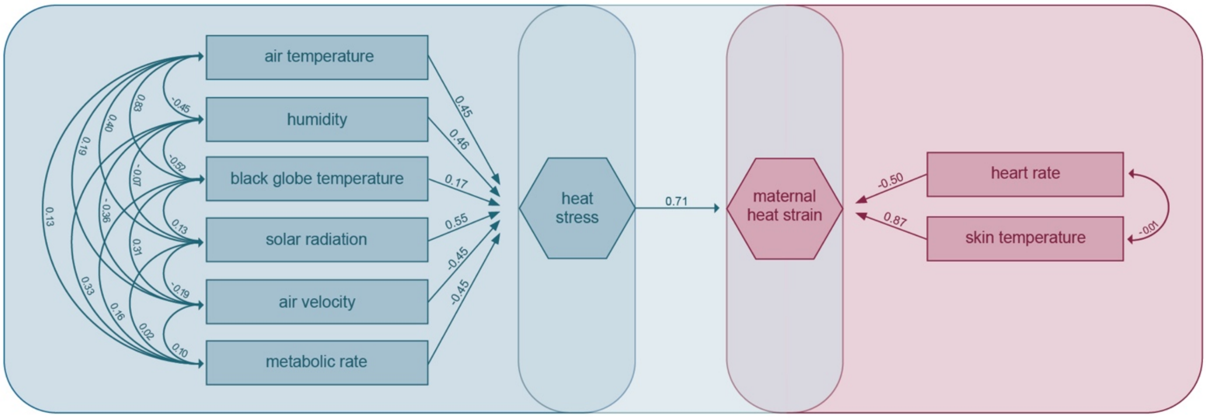

Figure 3. Composite confirmatory analysis with respective loadings of path coefficients between composite artefacts (heat stress and heat strain) and observable indicators (air temperature, relative humidity, black globe temperature, solar radiation, air velocity, metabolic rate, heart rate, skin temperature).

Assessment of model fit		
Indices	Optimal fitness	Obtained value
Chi square (X2/df)	1 - 3	1.28
Comparative fit index (CFI)	> 0.9	0.99
Root mean squared error of approximation (RMSEA)	< 0.1	0.06
Goodness-of-fit index (GFI)	> 0.9	0.95
Normed fit index (NFI)	> 0.9	0.97
Incremental fit index (IFI)	0 -1	0.99

Table 3. Indices showing the model fit of the confirmatory composite analysis. The table structure is based on the study of Yazdanirad et al. [33].

2.3. Discussion

Taken together, our findings demonstrate that physiological indicators of heat strain in pregnant women are significantly influenced by environmental conditions while working in the heat, particularly in humid conditions and in the third trimester of pregnancy compared to the second. This study provides information on the pathophysiological effects of heat stress on pregnant women and not on the respective health outcomes of mothers or babies. We applied a series of methods, namely the Pearson product moment correlation method, mixed effect linear models with random intercepts, and confirmatory composite analysis to assess the association between each environmental and physiological indicator. This approach enabled us to disentangle the independent effects of each of the environmental variables on a set of different physiological variables and assess the potential compound effects between climate variables, while taking into consideration variance inflation factors. Overall, our findings provide an input to quantify the risk of pregnant women experiencing pathophysiological effects from working in the heat and can thus support further research on adaptive measures to alleviate heat strain.

Our methodology allowed us to demonstrate that the heat strain of pregnant women was more severe under conditions above a relative humidity of 50%, whereby the impact of rising temperature on skin temperature increased at a greater rate. This is due to the limited capacity of the human body to thermoregulate in hot and humid environments, because the proportion of evaporated sweat, and thus the sweating efficiency, decreases with rising relative humidity above the 35 °C threshold [28]. The existence of the 35 °C temperature threshold as a human adaptability limit to heat stress [34] was found to be even lower by the recent study of Vecciello et al. [35] in non-pregnant individuals.

Furthermore, we found robust evidence for the increase in susceptibility to heat strain throughout pregnancy at rising temperatures across all physiological indicators, namely skin temperature, heart rate, tympanic temperature and the thereby estimated core temperature. More precisely, women in their third trimester of pregnancy experienced higher heat strain than women in their second trimester of pregnancy did. It would be interesting for future research to compare these findings with data from early pregnancy, given that a previous study has shown that the risk of heat-related stillbirth might be particularly high in early pregnancy [36], whilst a global analysis and meta-analysis detected an increased risk of preterm birth at exposure to extreme heat during the last seven days of gestation [25, 37].

Our study demonstrated the convergent validity of heat stress indices through correlations between each other as well as their construct validity through their correlations with skin temperature and tympanic temperature. The Heat Index, UTCI, Apparent Temperature and Wet Bulb Globe Temperature were strongly associated with each other, even though they incorporate different input variables such as relative humidity, solar radiation, black globe temperature and air velocity, in addition to air temperature. The underlying reason for the associations found is the strong weight that each of the heat stress indices assigns to air temperature as an input variable. Furthermore, the selected heat stress indices showed similar associations with both skin temperature and tympanic temperature, which supports their applicability to our study setting. Even though heat stress indices performed similarly in our assessment, we recommend including indices such as the UTCI or WBGT in heat-health warning systems, given that these indices incorporate air temperature, relative humidity and solar radiation, which showed associations to physiological variables in our study *(Section 2.2)*. These indices could potentially be included in heat-health warning systems as a preventive measure for heat strain. Heat stress indices would need to be communicated in a targeted way, such as through simply understandable risk levels, as to allow for the public to respond appropriately.

There are five key limitations to our study. First, we tested the applicability of four out of more than 100 existing heat stress indices [38]. However, the Heat Index, Apparent Temperature, WBGT, and UTCI are indices that are often referred to in the literature [26] and require input variables covered with our datasets, together with additional solar radiation modelling. We also tried to overcome this limitation by assessing the separate effects of environmental variables on maternal physiology, which increases the generalizability of the results. Second, given data availability constraints, our study design omitted variables such as clothing thermal insulation, systolic blood pressure, and diastolic blood pressure, which have been included in other studies [29, 33]. Likewise, water intake or cloud cover could have been added to the models as confounders. Third, we acknowledge the potential imprecision of results sourced from the matching of datasets with different temporal resolutions, especially for heart rate measurements, which fluctuate over time. We reached no clear conclusions about the effects of heat stress on heart rate and failed to determine construct validity of heat stress indices on heart rate, core temperature estimates or the physiological strain index, possibly due to behavioural adaptations to heat not captured in estimated metabolic rate. Even while applying a moving average merging technique *(Supplementary Table 5)* and confirmatory composite analysis *(Supplementary Table 9)*, we found no robust estimates for the compound effects of air temperature and relative humidity on heart rate, possibly also due to non-accounted behavioural responses. This limitation might be resolved in future studies while measuring metabolic rate more effectively to disentangle the effects of activity and heat stress. Fourth, we did not account for individual differences in our confirmatory composite analysis; therefore, our results do not allow us to make inferences about repeated measurements of the same study participants. Such individual-level differences were only included in our mixed effect models with random intercepts. Fifth, we considered a linear association between variables and did not account for non-linearity, based on previous assessments with this data [15].

Despite these limitations, our understanding of the interplay between environmental variables and the physiology of pregnant women in The Gambia first and foremost underlines the necessity of climate change mitigation and adaptation to protect one of the most vulnerable population subgroups from heat strain. We suggest developing adequate and targeted adaptation strategies that increase the resilience of pregnant women to climatic changes, given the evidence of high levels of physiological impacts while working in hot environments. To protect the maternal health of agricultural workers, particularly during the third trimester of pregnancy, when vulnerability to heat strain increases, measures that reduce exposure to heat stress, including work schedules adapted to climatic conditions, or measures that reduce the impacts of heat stress, such as protective clothing or microclimate cooling equipment, could be tested in future research [39]. The establishment of heat-health warning systems with tested heat stress indices will be crucial for the implementation of adaptive measures [18]. Cherisch et al. [17] suggest interventions to protect maternal and newborn health in Africa at the individual level through behavioral change, at the infrastructural level through changes in health systems and services, at the structural level through policy and financing options, or at the environmental level through nature-based solutions. For optimal policy design and implementation, adaptive measures should be developed in close collaboration with the local community, and investigations of the respective measures should be undertaken through a participatory research approach [40].

2.4. Methods

The study population consisted of 92 pregnant women from West Kiang, The Gambia, who had been recruited by Bonell et al. [15] through the local antenatal clinic and provided informed consent. Participants worked either on a small-scale farm, in agriculture or in a garden for more than 3 hours per day. Acutely ill participants, including those diagnosed with pre-eclampsia, eclampsia, gestational diabetes, or who had a history of heart disease were excluded from the study. A more detailed overview of the demographics, physical characteristics, and birth outcomes of the study participants is available in *Supplementary Table 1*. The study setting covers 9 villages within the West Kiang region: Jali, Janneh Kunda, Jiffarong, Kantong Kunda, Karantaba, Keneba, Kuli Kunda, Mandina, Manduar and Tankular. West Kiang is a district located in the Lower River Division of The Gambia and populated by 14,846 inhabitants. The main mode of subsistence is manual farming. Women work on average between 4.5 and 7.5 hours per day during pregnancy [41].

Observational data (i) were collected in the study of Bonell et al. [15], in which both environmental and physiological indicators were measured at different time points during pregnancy while the study participants performed daily agricultural tasks. The black globe temperature, dew point temperature, relative humidity, air temperature, and WBGT were collected using an HT200: heat stress WGBT meter. The wind speed was recorded with a portable Extech AN100 Thermo-Anemometer. Skin temperature and maternal heart rate were measured with an Equivital LifeMonitor. Core temperature and tympanic temperature were estimated based on skin temperature and heart rate. Metabolic rates were estimated through observed levels of activity [15]. The resolution of the datasets varied: Environmental parameters were available at hourly intervals, while physiological parameters were available at 5-minute intervals. Based on the environmental data points, we calculated heat stress indices with the R packages weathermetrics [42], rBiometeo [43] and HeatStress [44]. The study of Bonell et al. (2022), on which this research project is based, has been 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 [1].

The retrieved modelled data (ii) from the ERA5 hourly land reanalysis dataset contains hourly surface net solar radiation for the geocodes of Jali, Janneh Kunda, Jiffarong, Kantong Kunda, Karantaba, Keneba, Kuli Kunda, Mandina, Manduar and Tankular [11]. In total, we extracted 80 subsets, each of which covered the modelled solar radiation for one village and month within the study period from August 2019 until March 2020. The datasets are temporally resolved at 1-hour intervals and spatially resolved on 0.09° horizontal and vertical grids. The surface net solar radiation is indicated in units of joules per square meter (J/m^2) and represents the difference between the solar radiation reaching the Earth's surface and the solar radiation reflected from the surface through the albedo effect [11].

Given the varying time formats and resolutions of the abovementioned datasets (i-ii), we created uniform time stamps in POSIX.ct format and minimized the time differences between the data points to construct the final merged dataset. Every data point from the environmental dataset was matched with the average of each physiological variable over the previous hourly interval. The influence of external heart rate fluctuations on the results was tested by rematching heart rate values with environmental data points through a 5-minute moving average interval. Observations were matched with the respective study participants' gestational age, fitness status – measured through a 6-minute walking test – and the geographical location. While calculating work shift lengths, we added respective estimated metabolic rates for both halves of the work shift. Each datapoint was matched with the modelled solar radiation from the ERA5 land datasets of the respective location and closest in time. The final merged dataset consisted of observational (i) and modelled data (ii). The data distribution was verified through descriptive statistics, more specifically, through summary statistics tables, boxplots, probability density functions, QQ plots, and Kolmogorov-Smirnov tests, serving as a basis for outlier detection. We removed outliers of heart rate below 60 bpm, above 200 bpm, or below a confidence interval of 85%, as well as of skin temperature, which was three standard deviations away from the mean. The environmental data points remained complete.

Both separate and compound associations between environmental and health variables were investigated. The separate relationships between variables were assessed through the Pearson product moment correlation method and visualized through scatterplots. This methodology is in line with previous studies that have validated heat stress indices in the context of male farmers and mine workers in Iran [45, 29]. We assessed not only associations of environmental parameters with separate health variables, but also with a modified version of the physiological strain index – a composite index based on skin temperature, tympanic temperature, and heart rate. Core temperature was not measured due to practical as well as safety constraints associated with pregnancy [46, 15]. The Pearson product moment correlation analysis allowed us to assess both the convergent and construct validity of the heat stress indices.

The independent effects of the environmental variables on the physiological variables were assessed through mixed effect models with random intercepts. With this methodology, we accounted for individual differences between study participants. The variance inflation factor was computed to detect multicollinearity [47]. Sensitivity analysis was applied to determine the potential confounding factors of gestational age and fitness status. While integrating an interaction term between air temperature and relative humidity as well as between air temperature and gestational age, we tested for compound effects. Ultimately, the results from the mixed effect models with random intercepts were compared to those from the confirmatory composite analysis to enhance the robustness of our findings and assess the interplay between multiple environmental and physiological variables simultaneously [32].

2.5. Acknowledgments

We would like to acknowledge the communities in West Kiang, especially the pregnant participants enrolled in the observational study.

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2.6. Author Contributions

Conceptualization: CB, AMVC, AB
Data collection: AB
Data analysis: CB, AMVC, AB
Methodology: CB, AMVC, AB
Visualization: CB, AMVC, AB
Writing: CB, AMVC, AB
Revision: CB, AMVC, AB, AH, NM, JB, TS, TS, KAM, AMP

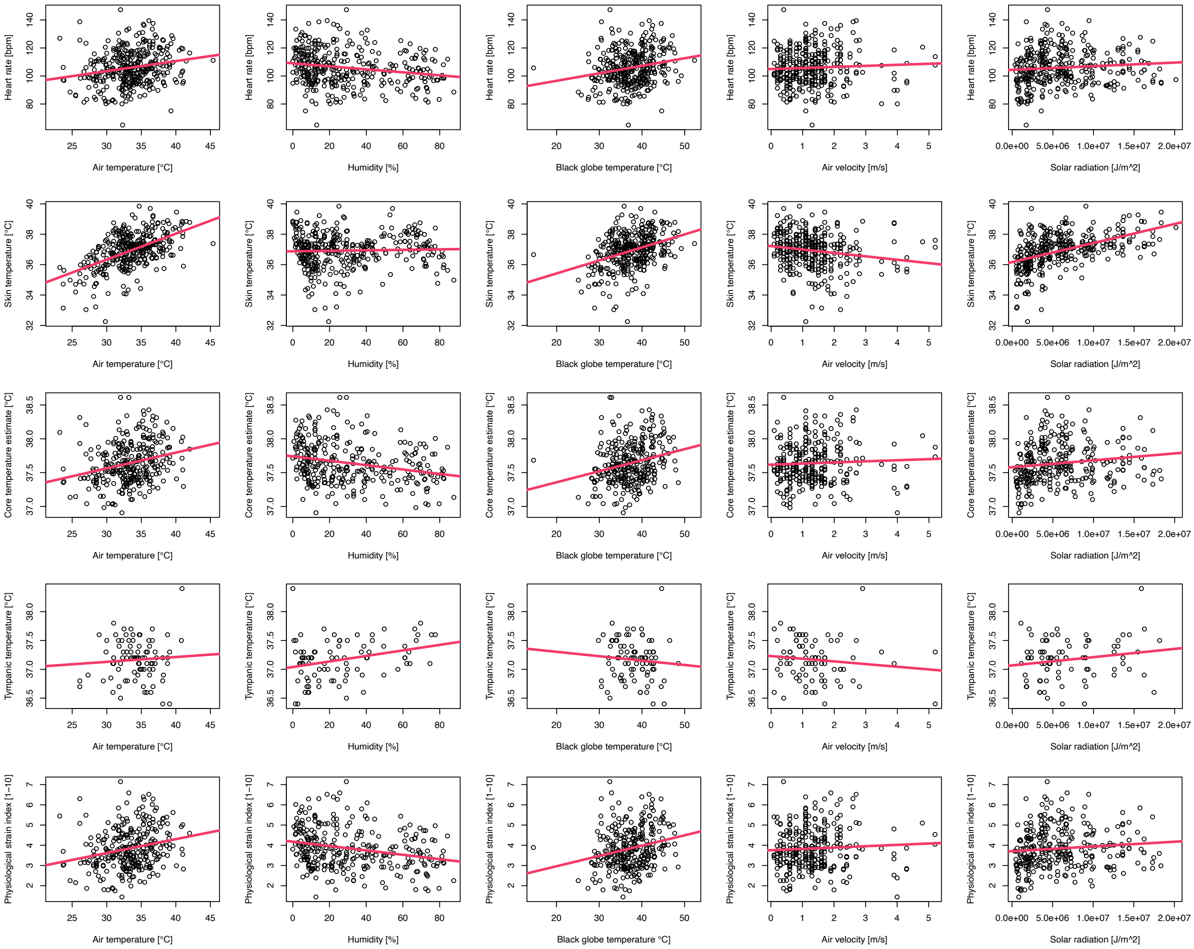
2.7. Data Availability

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

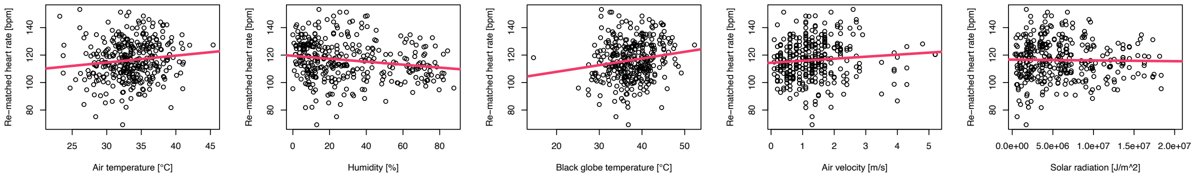
2.8. Additional Information

The authors declare no competing interests.

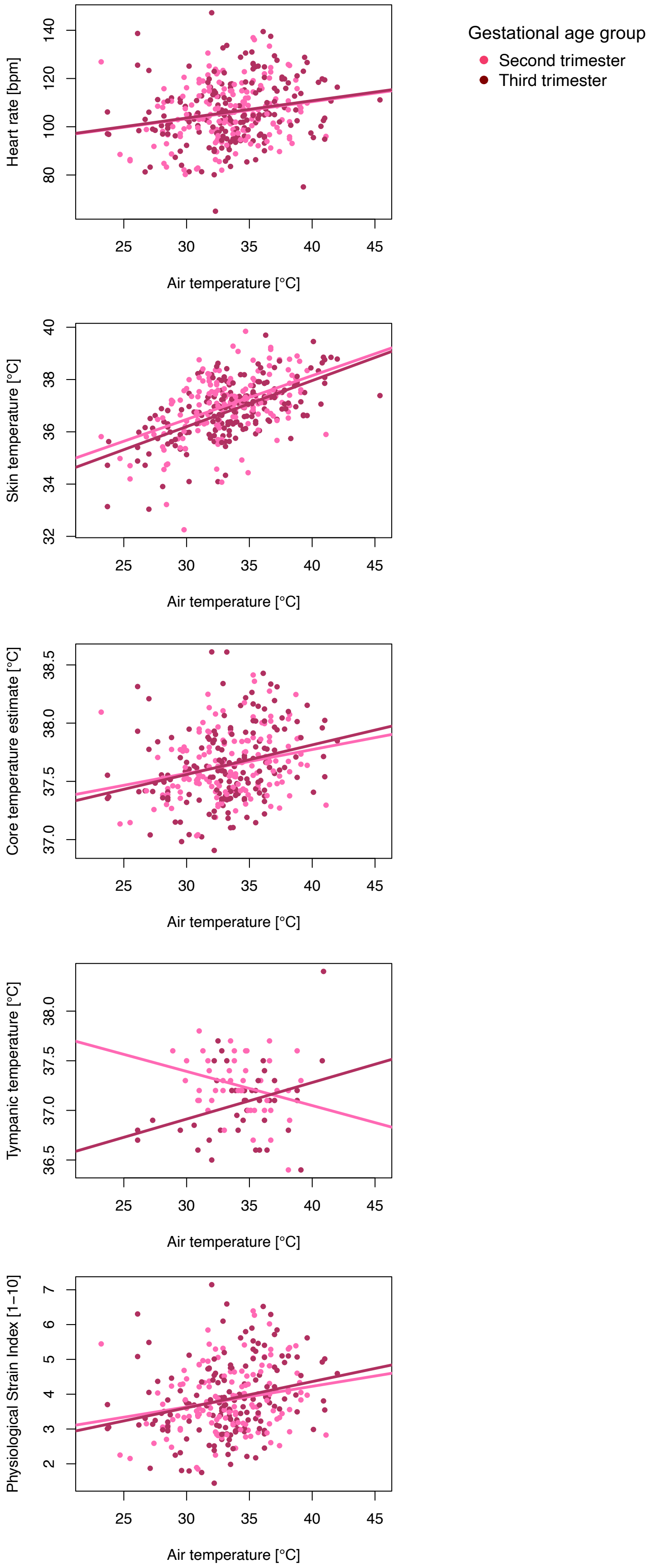
2.9. Supplementary Figures



Supplementary Figure 1. Scatterplots showing the separate associations between health variables and environmental variables. Each environmental data point was merged with the previous hourly average of the physiological variables.



Supplementary Figure 2. Scatterplots showing the separate associations between environmental variables and heart rate, dependent on different merging techniques. Each environmental data point was merged with the highest value of all 5-minute averages of heart rate within the previous hourly intervals (Supplementary Figure 1).



Supplementary Figure 3. Interaction effect between air temperature and gestational age on the association with health variables at a threshold of 27 gestational weeks, separating the second from third trimester of pregnancy.

2.10. Supplementary Tables

	Participants (n = 92)
Demographic parameters	
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%)
Obstetric history	
Gravida	4 (2–7)
Parity	3 (1–5.25)
Gestational age at visit, weeks	28.5 (23.6 - 32.9)
Weight	
Median, kg	61.9 (55.8–97.3)
BMI, kg/m2	23.0 (21.3–25.9)
Mid-upper arm circumference, cm	27.0 (25.1–29.7)
Percentage fat mass, %	28.7% (25.8–33.8)
Height, cm	162.9 (5.6)
Birth outcome	
Normal birth	53/91 (58%)*
Small for gestational age	24/91 (26%)*
Preterm	12/92 (13%)
Low birthweight	12/91 (13%)*
Stillbirth or intrapartum death	3/92 (3%)

Supplementary Table 1. Demographics, physical characteristics, and birth outcomes of participants. Reprinted from Bonell et al. [15].

r-values	Air temperature	Relative humidity	Black globe temperature	Air velocity	Solar radiation	Heat index	Universal Thermal Climate Index	Apparent Temperature	Wet Bulb Globe Temperature	Heart rate	Skin temperature	Core temperature estimate	Tympanic temperature	Physiological Strain index
Air temperature	1.00	-0.44 .	0.80 **	0.13	0.42 .	0.34 .	0.81 **	0.42 .	0.11	0.00	0.37 .	0.06	0.07	0.03
Relative humidity	-0.44 .	1.00	-0.46 .	-0.35 .	-0.08	0.65 *	0.16	0.60 *	0.82 **	-0.30 .	0.22	-0.29	0.30 .	-0.30 .
Black globe temperature	0.80 **	-0.46 .	1.00	0.25	0.11	0.24	0.59 *	0.23	0.03	0.00	0.18	0.03	-0.09	0.02
Air velocity	0.13	-0.35 .	0.25	1.00	-0.22	-0.23	-0.11	-0.39 .	-0.30 .	0.25	-0.25	0.25	-0.13	0.25
Solar radiation	0.42 .	-0.08	0.11	-0.22	1.00	0.19	0.39 .	0.33 .	0.16	-0.16	0.34 .	-0.09	0.18	-0.12
Heat index	0.34 .	0.65 *	0.24	-0.23	0.19	1.00	0.80 **	0.94 ***	0.91 ***	-0.35 .	0.43 .	-0.29	0.30 .	-0.32 .
Universal Thermal Climate Index	0.81 **	0.16	0.59 *	-0.11	0.39 .	0.80 **	1.00	0.86 **	0.65 **	-0.22	0.54 *	-0.14	0.26	-0.18
Apparent Temperature	0.42 .	0.60 *	0.23	-0.39 .	0.33 .	0.94 ***	0.86 **	1.00	0.92 ***	-0.33 .	0.54 *	-0.27	0.33 .	-0.30 .
Wet Bulb Globe Temperature	0.11	0.82 **	0.03	-0.30 .	0.16	0.91 ***	0.65 **	0.92 ***	1.00	-0.34 .	0.44 .	-0.30 .	0.31 .	-0.32 .
Heart rate	0.00	-0.30	0.00	0.25	-0.16	-0.35 .	-0.22	-0.33 .	-0.34 .	1.00	0.02	0.97 ***	-0.05	0.99 ***
Skin temperature	0.37 .	0.22	0.18	-0.25	0.34 .	0.43 .	0.54 *	0.54 *	0.44 .	0.02	1.00	0.10	0.50 *	0.06
Core temperature estimate	0.06	-0.29	0.03	0.25	-0.09	-0.29	-0.14	-0.27	-0.30 .	0.97 ***	0.10	1.00	-0.01	0.99 ***
Tympanic temperature	0.07	0.30 .	-0.09	-0.13	0.18	0.30 .	0.26	0.33 .	0.31 .	-0.05	0.50 *	-0.01	1.00	-0.03
Physiological Strain index	0.03	-0.30 .	0.02	0.25	-0.12	-0.32 .	-0.18	-0.30 .	-0.32 .	0.99 ***	0.06	0.99 ***	-0.03	1.00

Supplementary Table 2. Pearson correlation matrix of environmental and health parameters. The items were denoted as « » for neglectable correlation coefficients (±0.00 to ±0.30), « . » for low correlations (±0.30 to ±0.50), « * » for moderate correlations (±0.50 to ±0.70), « ** » for high correlations (±0.70 to ±0.90), and « *** » for very high correlations (±0.90 to ±1.00) [30]. The matrix was separated by the pool of environmental variables in the upper part and the pool of physiological variables in the lower part.

p-values	Air temperature	Relative humidity	Black globe temperature	Air velocity	Solar radiation	Heat index	Universal Thermal Climate Index	Apparent Temperature	Wet Bulb Globe Temperature	Heart rate	Skin temperature	Core temperature estimate	Tympanic temperature	Physiological Strain index
Air temperature		0.00	0.00	0.22	0.00	0.99	0.00	0.55	0.51	0.75	0.00	0.00	0.00	0.31
Relative humidity	0.00		0.00	0.00	0.45	0.00	0.04	0.01	0.00	0.00	0.00	0.14	0.00	0.00
Black globe temperature	0.00	0.00		0.02	0.29	0.97	0.10	0.77	0.41	0.88	0.03	0.00	0.03	0.76
Air velocity	0.22	0.00	0.02		0.04	0.02	0.02	0.02	0.24	0.02	0.03	0.33	0.00	0.00
Solar radiation	0.00	0.45	0.29	0.04		0.14	0.00	0.40	0.09	0.25	0.07	0.00	0.00	0.13
Heat index	0.99	0.00	0.97	0.02	0.14		0.87	0.00	0.63	0.00	0.00	0.04	0.00	0.00
Universal Thermal Climate Index	0.00	0.04	0.10	0.02	0.00	0.87		0.35	0.00	0.57	0.00	0.00	0.00	0.00
Apparent Temperature	0.55	0.01	0.77	0.02	0.40	0.00	0.35		0.89	0.00	0.01	0.19	0.01	0.00
Wet Bulb Globe Temperature	0.51	0.00	0.41	0.24	0.09	0.63	0.00	0.89		0.76	0.00	0.01	0.00	0.00
Heart rate	0.75	0.00	0.88	0.02	0.25	0.00	0.57	0.00	0.76		0.00	0.09	0.00	0.00
Skin temperature	0.00	0.00	0.03	0.03	0.07	0.00	0.00	0.01	0.00	0.00		0.00	0.00	0.00
Core temperature estimate	0.00	0.14	0.00	0.33	0.00	0.04	0.00	0.19	0.01	0.09	0.00		0.00	0.00
Tympanic temperature	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00		0.00
Physiological Strain index	0.31	0.00	0.76	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

Supplementary Table 3. P-values of Pearson correlation matrix of environmental and health parameters.

	Model 1: Heart rate	**Model 2: Skin temperature**	**Model 3: Core temperature**	**Model 4: Tympanic temperature**	**Model 5: Physiological Strain Index**
	p-value	p-value	p-value	p-value	p-value
Model A – environmental parameters and physiological parameters					
Air temperature	0.14	1.25e-11	0.06	0.05	0.14
Relative humidity	0.11	1.91e-7	0.09	1.15e-3	0.06
Air velocity	0.47	0.40	0.21	0.78	0.25
Black globe temperature	0.44	0.51	0.72	0.20	0.64
Solar radiation / 100.000	0.24	2.56e-5	0.92	0.47	0.44
Metabolic rate	0.98	0.50	0.65	0.67	0.57
Model B – interaction between air temperature and relative humidity					
Air temperature	5.7e-5	2.00e-16	2.97e-5	0.12	1.21e-3
Relative humidity	0.66	0.116	0.47	0.08	0.35
Air temperature · relative humidity	0.68	0.033	0.50	0.11	0.39
Model C – interaction between air temperature and gestational age					
Air temperature	0.05	$2.87e^{-16}$	0.02	0.13	0.10
Gestational age	0.19	0.48	0.12	0.01	0.09
Air temperature · gestational age	0.14	0.81	0.10	0.02	0.07

Supplementary Table 4. P-values of mixed effect linear models with random intercepts per participant. Model outputs are in Table 2.

	(a) Model 1: Heart rate		(b) Model 1: Re-matched heart rate	
	Estimate (95% CI)	p-value	Estimate (95% CI)	p-value
Model A – environmental parameters and physiological parameters				
Air temperature	0.59 (-0.19 ; 1.35)	0.14	0.37 (-0.44 ; 1.18)	0.37
Relative humidity	-0.08 (-0.18 ; 0.02)	0.11	-0.08 (-0.19 ; 0.04)	0.19
Air velocity	-0.60 (-2.25 ; 1.05)	0.47	-0.12 (-1.81 ; 1.58)	0.89
Black globe temperature	0.20 (-0.29 ; 0.68)	0.44	0.21 (-0.30 ; 0.72)	0.42
Solar radiation e^5	-0.02 (-0.06 ; 0.02)	0.24	-0.05 (-0.09 ; $-4.21e^{-3}$)	0.03
Metabolic rate	-0.03 (-2.12 ; 2.06)	0.98	0.01 (-2.33 ; 2.35)	0.99
AIC	2414.48	-	2360.86	-

Supplementary Table 5. Mixed effect models with random intercepts comparing two different merging techniques. (a) Each environmental data point was merged with the previous hourly average of heart rate. (b) Each environmental data point was merged with the highest value of all 5-minute averages of heart rate within the previous hourly interval.

	Model 1: Heart rate		Model 2: Skin temperature		Model 3: Core temperature		Model 4: Tympanic temperature		Model 5: Physiological Strain Index	
	Estimate (95% CI)	p-value	Estimate (95% CI)	p-value	Estimate (95% CI)	p-value	Estimate (95% CI)	p-value	Estimate (95% CI)	p-value
Model A – environmental parameters and physiological parameters										
Air temperature	0.54 (-0.24 ; 1.31)	0.17	0.20 (0.15 ; 0.26)	6.86e-12	0.02 (-7.69e-4 ; 0.04)	0.06	0.05 ($2.73e^{-3}$; 0.10)	0.05	0.05 (-0.01 ; 0.11)	0.12
Relative humidity	-0.06 (-0.16 ; 0.04)	0.24	0.02 (0.01 ; 0.03)	1.03e-6	$-1.50e^{-3}$ ($-3.99e^{-3}$; $1.01e^{-3}$)	0.25	0.01 ($2.80e^{-3}$; 0.01)	2.57e-3	$-5.50e^{-3}$ (-0.01 ; $2.75e^{-3}$)	0.20
Air velocity	-0.51 (-2.14 ; 1.16)	0.54	-0.06 (-0.19 ; 0.06)	0.34	-0.02 (-0.06 ; 0.02)	0.23	0.01 (-0.07 ; 0.09)	0.78	-0.07 (-0.21 ; 0.06)	0.28
Black globe temperature	0.19 (-0.29 ; 0.69)	0.43	-0.01 (-0.05 ; 0.02)	0.50	2.20e-3 ($1.03e^{-3}$; 0.01)	0.74	-0.02 (-0.06 ; 0.01)	0.20	0.01 (-0.03 ; 0.05)	0.66
Solar radiation e^5	-0.02 (-0.05 ; 0.02)	0.29	0.01 ($3.23e^{-3}$; $8.69e^{-3}$)	3.18e-5	$-6.12e^{-5}$ ($-1.03e^{-3}$; $9.09e^{-4}$)	0.90	7.25e-4 ($-1.10e^{-3}$; $2.60e^{-3}$)	0.45	$-1.29e^{-3}$ (-4.47 ; $1.91e^{-3}$)	0.43
Metabolic rate	0.21 (-1.84 ; 2.28)	0.84	-0.05 (-0.20 ; $8.95e^{-2}$)	0.48	$2.15e^{-2}$ (-0.04 ; 0.08)	0.47	0.02 (-0.07 ; 0.11)	0.66	0.08 (-0.10 ; 0.26)	0.40
Fitness level	0.03 ($1.48e^{-3}$; 0.06)	0.05	-1.64e-3 ($-3.78e^{-3}$; $4.85e^{-4}$)	0.13	$1.15e^{-3}$ ($3.02e^{-4}$; $1.99e^{-3}$)	0.01	$-2.72e^{-4}$ ($-1.77e^{-3}$; $1.23e^{-3}$)	0.73	$3.88e^{-3}$ ($1.10e^{-3}$; 0.01)	0.01

Supplementary Table 6. Mixed effect models with random intercepts with fitness status as an additional variable were used to verify potential confounding effects.

	Model 1: Heart rate		Model 2: Skin temperature		Model 3: Core temperature		Model 4: Tympanic temperature		Model 5: Physiological Strain Index	
	Estimate (95% CI)	p-value	Estimate (95% CI)	p-value	Estimate (95% CI)	p-value	Estimate (95% CI)	p-value	Estimate (95% CI)	p-value
Model A – environmental parameters and physiological parameters										
Air temperature	0.59 (-0.19 ; 1.36)	0.14	0.20 (0.14 ; 0.25)	2.18e-11	$1.93e^{-2}$ ($-1.08e^{-3}$; $3.93e^{-2}$)	0.06	0.04 (-0.01 ; 0.09)	0.10	0.05 (-0.02 ; 0.12)	0.14
Relative humidity	-0.08 (-0.19 ; 0.02)	0.12	0.02 (0.01 ; 0.02)	2.95e-6	-2.17e-3 ($-4.74e^{-3}$; $4.08e^{-4}$)	0.11	0.01 ($2.86e^{-3}$; 0.01)	2.03e-3	$-7.83e^{-3}$ (-0.02 ; 0.12)	0.08
Air velocity	-0.61 (-2.25 ; 1.05)	0.47	-0.06 (-0.18 ; 0.06)	0.33	$-2.65e^{-2}$ (-0.07 ; $1.44e^{-2}$)	0.21	0.01 (-0.07 ; 0.09)	0.78	-0.08 (-0.21 ; 0.05)	0.25
Black globe temperature	0.20 (-0.29 ; 0.69)	0.43	-0.01 (-0.04 ; 0.02)	0.63	$2.31e^{-3}$ (-0.01 ; 1.51)	0.72	-0.02 (-0.05 ; 0.02)	0.31	$9.77e^{-3}$ (-0.03 ; 0.05)	0.65
Solar radiation e^5	-0.02 (-0.06 ; 0.02)	0.23	0.01 (3.11e-3 ; 0.01)	4.42e-5	$-5.28e^{-5}$ ($-1.03e^{-2}$; $1.51e^{-2}$)	0.92	$7.16e^{-4}$ ($-1.07e^{-3}$; $2.56e^{-3}$)	0.46	$-1.28e^{-3}$ ($-4.51e^{-3}$; $1.99e^{-3}$)	0.44
Metabolic rate	-0.05 (-2.14 ; 2.06)	0.96	-0.06 (-0.20 ; 0.08)	0.43	$1.35e^{-2}$ (-0.04 ; $7.19e^{-2}$)	0.65	0.02 (-0.07 ; 0.11)	0.67	0.06 (-0.14 ; 0.25)	0.58
Gestational age	-0.02 (-0.28 ; 0.25)	0.90	-0.02 (-0.04 ; -0.01)	0.01	$5.03e^{-4}$ (-0.01 ; $7.45e^{-3}$)	0.89	-0.01 (-0.01 ; $1.69e^{-3}$)	0.11	$1.18e^{-3}$ (-0.02 ; 0.02)	0.92

Supplementary Table 7. Mixed effect models with random intercepts and gestational age as an additional variable were used to verify potential confounding.

	Model 1: Heart rate	Model 2: Skin temperature	Model 3: Core temperature	Model 4: Tympanic temperature	Model 5: Physiological Strain Index
	vif	vif	vif	vif	vif
Model A – environmental parameters and physiological parameters					
Air temperature	4.19	4.23	3.81	4.48	3.81
Relative humidity	1.67	1.69	1.73	1.53	1.73
Air velocity	1.13	1.13	1.17	1.14	1.21
Black globe temperature	3.40	3.49	3.03	4.09	3.03
Solar radiation e^5	1.58	1.56	1.61	1.43	1.62
Metabolic rate	1.10	1.10	1.16	1.08	1.16

Supplementary Table 8. Variance inflation factors (vif) of mixed effect models with random intercepts. The variables are denoted as « » for neglectable variance inflation factors ($0.00 < vif < 5.00$), « * » for high variance inflation factors that might be problematic ($5.00 < vif < 10.00$), and « ** » for variance inflation factors showing high signs of multicollinearity ($10.00 < vif$).

Confirmatory composite analysis		
Effect on heat stress		
	Loading (95% CI)	p-value
Air temperature	0.45 (-0.38 ; 0.68)	0.08
Relative humidity	0.46 (-0.61 ; 0.67)	0.15
Air velocity	-0.45 (-0.68 ; 0.59)	0.15
Black globe temperature	0.17 (-0.21 ; 0.42)	0.29
Solar radiation	0.54 (-0.54 ; 0.73)	0.09
Metabolic rate	-0.45 (-0.65 ; 0.59)	0.14
Effect on heat strain		
Heart rate	-0.50 (-0.71 ; 0.69)	0.16
Skin temperature	0.87 (-0.84 ; 0.977)	0.08
Heat stress	0.71 (-0.72 ; 0.83)	0.07

Supplementary Table 9. Results from confirmatory composite analysis. Loadings between observed variables (air temperature, relative humidity, air velocity, black globe temperature, solar radiation, heart rate and skin temperature) and composite artefacts (heat stress and heat strain).

3. Conclusion

3.1. Implications of the findings

Our study found two key results, which might be relevant for local climate change adaptation. First, we detected interactive effects between air temperature and humidity in the association with skin temperature. Thus, when defining interventions to reduce heat stress in occupational settings, strategies should not only consider air temperature and solar radiation but also humidity as a key component in cost-benefit analysis. For instance, for a potential intervention of planting trees on agricultural fields, the positive health benefits due to shielded solar radiation might be reduced by the cost of additional heat stress due to a higher humidity content. Second, we showed interactive effects between air temperature and gestational age in association with all physiological variables. Maternal heat strain increased at a higher rate after the 27th gestational week. Thus, gestational age could be included in strategic climate change adaptation, whereby women in their third trimester of pregnancy could be a group of priority.

Short-term benefits of this study on maternal heat strain in The Gambia might arise from a more detailed understanding of the interlinkages between exposure to extreme heat and the physiological responses in pregnant women. Through our methodology we determined separate, independent and compound associations, while applying Pearson product moment correlation analysis, mixed effect models with random intercepts and confirmatory composite analysis. However, while we found that environmental variables were associated with skin temperature and tympanic temperature across different models, we could not observe associations between environmental variables and heart rate or the thereby estimated core temperature, in contrast to the current state of the literature [26], due to behavioural adaptations being uncaptured in the estimated metabolic rate variable. This might have an implication for the collection of metabolic data in future studies, whereby measurement devices could be used to track physical activity.

Long-term benefits could be created through the development of local heat-health warning systems with the heat stress indices assessed in this study. While incorporating the UTCI or the WBGT, the respective risk levels associated to working outdoors could be communicated to the local population. This could potentially support the adaptation of work schedules of pregnant women in agriculture.

3.2. Research outlook

Having gained an insight into the research around the impacts of extreme heat on pregnant women working in subsistence agriculture in The Gambia, multiple possibilities to further advance the understanding of maternal heat strain remain. The methods applied in the present Master thesis could be further developed such as with inter-group comparisons through structural equation modelling to establish additional evidence on the influence of gestational age on heat strain, or with mediation analysis to further clarify the effect of humid heat. Furthermore, highly interesting research angles remain open such as an extended risk assessment with distributed lag non-linear models, a projection study or an experimental trial linked to climate change adaptation.

Regarding the extended risk assessment, it would be interesting to analogously collect data from non-pregnant women working in the heat in the same geographical area. This would allow to compare our findings and disentangle the effect of pregnancy from the effect of exposure to extreme heat, and ultimately allow to quantify by how many percentages the risk of experiencing heat strain increases for pregnant women compared to the baseline of non-pregnancy. This line of research could further be extended to men working in subsistence agriculture and wider age groups, whereby results on gender-specific and age-specific health risks of climate change impacts could be drawn. In terms of methodology, it would be interesting to apply distributed lag non-linear models [48] to address this research question. A stratified analysis could be implemented based on age, gender, and pregnancy status. Respective risk curves could be created with environmental heat stress as a model input and physiological heat strain as a model output. With this approach, the risk assessment of pregnant women working in subsistence agriculture could be further advanced and evidence of the relative vulnerability could be generated to include pregnant women as a priority group in the elaboration of climate change adaptation strategies.

Furthermore, it would be interesting to project future increases in heat exposure in West Kiang while focusing on the UTCI and WBGT as indices to assess the evolution of on-site work conditions under multiple climate change scenarios. Comparisons could be drawn under different Representative Concentration Pathways and Shared Socio-Economic Pathways. Such a study could focus on a similar approach as taken by the study of Casanueva et al. [18] which quantified the future risks of summer maximum heat exposure on occupational health in Europe. Another interesting element would be to quantify the contribution of human-induced climate change on maternal heat strain while applying a two-stage time series analysis and comparing the association of heat and maternal heat strain to a hypothetical exposure to heat that would have occurred under the absence of climate change [49].

An experimental trial on climate change adaptation could be developed based on initial qualitative research through a community-based participatory approach. Perceptions on adaptation methods could be collected, with the goal to gain a deeper understanding of local circumstances, barriers and opportunities linked to respective intervention possibilities, while taking into account cultural settings, workplace specificities and infrastructural situations [50]. Interventions to mitigate the impact of extreme heat stress might include protective equipment such as cooling vests, ventilation clothing, adapted work-rest cycles, and increased access to rest and hydration [51, 52, 53]. An experimental trial on each of the separate locally appropriate interventions would allow to assess the effect modification of these interventions in the exposure-response relationship between heat stress and maternal heat strain, while comparing to a control group where no intervention was applied. Such research might contribute to the foundation of local initiatives similar to the European HEAT-SHIELD project, which aims to protect occupational health in the context of climate change [27].

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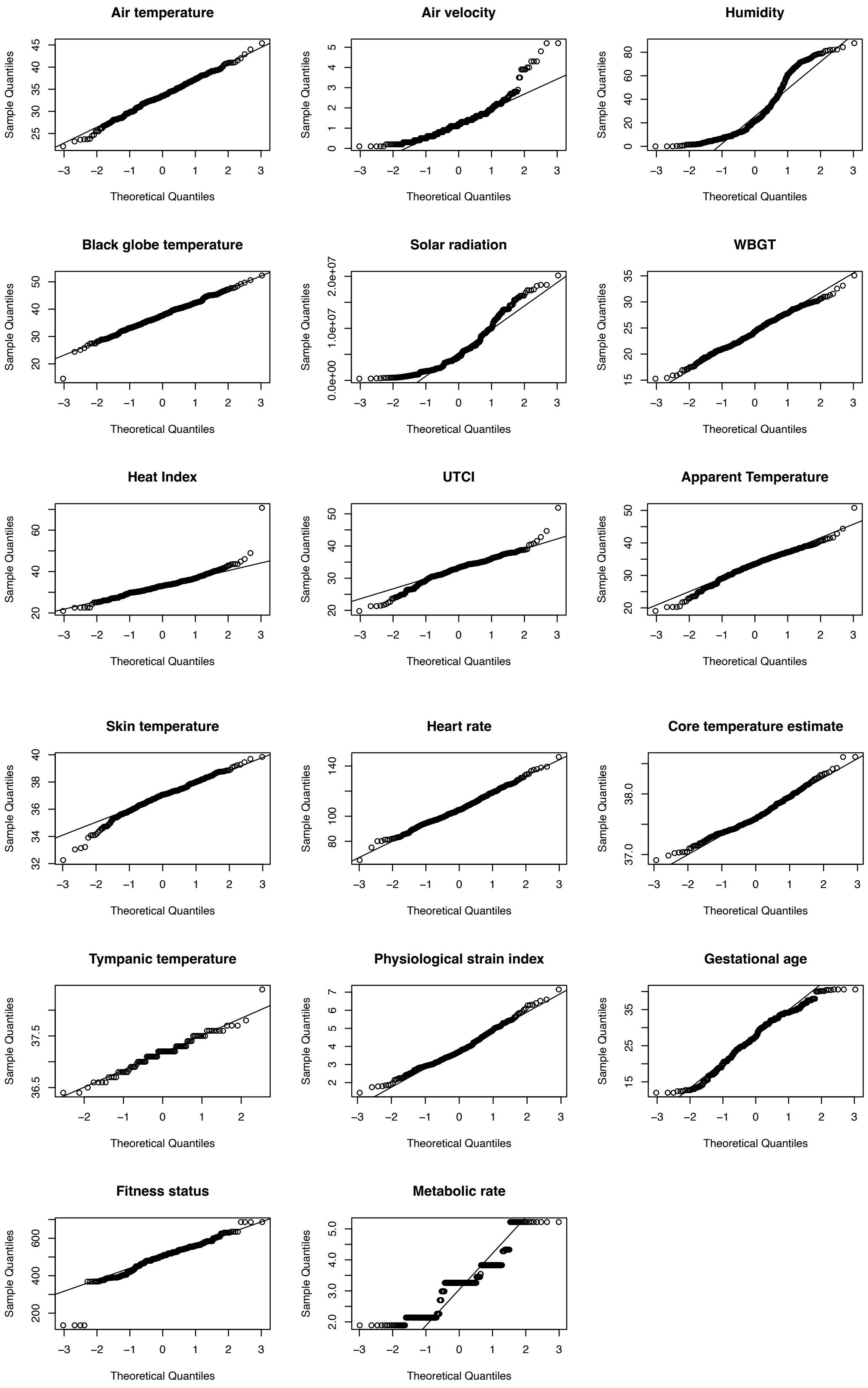
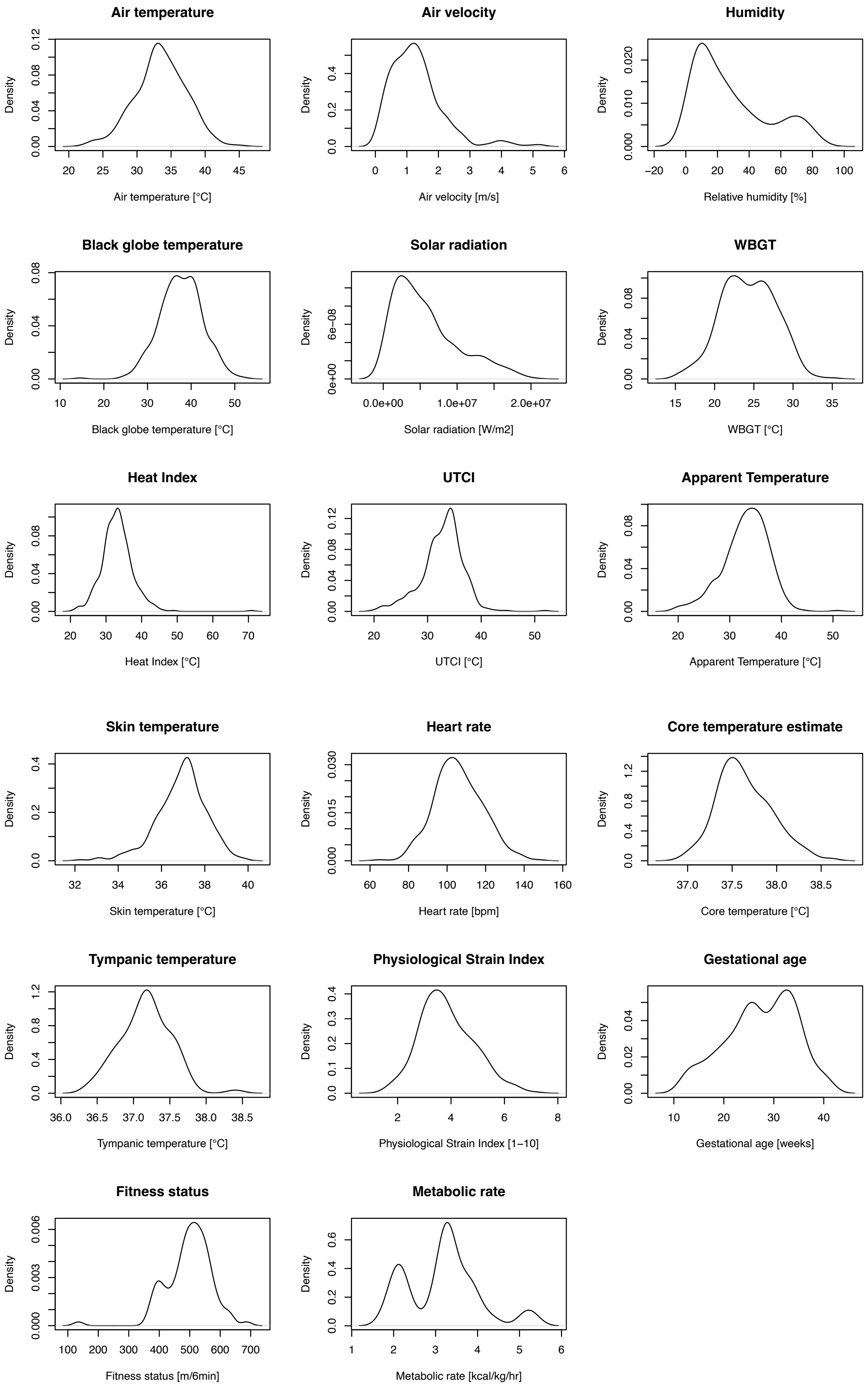
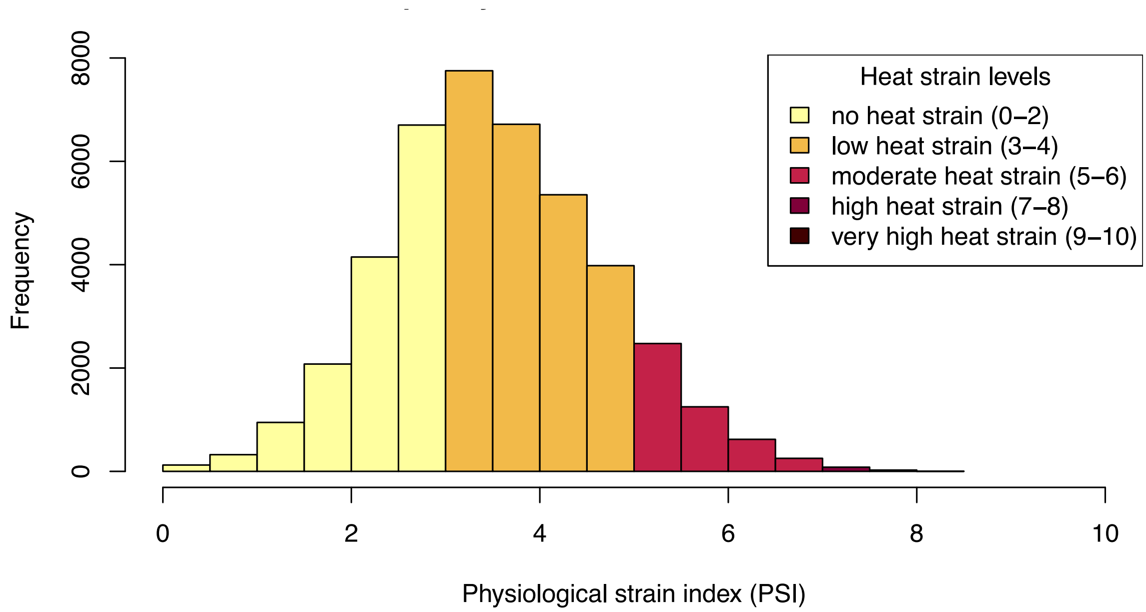
5. Appendix



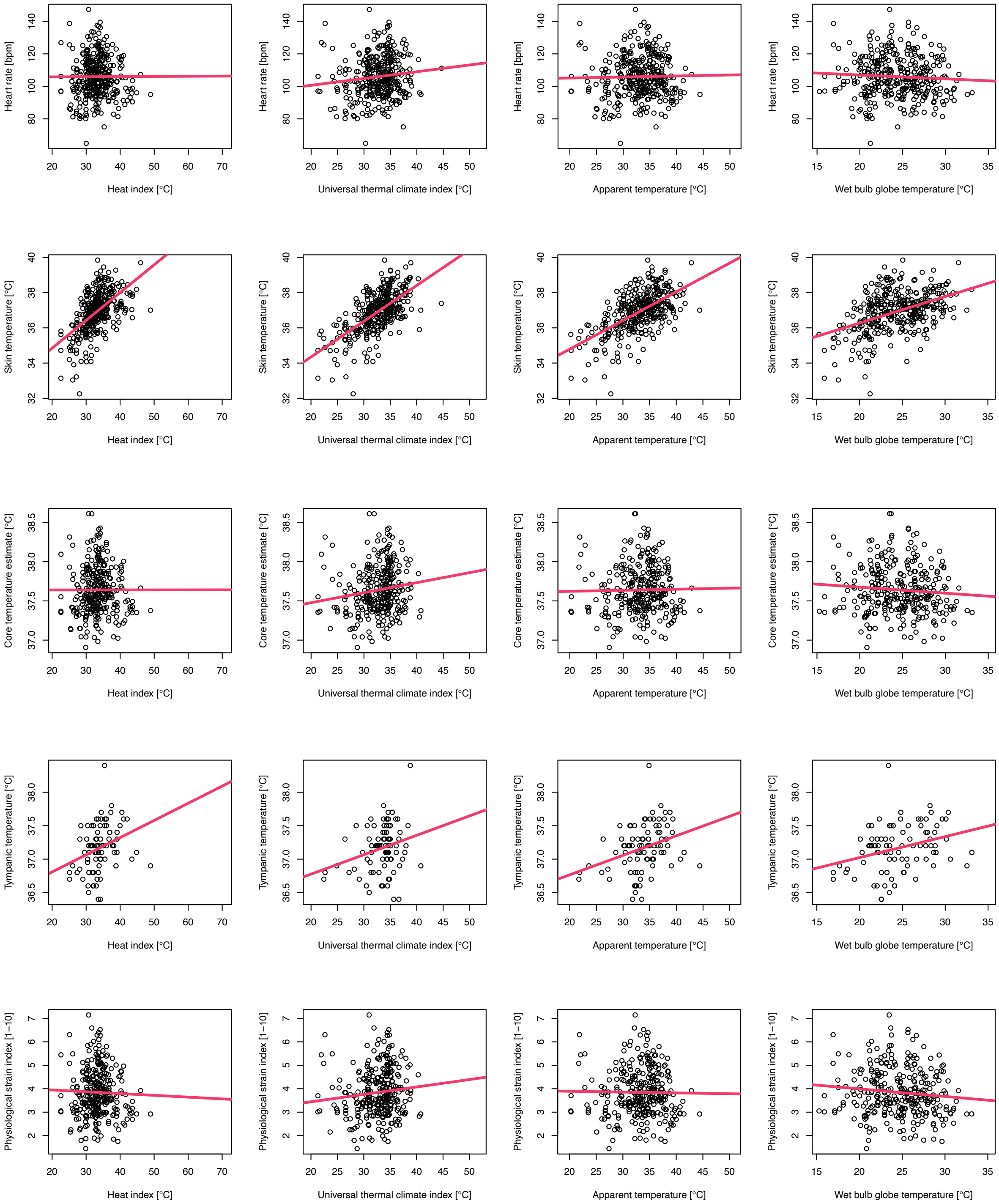
Supplementary Figure 4. Normal q-q plots of variables in the merged dataset.



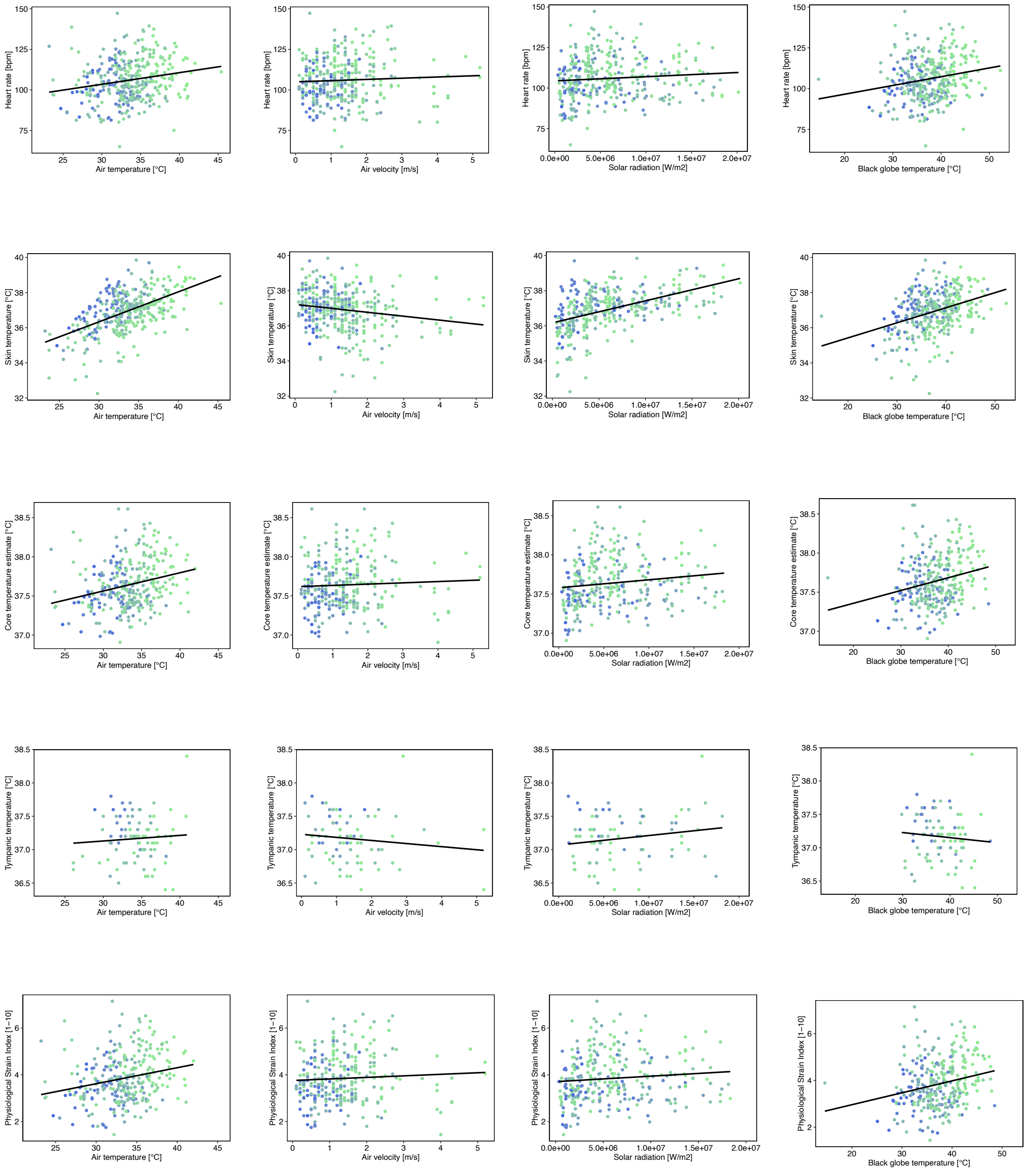
Supplementary Figure 5. Probability density functions of variables in merged dataset.



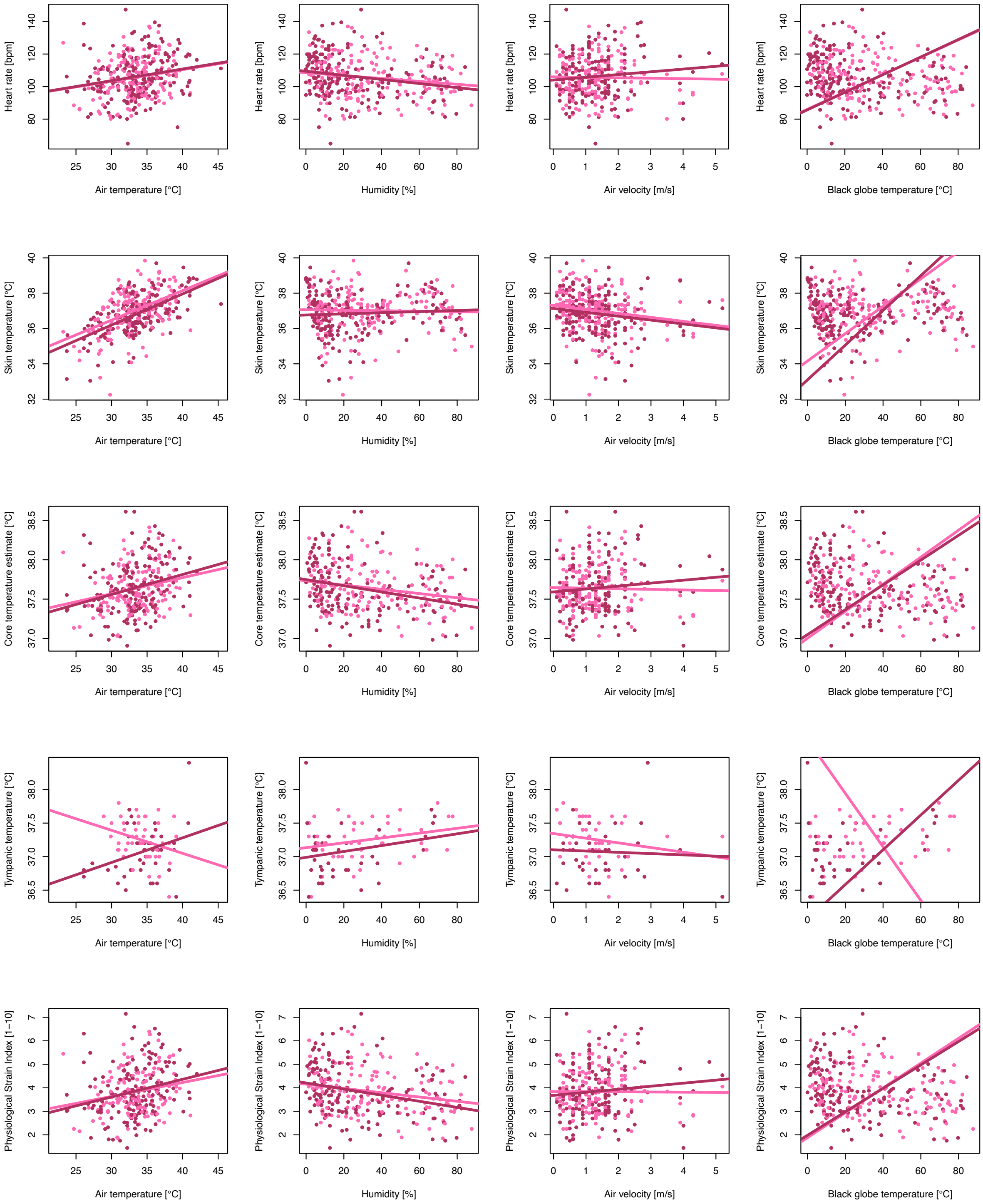
Supplementary Figure 6. Frequency table of heat strain levels observed in dataset.



Supplementary Figure 7. Scatterplots showing the separate associations between heat stress indices and physiological variables.



Supplementary Figure 8. Scatterplots showing the separate associations between heat stress indices and physiological variables with humidity as an effect modifier.



Supplementary Figure 9. Scatterplots showing the separate associations between heat stress indices and physiological variables with gestational age as an effect modifier.

Declaration of consent

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