REPORT ON PREDICTIVE HEAT WARNING THRESHOLDS

Deliverable 3.3

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REPORT ON PREDICTIVE HEAT WARNING THRESHOLDS

HIGH HORIZONS – D3.3

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Abbreviations

Abbreviation	Definition/Description
BMI	Body mass index
C3S	Copernicus Climate Change Service
CI	Confidence interval
DLNM	Distributed lag nonlinear model
DTR	Diurnal temperature range
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	The 5th European Centre for Medium-Range Weather Forecasts Reanalysis Product
EU	European Union
EW4All	Early Warnings for All Initiative
EWS	Early Warning System
FAR	False alarm ratio
FB	Frequency bias
HHWS	Heat Health Warning System
IPCC	Intergovernmental Panel on Climate Change
PAF	Population attributable fraction
PEM	Period of excess mortality
POD	Probability of detection
UN	United Nations
UTCI	Universal Thermal Climate Index
WBGT	Wet Bulb Globe Temperature (a heat stress index)
WHO	World Health Organization
WMO	World Meteorological Organization

1 Introduction

1.1 Purpose of the document

This deliverable presents heat health risk thresholds found in literature, threshold related results from WP2 data analysis (deliverable 2.3), methods of determination of the thresholds, heat stress indices, and recommended thresholds at different heat risk levels of the heat health warning system (HHWS) for pregnant and postpartum women, infants and health workers. The selected cut-off thresholds will be implemented in the personalised early warning system (EWS) that the HIGH Horizons consortium is building for pregnant women, infants and health workers, based on ClimApp. The aim of identifying the heat health risk thresholds is to enable the EWS to use these pre-determined trigger levels of heat stress to alert impending heat health risks and provide advice to pregnant and postpartum women, caregivers of infants and health workers to take actions to reduce health risks.

1.2 Relation to other project work

This deliverable is building on and feeding into other deliverables, including:

- D2.3 Heat-health analysis report 1 (November 2023), which reports on the overall risk of preterm birth and heat exposure across countries;
- D3.5 Report on photo voice sub-study, and the locally-adapted and optimized messaging (February 2024), with the findings being implemented in the personalised and context-specific ClimApp-MCH;
- D3.4 Developed ClimApp-MCH EWS prototype (due March 2024), which will be tested by pregnant and postpartum women and by health workers in South Africa, Sweden and Zimbabwe;
- D5.3 Evaluation of experiences and effectiveness of EWS and messages targeting pregnant and postpartum women, and infants (due March 2026).

2 Background

The world is warming at a faster rate due to climate change. Global temperatures reached exceptionally high levels in 2023 according to the Copernicus Climate Change Service (C3S) implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) [1]. Deadly heatwaves and extreme heat affect all inhabited world regions [2]. According to The Intergovernmental Panel on Climate Change (IPCC), future health risks of injuries, disease and death will increase due to more intense and frequent temperature extremes which cause the greatest mortality of all extreme weather events [3]. There are already more than 350 000 deaths annually from extreme heat [4]. Heat-related mortality and morbidity will continue to rise dramatically.

The risks of heat impact on occupational and public health have been assessed and well documented [5-8]. The heat hazard has been identified. Nevertheless, another at risk population that is often overlooked are pregnant women, who mostly are not targeted by public health campaigns or heat warning interventions [9-10]. More work needs to be done in order to protect and prevent the consequences of the heat impact on the health of the vulnerable pregnant and postpartum women, infants and health workers. A qualitative, pilot project carried out by Monteblanco et al. points towards the great need for improved training of communities and early warnings of extreme heat events in order to limit the heat exposure and negative health consequences of pregnant women [10].

Heat health warning system for pregnant and postpartum women, infants and health workers

When heat hazard and vulnerability are identified, heat health warning systems and services specifically targeting the vulnerable groups must be developed to communicate the heat health risk information and warnings. The warnings and advice messages enable the individual users of the HHWS and health communities to respond to the warnings, build response capabilities, prepare heat action plans and take actions to reduce the impact of the risks.

The Early Warnings for All Initiative (EW4All) was formally launched by the UN Secretary-General in November 2022 at the COP27 meeting [11]. The Initiative calls for the whole world to be covered by an early warning system by the end of 2027. To take advantage of this initiative and impetus, the health sector can improve the existing HHWS for the general population by targeting vulnerable groups. Heat Health Warning Systems use climate and weather forecasts and pre-determined trigger levels (thresholds) of heat stress to provide advice to the public and initiate public health interventions designed to reduce health risks before, during, and after periods of extreme heat [12].

Research has repeatedly demonstrated several medical consequences that occur when pregnant women are exposed to heat that have crossed certain thresholds. These include placental abruption, which bear significant risks for both the pregnant women and her infant, preterm birth, stillbirth, miscarriages, foetal growth restrictions that lead to low birth weight, and adverse maternal mental health [13].

HHWS have the potential to act as crucial intervention gateways for providing individualized protection. However, the current state of Early Warning System (EWS) only provides warnings and advice to the public, but does not specifically target maternal, newborn or child vulnerable groups. It lacks sensitivity due to primarily focusing on air temperature and failing to address pertinent factors such as other thermal climate factors (air humidity, solar radiation, air velocity) and individual circumstances. Moreover, the existing early warning systems often do not entail locally relevant messaging that is co-designed with the communities they serve. Moreover, the trigger levels, i.e. the thresholds, for the purpose of providing heat health early warnings for the vulnerable pregnant and postpartum women, and infant groups need to be determined, particularly by integrating heat stress indices (heat metrics) that take into account multiple thermal climate variables and individual vulnerabilities.

3 Literature on heat exposure thresholds for the vulnerable groups

Early heat health interventions should provide timely alerts to pregnant women to mitigate health risks [13]. The effects of heat stress levels causing critical thermal physiological responses and adverse health effects in pregnant and postpartum women, infants and children are not yet well studied. Although there are extreme heat warnings and certain thresholds have been calculated, these often are not correlated with adverse health effects [13]. Limited epidemiological studies focusing on the threshold levels were carried out, mostly specific to some countries. Such thresholds are largely undetermined for most countries.

According to a population-based cohort study in China, Ren et al. (2023) focused on the increased occurrence of preterm birth when pregnant women are exposed to high temperatures [14]. In this study a population attributable fraction (PAF) was calculated to estimate the proportional reduction of adverse health outcomes when the risk factor, for instance heat, was reduced to an alternative, ideal exposure level. The PAF calculation was applied across different critical periods of pregnancy to determine the threshold at which an early warning system would most effectively minimize preterm birth given that pregnant women avoid this heat exposure. The results showed that pregnant women had greater susceptibility of preterm birth risk to increased heat events during specific gestational periods: early in the pregnancy (gestational week 1 – 4), mid pregnancy (gestational week 21 – 24), to late pregnancy (gestational week 29 – 32) and the four weeks preceding delivery. The heat exposure thresholds were determined to be daily maximum temperature at the 90th percentile of the distribution or 30 °C lasting for at least one day. The study calculated the summed PAF to be 15.2%

(95% CI: 5.0%, 25.6%), suggesting that early warnings could have prevented more than 15% of all preterm birth cases, if the pregnant women had taken appropriate action to avoid the exposure to extreme heat.

Ravanelli et al. (2019) focused their research on the concerns about risks induced through attaining harmful core temperatures while pregnant [15]. A critical maternal core temperature threshold, the so-called teratogenic threshold during pregnancy, was identified through previous animal model studies that demonstrated the correlation between hyperthermia (41°C–43°C) during pregnancy and foetal malformation and difficulties with the pregnancy [15]. Later studies in humans supported these findings, demonstrating a high risk of foetal malformations in cases of severe hyperthermia, often induced by fever of the mother during pregnancy. Research agrees that maternal core temperatures should therefore not exceed 39°C, to protect the foetus from a heightened teratogenic risk. It is therefore unsurprising that pregnant women typically are advised to avoid heat stress due to the risk of exceeding the teratogenic threshold of 39.0°C [15].

A different study has addressed the current heat health warning system used in South Africa, which rely on fixed temperature thresholds, but lack the association to negative health consequences [16]. A particular method, the distributed lag nonlinear models (DLNM) was analysed in this study and discussed for its suitability. It ultimately emerged as the most significant predictor of mortality, with robust associations observed across 40 out of the 52 South African districts. The DLNM is a statistical tool that analyses the complex and dynamic relationship between exposure variables, allowing for accurate and nuanced assessments of for instance health impacts of heatwaves and other environmental factors across time [16]. It allows researchers to explore how the effects of exposures, such as temperature can vary at different lags, the outcome variable, such as heat strain may not follow a linear pattern. It further allows for the examination of both the immediate and delayed effects exposure on health outcomes, while considering the potentially non-linear nature of the relationship of the variables.

Kapwata et al., (2024) argue that in heat health related research, DLNM analyses are particularly useful for examining the relationship between temperature exposure and mortality and morbidity outcomes over time [16]. Having calculated the daily maximum and minimum temperatures and diurnal temperature range (DTR), this study found maximum temperature to consistently emerge as the most significant predictor of mortality across the 52 South African districts during the summer months (October - March). Furthermore, DLNMs were used to estimate HHWS threshold values. Threshold values with district specific temperature metrices were computed using a threshold regression. Threshold regression models are a subclass of linear regression models in which a specific predictor influences the outcome at individual points or thresholds. These regression models therefore allow coefficients to vary across different regions. By definition, these regions can either be above or below a certain threshold. Maximum thresholds (in °C) for mortality for each of the 52 districts in South Africa were estimated from threshold regression. The threshold in the districts varies in a wide range between 33.3 – 36.5 °C, 29.3 – 33.3 °C, 14.1 – 29.3 °C, and ≤14.1 °C.

Currently, the World Meteorological Organization (WMO) and the World Health Organization (WHO) do not provide guidance nor recommendation for a specific weather variable or exposure measure to be incorporated in the calculation of HHWS [16]. Operational HHWS therefore differ widely in heat indicators on which they base their thresholds, including maximum temperature, minimum temperature, mean temperature, apparent temperature, etc. Nevertheless, to increase the effectiveness of HHWS and to increase the accuracy of respective thresholds, heat indicators in HHWS should use variables that are easy to forecast with a certain level of confidence for increased accuracy in the prediction of heat events [16]. Temperature forecasts of up to five-day periods are considered within the acceptable level of confidence for heat health early warning. The study highlights the importance of thresholds focused on specific geographical areas as a prerequisite of effective HHWS [16]. The study repeatedly demonstrates and strongly recommends the integration of maximum temperature thresholds for effective HHWS design to issue timely alerts, considering local climatic and thermal conditions, thereby aiming to reduce heat related morbidity and mortality [16].

The study also points out that using heat-specific deaths as a variable instead of periods of excess mortality (PEM) when temperatures exceed a certain percentile theoretically would increase reliability of results. However, heat-related deaths are most often misclassified as deaths due to other conditions, such as heart attacks, cardiovascular disease and respiratory disease. Only about 10 heat-related deaths per year have been recorded in South Africa from 1997 to 2013, suggesting a major underreporting [16]. Finally, an important point raised by Kapwata et al., 2024, is the use of mortality vs. morbidity as a health outcome measure. Heat related health outcomes have been found to be recorded more accurately using parameters such as hospitalizations (including emergency department visits) and ambulance callouts. However, similarly to the difficulties mentioned with heat-specific deaths, South Africa would face various challenges linked to controlled access to data or slow digitalization of records. Data quality difficulties would hinder researchers in gaining accurate insights into the actual statistics.

4 Heat stress indices: air temperature vs integrated heat stress indices

A recent scoping review within the HIGH Horizons project focusing on heat indices used to measure the effects of heat on maternal and perinatal health found a range of methods used across four types of heat index and a broad lack of understanding on heat indices [17]. The studies by Guigma et al. (2020) suggest that the choice of thermal index is important for ensuring an appropriate thermal index reflecting the risk to various exposed populations. In this report, we focus on air temperature (Ta), wet bulb globe temperature (WBGT) and universal thermal climate index (UTCI).

4.1 Air temperature

Air temperature is a widely used single thermal climate variable in epidemiological studies to find out the relationship between heat such as heat waves and health outcomes such as pre-term birth and mortality. Air temperature is forecasted and available in historical weather datasets.

In international standards for thermal environments and meteorological terms, air temperature (Ta) is the temperature of the air, which should be measured with a sensor that is protected against radiation (ISO 7726:2002) such as solar radiation or heat radiation from other sources but allows air to flow around the sensor. Air temperature and air velocity around the body determines convective heat exchange between the body and the environment. Although air temperature data are easily accessible and widely used in epidemiological studies, air temperature does not consider the effects of solar radiation, humidity and air velocity in complex thermal environments. For instance, when two people are exposed to the same air temperature in summer, but one is in the shade, another person is in the sun. The heat exposures on human body heat exchange, heat balance and health responses are quite different. Therefore, more comprehensive heat stress indices (heat indicators) such as the wet bulb globe temperature (WBGT) and universal thermal climate index (UTCI) may have advantages to capture the whole picture of the heat impact on health.

4.2 Wet Bulb Globe Temperature (WBGT)

WBGT is among the most widely used occupational heat stress indices in the world [18-19] and its inclusion in international (ISO 7243) and national (ACGIH 2009) standards indicates that it has been widely accepted since it was developed in the

1950s. The WBGT index integrates four thermal climate variables (air temperature, air humidity, air velocity and radiant heat), and it is used as a screening index for the assessment of occupational heat stress in workplaces [18-19]. WBGT is an international standard "ISO 7243 Hot environments - estimation of the heat stress on working man, based on the WBGT index (wet bulb globe temperature)". Current WBGT index reference values (thresholds) have considered four thermal climate variables, physical activity intensity, heat acclimatization and clothing worn. Human heat balance, thermoregulation and heat exchange between the body and the environment are affected by our physical activity intensity. The higher the level of physical activity we do, the more heat is produced in our body (internal metabolic heat). Clothing hinders the heat exchange between the body and the environment. Those who are well trained and acclimatized to heat have better thermoregulation capacities. In view of the multifactorial integration, WBGT should be a better heat stress index than the single variable air temperature. However, there are not many epidemiological studies that use WBGT as an indicator of heat exposure. Therefore, it is not well known at which WBGT level (threshold) the adverse health effect is critical.

4.3 Universal Thermal Climate Index (UTCI)

About 15 years ago, a Universal Thermal Climate Index (UTCI) (2009) [20-23], based on an advanced human thermoregulation model, directly uses meteorological data to predict the impact of outdoor climate on thermal physiological and perceptual responses [21-23]. The UTCI equivalent temperature (°C) provides a one-dimensional characteristic of complex thermal environments as determined by air temperature, heat radiation, humidity and wind speed. The UTCI equivalent temperature for a given combination of wind, radiation, humidity and air temperature is defined as the air temperature of a reference environment, which produces the same heat strain (physiological responses such as sweating, shivering, skin wettedness, skin blood flow, core, mean skin and face temperatures) as the actual environment [20-23]. The reference environment is defined as an environment with 50% relative humidity, still air (v_a = 0.5 m/s at 10m height, about 0.3 m/s at 1.1 m height) and mean radiant temperature equal to air temperature [20-23]. People in the standard conditions are assumed to have a fixed moderate metabolic rate (135 W/m^2, corresponding to the physical activity level of walking at 4 km/h on the level) and with typical clothing for urban populations.

The global historical UTCI dataset is computed using the ERA5 reanalysis from the European Centre for Medium-Range Forecasts. ERA5 combines model data with observations from across the world to provide a globally complete and consistent description of the Earth's climate and its evolution in recent decades. This dataset represents the current state-of-the-art for bioclimatology data record production. The dataset currently covers 01/01/1940 to near real time and is regularly extended as ERA5 data become available (Thermal comfort indices derived from ERA5 reanalysis (copernicus.eu)) [1]. Further studies on the relationship between historical UTCI and health outcomes such as preterm birth and other health outcomes are needed to provide scientific evidence to set up heat health risk warning thresholds. For early warnings, UTCI should be calculated/predicted based on weather forecast data [24]. Several case studies in different countries showed that UTCI is suitable in developing effective early warning systems and can capture heatwaves including in the context of forecasting for Africa [24-27].

Using data from across 24 years, Di Napoli et al., (2019) identified so-called periods of excess mortality. PEMS are defined as periods in which the observed number of deaths exceeds the expected baseline number of deaths. These are collected and analysed to understand the association between heat exposure and increased mortality rates. In order to generate accurate heat thresholds, the study selects UTCI thresholds based on their ability to predict PEMs accurately, which were selected at certain percentiles (90th, 95th, 98th, and 99.5th) and analysed for their ability to predict PEMs [25].

Through extracting daily UTCI values and calculating UTCI threshold maps, thresholds are determined which according to Di Napoli et al.'s calculations must exceed at least three consecutive days to be considered a PEM [25]. In more detail, the calculation of thresholds involves several steps, including 1) data collection of daily minimum, maximum and mean UTCI values during a specific time, typically during the hottest period, 2) UTCI threshold maps generated at different percentiles such as 90th, 95th, 98th, and 99.5th percentiles, which correspond to different levels of heat stress. The 99.5th percentile aligns with the three-standard-deviation range is typically selected by the researchers to be defining the PEMs, 3) threshold selection, oftentimes determined for each city or location of interest, 4) threshold extrapolation, where daily maximum, minimum and mean UTCI values are extrapolated from the heat stress dataset and averaged across a 3-day window. This way, the cumulative effect of heat stress over time is calculated. 5) as a final step, these thresholds are applied to identify periods of elevated heat stress. For instance, if the daily 3-day-averaged UTCI maximum value exceeds the threshold at the 95th percentile, it identifies a period of heightened heat stress. According to Di Napoli et al., (2019), these steps of threshold calculations can be verified using metrices such as probability of detection (POD), false alarm ratio (FAR), and frequency bias (FB). These are the forecast verification metrics that ECMWF rely on in their suite, which serve as tools to assess the sensitivity and specificity of the newly calculated heat health thresholds, ultimately minimize false alarms. Thresholds can thereafter be adjusted and optimized based on performance evaluation to improve effectiveness in identifying heat waves that carry significant health impacts [25].

Further analysis of the relationship between health outcomes and multiple heat indices including WBGT and UTCI in WP2 of this project is being explored. Once the heat exposure thresholds are identified, the values will be updated and used in the EWS ClimApp-MCH.

5 Heat health data analysis of new datasets in WP2

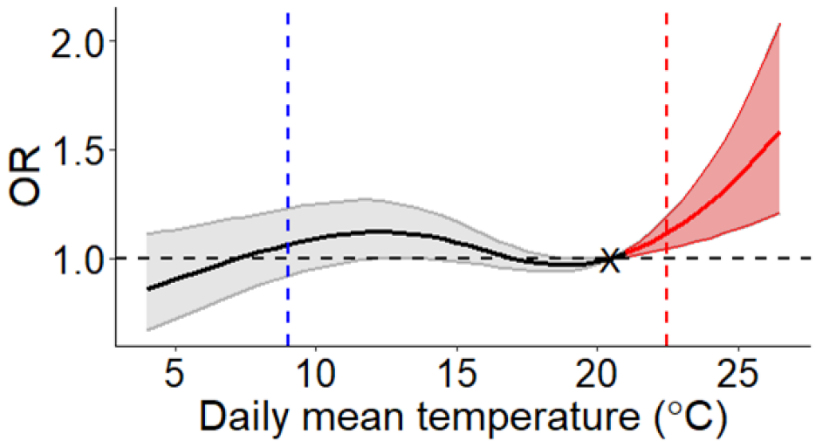
The results of new data analysis in WP2 (see deliverable D2.3) for both the preterm birth and all-cause mortality in children under the age of five demonstrate that the universal thresholds for indication of risk of heat stress in heat metrics such as the UTCI and WBGT are not applicable. Different climate zones have different thresholds.

For the whole year from the preterm birth study the 75th percentile of heat exposure level could represent a robust threshold with the evidence presented, because it does not over warn, but still captures a rise in risk that is not evident in the higher percentile values like the 90th and 95th. However, based on previous studies, e.g. Guigma et al. (2020) [27], Brimicombe (2022), the partners in WP2 for the new data analysis suggest that a seasonal threshold approach is taken either for periods of 30 days or across climate zones defined seasons, because of the results seen in the all-cause mortality in children under the age of five.

The results of the data from South Africa between 01 April 2016 and 31 March 2022 showed that the risk of preterm birth increased significantly ($p < 0.05$) as daily mean air temperatures rose above 20.5°C (Figure 1). The 95th percentile daily mean air temperature (22.5 °C) could be potentially used as a heat threshold for warning heat health risks. However, the daily mean air temperature is an average temperature over day and night, which is not commonly used in weather forecasts. The effects of other thermal climate variables such as humidity, radiant heat from solar radiation, and wind on health outcomes are not considered. The integrated heat stress indices such as WBGT and UTCI are yet to be used for further analysis of the dataset from South Africa.

From the availability of historical weather data and epidemiological methodology point of view, air temperatures including daily maximum and minimum temperatures are easily accessible. However, from human thermal environments interaction perspective, air temperature is a single thermal climate variable that affects the human body heat exchange and may not capture the whole picture of the impact of heat on health outcomes. Individual vulnerability of these vulnerable groups will also play an important role.

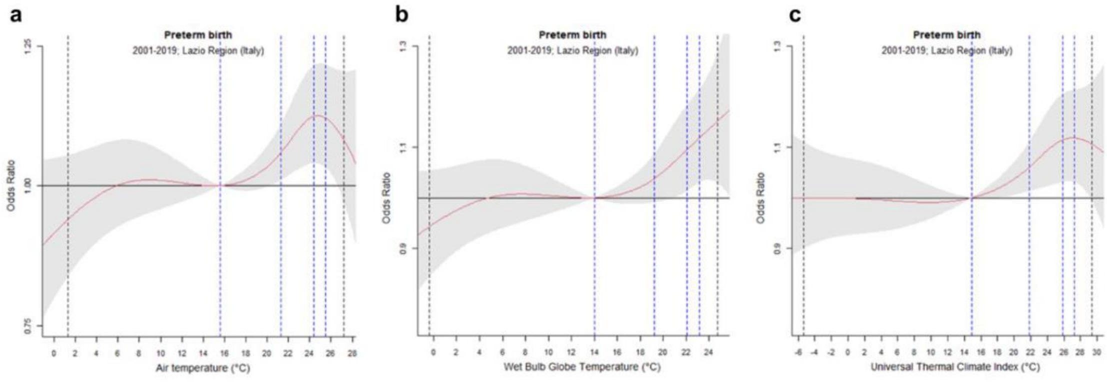
Figure 1. Association between daily mean 2m air temperature and odds ratio (OR) of preterm birth 0-6 days before delivery (SA data)



Note: X indicates temperature of minimum effect (20.5°C). Blue dashed line indicates 5th percentile of daily mean temperature (9°C) and red dashed line indicates the 95th percentile (22.5°C)

On the other hand, the analysis using air temperature, WBGT and UTCI for Italian data showed similar health risk (preterm birth) with odds ratio (OR) OR = 1.121 (95% CI, 1.033; 1.217), OR = 1.118 (95% CI, 1.030; 1.214) and, OR = 1.118 (95% CI, 1.031; 1.212) when comparing the 95th vs the 50th percentile of the three heat metrics. The corresponding heat metrics values at 95th percentile are air temperature Ta = 25.5 °C, WBGT=23.2 °C, UTCI=27.3 °C (Figure 2 and Deliverable D2.3). According to these results of Italian data, each of the three heat metrices can be used as a heat health warning threshold, although their absolute values are different.

Figure 2. Association between air temperature, WBGT and UTCI during the week preceding births and the risk of preterm births (Italian data)



Note: a) air temperature, b) wet bulb globe temperature (WBGT) and c) universal thermal climate index (UTCI) (the lines represent the 1st, 50th, 75th, 90th, 95th and 99th percentile).

Similar analysis using air temperature, WBGT, UTCI and health data from Sweden showed that when the pre-term birth risk OR increased to 1.1, the 95th percentile of the air temperature, WBGT and UTCI were 19.9 °C, 18.7 °C and 16.8 °C. This UTCI temperature (16.8 °C) is low and is categorized as no thermal stress based on UTCI thermal stress categories (Table 2). The challenge we face here is at which UTCI level the early warning should be triggered. Further research is needed.

Comparing the 95th percentile of the heat metrics, it is apparent that at the same percentile and same heat health risk level (OR), the absolute values of the three heat metrices are different, which may be attributed to variability in levels of acclimatization to heat in different climate zones. The difference suggests that it may be necessary to use distinct heat thresholds, e.g., air temperature 22.5 (daily mean), 25.5 and 19.9 °C for South Africa, Italy and Sweden respectively, and to use UTCI thresholds 27.3 and 16.8 °C for South Africa and Sweden as moderate heat health risk.

6 Heat stress thresholds based on integrated heat stress indices and human heat balance models

6.1 Wet Bulb Globe Temperature (WBGT)

$WBGT_{eff}$ reference values are calculated from WBGT values and adjusted for clothing. The reference values are the threshold levels on a sustainable level of heat stress exposure for healthy adults (Table 1). The body core temperatures of workers working in the thermal environment conditions below the reference values for 8-hour work shift will not rise over 38 °C.

The WBGT thresholds values are used in the smartphone tool ClimApp to provide heat stress warnings and advice [28]. As the WBGT was mainly developed for occupational heat stress assessment, it can be directly used for heat health risk warning for health workers. Recent studies by this project consortium partners in WP2 (deliverable 2.3) showed the relationship between WBGT and pre-term birth. A recent literature review only found three studies of maternal health and pregnancy outcomes using WBGT [17]. The field study of the use of UmbiFlow™ by Bonell et al (2023) to assess the impact of heat stress on fetoplacental blood flow for a total of 40 participants, 23 normal births and 17 adverse pregnancy outcomes, indicated that a potential threshold value for placental insufficiency at 30°C by WBGT [29]. This level of heat exposure seems to be high for the vulnerable groups according to the WBGT reference values in Table 1 below [30]. More research is needed to provide robust scientific evidence to support the use of WBGT thresholds for health risk warnings for pregnant and postpartum women and infants.

Table 1. WBGT$_{eff}$ reference (threshold) values for (un)acclimatized people for five classes of metabolic rate (physical work intensity) (ISO 7243:2017)

Metabolic rate (class)	Metabolic rate (W)	WBGT reference limit for persons acclimatized to heat (°C)	WBGT reference limit for persons unacclimatized to heat (°C)
Class 0 **Resting metabolic rate**	115	33	32
Class 1 **Low metabolic rate**	180	30	29
Class 2 **Moderate metabolic rate**	300	28	26
Class 3 **High metabolic rate**	415	26	23
Class 4 **Very high metabolic rate**	520	25	20

6.2 Universal Thermal Climate Index (UTCI)

Based on UTCI values, thermal stress including heat and cold stress are categorized into the following levels (Tabel 2) [30].

Table 2. UTCI equivalent temperature categories in terms of thermal stress (including heat and cold stress; Błażejczyk, et al. 2014).

UTCI range (°C)	Stress Category	
Above +46	4	Extreme heat stress
+38 to +46	3	Very strong heat stress
+32 to +38	2	Strong heat stress
+26 to +32	1	Moderate heat stress
+9 to +26	0	No thermal stress *
+9 to 0	-1	Slight cold stress
0 to -13	-2	Moderate cold stress
-13 to -27	-3	Strong cold stress
-27 to -40	-4	Very strong cold stress
Below -40	-5	Extreme cold stress

These UTCI range and categories can be used to provide different levels of heat stress warnings. As described the same study by Bonell et al (2023) above [29], the results of the use of UmbiFlow™ to assess the impact of heat stress on fetoplacental blood flow for a total of 40 participants, 23 normal births and 17 adverse pregnancy outcomes, indicated that a potential threshold value for placental insufficiency at 32°C by UTCI.

7 WHO expert panel opinions

The WHO Expert Group was established, and the first scoping meeting was held on 25 and 26 April 2023 (deliverable 3.1). The experts will also identify thresholds of heat stress to be used in systems for early notification and early warning related to extreme heat. The Delphi method and procedure is being planned to engage the experts for the identification of the thresholds as there is insufficient scientific evidence for the heat exposure thresholds that can be used to trigger heat health early warning for pregnant and postpartum women, infants and health workers[1]. It is planned that the expert group will be re-convened to reach a consensus on the thresholds in the beginning of 2025. Accordingly, the heat thresholds for the early warning will be updated.

8 Thresholds for different vulnerable groups

Pregnant and postpartum women, infant, children and health workers have different thermoregulatory capacities. Their tolerance to heat is different.

[1]A method guide for a consensus process to develop criteria and thresholds that will inform the adoption of thermal stress thresholds for maternal, newborn, and child health from extreme heat exposure has been drafted and is waiting for clearance by the WHO Expert Group in April 2024.

Therefore, it is important to set up heat health risk thresholds for different vulnerable groups for individualized warnings.

There are multiple physiological changes that occur during a human pregnancy that could affect thermoregulation [31-32]. Children employ a different thermoregulatory strategy, since they have a higher ratio of body surface area to mass than adults. Therefore, children rely more on dry heat dissipation by their larger relative skin surface area than on evaporative heat loss. Furthermore, children's sweating rates are lower than those of adults [31-32]. In extremely hot environments where evaporation is the only heat loss avenue, the heat risk is greater for children. Newborns and infants rely on adults' help to take behaviour actions to move to cooler places. It therefore is necessary to use different thresholds for

1. pregnant women to prevent from heat strain, placental abruption, preterm birth, low weight birth, stillbirth, etc.,
2. postpartum women and infants to prevent from heat strain and morbidity of the mother and infant,
3. health workers to prevent heat strain and heat related illnesses. Existing occupational heat stress indices, reference values and categories can be applied to health workers.

8.1 Threshold levels (heat risk levels)

The widely used occupational heat stress index WBGT and biometeorological thermal stress index UTCI thresholds are determined and categorized based on human thermal physiological and perceptual responses (e.g. body core temperature change, dehydration, perceived thermal sensation) to heat. However, these two indices do not necessarily represent adverse health outcomes with clinical consequences. On the other hand, determination of thresholds levels using adverse health consequences such as preterm birth, stillbirth, and mortality compared to physiological responses and symptoms as health indicators to warn heat health risks may not be EARLY and sensitive enough to be able to capture early phase health responses and protect the health of these vulnerable groups. The earlier heat strain responses can be detected, and warnings provided, the better the protection of the vulnerable groups for the heat health risks will become. A proactive and early warning may need to consider the following responses to heat:

1. heat strain: thermal physiological and perceptual responses like increased body core temperature (hyperthermia), dehydration, and increased perception of heat stress/thermal sensation, thermal discomfort.
2. adverse health effects with clinical implications: mental discomfort, heat related symptoms, pre-term birth, low weigh birth, increased risk of heat exhaustion, heat stroke.
3. mortality: stillbirth, all-cause mortality.

According to the above categories of health responses, thresholds can be divided into the following levels:

1. Low risk (thermal discomfort)
2. Moderate risk (moderate heat stress/strain, increased core temperature in the range about 37.5 - 38.0 °C, increased risk of dehydration, perception of heat stress/thermal sensation: warm):
3. **High risk** (high heat stress/strain, increased core temperature in the range about 38.0 - 38.5 °C, increase risk of dehydration 2-3%, perception of heat stress/thermal sensation: hot, increased pre-term birth, e.g. RR 1.1 – 1.2):
4. **Very high risk** (very high heat stress/strain, increased core temperature >38.5 °C, increase risk of dehydration >3%, perception of heat stress/thermal sensation: very hot, risk of heat stroke, stillbirth/all-cause mortality, e.g. RR >1.2).

8.2 Thresholds for different climate zones and seasonal thresholds to account for spatial and temporal variations

It is suggested that a seasonal threshold approach is taken either for periods of 30 days or across climate zones defined seasons based on the results in WP2 (deliverable 2.3) of all-cause mortality in children under the age of five. Further data analysis of the summer season using maximum daily air temperature, WBGT and UTCI for each of the three countries (South Africa, Sweden and Zimbabwe) would help to find out the 90th, 95th, 99th percentiles of heat exposure levels and contribute to different levels of the heat health early warning thresholds.

9 Validation and modification of the thresholds using new data collected by ClimApp-MCH app

During the evaluation phase of the EWS, it is expected that participants (users of the app) will submit their heat exposure and responses data through ClimApp-MCH app to the High Horizons project consortium. The data will be used to analyse the relationship between heat exposure and body responses. The results are assumed to provide new scientific evidence to validate or fine tune the heat health risk warnings thresholds for the four vulnerable groups. Accordingly, the thresholds will be updated when new data and results become available.

10 Suggested thresholds

Based on the results of data analysis in WP2 (deliverable 2.3), literature and existing occupational heat stress thresholds, we suggest the following thresholds to trigger heat health risk warnings for newborns, infants, pregnant and postpartum women, and health workers who take care of these vulnerable groups (Table 3). These suggested thresholds should be updated when new scientific evidence and/or experts opinions become available.

Values in bold are from WP2 deliverable 2.3 and from occupational heat stress thresholds and categories for workers. Although heatwaves are assumed to be somewhat different in nature across South Africa and Zimbabwe, as a starting point, the same thresholds will be applied to both countries as there is no data for Zimbabwe. Other thresholds are derived by 10% increase or decrease for one level higher or lower heat risk. Newborns and infants are assumed to be more sensitive to heat, therefore the thresholds are suggested as 10% lower (risk is higher) compared to pregnant and postpartum women. These partly arbitrarily determined thresholds should be validated and updated when new data and results become available. An alternative way to determine the threshold heat risk levels is to calculate the 75th (low heat risk), 95th (medium heat risk), 98th (high heat risk) and 99th (very high heat risk) percentiles of heat exposure indices, e.g. UTCI.

In the next steps data analysis, from weather forecasts and warning point of view, using daily maximum air temperature may be a good option instead of daily mean air temperature. And as suggested in deliverable 2.3, thresholds (95th percentile of daily maximum air temperatures, WBGT and UTCI) during summer season in the three countries can better capture the temporal and spatial variations of the heat risks.

Table 3. Suggested thresholds (°C) for the three vulnerable groups in three countries

Heat stress indices	Threshold levels	HHWS thresholds		
		Newborns, infants	Pregnant and postpartum women	Health workers
Air temperature ($T_{daily\ mean}$)	Low risk	18.3 (SA), 16.1 (SW), 18.3 (Zim)	20.3 (SA), 17.9 (SW), 20.3 (Zim)	22.5 (SA), 19.9 (SW), 22.5 (Zim)
	Medium risk	20.3 (SA), 17.9 (SW), 20.3 (Zim)	**22.5 (SA), 19.9 (SW), 22.5 (Zim)**	24.8 (SA), 21.9 (SW), 24.8 (Zim)
	High risk	22.5 (SA), 19.9 (SW), 22.5 (Zim)	24.8 (SA), 21.9 (SW), 24.8 (Zim)	27.3 (SA), 24.1 (SW), 27.3 (Zim)
	Very high risk	24.8 (SA), 21.9 (SW), 24.8 (Zim)	27.3 (SA), 24.1 (SW), 27.3 (Zim)	30.0 (SA), 26.5 (SW), 30.0 (Zim)
$WBGT_{\_daily\ mean}$	Low risk	15.1 (SW)	16.8 (SW)	**20**
	Medium risk	16.8 (SW)	**18.7 (SW)**	**23**
	High risk	18.7 (SW)	20.1 (SW)	**26**
	Very high risk	20.1 (SW)	22.2 (SW)	**29**
$UTCI_{\_daily\ mean}$	Low risk	22.1 (SA), 13.7 (SW), 22.1 (Zim)	24.6 (SA), 15.2 (SW), 24.6 (Zim)	**9 – 26**
	Medium risk	24.6 (SA), 15.2 (SW), 24.6 (Zim)	**27.3 (SA), 16.8 (SW), 27.3 (Zim)**	**26 – 32**
	High risk	27.3 (SA), 16.8 (SW), 27.3 (Zim)	30.0 (SA), 18.5 (SW), 30.0 (Zim)	**32 - 38**
	Very high risk	30.0 (SA), 18.5 (SW), 30.0 (Zim)	33.0 (SA), 20.4 (SW), 33.0 (Zim)	**>38**

Note: SA: South Africa, SW: Sweden, Zim: Zimbabwe.

In addition to external heat, individual factors such as age, body mass index (BMI) before pregnancy, gestation period may also affect human body responses to heat and health outcomes. The thresholds values in Table 3 should be adjusted to provide more individualized heat health early warning system after the results of the relationship between these individual vulnerabilities and health outcomes are found. Before that, the messages in the heat health early warning system (deliverable 3.5 locally adapted and optimized messaging) can be particularly co-developed with the vulnerable groups to provide specific advice and recommendations for specific target groups.

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