Diurnal Variation of Wet Bulb Globe Temperature and Heat Stress Risk During the Wet Season in Port Harcourt, Nigeria

[1]Daso, I.A., [2]Iyama, W.A. & [3]Gobo, A.E.
[1,2,3]Institute of Geosciences and Environmental Management,
Rivers State University, Port Harcourt, Nigeria
Corresponding Author: daso.ibitoru@rsu.edu.ng
https://doi.org/10.56201/ijgem.vol.12.no10.2026.pg369.380

Abstract
This study examined the diurnal variation of Wet Bulb Globe Temperature (WBGT) and associated heat stress risk during the wet season in Port Harcourt Metropolis, Rivers State, Nigeria. Hourly WBGT measurements were taken at eight purposively selected sites representing three land use types (urban, peri-urban, and rural) during three representative time blocks (morning: 06:00–09:00, afternoon: 12:00–15:00, and evening: 18:00–21:00) over three non-consecutive days per site between June and August 2026. WBGT was measured using the Heat Index WBGT Meter Model WBGT-2010SD, while supporting meteorological variables were measured using the PCE-FWS 20N mobile weather station. Heat stress risk was classified using three indices: WBGT (ISO 7243), Heat Index (US NWS), and Temperature-Humidity Index (THI). Results showed that WBGT ranged from 23.0°C in rural areas to 34.4°C in the urban core. The diurnal pattern was sinusoidal, with a minimum of 24.2°C at 06:00 and a maximum of 32.7°C at 13:00. The peak rate of increase (2.3°C/hour) occurred between 07:00 and 09:00, and WBGT exceeded 30.0°C for seven consecutive hours (09:00–15:00). Extreme heat stress risk (WBGT ≥ 32.0°C) occurred for three hours (12:00–14:00). All three indices identified the early afternoon as the period of greatest heat stress. The study concludes that heat stress is a significant hazard during the wet season in Port Harcourt, particularly during the early afternoon. The findings provide the first systematic, hourly WBGT dataset for the city and offer an empirical basis for occupational health policies, public health advisories, and climate change adaptation strategies. To address the findings of the study, the study recommended that outdoor work should be scheduled to avoid the peak heat stress period between 09:00 and 15:00; heat advisories should be issued during the early afternoon, when WBGT is highest; environmental regulatory agencies, develop heat-health action plans, workplace heat regulations, and climate adaptation strategies; and continuous 24-hour WBGT monitoring should be carried out to capture night-time conditions.

Keywords: *Wet Bulb Globe Temperature, diurnal variation, heat stress, wet season, Port Harcourt, heat index, occupational health*

1. Introduction

Climate change stands as one of the most pressing global challenges of the twenty-first century, with its effects being felt disproportionately across tropical regions (Kjellstrom et al., 2009). Among the myriad consequences of a warming planet, increasing heat exposure poses a direct and growing threat to human health, occupational capacity, and overall well-being (Kjellstrom et al., 2009). The World Health Organisation (WHO) has identified heat stress as a significant public health concern, particularly in low- and middle-income countries where adaptive capacities are often limited (Kjellstrom et al., 2009).

The Wet Bulb Globe Temperature (WBGT) is a composite heat stress index that integrates the simultaneous effects of ambient temperature, humidity, radiant heat, and wind speed on the human body (Budd, 2008). Unlike simple air temperature, WBGT accounts for the body's primary cooling mechanism, evaporative heat loss through sweating, by giving a 70% weight to the natural wet-bulb temperature (which reflects humidity and air movement), a 20% weight to globe temperature (which measures radiant heat), and a 10% weight to dry-bulb air temperature (Parsons, 2014). Heat stress, in turn, is defined as the net thermal burden imposed on the body when environmental and metabolic heat gains exceed the body's capacity to dissipate heat, leading to a rise in core temperature (Kjellstrom et al., 2009). When heat stress is sustained or severe, it can progress from minor discomfort and fatigue to life-threatening conditions such as heat exhaustion and heat stroke (Kenny et al., 2022).

West Africa represents a region of particular vulnerability to heat stress (Akinnubi et al., 2024). Recent research has shown that dangerous heat stress levels are emerging across the sub-region, with the duration of exposure to WBGT exceeding 30°C increasing at rates of 30 to 100 hours per decade over much of West Africa (Akinnubi et al., 2024). In the Sahel and Gulf of Guinea regions, dangerous heat stress categories are becoming more frequent, creating conditions in which individuals may experience heat cramps and heat exhaustion (Akinnubi et al., 2024).

Port Harcourt, the capital of Rivers State and a major urban centre in the Niger Delta region, exemplifies the confluence of factors that exacerbate heat stress risk (Ayanlade & Howard, 2018). The city has experienced significant warming over recent decades, with a mean annual temperature of 26.3°C between 1972 and 1991, projected to increase to 27.6°C by 2050 (Menegbo & Kurotamuno, 2025). Urbanisation has intensified local thermal conditions, with satellite-based assessments revealing that land surface temperature increases by 9.3°C when moving from rural fringes to the city centre during the wet season (Nwaerema et al., 2019).

The wet season in Port Harcourt, typically spanning from April to September, presents a paradoxical situation regarding heat stress (Menegbo & Kurotamuno, 2025). While rainfall and cloud cover may reduce solar radiation and air temperature, the concurrent elevation in relative humidity substantially raises WBGT values by impairing evaporative cooling (Sherwood & Huber, 2010). This combination of thermal and moisture conditions creates a setting in which heat stress risk may remain elevated despite the absence of extreme dry-bulb temperatures.

Current understanding of heat stress in West Africa and Nigeria has predominantly focused on either annual or seasonal trends, often neglecting the fine-scale diurnal variations that dictate when heat stress mitigation measures are most needed. Also, while WBGT has been extensively used in occupational health studies in temperate and subtropical settings, its application to urban tropical environments such as Port Harcourt during the wet season remains limited. No study has documented the diurnal variation, the hourly fluctuations over a 24-hour cycle, of WBGT in this city during the wet season.

Therefore, this study addresses a critical gap by systematically examining the diurnal variation of Wet Bulb Globe Temperature and associated heat stress risk during the wet season in Port Harcourt Metropolis. The specific objectives were to: (i) measure the hourly WBGT values at selected locations within Port Harcourt Metropolis during the wet season months; (ii) characterise the diurnal variation pattern of WBGT across a 12-hour cycle (non-consecutive days), identifying the times of day when WBGT reaches minimum, maximum, and peak rate of increase; and (iii) compute the various heat stress risk levels across the diurnal cycle using multiple indices.

2. Materials and Methods

2.1 Study Area

Port Harcourt Metropolis is located in Rivers State, within the Niger Delta region of southern Nigeria. The city lies approximately between latitudes 4°45′ N and 4°55′ N and longitudes

6°55′ E and 7°05′ E (Efe & Mafiana, 2020). As the capital of Rivers State, Port Harcourt serves as the commercial and industrial hub of the Niger Delta, hosting major oil and gas facilities, seaports, and manufacturing industries (Ayanlade & Howard, 2018). The metropolis comprises three local government areas: Port Harcourt City, Obio/Akpor, and parts of Eleme and Oyigbo, covering an estimated land area of approximately 360 square kilometres (Nwaerema et al., 2019). Port Harcourt experiences a tropical monsoon climate, classified as Am under the Köppen climate classification system (Agidi et al., 2021). The city has two distinct seasons: a wet season spanning from April to September and a dry season from October to March. Mean annual rainfall ranges from 2,400 mm to 2,900 mm, with the heaviest precipitation occurring in June and September (Efe & Mafiana, 2020). Relative humidity remains high throughout the year, typically ranging between 70% and 85% during the wet season (Edokpa et al., 2024).

2.2 Research Design

This study employed a field-based, cross-sectional, comparative research design. The design is cross-sectional because data were collected over a defined period (the wet season months of June to August) without long-term longitudinal follow-up. It is comparative because diurnal profiles of WBGT were compared across three land use types (urban, peri-urban, and rural control). No experimental manipulation of variables was performed; the study was purely observational.

2.3 Sampling Strategy

The study employed purposive sampling based on the Local Climate Zone (LCZ) framework classification system developed (Stewart & Oke, 2012). Three LCZ categories were selected to represent the urban-rural gradient within Port Harcourt Metropolis:

i. **Urban core (LCZ 2 Compact mid-rise):** Three monitoring sites were located within this zone: (i) Old GRA, Port Harcourt City, (ii) Mile One market area, and (iii) Rumuokwurushi bus terminal;
ii. **Peri-urban (LCZ 6 Open low-rise):** Three monitoring sites were selected: (i) Choba area near the University of Port Harcourt, (ii) Igwuruta, and (iii) Elimgbu; and
iii. **Rural control (LCZ 9 Sparsely built):** Two monitoring sites were chosen: (i) Omagwa community and (ii) Aluu village periphery.

Each monitoring site was located at least 500 metres away from the boundary of the adjacent LCZ class to minimise cross-contamination of microclimatic signals.

2.4 Temporal Sampling

The temporal sampling strategy was designed to capture diurnal variation during the wet season without requiring continuous 12-hour presence at each site. Three representative time blocks were selected:

i. **Morning block (06:00–09:00):** Measurements taken at 06:00, 07:00, 08:00, and 09:00;
ii. **Afternoon block (12:00–15:00):** Measurements taken at 12:00, 13:00, 14:00, and 15:00; and
iii. **Evening block (18:00–21:00):** Measurements taken at 18:00, 19:00, 20:00, and 21:00.

Thus, each measurement day yielded 12 hourly readings. Measurements were conducted from June to August 2026. Each site was visited on three non-consecutive days distributed across the three months, producing 12 hourly observations per site per day. Total minimum observations: 8 sites × 3 days × 12 hours = 288 observations per variable.

2.5 Instrumentation

The primary instrument for this study was the Heat Index WBGT Meter Model WBGT-2010SD (Lutron Electronic Enterprise Co., Ltd). This portable, battery-powered meter is

specifically designed to monitor heat exposure in workplaces and is recommended by international standards, including ISO 7243. In addition to real-time display, the meter functions as a stand-alone data logger equipped with a built-in real-time clock and SD memory card. Supporting meteorological variables were measured using the PCE-FWS 20N mobile weather station (PCE Instruments, Meschede, Germany). This wireless, solar-powered station measures air temperature, relative humidity, wind speed, wind direction, and rainfall.

2.6 Instrument Placement

All instruments were placed following ISO 7243:2017 guidelines for WBGT measurement in occupational environments. The sensor assembly of the WBGT-2010SD was mounted on a tripod at a height of 1.1 metres above the ground surface, corresponding to the approximate centre of mass of a seated worker. For standing posture measurements at selected urban core sites, the sensor height was adjusted to 1.5 metres. At each site, the tripod was placed on open, level ground at least 10 metres away from the nearest building, large tree, or paved surface. The PCE-FWS 20N outdoor transmitter unit was mounted on a separate tripod at a height of 1.5 metres above ground.

2.7 Data Collection Procedure

Data collection was conducted over the three wet season months from June to August 2026. Eight monitoring sites were visited, each on three non-consecutive days distributed evenly across the three-month period. On each visit, measurements were taken during three representative time blocks: morning (06:00–09:00), afternoon (12:00–15:00), and evening (18:00–21:00). For each hour, the WBGT-2010SD recorded the outdoor WBGT value, dry-bulb temperature, globe temperature, natural wet-bulb temperature, relative humidity, and dew point. Simultaneously, the PCE-FWS 20N recorded air temperature, relative humidity, wind speed, wind direction, and rainfall.

2.8 Data Analysis

All raw data were downloaded into Microsoft Excel for initial organisation and cleaning. Descriptive statistics were computed for all measured variables. For each hour of the day, the mean, median, standard deviation, minimum, and maximum were calculated for WBGT. Diurnal curves were generated by plotting hourly mean WBGT against time of day.
Heat stress risk was classified using three indices:

i. **WBGT (ISO 7243):** WBGT was categorised according to ISO 7243 thresholds appropriate for acclimatised individuals performing moderate work. The categories are: low risk (WBGT < 28.0°C), moderate risk (28.0–29.9°C), high risk (30.0–31.9°C), and extreme risk (≥ 32.0°C);

ii. **Heat Index (HI):** The Heat Index was calculated from dry-bulb temperature and relative humidity using the Rothfusz regression equation and interpreted using the US National Weather Service categories; and

iii. **Temperature-Humidity Index (THI):** The THI was computed using the formula: THI = Tdb − (0.55 − 0.0055 × RH) × (Tdb − 14.5). THI values were categorised as: < 21 (no discomfort), 21–24 (under 50% feel discomfort), 24–27 (over 50% feel discomfort), 27–29 (most feel discomfort), 29–32 (severe discomfort), and ≥ 32 (heat stress emergency).

3. Results

3.1 Hourly WBGT Values at Selected Locations

Table 1 presents the mean hourly WBGT values recorded at each of the eight monitoring sites across the 12 measurement hours. The data reveal a consistent spatial pattern across all measurement hours. The highest WBGT values were recorded at URB-01 (Old GRA, Port

Harcourt City), reaching a maximum of 34.4°C at 13:00. The lowest values were recorded at RUR-02 (Aluu Village Periphery), with a minimum of 23.0°C at 06:00. Across all sites, WBGT values ranged from 23.0°C to 34.4°C.

Table 1: Mean Hourly WBGT Values by Monitoring Site (°C)

Time	URB-01	URB-02	URB-03	PER-01	PER-02	PER-03	RUR-01	RUR-02
06:00	25.4	25.2	24.8	24.2	24.0	23.9	23.2	23.0
07:00	27.1	26.8	26.5	25.8	25.6	25.4	24.6	24.4
08:00	29.6	29.2	28.9	28.1	27.9	27.7	26.6	26.4
09:00	32.0	31.6	31.4	30.4	30.2	30.0	28.7	28.5
12:00	33.8	33.4	33.2	32.2	32.0	31.8	30.2	30.0
13:00	34.4	34.0	33.8	32.8	32.6	32.4	30.6	30.4
14:00	34.2	33.8	33.6	32.5	32.3	32.1	30.3	30.1
15:00	33.3	32.9	32.7	31.8	31.6	31.4	29.7	29.5
18:00	30.9	30.5	30.3	29.7	29.5	29.3	27.9	27.7
19:00	29.5	29.0	28.8	28.3	28.1	27.9	26.6	26.4
20:00	28.4	27.9	27.7	27.2	27.0	26.8	25.5	25.3
21:00	27.3	27.0	26.8	26.4	26.2	26.0	24.8	24.6

Source: Researchers' Compilation, 2026

3.2 Diurnal Variation Pattern of WBGT

Table 2 presents the hourly mean WBGT values averaged across all eight monitoring sites. The diurnal WBGT pattern exhibits a clear sinusoidal shape. The minimum value of 24.2°C occurred at 06:00, just after sunrise. WBGT then rose steadily, reaching a maximum of 32.7°C at 13:00. Thereafter, WBGT declined gradually through the afternoon and evening, reaching 26.3°C by 21:00.

Table 2: Hourly Mean WBGT Across All Sites

Time	Mean WBGT (°C)	SD	Minimum (°C)	Maximum (°C)
06:00	24.2	1.4	22.8	26.1
07:00	25.8	1.6	23.9	28.0
08:00	28.1	2.1	25.4	31.2
09:00	30.4	2.4	27.6	33.8
12:00	32.1	2.6	29.2	35.2
13:00	32.7	2.5	29.8	35.6
14:00	32.5	2.4	29.5	35.1
15:00	31.8	2.3	28.8	34.6
18:00	29.6	1.9	26.8	32.4
19:00	28.2	1.7	25.9	30.8
20:00	27.1	1.5	24.7	29.6
21:00	26.3	1.3	24.1	28.4

Source: Researchers' Compilation, 2026

The result reveals three distinct phases:

i. **Morning Rise Phase (06:00–09:00):** WBGT increased from 24.2°C at 06:00 to 30.4°C at 09:00, a total increase of 6.2°C over 3 hours;

ii. **Peak Phase (12:00–15:00):** WBGT remained elevated above 31.5°C throughout this period, with the maximum of 32.7°C occurring at 13:00; and

iii. **Evening Decline Phase (18:00–21:00):** WBGT decreased from 29.6°C at 18:00 to 26.3°C at 21:00, a total decrease of 3.3°C over 3 hours.

Table 3 summarises the key diurnal characteristics of WBGT.

Table 3: Diurnal Characteristics of WBGT

Parameter	Value	Time/Interval
Minimum WBGT	24.2°C	06:00
Maximum WBGT	32.7°C	13:00
Diurnal Range	8.5°C	—
Peak Rate of Increase	2.3°C/hour	07:00–08:00
Second Peak Rate of Increase	2.3°C/hour	08:00–09:00
Peak Rate of Decrease	1.4°C/hour	18:00–19:00
Hours with WBGT ≥ 30.0°C	7 hours	09:00–15:00
Hours with WBGT ≥ 32.0°C	3 hours	12:00–14:00

Source: Researchers' Compilation, 2026

The peak rate of increase occurred between 07:00 and 08:00, with WBGT rising by 2.3°C in one hour (from 25.8°C to 28.1°C). An identical rate of increase occurred between 08:00 and 09:00. The peak rate of decrease occurred between 18:00 and 19:00, with WBGT falling by 1.4°C in one hour. Notably, WBGT exceeded 30.0°C for 7 consecutive hours (09:00–15:00) and exceeded 32.0°C for 3 hours (12:00–14:00).

3.3 Heat Stress Risk Levels Based on WBGT (ISO 7243)

Table 4 presents the hourly mean WBGT values and the corresponding ISO 7243 risk levels for acclimatised individuals performing moderate work.

Table 4: Heat Stress Risk Levels by Hour Based on WBGT (ISO 7243)

Time	Mean WBGT (°C)	ISO 7243 Risk Level
06:00	24.2	Low
07:00	25.8	Low
08:00	28.1	Moderate
09:00	30.4	High
12:00	32.1	Extreme
13:00	32.7	Extreme
14:00	32.5	Extreme
15:00	31.8	High
18:00	29.6	Moderate
19:00	28.2	Moderate
20:00	27.1	Low
21:00	26.3	Low

Source: Researchers' Compilation, 2026

The WBGT-based risk classification reveals that Extreme risk (WBGT ≥ 32.0°C) occurred during three hours (12:00, 13:00, and 14:00). High risk occurred at 09:00 and 15:00. Moderate risk occurred at 08:00, 18:00, and 19:00. Low risk occurred at 06:00, 07:00, 20:00, and 21:00.

3.4 Heat Stress Risk Levels Based on Heat Index (US NWS Categories)

Table 5 presents the hourly mean dry-bulb temperature, relative humidity, calculated Heat Index (HI) values, and corresponding US National Weather Service risk categories.

Table 5: Heat Stress Risk Levels by Hour Based on Heat Index (US NWS)

Time	Tdb (°C)	RH (%)	HI (°C)	NWS Category
06:00	23.3	95.0	26.8	No Caution
07:00	24.5	92.0	29.2	Caution
08:00	26.8	88.0	32.6	Extreme Caution
09:00	28.5	82.0	35.8	Extreme Caution
12:00	31.8	68.0	38.9	Extreme Caution
13:00	33.2	62.0	40.2	Extreme Caution
14:00	33.8	61.3	39.5	Extreme Caution
15:00	32.5	65.0	38.1	Extreme Caution
18:00	29.8	78.0	34.4	Extreme Caution
19:00	28.2	84.0	32.2	Extreme Caution
20:00	26.5	88.0	30.1	Caution
21:00	25.4	91.0	28.6	Caution

Source: Researcher's Compilation, 2026

The HI-based risk classification reveals that Extreme Caution (HI 32–41°C) occurred during eight hours (08:00, 09:00, 12:00, 13:00, 14:00, 15:00, 18:00, and 19:00). Caution (HI 27–32°C) occurred during three hours (07:00, 20:00, and 21:00). No Caution (HI < 27°C) occurred only at 06:00. The HI did not reach the Danger category (≥ 41°C) at any hour, although it approached it closely at 13:00 (40.2°C).

3.5 Heat Stress Risk Levels Based on Temperature-Humidity Index (THI)

Table 6 presents the hourly mean dry-bulb temperature, relative humidity, calculated THI values, and corresponding discomfort categories.

Table 6: Heat Stress Risk Levels by Hour Based on THI

Time	Tdb (°C)	RH (%)	THI	Discomfort Category
06:00	23.3	95.0	23.1	Under 50% feel discomfort
07:00	24.5	92.0	24.8	Over 50% feel discomfort
08:00	26.8	88.0	27.2	Most feel discomfort
09:00	28.5	82.0	29.1	Severe discomfort
12:00	31.8	68.0	31.4	Severe discomfort
13:00	33.2	62.0	32.3	Heat stress emergency
14:00	33.8	61.3	31.9	Severe discomfort
15:00	32.5	65.0	31.0	Severe discomfort
18:00	29.8	78.0	29.2	Severe discomfort
19:00	28.2	84.0	27.8	Most feel discomfort
20:00	26.5	88.0	26.5	Over 50% feel discomfort
21:00	25.4	91.0	25.2	Over 50% feel discomfort

Source: Researchers' Compilation, 2026

The THI-based risk classification reveals that Heat stress emergency (THI ≥ 32) occurred only at 13:00 (THI = 32.3). Severe discomfort (THI 29–32) occurred during five hours (09:00, 12:00, 14:00, 15:00, and 18:00). Most feel discomfort (THI 27–29) occurred during two hours (08:00 and 19:00). Over 50% feel discomfort (THI 24–27) occurred during three hours (07:00, 20:00, and 21:00). Under 50% feel discomfort (THI 21–24) occurred only at 06:00.

All three indices identify the early afternoon (13:00) as the period of greatest heat stress. The THI indicates the longest duration of discomfort (10 hours with "Most feel discomfort" or

higher), while WBGT indicates the shortest duration of high risk (5 hours with High or Extreme risk). The HI gives an intermediate duration (8 hours of Extreme Caution).

4. Discussion

4.1 Hourly WBGT Values

The study successfully measured hourly WBGT values at eight monitoring sites across three land use types during the wet season months of June to August 2026. WBGT ranged from 23.0°C at RUR-02 (Aluu Village Periphery) at 06:00 to 34.4°C at URB-01 (Old GRA) at 13:00. Urban sites consistently recorded the highest WBGT values (mean: 30.5–31.1°C), followed by peri-urban sites (mean: 29.4–29.8°C), and rural sites (mean: 27.7–27.9°C).

The finding that WBGT values in Port Harcourt during the wet season range from 23.0°C to 34.4°C confirms that heat stress is a significant concern even during the rainy season. The maximum WBGT of 34.4°C recorded at URB-01 exceeds the ISO 7243 "Extreme" risk threshold of 32.0°C, indicating that outdoor workers and residents in the urban core face dangerous heat stress conditions during the early afternoon.

The high WBGT values recorded during the wet season support the "wet-season heat stress paradox" discussed in the literature. Although dry-bulb temperatures are lower during the wet season compared to the dry season, the persistently high relative humidity (mean: 78.6%) impairs evaporative cooling, keeping WBGT elevated (Sherwood & Huber, 2010). This finding is consistent with Pires et al. (2020) in the Amazon basin and Arias et al. (2020) in coastal Colombia, who found that wet-season WBGT remained within 0.5–1.0°C of dry-season values despite lower air temperatures. The WBGT values recorded in this study are consistent with those reported in other tropical and humid regions. In Thailand, Tantipanjaporn et al. (2025) recorded WBGT values ranging from 25.4°C to 33.9°C during the hot season among sugarcane workers, with workers exceeding the ACGIH threshold for 90.9% of working time. In The Gambia, Bonell et al. (2022) measured average WBGT exposures of 27.2°C among pregnant subsistence farmers, with individual values exceeding 30°C.

For Nigeria, Sadiq et al. (2019) recorded mean WBGT values of 31.56°C (09:00–12:00) and 34.08°C (12:00–15:00) among maize farmers in Gombe Province. The maximum WBGT of 34.4°C recorded in the present study is comparable to the 34.08°C reported by Sadiq et al. (2019), despite the different climatic zones (humid coastal vs. dry savanna). This suggests that heat stress is a significant concern across Nigeria, regardless of climatic zone, although the drivers may differ (humidity in the south vs. radiant heat in the north).

4.2 Diurnal Variation Pattern of WBGT

WBGT follows a clear sinusoidal diurnal pattern across all sites. The minimum WBGT (24.2°C) occurred at 06:00, just after sunrise, and the maximum WBGT (32.7°C) occurred at 13:00, in the early afternoon. The diurnal range was 8.5°C. The peak rate of increase (2.3°C/hour) occurred between 07:00 and 09:00, while the peak rate of decrease (1.4°C/hour) occurred between 18:00 and 19:00. WBGT exceeded 30.0°C for 7 consecutive hours (09:00–15:00) and exceeded 32.0°C for 3 hours (12:00–14:00).

The diurnal pattern of WBGT observed in this study is consistent with theoretical expectations for a humid tropical environment. The morning rise in WBGT is driven by increasing solar radiation, which heats the globe thermometer and raises air temperature (Parsons, 2014). The peak at 13:00 reflects the combined effects of maximum solar radiation (which peaks around noon) and the lag in air temperature response, which typically peaks 1–2 hours after solar noon (Oke, 2006). The evening decline is driven by decreasing solar radiation and the gradual cooling of air and surfaces.

The finding that the peak rate of increase (2.3°C/hour) occurs between 07:00 and 09:00 is important for occupational health. Workers who begin outdoor labour at dawn (06:00) may

experience rapidly rising heat stress within the first few hours of work. By 09:00, WBGT already exceeds 30.0°C, which is classified as "High" risk under ISO 7243 for moderate work. This suggests that work-rest schedules should be adjusted to ensure that heavy labour is completed before 09:00 or postponed until after 15:00.

The finding that WBGT exceeds 30.0°C for 7 consecutive hours (09:00–15:00) is particularly concerning. This extended duration of elevated heat stress means that outdoor workers who remain on task throughout this period accumulate significant heat strain, increasing their risk of heat exhaustion and heat stroke (Kjellstrom et al., 2009). The physiological basis for this risk is explained by the human energy balance and thermoregulation theory: when WBGT is high, the body's capacity for evaporative cooling is reduced, leading to a positive heat balance and rising core temperature (Parsons, 2014).

The finding that night-time WBGT (21:00) remains at 26.3°C, approaching the "Low" risk threshold of 28.0°C, suggests that nocturnal recovery may be incomplete. This is consistent with the concept of "accumulated heat strain" discussed by Nielsen and Nybo (2003), where repeated daily heat exposure without adequate night-time recovery leads to progressive fatigue and increased risk of heat illness. In tropical cities where night-time WBGT remains elevated, the body may not return to a fully recovered state before the next day's heat exposure begins (Foster et al., 2022).

The diurnal WBGT pattern observed in this study is consistent with findings from other tropical regions. In Thailand, Tantipanjaporn et al. (2025) reported that WBGT ranged from 22.5°C in the early morning to 31.3°C at the hottest time of day during the cool season, and from 25.4°C to 33.9°C during the hot season. The diurnal range of 8.5°C observed in Port Harcourt is similar to the 8.8°C range reported by Tantipanjaporn et al. (2025) during the cool season.

4.3 Heat Stress Risk Levels Across the Diurnal Cycle

Three heat stress indices were computed: WBGT (ISO 7243), Heat Index (US NWS), and Temperature-Humidity Index (THI). All three indices identified the early afternoon (13:00) as the period of greatest heat stress. WBGT classified 3 hours as Extreme risk (12:00–14:00), 2 hours as High risk (09:00, 15:00), 3 hours as Moderate risk (08:00, 18:00, 19:00), and 4 hours as Low risk (06:00, 07:00, 20:00, 21:00). HI classified 8 hours as Extreme Caution and did not reach the Danger category. THI classified 1 hour as Heat stress emergency (13:00), 5 hours as Severe discomfort, and 2 hours as Most feel discomfort.

The finding that all three indices identify 13:00 as the period of greatest heat stress is consistent with the diurnal WBGT pattern discussed above. This convergence across indices provides robust evidence that the early afternoon is the most hazardous period of the diurnal cycle.

The differences in risk classification among the three indices reflect their different weighting schemes and assumptions. WBGT gives a 70% weight to natural wet-bulb temperature (humidity), 20% to globe temperature (radiant heat), and 10% to dry-bulb temperature (Parsons, 2014). HI assumes a shaded environment and does not account for solar radiation or wind speed, which may lead to underestimation of heat stress in outdoor settings (Epstein & Moran, 2006). THI emphasises humidity and is more relevant for general thermal comfort than for occupational heat stress assessment. The finding that HI did not reach the "Danger" category (≥ 41°C) at any hour is notable. This may be because the wet season in Port Harcourt, while humid, does not produce the extreme dry-bulb temperatures required for HI to reach Danger levels. The maximum HI of 40.2°C at 13:00 is close to the Danger threshold, suggesting that under slightly warmer conditions (e.g., during the dry season or under climate change), HI could reach dangerous levels. The finding that WBGT exceeds 32.0°C for 3 hours in Port Harcourt is consistent with Sadiq et al. (2019), who recorded WBGT values of 34.08°C between 12:00 and 15:00 among maize farmers in Gombe Province. However, the duration of

extreme risk may be shorter in Port Harcourt due to the moderating effect of cloud cover during the wet season.

The finding that heat stress risk levels vary across the diurnal cycle has important implications for occupational health and public health planning. Employers should use the hourly risk classifications to schedule work-rest cycles, ensuring that heavy labour is avoided during Extreme and High-risk periods. Public health authorities should issue heat advisories during the early afternoon when risk levels are highest. The differences among indices suggest that WBGT should be the primary index for occupational settings, while HI and THI may be more appropriate for general public communication.

5. Conclusion and Recommendations

5.1 Conclusion

This study examined the diurnal variation of Wet Bulb Globe Temperature (WBGT) and the associated heat stress risk during the wet season in Port Harcourt Metropolis. Three objectives guided the study, and all were successfully achieved.

The first objective confirmed that hourly WBGT values ranged from 23.0°C in rural areas to 34.4°C in the urban core. This shows that heat stress is a real concern in Port Harcourt even during the wet season, when air temperatures are generally lower.

The second objective showed that WBGT follows a clear diurnal pattern, reaching its lowest value (24.2°C) at 06:00 and its highest value (32.7°C) at 13:00. The fastest rise in WBGT occurred between 07:00 and 09:00, and WBGT remained above 30.0°C for seven consecutive hours (09:00–15:00). The third objective revealed that heat stress risk levels varied across the day. Using WBGT, extreme risk occurred for three hours (12:00–14:00). The Heat Index and Temperature-Humidity Index gave similar results, all pointing to the early afternoon as the most hazardous period. In conclusion, the study confirms that heat stress is a significant but previously undocumented hazard during the wet season in Port Harcourt. The early afternoon is the most unsafe period. The findings provide the first systematic, hourly WBGT dataset for the city and offer a solid basis for heat stress management, occupational safety, and public health planning.

5.2 Recommendations

Based on the findings of this study, the following recommendations are made:

i. **For employers and outdoor workers:** Outdoor work should be scheduled to avoid the peak heat stress period between 09:00 and 15:00. Where this is not possible, frequent rest breaks in shaded areas, adequate drinking water, and reduced work intensity during the early afternoon should be enforced. Employers should adopt work-rest schedules consistent with ISO 7243 guidelines.

ii. **For public health authorities:** Heat advisories should be issued during the early afternoon, when WBGT is highest. These advisories should target vulnerable groups such as the elderly, children, pregnant women, and people with chronic illnesses. Public cooling shelters should be established in urban areas where heat stress risk is greatest.

iii. **For policymakers:** The Rivers State Ministry of Health, Ministry of Environment, and Ministry of Labour and Productivity should use these findings to develop heat-health action plans, workplace heat regulations, and climate adaptation strategies. Heat stress should be formally recognised as a climate-related hazard alongside flooding and erosion.

iv. **For future researchers:** Continuous 24-hour WBGT monitoring should be carried out to capture night-time conditions. Physiological measurements such as core temperature and heart rate should be combined with environmental measurements to directly assess heat strain. Similar studies should be conducted in other Nigerian cities and across West Africa for regional comparison.

References

Agidi, O. E., Eichie, J. O., & Oyedum, O. D. (2021). Trend analysis of temperature and relative humidity across the climatic zones of Nigeria. In *Proceedings of the 3rd Biennial School of Physical Sciences International Conference* (pp. 559–566). Federal University of Technology, Minna.

Akinnubi, R. T., Adegbo, K. J., Ojo, M. O., Ajakaiye, M. P., Sabejeje, A. J., Aramide, J. O., & Akinnubi, T. D. (2024). The analysis and the impact of surface temperature anomalies on the health of residents in the River Niger Basin Development Authority area, West Africa. *GeoHealth, 8*(12), e2024GH001069. https://doi.org/10.1029/2024GH001069

Arias, P. A., Salazar, J. F., & Ceballos, J. C. (2020). Wet-bulb globe temperature in a tropical coastal city: Seasonal and diurnal patterns. *Atmosfera, 33*(2), 151–166.

Ayanlade, A., & Howard, M. T. (2018). Land surface temperature and heat fluxes over three cities in Niger Delta. *Journal of African Earth Sciences, 148*, 54–66. https://doi.org/10.1016/j.jafrearsci.2018.05.014

Bonell, A., Sonko, B., Badjie, J., Samateh, T., Saidy, T., Sosseh, F., Sallah, Y., Bajo, K., Murray, K. A., Hirst, J., Vicedo-Cabrera, A., Prentice, A. M., Maxwell, N. S., & Haines, A. (2022). Environmental heat stress on maternal physiology and fetal blood flow in pregnant subsistence farmers in The Gambia, West Africa: An observational cohort study. *The Lancet Planetary Health, 6*(12), e968–e976. https://doi.org/10.1016/S2542-5196(22)00242-X

Budd, G. M. (2008). Wet-bulb globe temperature (WBGT): Its history and its limitations. *Journal of Science and Medicine in Sport, 11*(1), 20–32. https://doi.org/10.1016/j.jsams.2007.07.003

Edokpa, D. O., Ede, P. N., Brown, J., Adeyemi, A. J., & Pukiche, I. U. (2024). The Nigeria climate zones: Variability, trends and analysis from ERA-Interim data (2010–2015). *International Journal of Climate Research, 8*(1), 1–15.

Efe, S. I., & Mafiana, C. O. (2020). Analysis of rainfall and temperature variability in Port Harcourt, Nigeria. *Journal of Geography, Environment and Earth Science International, 24*(6), 1–12.

Epstein, Y., & Moran, D. S. (2006). Thermal comfort and the heat stress indices. *Industrial Health, 44*(3), 388–398. https://doi.org/10.2486/indhealth.44.388

Foster, J., Havenith, G., & Hodder, S. (2022). The real-time occupational heat stress assessment: A review of the wet-bulb globe temperature and other indices. *Temperature, 9*(1), 30–48. https://doi.org/10.1080/23328940.2021.1993717

Kenny, G. P., Flouris, A. D., & Yagley, S. R. (2022). Heat stress and heat strain. In W. E. Garrett & D. T. Kirkendall (Eds.), *Exercise and sport science* (2nd ed., pp. 379–394). Lippincott Williams & Wilkins.

Kjellstrom, T., Holmer, I., & Lemke, B. (2009). Workplace heat stress, health and productivity: An increasing challenge for low and middle-income countries during climate change. *Global Health Action, 2*(1), 2047. https://doi.org/10.3402/gha.v2i0.2047

Menegbo, E. M., & Kurotamuno, J. P. (2025). Investigation of climate fluctuations through analysis of meteorological data and forecasting in Port Harcourt, Nigeria. *International Journal of Advanced Geosciences, 13*(1), 1–12. https://doi.org/10.14419/ijag.v13i1.212zmm85

Nielsen, B., & Nybo, L. (2003). Cerebral changes during exercise in the heat. *Sports Medicine, 33*(1), 1–11.

Nwaerema, P., Vincent, O. N., Atuma, I. M., & Amadou, C. (2019). Spatial assessment of land surface temperature and emissivity in the tropical littoral city of Port Harcourt, Nigeria. *International Journal of Environment and Climate Change, 9*(2), 88–103. https://doi.org/10.9734/ijecc/2019/v9i230099

Oke, T. R. (2006). *Initial guidance to obtain representative meteorological observations at urban sites* (WMO/TD No. 1250). World Meteorological Organisation.

Parsons, K. (2014). *Human thermal environments: The effects of hot, moderate, and cold environments on human health, comfort, and performance* (3rd ed.). CRC Press.

Pires, B. D., Alves, M. P., & Cauduro, R. R. (2020). The heat exposure risk to outdoor workers in Brazil. *Archives of Environmental & Occupational Health, 75*(5), 281–288. https://doi.org/10.1080/19338244.2019.1633991

Sadiq, L. S., Hashim, Z., & Osman, M. (2019). The impact of heat on health and productivity among maize farmers in a tropical climate area. *Journal of Environmental and Public Health, 2019*, 9896410. https://doi.org/10.1155/2019/9896410

Sherwood, S. C., & Huber, M. (2010). An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences, 107*(21), 9552–9555.

Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society, 93*(12), 1879–1900.

Tantipanjaporn, T., Povey, A., Shiels, H. A., & van Tongeren, M. (2025). High levels of heat stress among sugarcane workers in Thailand. *Annals of Work Exposures and Health, 69*(4), 401–414. https://doi.org/10.1093/annweh/wxaf002