

Comparison between Wet Bulb Globe Temperature (WBGT) App Prototype and WBGT Monitor
to Assess Heat Stress Risk in Groundskeeping in an Eastern North Carolina University Setting

by

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The wet bulb globe temperature (WBGT) index is the preferred environmental heat metric for occupational heat-related illness (HRI) prevention. However, WBGT data may not always be easily accessible for workplace heat stress evaluation. Thus, there is a need for well-designed WBGT-based tools that offer reliable, more accessible, and cheaper WBGT risk information for HRI prevention. A WBGT web application (app) prototype was developed by East Carolina University professors to calculate the current and forecasted WBGT, but it had not been tested for accuracy. Consequently, the purpose of this study was to assess the reliability of the app prototype in providing accurate heat stress risk information for groundskeepers in eastern North Carolina by comparing the WBGT indices and risk levels from the app (WBGT_{app}) with those derived from heat stress monitor (WBGT_{ins}). Heat stress monitoring was conducted on campus from March to August 2023 using a heat stress monitor. The outdoor WBGT index was recorded for 81 d, and the hourly mean WBGT indices were compared to the American Conference Governmental Industrial Hygienists (ACGIH) Threshold Limit Values and action limits for heat stress. Heat stress risk levels were assigned to WBGT indices based on workload. The app prototype was used to record hourly WBGT indices and their corresponding risk levels. Data analysis was conducted using t-tests, Pearson correlation tests, and cross-tabulation to assess the app's reliability in evaluating

workplace heat stress risk. The study found that the hourly mean WBGT_{app} index was significantly higher ($P<0.01$) than the WBGT_{ins} index, but the difference between the overall average of the daily mean WBGT_{app} and the daily mean WBGT_{ins} was not statistically significant. There is a strong, positive correlation between the hourly mean WBGT_{app} and WBGT_{ins} indices ($r=0.94$, $P<0.01$), between the daily mean WBGT_{app} and WBGT_{ins} indices ($r=0.97$, $P<0.01$), and between the daily maximum WBGT_{app} and WBGT_{ins} indices ($r=0.94$, $P<0.01$). The hourly mean WBGT_{ins} indices ranged from 8.35 – 33.03 °C, while the hourly mean WBGT_{app} indices ranged from 6.11- 37.78 °C. The app correctly identified 73-88% of minimal-risk conditions, depending on workload type, and was most reliable in identifying extreme-risk conditions at 97%, 95%, and 93% for light, moderate, and heavy workloads, demonstrating its capability to protect workers, especially for severe heat stress risk conditions. The WBGT app prototype is a promising tool for assessing heat stress risk, providing early warnings, and offering affordability and convenience for occupational heat stress prevention.

Comparison between WBGT App Prototype and WBGT Monitor to Assess Heat Stress

Risk in Groundskeeping in an Eastern North Carolina University Setting

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CHAPTER I. INTRODUCTION

Heat stress has several negative health impacts that might be harmful to workers, particularly in an excessively hot environment (Glaser et al., 2022). Excessive heat exposure may lead to heat-related illnesses (HRIs), such as heat exhaustion, heat cramps, heat rashes, and heat stroke (National Institute for Occupational Safety and Health, 2020). One serious HRI that must be addressed quickly in any workplace is heat stroke because, if untreated, it can be lethal and/or life-threatening (Huss et al., 2013). Heat can also increase the risk of workplace injuries due to sweaty hands, clouded protective goggles, and disorientation (NIOSH, 2020). Additionally, inadvertent contact with hot surfaces or steam can result in burns (NIOSH, 2020). Between 2006 and 2016 in the United States, 670 fatalities were recorded each year as being caused by exposure to excessive heat among the general population (Sarofim et al., 2016). Workers in outdoor occupations (e.g., farmers, foresters, construction workers, miners, and groundskeepers) have a high degree of heat exposure during some seasons due to hot work environments. To implement essential preventative measures, it is crucial for outdoor workers to understand the degree of their heat exposure and the health risk it entails.

Wet bulb globe temperature (WBGT) is the gold standard for assessing environmental heat metrics for HRI prevention in the workplace and is typically measured using a heat stress monitor. However, WBGT may not always be easily accessible for worksite heat stress evaluation due to many factors, such as a lack of monetary means to purchase the necessary instruments. The Occupational Safety Health Administration (OSHA)-NIOSH Heat Safety Tool, a mobile app that provides current and forecasted heat index and its corresponding risk, has been considered as an alternative tool for assessing environmental heat metrics in the workplace (Centers for Disease Control and Prevention, 2017). However, this heat index-based app was found to be inaccurate in

assessing high and extreme heat stress risks at any workload type and was not recommended for use in occupational heat stress assessment, particularly in agricultural settings (Dillane and Balanay, 2020).

Thus, a well-designed mobile app that delivers WBGT risk information may still be needed as an alternative tool that is easily available and provides trustworthy information on heat stress risk for use by outdoor workers (Dillane and Balanay, 2020). More research on WBGT-based apps is highly recommended because the OSHA-NIOSH app may not always be dependable in workplaces where workers are performing heavy workloads. The goal of this study is to evaluate the reliability of a WBGT app prototype in providing accurate WBGT indices compared to WBGT measured by a heat stress monitor.

CHAPTER II. LITERATURE REVIEW

Thermoregulation

Humans are warm-blooded organisms and can generally maintain a stable internal body temperature regardless of external influences. While the normal body temperature ranges from 35 to 37.5 °C (97.9 to 99.5 °F), the body has mechanisms to deal with temperatures ranging from 35 to 40 °C (95.0 to 105.8 °F), after which they are incapable of self-regulation and compensation for external thermal demand (Leiva and Church, 2022). The body's core temperature is dependent on heat exchange with the environment, metabolic heat generation, and mechanical effort (Boulant et al., 1998).

Heat exchange with the environment can occur in a variety of ways: radiative loss, conductive loss, evaporative loss, and convective loss (Boulant et al., 1998). As the outside temperature and humidity rises, radiation and conduction become inefficient, and heat evaporative dissipation becomes the dominant way for the body to cool itself. Thermoreceptors in the skin, organs and spinal cord convey information to the hypothalamic preoptic area through nerve fibers. This reaction causes autonomic and behavioral changes that aid in restoring body temperature to normal (Boulant et al., 1998).

Heat-Related Illnesses and Associated Treatment

Heat-related illness (HRI) is triggered by prolonged exposure to unusually high temperatures and humidity. These HRIs occur on a spectrum, with dysregulation of the body's thermoregulatory ability tipping the scale and differ in terms of both appearance and severity (Kenny et al., 2018).

HRI is a widespread global problem. Year after year, the National Oceanic and Atmospheric Administration (NOAA) has shown it to be the leading cause of weather-related fatalities (NOAA,

2021). High temperature and humidity, alcohol intake, hydration status, age (older and younger), obesity, and concomitant medical conditions (e.g., diabetes mellitus, infections, skin disorders, cerebrovascular accident, sickle cell) are risk factors that can lead to the development of HRI. Aside from the indicated age range, athletes and teenagers are also prone to heat-related illnesses due to their exercise (Kenny et al., 2010). In addition, some younger children are especially vulnerable to HRI due to a combination of variables, including decreased blood volume, immature thermoregulatory systems, an increased surface area to body mass ratio, and a poorer capacity to acclimate to hotter environments (CDC, 2013). The symptoms of HRI differ depending on the type of illness and may include heat edema, heat rash, heat syncope, and heat cramps. A person experiencing HRI with effects on the central nervous system may experience seizures, delirium, and coma (Rodgers et al., 2018; Howe et al., 2007).

Heat exhaustion is a reaction to the removal of water and salt from the body due to sweat. Heavy sweating, excessive weariness or weakness, disorientation and dizziness, wet itchy skin, muscular cramps, pale/flushed skin tone, small increase in body temperature, and rapid and deep breathing are all symptoms of heat exhaustion (NIOSH, 2014). Heat exhaustion, if not addressed promptly, can lead to heat stroke. To manage heat exhaustion, affected individuals are advised to sit or lie down in the shade, drink lots of water, use ice packs to cool as required, seek medical attention if symptoms do not improve within an hour, and stay at home for the remainder of the day to recover (OSHA, n.d.(e)).

Heat stroke can be fatal if not treated immediately. The body's core temperature can rise to 41.1°C in 10 to 15 min. Sweating ceases, removing the body's natural cooling function. Dizziness and disorientation, chills, loss of coordination, pounding headache, hallucination, elevated body temperature, and dry, heated, skin or excessive perspiration are among the symptoms of heat stroke

(NIOSH, 2014). Emergency medical personnel should be summoned promptly, and the individual suffering heat stroke should be relocated to a cool, shady environment. Attempts should be made to cool the individual (e.g., immersing garments in water or spraying them with water) until emergency medical personnel arrive (NIOSH, 2014). Ease or remove outer garments to allow the worker cool down, insert ice packs in underarm, fan and supply water to drink as quickly as possible, and never leave the person alone until medical care comes (OSHA, n.d.(e)).

On extremely hot and humid days, the primary treatment for heat illness is to move the individual involved to a cool environment. Student athletes must take periodic breaks for water or sports drinks and spend as much time indoors as feasible. Benign conditions such as heat edema, syncope, rash, and cramping can be treated with supportive care. Those with more severe illnesses can be transferred to a higher level of care (Diller et al., 2015).

Occupational Exposures to Heat Stress

As a result of exposure to hot work settings, thousands of employees are at risk of getting sick every year. Most individuals who are exposed to such high heat levels suffer chronic medical conditions, while some others develop heat allergies (Wang and Song, 2017). When working circumstances are poor, employees often perform ineffectively. There is a possibility of body temperature increase due to routine metabolic processes and heat from the sun when working in a hot area, as evidenced by research showing that employees respond differently when exposed to varied situations (Venugopal et al., 2016; Wang and Song, 2017). Outdoor workers are frequently the first to be exposed to the consequences of environmental circumstances. They could be exposed to hot environments for longer periods of time and at higher intensities than indoor workers and this may lead to increased severity and prevalence of occupational hazards and exposures. According to recent research, rising ambient temperatures can lead to outdoor workers being

exposed to heat more frequently, intensely, and for longer periods of time. This could potentially lead to more cases of HRI such as tiredness, increased sensitivity to exposure to toxic, heat exhaustion, and heat stroke (Kiefer et al., 2016). The risk of harm or safety failures might rise when workers are exposed to higher temperatures since this can cause a reduction in alertness (Kjellstrom et al., 2009). High temperatures may also increase the amount of air pollution in the atmosphere, particularly the tropospheric ozone (Ainsworth et al., 2012). Outdoor workers are more likely to be exposed to air pollutants, which have been associated with long-term negative impacts on health including respiratory conditions and allergic reactions (Kjellstrom et al., 2009; Nilsson et al., 2010; International Labour Office, 2019; Gubernot et al., 2014).

The majority of the year is spent working outdoors for groundskeepers, which exposes them to heat and ultraviolet (UV) rays from the sun and increases their risk of developing linked health problems (Beck et al., 2018). Working outside at construction sites exposes construction employees to a variety of health risks, including thermal stress, which has a negative influence on their physical, mental, and occupational efficiency (Venugopal et al., 2016). Construction workers exposed to high temperatures are at an increased risk of heat stress, which can result in an accelerated heartbeat and blood pressure, stress and weariness, heatstroke, and persistent heart diseases (Abokhashabah et al., 2020). Other examples of outdoor occupations that are exposed to heat stress are agricultural workers (Luque et al., 2019) and miners (Nunfam et al., 2020).

Control Measure to Prevent Heat Stress

According to OSHA, more than half of heat-related deaths occur on a worker's first day on the job (Arbury, 2014). More than 70% of heat-related fatalities occur during the first week of employment (Tustin, 2018). These tragedies can be minimized if organizations take steps to protect and train new employees (OSHA, n.d. (a)).

Heat risks should be addressed among supervisors and workers through training and education. Workers should also be routinely educated on heat stress prevention and first aid, types of HRIs, and how to detect typical signs and symptoms (OSHA, n.d.(a)). Workers should be aware that wearing some forms of personal protective equipment (e.g., respirators and impermeable garments) might increase the risk of heat-related illness (OSHA, n.d.(a)). Employers should supply cool water for employees to drink. Proper hydration is vital for avoiding HRIs and cool potable water is suitable for brief tasks. Workers should be urged to drink at least one cup (8 ounces) of water every 20 min when working in hot conditions, not simply when thirsty (OSHA, n.d.(a)). Employers should supply electrolyte-containing liquids, such as sports drinks, for lengthier occupations lasting more than two hours, to help prevent electrolyte loss that can result in muscular cramps and other severe health issues (OSHA, n.d.(a)). Water or other fluids given by the employer should not only be cool, but also in a location known to the workers, close to the task, convenient to obtain, and in sufficient amount for the length of the labor (OSHA, n.d.(a)).

When heat stress is excessive, employers should require workers to take breaks. As heat stress increases, so should the length and frequency of rest intervals (OSHA, n.d.(a)). Workers should take lengthy enough breaks to recover from the heat. Workers will be able to resume work more quickly if they relax in a cooler place. If there is no cool place for workers to relax, breaks should be extended (OSHA, n.d.(a)). Workers should be provided with a cool area where they may rest and recuperate from the heat. In outdoor settings, this may be a shady environment, an air-conditioned vehicle, a nearby structure or tent, or an area equipped with fans and misting equipment. Workers should be permitted to relax in a cool or air-conditioned place away from heat sources such as ovens and furnaces when working inside (OSHA, n.d.(a)).

Acclimatization, another important measure to prevent HRI, is defined as the collection of adaptive physiological modifications that occur when a person is gradually exposed to a hot environment (NIOSH, 2018). These physiological improvements include improved sweating performance (earlier sweat start, more sweat production, and less electrolyte loss in sweat), stability of the circulation, and the capacity to function at lower core body temperature and pulse rate (NIOSH, 2018). While people are exposed to hot conditions, especially when performing hard labor in hot environments, their bodies adapt in a variety of ways (Larranaga, 2000a). To acclimate employees, their exposure time in hot ambient circumstances is progressively increased over a 7-14-day period. Compared to workers who have had some exposure, new workers will require more time to acclimate (NIOSH, 2018). Workers who go home for the weekend or take a few days off from work can still maintain their acclimatization. However, if they are away for a week or more, there may be a major decrease in the advantageous adaptations, increasing the risk of HRIs and necessitating a gradual re-acclimatization to the hot environment (NIOSH, 2018).

Occupational Heat Stress Assessment

The impact of heat on those who work in already heated workplaces in hot climatic zones will undoubtedly rise due to global warming (Smith et al., 2014; Błażejczyk et al., 2014; Spector et al., 2014). In some parts of the world, the rising incidence of this environmental health concern will endanger both public and worker health (Kjellstrom et al., 2009; Lundgren et al., 2013; Błażejczyk et al., 2014; Spector et al., 2014).

Four thermal climatic elements are needed to assess occupational heat stress: air temperature, humidity, air velocity, and heat radiation. This may be done using ground station data that is currently accessible. However, there are difficulties in using meteorological data to quantify occupational heat stress in the context of climate change since not all significant climatic elements

(e.g., solar radiation in W/m^2) have historically been directly observed by weather stations (Parsons, 2013). A weather station typically measures the following variables: air temperature, air pressure, humidity, wind velocity, wind direction, and rain. Furthermore, because interior surroundings might differ from outdoor environments, it is not simple to transfer outdoor measures into the assessment of indoor workplace circumstances (De Dear and Brager, 1998; Błażejczyk et al., 2014; Yang et al., 2014). For instance, weather stations are positioned as far from key obstructions and nearby heat sources as feasible (e.g., heat in a workplace), and air velocity is often monitored at a standard height of 10 meters. Additionally, clothes (e.g., protective garments) and internal metabolic heat generation in the body (physical work intensity) have an influence on the exchange and balancing of body heat with the outside environment. As a result, it is vital to strengthen the assessment process for evaluating the scope of the issue and for creating effective individual, workplace and societal responses connected to climatic parameters (Kjellstrom and McMichael, 2013).

Wet-Bulb Globe Temperature as an Environmental Heat Metric

The Wet Bulb Globe Temperature (WBGT) is a measure of heat stress that considers all four key ambient heat components: air temperature, relative humidity, wind speed, and solar radiation, allowing the WBGT to provide significant benefits over other environmental heat assessments (OSHA, n.d.(b)). The WBGT is distinct from the heat index, which considers temperature and relative humidity, and is determined for shaded locations (NOAA, n.d). WBGT is considered the gold standard for determining ambient heat stress during physical activities (Cooper et al., 2017; Larranaga, 2000b). The heat index does not take wind, sunshine, radiant heat sources, or workload into consideration (OSHA, n.d.(b)), which may inaccurately estimate the overall heat stress experienced by workers.

A WBGT monitor contains three different types of thermometers: (1) dry bulb thermometer to determine the temperature of the surrounding air; (2) natural wet bulb thermometer to determine evaporative cooling capacity; and (3) black globe thermometer to determine radiant heat. During heat stress monitoring, the WBGT monitor should be placed near the work area (e.g., placed in direct sunlight if the job is in direct sunlight) (OSHA n.d.(b)).

There are two formulae used to calculate the WBGT index using the three directly measured temperatures, depending on whether the measurement is recorded indoor (i.e., sun heat source is improbable) or outside (i.e., sun heat source is most probable) (OSHA, n.d.(c)). The cumulative sum of the natural wet bulb temperature (T_w), the globe temperature (T_g), and the dry bulb temperature (T_a) is known as the outdoor WBGT ($WBGT_{out}$) (Liljegren et al., 2008), as shown in Eq. 1.

$$WBGT_{out} = 0.7T_w + 0.2T_g + 0.1T_a \quad (\text{Eq. 1})$$

The formula for indoor WBGT ($WBGT_{in}$) is shown in Eq. 2. The WBGT monitor does not utilize the dry bulb temperature in indoor environments since the globe and the dry bulb temperatures should be equal without radiant heat. The globe temperature is utilized because it can detect non-solar radiant heat sources if they exist (OSHA, n.d.(c)).

$$WBGT_{in} = 0.7T_{nw} + 0.3T_g \quad (\text{Eq. 2})$$

WBGT is the most common occupational heat stress index used globally (Parsons, 2014; Havenith et al., 2015). Its inclusion in worldwide [e.g., ISO 7243] and national (e.g., American Conference of Governmental Industrial Hygienists [ACGIH]) standards demonstrates that it has been widely recognized since it was invented by the United States Army in the 1950s (Yaglou and Minord, 1957). The WBGT index has been evaluated in a wide range of climatic situations, and quantifiable correlations have been established between WBGT and the employee cycles required

to prevent heat stress impacts at the worksite. The WBGT index is used in national and international guidelines to identify occupational heat stress concerns, even though there are more precise ways based on unique physiological data to quantify heat strain in a single worker (Lemke et al., 2012).

The WBGT index can be used as a screening tool for the evaluation of heat stress (Parsons, 2013; Epstein et al., 2006). It is applicable to evaluating the average impact of heat on people during an 8-hour workday and during hourly work periods in calculating work rest cycles. However, the WBGT reference values do not apply to evaluating heat stress experienced during extremely brief intervals (Parsons, 2013). In hot climates, both with and without sun radiation, WBGT may be assessed. Specific types of measuring instruments should be used in accordance with the standards (ISO 7243) (Parsons, 2013; Havenith et al., 2015). WBGT was intended and initially utilized in the 1950s as part of a successful operation to suppress significant epidemics of HRI in the United States Army and Marine Corps training camps. Control procedures based on air temperature and humidity, applied to all trainees equally, had proven beneficial, but had come at a high cost in terms of compliance in the form of wasted training time. New control methods implemented in 1956 lowered heat sickness even more and resulted in fewer lost training hours. Important developments to protect the most susceptible trainees were: (1) using WBGT instead of temperature and humidity, which also responds to sun and wind, (2) using epidemiological analysis of fatality data to detect high levels of WBGT and susceptible trainees, and (3) by halting training at lower WBGT levels and enhancing the trainees' heat tolerance in specialized conditioning platoons. This initiative is extremely important for preventing heat sickness in athletes (Budd, 2008).

Nonetheless, the WBGT index has several limitations. For example, measuring its variables, notably the black globe temperature, takes a lengthy time. Local meteorological data can be utilized in environmental assessments or occupational exposure monitoring in outdoor workplaces instead of direct measurement of heat stress, which is generally time-consuming and costly (Hajizadeh et al., 2014). There is a significant issue with using meteorological data to calculate the WBGT index, which is the absence of observations of the black globe temperature by weather stations in most nations (Turco et al., 2009).

Estimation of WBGT Index Using Weather Data

After a heat-related health occurrence, measuring WBGT on-site with a meter can give a precise localized assessment of the heat hazard at the time. In contrast to historic weather data from a remote point, WBGT monitoring will capture radiant heat and wind reduction effects from jobsite buildings or heat sources (OSHA, n.d.(c)).

Weather service data or weather forecasting are the most readily available data sources for assessing time patterns of occupational heat exposure at the populations (Lemke et al., 2012). Numerous mathematical procedures to determine WBGT from ground station data have been published and are important for assessing the effects of climate change, particularly where there are no conventional measuring tools and no direct data measurements (Błażejczyk et al., 2012; Lemke et al., 2012).

Common weather forecasts log hourly temperature, wind velocity, and relative humidity (or more often, if necessary). Additionally, measurements of rain, wind velocity, sunlight, and atmospheric pressure are frequently taken. Most major cities' airports have historical data that dates back several decades or more (Lemke et al., 2012). Predictive models of WBGT help determine local work practices in advance using projected (or historical) climatic variables, as mentioned in

the NIOSH criteria (NIOSH, 2016) and for analyzing the local environment for heat stress. When the required meteorological input data are available, it may be beneficial to compute WBGT for many sites to attain the highest level of accuracy. It also implies that computing WBGT can be as beneficial as using a device that necessitates meticulous, time-consuming attention to measure WBGT (Liljegren et al., 2008).

OSHA Outdoor WBGT Calculator

Using standard meteorological data, the OSHA Outdoor WBGT Calculator calculates the outdoor WBGT index (OSHA, n.d.(g)). It determines the solar irradiation from a clear sky using the Kasten-Czeplak algorithm (Sandia, 2012) and then calculates WBGT using the heat and mass transfer algorithm by Liljegren et al. (2008).

To calculate the WBGT index, the following parameters should be provided: 1) date; 2) local time and time zone; 3) latitude (0 to 90°); 4) longitude (0 to 180°); 5) air (dry bulb) temperature (°F); 6) relative humidity (%); 7) wind speed (mph); 8) barometric pressure (inches of mercury [Hg]). The calculator also asks if the wet bulb temperature (°F) and solar irradiance (W/m^2) are known or unknown. The calculator output provides either of these estimated WBGT indices: 1) WBGT in direct sunlight or in shade when solar irradiance is unknown, and 2) WBGT when solar irradiance is known and provided (OSHA, n.d.(g)).

If a WBGT meter or records are not accessible, the Argonne National Laboratory (ANL) created a separate downloadable application (i.e., calculator) that employs literature-supported algorithmic equations to calculate WBGT from previous or current weather information accessible via the internet. The calculator employs an outdoor wet bulb globe temperature model described by Liljegren et al (2008). Similar to the OSHA Outdoor WBGT Calculator described above, the following data is used by the ANL WBGT Calculator to calculate WBGT: 1) air temperature, °F

or °C, 2) solar irradiance, W/m², 3) wind speed, mph or m/s, 4) relative humidity, %, 5) date and time, 6) barometric pressure, inches of Hg or millibars, 7) longitude and latitude (OSHA, 2017). The accuracy of the WBGT computations depends on the information supplied into the ANL WBGT Calculator. When the data source (e.g., a weather station) measures direct sun, humidity, and wind speed at a similar intensity to the workplace, the estimated WBGT is more accurate. Otherwise, the WBGT calculation estimations will not be correct if the time, date, longitude, latitude, or barometric pressure values are not exact. For instance, the ANL WBGT Calculator adjusts irradiance before computing the WBGT using the date and time, longitude, latitude, and barometric pressure (OSHA, n.d.(g))

Mobile Application (App) for Heat Stress

The OSHA-NIOSH Heat Safety Tool mobile app is a great resource for scheduling outdoor work activities, depending on how hot it feels during the day. It provides a real-time heat index as well as hourly forecasts for a specific location. It also includes OSHA and NIOSH guidelines for workplace safety and health-related to heat stress (OSHA n.d.(f)).

The OSHA-NIOSH Heat Safety Tool app has the following features: (1) a visual representation of the current heat index and related danger levels for current or selected geographic area; (2) specific precautionary suggestions for heat index-related risk levels; (3) an hourly prediction of heat index readings, danger levels, and advice for outdoor work activities that is interactive; (4) user control for location, temperature, and humidity that you may change to compute for different situations; and (5) HRI signs and symptoms, as well as first aid (NIOSH, 2022).

There are important considerations while using the OSHA-NIOSH app. First, heat index numbers were developed for shaded, light wind circumstances. However, exposure to direct

sunlight can raise heat index readings by up to -9.44°C . Secondly, the simplicity of the heat index makes it an excellent choice for many outdoor work settings if no additional radiant heat sources are present (e.g., fires or hot machinery). However, NIOSH advises adopting WBGT-based Recommended Exposure Limits (RELs) and Recommended Alert Limits (RALs) in hot areas. Thirdly, although using the heat index or WBGT is vital, other variables such as severe physical activity can also create heat stress in employees. Employers should have a strong heat stress prevention program in place to safeguard their personnel. Lastly, NIOSH and OSHA are reviewing new scientific data on heat index levels and determining how to appropriately use the growing information. It is critical to download updates on a frequent basis to guarantee that users are running the most recent app (NIOSH, 2022).

Dillane and Balanay (2020) investigated the reliability of the previous version (3.1) of the OSHA-NIOSH app by comparing with the heat stress risk levels derived from WBGT measured by local heat stress monitors. Study findings indicated that the app was inaccurate in assessing high and extreme risks at any workload type and lead to the conclusion that the use of the app for occupational heat stress assessment in agricultural settings is not recommended (Dillane and Balanay, 2020). Thus, a well-designed mobile app that delivers WBGT risk information may satisfy the need for more easily available and trustworthy information on heat stress risk and HRI preventative methods that may be utilized by agricultural workers and other similar outdoor workers (Dillane and Balanay, 2020).

According to preliminary research, farm supervisors may be open to using a mobile app that provides local weather information and safety tips for avoiding heat exhaustion (Santos et al., 2022). Additionally, a mobile application that informs users of projected heat stress depending on the surroundings, activity level, attire, and acclimatization has been developed and validated.

Interventions emphasizing water intake, shade, and relaxation have been successful in reducing the negative health consequences of heat among sugarcane workers in Central America (Santos et al., 2022). It is critical to utilize the heat safety tool app to monitor weather conditions to ensure that employees take suggested breaks to recuperate from minor heat stress symptoms (Luque et al., 2020).

CHAPTER III. PURPOSE OF STUDY

The main purpose of this proposed study was to investigate the reliability of a WBGT app prototype in providing accurate heat stress risk information for university-based groundskeeping workers in eastern North Carolina. The reliability of the app was assessed by comparing the WBGT data obtained by the app with the WBGT data measured by the heat stress monitor as the gold standard method.

The specific aims of this proposed study were to:

1. Assess the heat stress exposure of ECU groundskeepers using WBGT indices as compared to the ACGIH Threshold Limit Values (TLVs) and action limits.
2. Determine the correlation between WBGT index measured by a heat stress monitor and WBGT index calculated by the WBGT app prototype.
3. Compare the WBGT index calculated by the WBGT app prototype to the WBGT index measured by the heat stress monitor.
4. Compare the heat stress risk level obtained from the WBGT app prototype to the heat stress risk level derived from heat stress monitor measurements.

CHAPTER IV. HYPOTHESIS AND RESEARCH QUESTIONS

On the basis of the research goals and review of the literature, the following hypotheses and research questions were developed to guide the research investigation.

Null Hypothesis: There is no significant difference between the WBGT index measured by heat stress monitor and WBGT calculated by WBGT app prototype.

Alternative Hypothesis: There is significant difference between the WBGT measured by heat stress monitor and WBGT calculated by WBGT app prototype.

Research Questions:

1. Is the heat stress exposure of groundskeepers acceptable based on WBGT indices in relation to the ACGIH Threshold Limit Values (TLVs) and action limits?
2. Is there a correlation between the WBGT measured by a heat stress monitor and WBGT calculated by the WBGT app prototype?
3. How reliable is the WBGT app prototype in giving accurate up-to-date WBGT index for groundskeepers compared to the heat stress monitor as the gold standard method for environmental heat assessment?

CHAPTER V. SIGNIFICANCE OF THE STUDY

There are no published studies evaluating groundskeepers' exposure to occupational risks using the WBGT app prototype and then comparing obtained WBGT measurements with the traditional WBGT monitor. The accuracy of portable WBGT monitors has been evaluated in previous research. One of these studies was utilized to evaluate the accuracy of several available commercial WBGT monitors to a reference device that was standardized (Copper et al., 2017). Dr. Jo Anne Balanay and Dr. Sinan Sousan, with the support of the ECU Office of Licensing and Commercialization, developed a WBGT web app prototype as a product of their NSF-funded Innovation Corps (I-Corps™) App Development Training in Fall 2020. This app provides the calculated WBGT index (i.e., preferred environmental heat metric), which makes it different from the OSHA-NIOSH Heat Safety Tool app that provides heat index as an alternative but less preferred environmental heat metric for occupational exposure assessment. The aim of this first-of-its-kind study is to determine whether or not this WBGT app prototype can be relied upon to provide groundskeepers with reliable information on the risk of heat stress.

Finding a reliable tool that is WBGT-based is crucial since the OSHA-NIOSH Safety Tool app, which is heat index-based, was found to be inaccurate in severe heat stress risk conditions. Here, the WBGT App prototype is tested to determine its dependability in providing correct information about heat stress risks for groundskeepers. This app may benefit small-scale industries and businesses with limited financial resources since it would be cheaper than heat stress monitors. It could also benefit industries that do not have dedicated industrial hygienists because the app will be simpler and does not require complicated training for use and data interpretation. This study investigates how workers may be monitored for heat exposure and how to prevent heat-related illnesses, including heat stroke and heat exhaustion. Moreover, results of this study could benefit

to supervisors because they can potentially use the tool (i.e., app) evaluated here to alert workers about taking preventive measures to reduce heat stress risk. Findings can be used to further improve the app by integrating necessary adjustments and calibrations.

CHAPTER VI. METHODOLOGY

Monitoring Site

Area monitoring was used to determine groundskeepers' exposure to heat stress. The monitoring site was located in front of the Carol Belk Building on the campus of East Carolina University in Greenville, NC. The 210-acre lot where the Carol Belk Building is located consists of concrete parking lots, grassy areas, and a variety of trees, shrubs, and other plants.

Heat Stress Monitoring

A heat stress monitor (QUESTemp34, 3M, Oconomowoc, WI) was placed on a tripod at above the ground at the monitoring site to collect data. The heat stress monitor had been calibrated by the manufacturer within one year prior to data collection. For 8-10 hours between 8:00 AM and 6:00 PM on each monitoring day, the dry bulb, wet bulb, globe temperatures (°C), outside WBGT index (°C), and relative humidity (%) were recorded minute-by-minute. To ensure that the summer season was covered, monitoring was conducted from March to August 2023. See Appendix A for the Heat Stress Monitoring Protocol.

Comparison of WBGT with ACGIH TLVs and Action Limits

The ACGIH Threshold Limit Values (TLVs) and action limits for heat stress exposure were compared with the hourly mean WBGT indices (ACGIH, 2022). Screening parameters for ACGIH TLV and action limit for heat stress exposure consider the workload as well as the work-rest regimen (ACGIH, 2022). Groundkeepers performed tasks throughout all types of workloads (i.e., light, moderate, heavy). Light work performed by the groundskeepers included the operation of riding mowers and sweepers. Moderate work included placing recycling and trash cans for events, planting shrubs and flowers, weeding, edging, and routine trash collection. Finally, heavy work

included mowing the lawn with a push mower and raking leaves with a hand rake, laying mulch, cutting trees and bushes, erecting bleachers, and operating backpack blowers and sprayers (Beck et al., 2018). The TLVs and action limits were compared with the hourly mean WBGT indices to determine whether these exposure limits were ever exceeded. Workload and task assumptions were created without surveying the workforce. Under the assumption that employees were assigned tasks within the 50-75% category based on a 2-hour work/recovery cycle, the TLVs and action limits utilized for comparison were 31.0°C and 28.5°C for light workload, 29.0°C and 26.0°C for moderate workload, and 27.5°C and 24.0°C for heavy workload (ACGIH 2022).

Assignment of TLV-based Risk Levels to WBGT Indices

To assign risk levels to the hourly mean WBGT indices acquired from heat stress monitoring, Dillane and Balanay (2020) created Table 1, which defined the ranges of WBGT indices for each risk level based on workload and its accompanying metabolic rate. The risk classifications were categorized into 5 levels: minimal, low, moderate, high, and extreme. Figure 1, also developed by Dillane and Balanay (2020), illustrates the five risk level zones according to the WBGT index and metabolic rate, from which the parameters presented in Table 1 were determined. Figure 1 was adapted from the ACGIH TLV and action limit for heat stress (ACGIH, 2022) and research by Morris et al. (2019). Employees who are acclimated to the heat (Morris et al., 2019; NIOSH, 2016; OSHA, 2017) fall below the ACGIH TLV for heat stress (ACGIH, 2022), which acts as the bottom boundary of the "high risk" zone. The bottom boundary of the "low risk" region is defined by the dashed lines, which is an illustration of the action limit (ACGIH, 2022) intended for employees who are not yet acclimatized (Morris et al., 2019; NIOSH, 2016; OSHA, 2017). According to the "50-75%" work allocation provided as the bottom

bounds of "extreme risk" and "moderate risk" zones, the dashed-dotted and dotted lines reflect the TLVs and action limits, respectively, for light, moderate, and heavy workloads (Figure 1).

Table 1. WBGT index range (°C) used to assign heat stress risk level by workload.

Risk Level	Workload			
	Light	Moderate	Heavy	Very Heavy
Minimal	<28.1	<25.0	<23.0	<21.6
Low	28.1 – 28.6	25.0 – 25.7	23.0 – 24.1	21.6 – 23.0
Moderate	28.7 – 30.7	25.8 – 28.1	24.2 – 26.5	23.1 – 25.4
High	30.8 – 31.0	28.2 – 28.8	26.6 – 27.5	25.5 – 26.6
Extreme	≥31.1	≥28.9	≥27.6	≥26.7

Reference: Dillane and Balanay, 2020

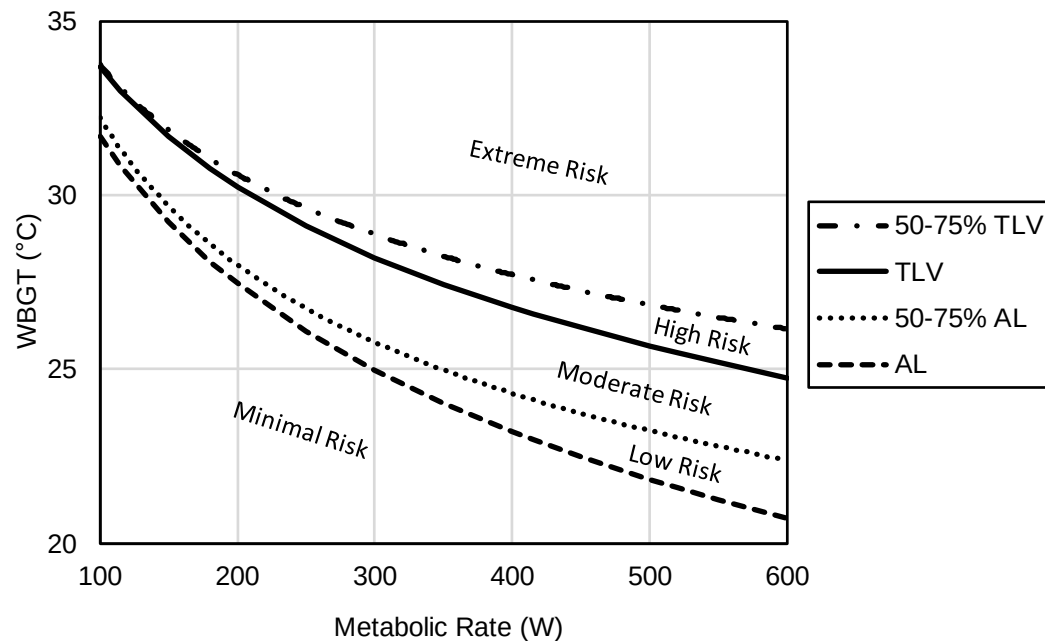


Figure 1. Risk level zones for heat stress adapted from ACGIH TLV and action limit (AL).

Reference: Dillane and Balanay, 2020

Use of WBGT App Prototype

A WBGT web app prototype (i.e., WBGT app) had been previously developed by Dr. Jo Anne Balanay and Dr. Sinan Sousan, with the support of the ECU Office of Licensing and Commercialization, as a product of their NSF-funded Innovation Corps (I-Corps™) App Development Training in Fall 2020. The app automatically calculates the estimated current and forecasted WBGT indices using weather data collected from regional weather stations, which correspond to the zip code provided by the app user. The weather data collected by the app from regional weather stations includes: 1) air temperature (°F), 2) relative humidity (%), 3) wind speed (mph), and 4) barometric pressure (inHg). Solar irradiance (W/m^2) is calculated by the app using the date, time and location with the assumption of direct sunlight (i.e., no clouds; clear sky). The app uses a free weather application programming interface (API) from OpenWeatherMap (<https://openweathermap.org/api>) to access current weather data and hourly forecasts for the next 12 h. Weather data, latitude, longitude, date and time of day are used by the app to estimate the WBGT index using a heat and mass transfer algorithm developed by Liljegren et al. (2008), which is also currently used by the OSHA Outdoor WBGT calculator (<https://www.osha.gov/heat-exposure/wbgt-calculator>) via an open source-licensed software produced by UChicago Argonne, LLC under Contract No. DE-AC02-06CH11357 with the Department of Energy (downloadable at http://www.osha.gov/dts/osta/otm/otm_iii/wbgtutil.zip). The WBGT app is accessed for data collection at <https://www2.ecu.edu/digitalmarket/digitalmarket/Pay/WBGT/index.html> using a smart phone with internet connection. Since the WBGT app was web-based, it could also be accessed using any tablet or computer device with internet connection, if necessary.

Similar to the WBGT measured by the heat stress monitor, the app calculated WBGT indices were also automatically assigned a corresponding heat stress risk level (minimal, low,

moderate, high, extreme) depending on the selected workload level (light, moderate, heavy, very heavy) using Table 1 (Dillane and Balanay, 2020). Figure 2b shows the app input page wherein the zip code was typed in and the workload level was selected from a dropdown menu. Once the ‘Submit’ button is clicked, the output page provides the current and hourly forecasted WBGT indices and their corresponding heat stress risk levels (Figure 2c).

The WBGT app was used in this study to collect data on the current hourly ambient temperature (°C), WBGT index (°C) and corresponding risk level based on three workload types (light, moderate and heavy). App data was recorded at the start of every hour from 8:00 AM to 5:00 PM at each monitoring day. The zip code for Greenville, NC (27858) was used in the app to collect data that were location-specific to the monitoring site. See Appendix B for the WBGT app protocol.

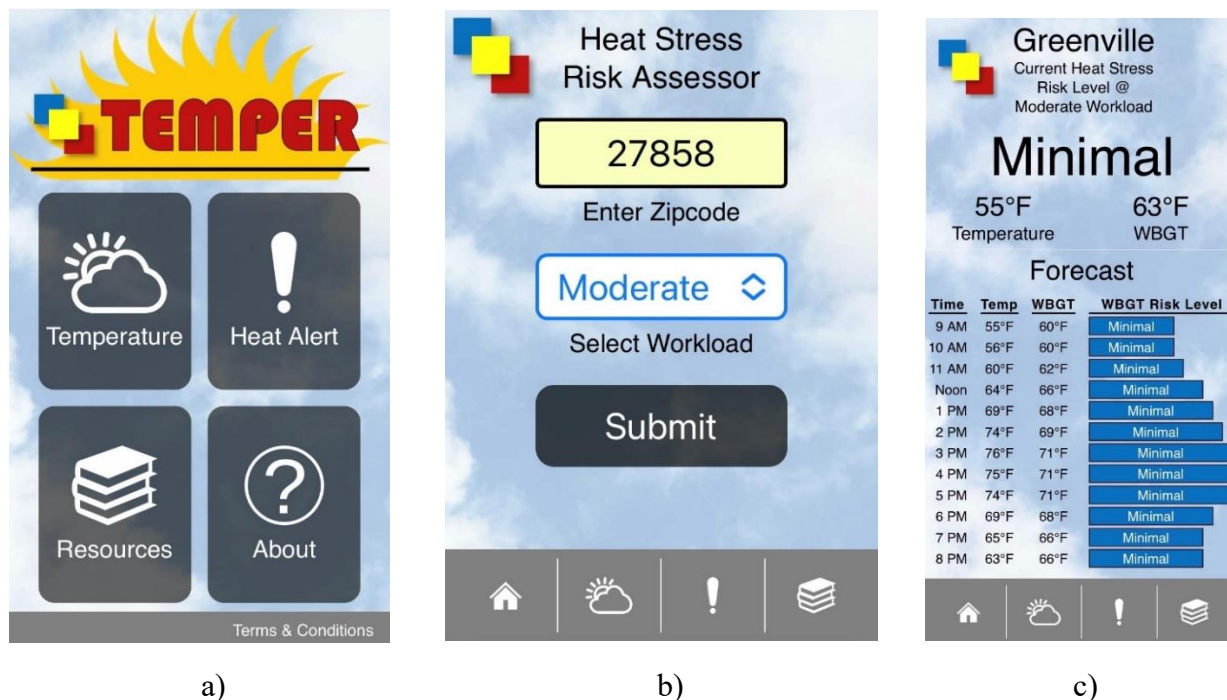


Figure 2. Screenshots of the WBGT web app prototype: a) launch screen, b) zip code and workload input page; c) current and forecasted WBGT output page

Comparison between Heat Stress Monitoring and App Data

The estimated current WBGT index calculated by the app was compared to the WBGT index locally measured by a reference (i.e., gold standard) heat stress monitor that was set up at the monitoring site. Data from the WBGT app and heat stress monitoring were evaluated using two different comparison methods: (1) instrument-measured hourly mean, daily mean, and daily maximum WBGT ($WBGT_{ins}$) vs. app-calculated hourly mean, daily mean and daily maximum WBGT ($WBGT_{app}$); and (2) hourly WBGT risk level derived from $WBGT_{ins}$ vs. hourly WBGT risk level derived from the $WBGT_{app}$. Only data pairs ($WBGT_{ins}/WBGT_{app}$) that were time-matched (i.e., same day, same hour, same location) were used for comparison. The time-matched hours used were between “8:00 AM” and “5:00 PM”, and the number of hours per day ranged from 8–10h. The $WBGT_{ins}$ and $WBGT_{app}$ were compared by day and time and assessed for correlation. The reliability of the WBGT app in assessing workplace heat stress risk was determined by the percentage of hourly $WBGT_{ins}$ risk levels, under different workloads, that had the same hourly $WBGT_{app}$ risk levels. This aimed to compare the similarity between the assigned risk levels from the $WBGT_{ins}$ and the $WBGT_{app}$, with a higher percentage of agreement on risk assignments indicating higher app reliability.

Data Analysis

The daily mean, minimum, maximum and standard deviation of both $WBGT_{ins}$ and $WBGT_{app}$ indices were determined. Time series plots were created to demonstrate hourly and daily trends of WBGT indices, and scatterplots were created to visualize the paired WBGT index values. The $WBGT_{app}$ index was assessed for accuracy by comparing with the $WBGT_{ins}$ index locally measured by the reference heat stress monitor. Independent sample t-test was conducted to compare the hourly mean WBGT indices estimated by the app and measured by the heat stress

monitor. Pearson correlation test was conducted to assess the strength and direction of association between the WBGT_{ins} and WBGT_{app} indices. Cross tabulation was used to analyze the relationship between risk level categories based on both WBGT_{ins} and WBGT_{app} indices. Statistical Package for Social Sciences (SPSS Statistics, version 29.0.1.0, IBM, Armonk, NY) was used to analyze the data. A *P* value of <0.05 was considered as statistically significant.

CHAPTER VII. RESULTS

WBGT Indices Measured by WBGT Monitor (WBGT_{ins})

Figure 3 shows the hourly mean WBGT indices measured by the monitor. The hourly mean WBGT_{ins} index for the entire monitoring period ranged from 8.4-33.0 °C, with an overall average of the hourly mean WBGT_{ins} index (24.6 ± 4.9 °C, n= 790) The highest hourly mean WBGT_{ins} index (33.0 °C) at the Belk building monitoring site was measured at 12:00 PM, while the lowest hourly mean WBGT_{ins} index (8.4°C) at Belk building was measured 8:00 AM.

Figure 4 compares the daily mean and maximum WBGT indices measured by monitoring day during the entire period and demonstrates an increasing trend in WBGT indices from June to August. The highest daily maximum WBGT_{ins} index at 34.2 °C was recorded on July 7, 2023, while the lowest daily maximum WBGT_{ins} index at 16.6 °C was recorded on March 22, 2023. The highest daily mean WBGT_{ins} index at 31.7 °C was recorded on August 8, 2023 while the lowest daily mean WBGT_{ins} index at 13.2 °C was recorded on March 22, 2023.

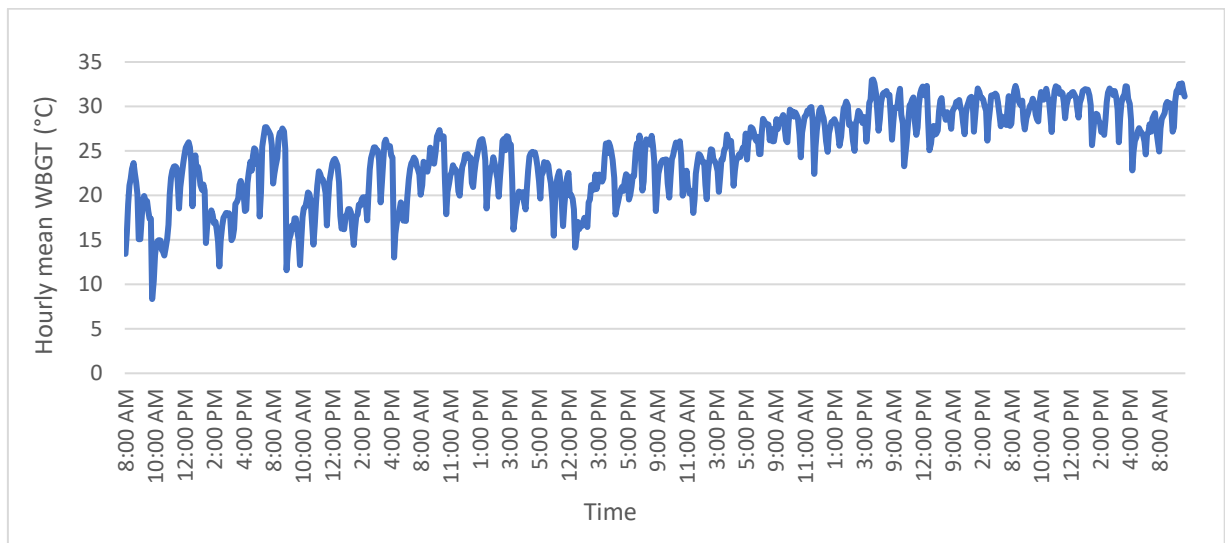


Figure 3. Hourly mean WBGT Indices measured by WBGT Monitor (WBGT_{ins}), March 1 – August 26, 2023

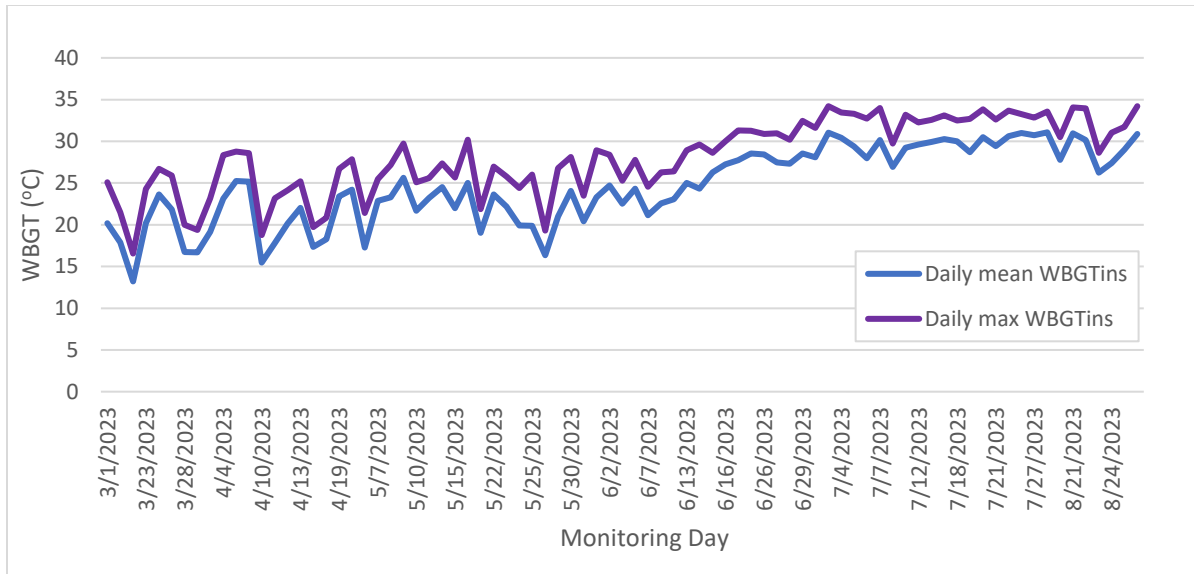


Figure 4. Daily mean and daily maximum WBGT indices measured by WBGT Monitor (WBGT_{ins})

WBGT Indices Measured by WBGT App Prototype (WBGT_{app})

Figure 5 shows the hourly mean WBGT indices measured during the entire monitoring period. The hourly mean WBGT indices for the entire monitoring period ranged from 6.1-37.8 °C, with an overall average of the hourly mean WBGT_{app} index (25.7 ± 5.8 °C, $n= 790$). The highest hourly mean WBGT app index (37.8 °C) was measured at 1:00 PM, while the lowest hourly mean WBGT index (6.1 °C) was at 8:00 AM.

Figure 6 compares the daily mean and maximum WBGT indices measured by monitoring day during the entire period and demonstrates an increasing trend in WBGT indices from June to August. The highest daily maximum WBGT at 37.8 °C was recorded on July 3, 2023, while the lowest daily maximum WBGT at 16.1 °C was recorded on April 10, 2023. The highest daily mean WBGT at 34.3 °C was recorded on August 8, 2023 while the lowest daily mean WBGT at 13.1 °C was recorded on April 10, 2023. Comparing the same month for both monitor and app, the

difference between the overall daily mean WBGT_{app} index (25.7 ± 5.3 °C, n= 81) and the daily mean WBGT ins index (24.6 ± 4.6 °C, n=81) was not statistically significant ($t(160) = 1.44$, $P=0.15$). Similarly, the difference between the overall average of the daily maximum WBGT_{app} index (28.4 ± 5.2 °C, n=81) and the daily maximum WBGT_{ins} index (28.1 ± 4.4 °C), n=81) was not statistically significant ($t(160) = 0.39$, $P=0.69$).

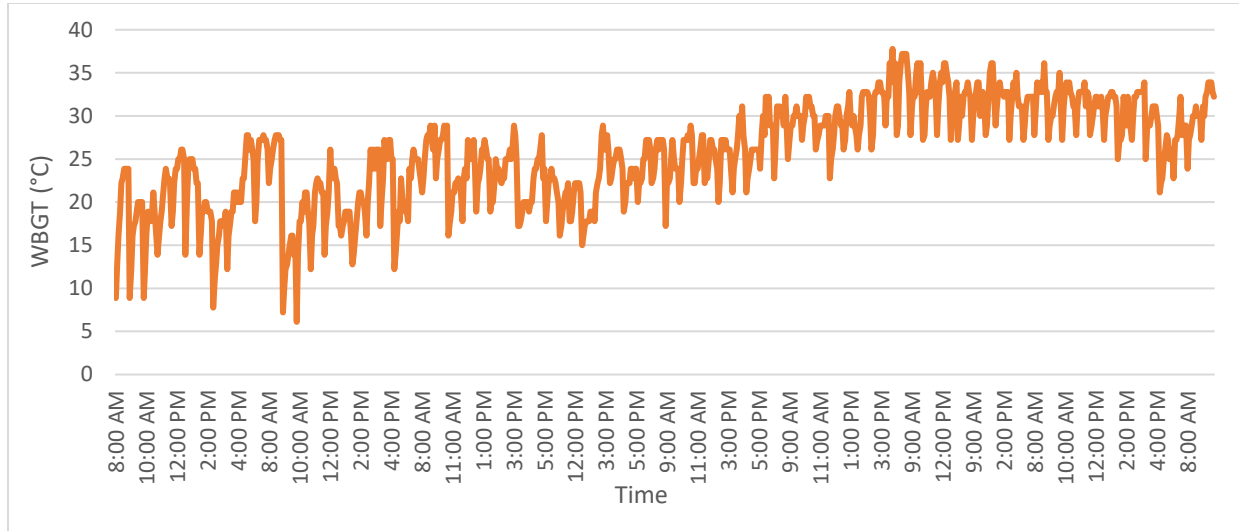


Figure 5. Hourly mean WBGT Indices measured by WBGT app prototype (WBGT_{app}), March 1 – August 26, 2023

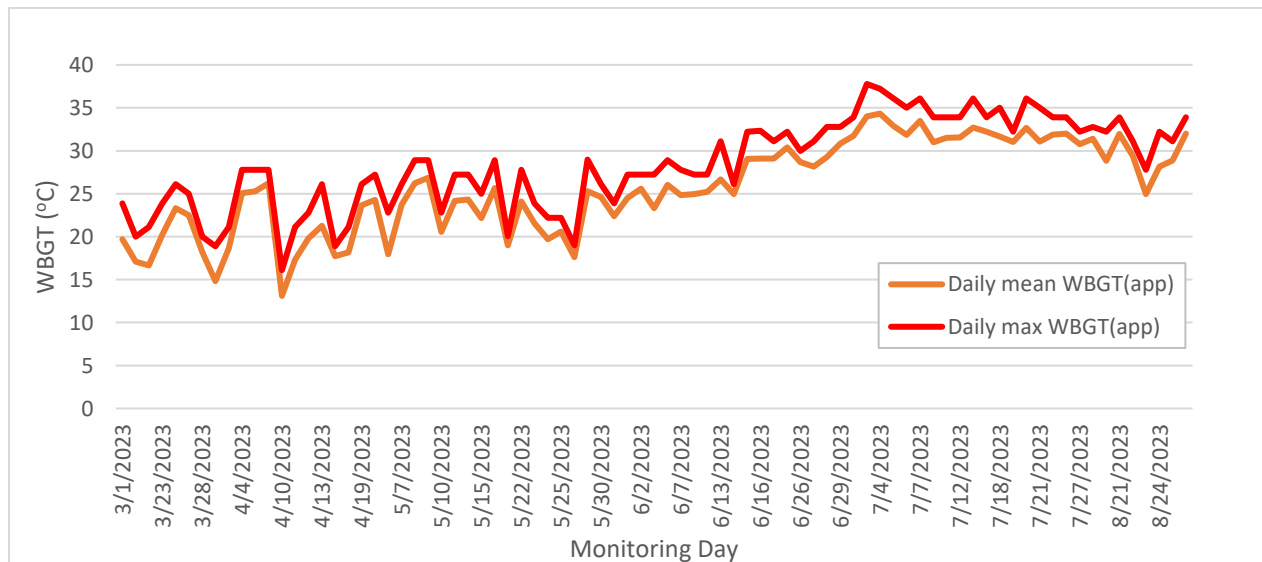


Figure 6. Daily mean and daily maximum measured by WBGT app prototype (WBGT_{app})

Comparison of WBGT Index with ACGIH TLVs and Action Limit

Table 2 illustrates the number and percentage of mean hourly WBGT indices that exceed the TLVs and action limits, broken down by month and method for three separate workload categories. The data reveals the number and percentage of these indices likely to exceed the monthly benchmarks under three distinct workload levels.

Overall, for WBGT indices measured by the heat stress monitor (WBGT_{ins}), 9.1% for light, 21.7% for moderate, and 32.5% for heavy workload exceeded the TLVs, while 25.5% for light workloads, 43.0% for moderate workloads, and 56.6% for heavy workloads surpassed the action limit (Table 2). In a monthly breakdown, July recorded the most TLV exceedances at 31.1% for light workload, 68.9% for moderate workload, and 87.6% for heavy workload. From March through May, all WBGT indices remained within the TLVs for all workloads, except in April, where 2.5% surpassed the TLV for heavy workloads (Table 2). Between March and August, action limit exceedances varied, with 0.0% for light workloads in March and May, increasing significantly in the following months, particularly for moderate and heavy workloads, where it reached as high as 97.2% and 99.4%, respectively, in July.

Overall, for WBGT indices measured by the app prototype (WBGT_{app}), 23.5% for light workload, 29.0% for moderate workload, and 39.4% for heavy workload exceeded the TLVs. However, the action limits were exceeded across all workload levels, increasing with workload severity from 34.4 – 60.3%. In a monthly analysis, July was marked by the most TLV exceedances, registering 76.3% for light work, 81.9% for moderate workload, and 93.2% for heavy workload. Between March and May, all indices for light and moderate workload were within the TLVs. However, the exceedance percentage for heavy workload ranged from 0.0 to 93.2% from March to August. As for the exceedances of the action limit, July was observed to have the highest,

ranging from 88.1 to 100% for light to heavy workloads. March to August had action limit exceedance percentages from 0.0% to 88.1% for light work, 2.5% to 99.4% for moderate work, and 10.0 to 100.0% for heavy workload. The lowest AL exceedance percentage is observed in March with 0.0% for light workload, 2.5% for moderate workload, and 10.0% for heavy workload (Table 2).

Table 2. Number and percentage of hourly mean WBGT index exceeding the ACGIH Threshold Limit Values (TLV) and Action Limits (AL) for heat stress exposure based on workload assumptions by method and month.

Month	No. of hours	Light Workload				Moderate Workload				Heavy Workload			
		>TLV		>AL		>TLV		>AL		>TLV		>AL	
		n	%	n	%	n	%	n	%	n	%	n	%
WBGT Measured by Heat Stress Monitor (WBGT _{ins})													
March	80	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	6	7.5
April	120	0	0.0	0	0.0	0	0.0	12	10.0	3	2.5	33	27.5
May	176	0	0.0	0	0.0	0	0.0	13	7.4	0	0.0	42	23.9
June	178	0	0.0	33	18.5	19	10.7	89	50.0	57	32.0	132	74.2
July	177	55	31.1	133	74.1	122	68.9	172	97.2	155	87.6	176	99.4
August	60	17	28.3	54	69.2	31	51.7	54	90.0	42	70.0	59	98.3
Total	791	72	9.1	202	25.5	172	21.7	340	43.0	257	32.5	448	56.6
WBGT Measured by App Prototype (WBGT _{app})													
March	80	0	0.0	0	0.0	0	0.0	2	2.5	0	0.0	8	10.0
April	120	0	0.0	0	0.0	0	0.0	29	24.2	6	5.0	36	30.0
May	176	0	0.0	6	3.4	0	0.0	37	21.0	13	7.4	58	33.0
June	178	30	16.9	71	39.9	53	29.8	131	73.6	85	47.8	143	80.3
July	177	135	76.3	156	88.1	145	81.9	176	99.4	165	93.2	177	100.0
August	60	21	35.0	39	65.0	29	50.0	52	86.7	43	71.7	55	91.7
Total	791	186	23.5	272	34.4	229	29.0	427	54.0	312	39.4	477	60.3

Correlation and comparison between WBGT_{ins} and WBGT_{app}

Overall comparison of WBGT_{ins} vs. WBGT_{app}

Figure 7 compares the hourly mean WBGT_{ins} and WBGT_{app} indices. Figure 7A compares the two indices for the entire monitoring period from March to August 2023, demonstrating an increased trend. Figure 7B takes a closer look at the WBGT_{ins} and WBGT_{app} during the month of July only to have a clearer comparison of both indices. In both Figures 7A and 7B, each monitoring day showed similar patterns for the hourly indices, wherein the WBGT values were lowest at the start of the day, highest at the middle of the day, and slightly decreased at the end of the day. Comparing the two index values, the WBGT_{app} tended to be higher than the WBGT_{ins}.

The overall average of the hourly mean WBGT_{app} index (25.7 ± 5.8 °C, n=790) was significantly higher ($t(1578)=4.04$, $P<0.01$) than the overall average of the hourly mean WBGT_{ins} index (24.6 ± 4.9 °C, n=790). However, the difference between the overall average of the daily mean WBGT_{app} index (25.7 ± 5.3 °C, n=81) and of the daily mean WBGT_{ins} index (24.6 ± 4.6 °C, n=81) was not statistically significant ($t(160)=1.44$, $P=0.15$). Similarly, the difference between the overall average of the daily maximum WBGT_{app} index (28.40 ± 5.21 °C, n=81) and of the daily maximum WBGT_{ins} index (28.1 ± 4.4 °C, n=81) was not statistically significant ($t(160)=0.39$, $P=0.69$).

There is a strong, positive correlation ($r \geq 0.7$) between the hourly mean WBGT_{app} and WBGT_{ins} indices ($r=0.94$, $P<0.01$) (Figure 8), between the daily mean WBGT_{app} and WBGT_{ins} indices ($r=0.97$, $P<0.01$) (Figure 9) and between the daily maximum WBGT_{app} and WBGT_{ins} indices ($r=0.94$, $P<0.01$) (Figure 10).

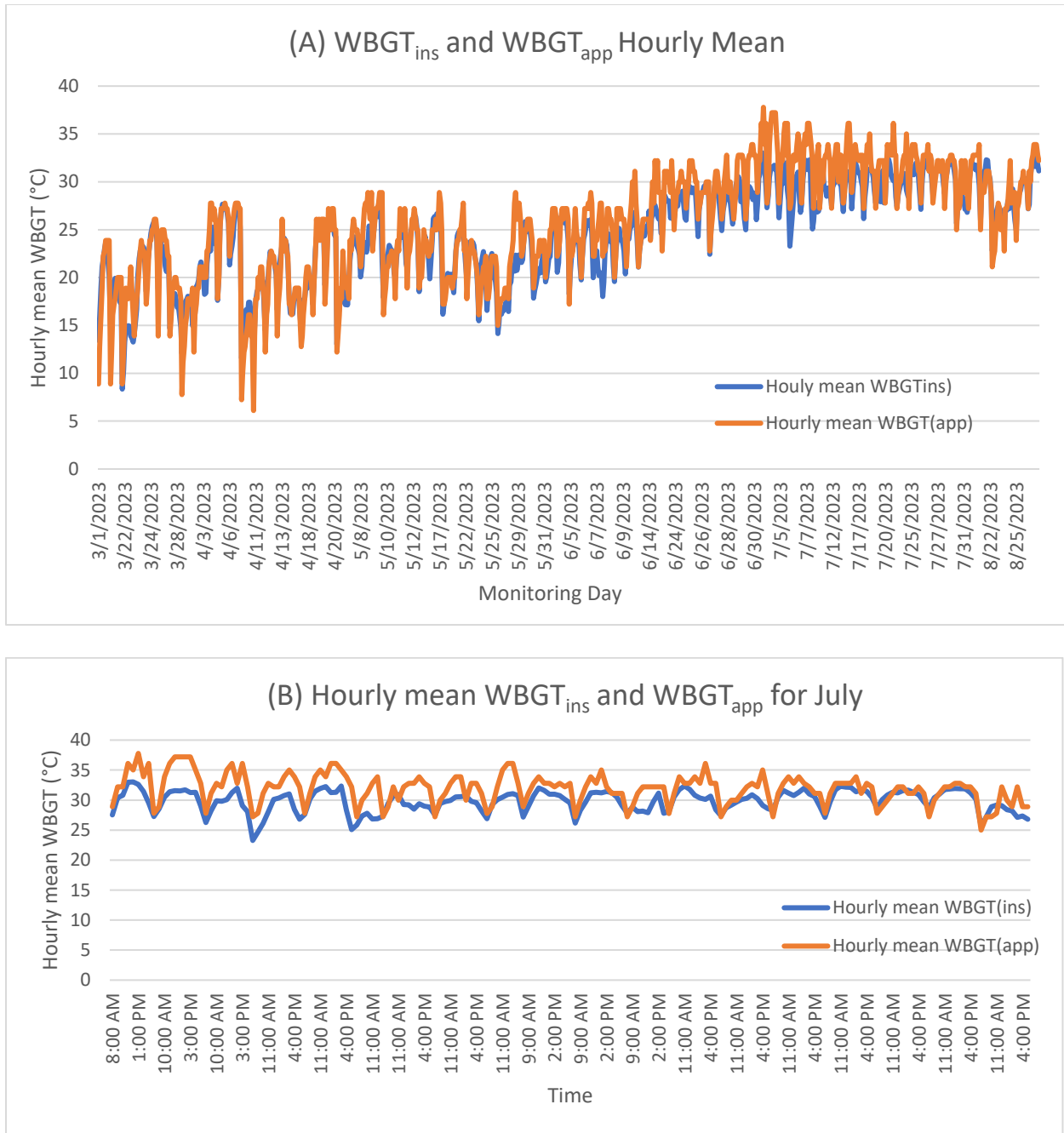


Figure 7. Hourly mean WBGT_{ins} and WBGT_{app} indices: (A) the entire study period (March-August 2023), and (B) the month of July.

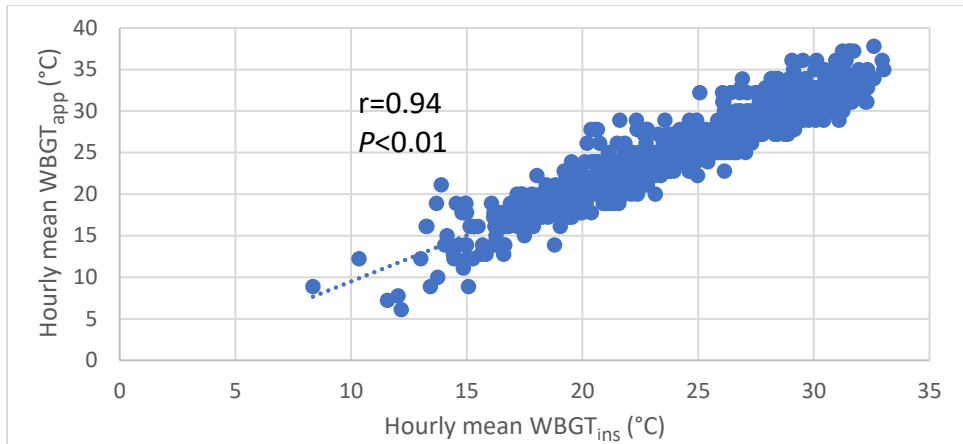


Figure 8. Correlation between hourly mean WBGT_{ins} (°C) and WBGT_{app} (°C).

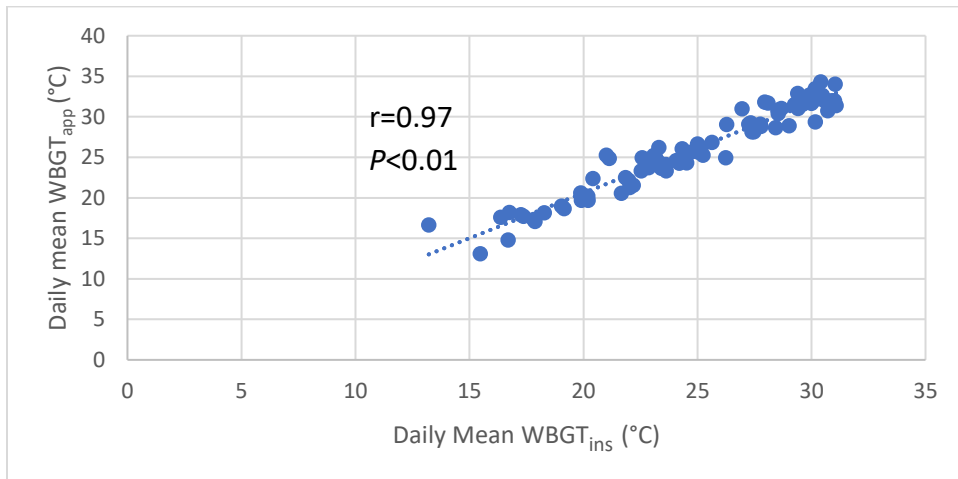


Figure 9. Correlation between daily mean WBGT_{ins} (°C) and WBGT_{app} (°C).

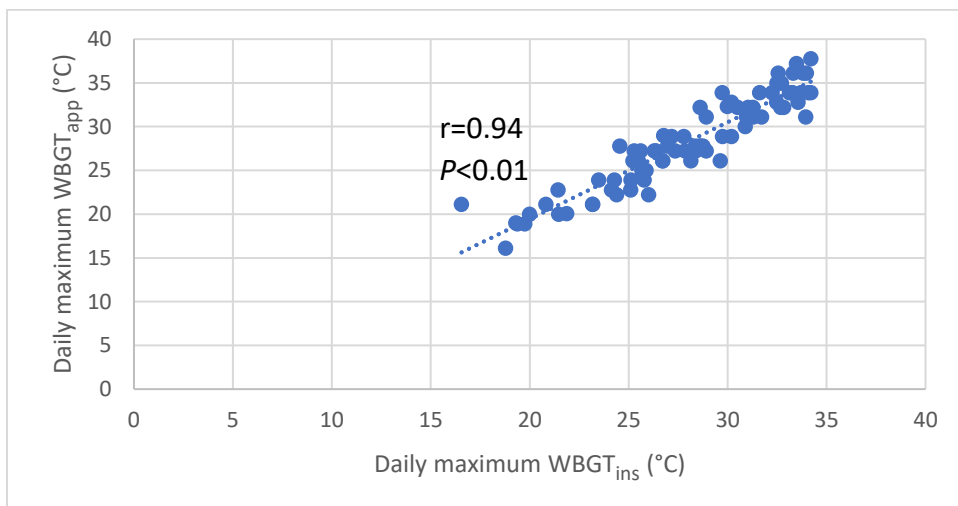


Figure 10. Correlation between daily maximum WBGT_{ins} (°C) and WBGT_{app} (°C).

Comparison of WBGT_{ins} vs. WBGT_{app} indices by month

Table 3 summarizes the comparison data between the WBGT_{ins} and WBGT_{app} indices' hourly mean, daily mean, and daily maximum by month. For March, the monthly average of the hourly mean (19.1 ± 4.4 °C, n=80), daily mean (19.1 ± 2.9 °C, n=8) and daily maximum (22.4 ± 2.7 °C, n=8) WBGT_{app} indices were not significantly different ($P=0.60$, $P=0.86$ and $P=0.97$, respectively) from the monthly average of the hourly mean (18.8 ± 3.9 °C, n=80), daily mean (18.8 ± 3.3 °C, n=8) and daily maximum (22.4 ± 3.6 °C, n=8) WBGT_{ins} indices (Table 3).

Similarly for April, the monthly average of the hourly mean (20.9 ± 4.9 °C, n=120), daily mean (20.9 ± 4.1 °C, n=12) and daily maximum (23.7 ± 4.0 °C, n=12) WBGT_{app} indices were not significantly different ($P<0.90$, $P=0.96$ and $P=0.54$, respectively) from the monthly average of the hourly mean (21.0 ± 3.9 °C, n=120), daily mean (21.0 ± 3.3 °C, n=12) and daily maximum (24.6 ± 3.6 °C, n=12) WBGT_{ins} indices (Table 3).

For May, the monthly average of the hourly mean WBGT_{app} index (22.6 ± 3.4 °C, n=175) was significantly higher ($t(348)=2.34$, $P=0.02$) than the monthly average of the hourly mean WBGT_{ins} index (21.8 ± 3.0 °C, n=175). However, the monthly average of the daily mean (22.6 ± 2.8 °C, n=18) and daily maximum (25.1 ± 3.1 °C, n=18) WBGT_{app} indices were not significantly different ($t(34)=0.89$, $P=0.38$; ($t(34)=-0.48$, $P=0.63$)) than the monthly average of the daily mean (21.8 ± 2.6 °C, n=18) and daily maximum (25.6 ± 2.8 °C, n=18) WBGT_{ins} indices (Table 3).

For June, the monthly average of the hourly mean WBGT_{app} index (27.4 ± 3.3 °C, n=178) and daily mean (27.4 ± 2.5 °C, n=18) WBGT_{app} indices were significantly higher ($t(354)=5.36$, $P<0.01$; ($t(34)=2.14$, $P=0.04$) than the monthly average of the hourly mean (25.6 ± 2.8 °C, n=178) and daily mean (25.6 ± 2.4 °C, n=18) WBGT_{ins} indices. However, the monthly average of the daily maximum WBGT_{app} index (29.9 ± 2.5 °C, n=18) was not significantly different ($t(34)=1.03$,

$P=0.31$) from the monthly average of the daily maximum ($29.1 \pm 2.3^{\circ}\text{C}$, $n=18$) WBGT_{ins} indices (Table 3).

For July, the monthly average of the hourly mean ($31.9 \pm 2.5^{\circ}\text{C}$, $n=352$), daily mean ($31.9 \pm 1.3^{\circ}\text{C}$, $n=19$) and daily maximum ($34.6 \pm 1.7^{\circ}\text{C}$, $n=19$) WBGT_{app} indices were significantly higher ($t(352)=9.22$, $P<0.01$; $t(36)=5.60$, $P<0.01$; $t(36)=3.81$, $P<0.01$) than the monthly average of the hourly mean ($29.8 \pm 1.8^{\circ}\text{C}$, $n=352$), daily mean ($29.7 \pm 1.2^{\circ}\text{C}$, $n=19$) and daily maximum ($32.8 \pm 1.1^{\circ}\text{C}$, $n=19$) WBGT_{ins} indices (Table 3).

For August, the monthly average of the hourly mean ($29.2 \pm 3.2^{\circ}\text{C}$, $n=60$), daily mean ($29.2 \pm 2.6^{\circ}\text{C}$, $n=6$) and daily maximum ($31.7 \pm 2.3^{\circ}\text{C}$, $n=6$) WBGT_{app} indices were not significantly different ($t(118)=2.3$, $P=0.82$; $t(10)=0.09$, $P=0.93$; $t(10)=-0.46$, $P=0.65$) from the monthly average of the hourly mean ($29.1 \pm 2.3^{\circ}\text{C}$, $n=60$), daily mean ($29.1 \pm 1.9^{\circ}\text{C}$, $n=6$) and daily maximum ($32.3 \pm 2.2^{\circ}\text{C}$, $n=6$) WBGT_{ins} indices (Table 3).

Table 3. Comparison of hourly mean, daily mean and daily maximum between WBGT_{ins} and WBGT_{app} indices by month

Month	n	WBGT _{ins} (°C)	WBGT _{app} (°C)	T	df	P-value
Hourly Mean						
March	80	18.8 ± 3.9	19.1 ± 4.4	0.53	158	0.60
April	120	21.0 ± 3.9	20.9 ± 4.9	-0.13	238	0.90
May	175	21.8 ± 3.0	22.6 ± 3.4	2.34	348	0.02*
June	178	25.6 ± 2.8	27.4 ± 3.3	5.36	354	<0.01*
July	352	29.8 ± 1.8	31.9 ± 2.5	9.22	352	<0.01*
August	60	29.1 ± 2.3	29.2 ± 3.2	0.23	118	0.82
Daily Mean						
March	8	18.8 ± 3.3	19.1 ± 2.9	0.18	14	0.86
April	12	21.0 ± 3.3	20.9 ± 4.1	-0.05	22	0.96
May	18	21.8 ± 2.6	22.6 ± 2.8	0.89	34	0.38
June	18	25.6 ± 2.4	27.4 ± 2.5	2.14	34	0.04*
July	19	29.7 ± 1.2	31.9 ± 1.3	5.60	36	<0.01*
August	6	29.1 ± 1.9	29.2 ± 2.6	0.09	10	0.93
Daily Maximum						
March	8	22.4 ± 3.6	22.4 ± 2.7	-0.04	14	0.97
April	12	24.6 ± 3.6	23.7 ± 4.0	-0.62	22	0.54
May	18	25.6 ± 2.8	25.1 ± 3.2	-0.48	34	0.64
June	18	29.1 ± 2.3	29.9 ± 2.5	1.03	34	0.31
July	19	32.8 ± 1.1	34.6 ± 1.7	3.81	36	<0.01*
August	6	32.3 ± 2.2	31.7 ± 2.3	-0.46	10	0.65

*Statistically significant difference ($P < 0.05$)

Correlation between WBGT_{ins} vs. WBGT_{app} indices by month

Table 4 summarizes the correlation data between the WBGT_{ins} and WBGT_{app} indices' hourly mean, daily mean and daily maximum by month. For March, there was a strong, positive correlation ($r \geq 0.7$) between the hourly mean ($r=0.83$, $P<0.01$) (Figure 11A), between the daily mean ($r=0.87$, $P<0.01$) (Figure 11B) and between the daily maximum ($r=0.85$, $P<0.01$) (Figure 11C) WBGT_{app} and WBGT_{ins} indices.

Similar correlations were also observed for the months of April, May, June and August. For April, there is a strong, positive correlation ($r \geq 0.7$) between the hourly mean ($r=0.96$, $P<0.01$) (Figure 12A), between the daily mean ($r=0.98$, $P<0.01$) (Figure 12B) and between the daily maximum ($r=0.97$, $P<0.01$) (Figure 12C) WBGT_{app} and WBGT_{ins} indices. For May, there was a strong, positive correlation between the hourly mean ($r=0.84$, $P<0.01$) (Figure 13A), between the daily mean ($r=0.90$, $P<0.01$) (Figure 13B) and between the daily maximum ($r=0.85$, $P<0.01$) (Figure 13C) WBGT_{app} and WBGT_{ins} indices. For June, there was a strong, positive correlation between the hourly mean ($r=0.85$, $P<0.01$) (Figure 14A), between the daily mean ($r=0.92$, $P<0.01$) (Figure 14B) and between the daily maximum ($r=0.71$, $P<0.01$) (Figure 14C) WBGT_{app} and WBGT_{ins} indices. For August, there was a strong, positive correlation between the hourly mean ($r=0.89$, $P<0.01$) (Figure 16A), between the daily mean ($r=0.95$, $P<0.01$) (Figure 16B), and between the daily maximum ($r=0.83$, $P=0.04$) (Figure 16C) WBGT_{app} and WBGT_{ins} indices.

For July, however, the strength of correlation between WBGT_{app} and WBGT_{ins} indices was different. There was a moderate ($0.5 < r < 0.7$), positive correlation between the hourly mean ($r=0.63$, $P<0.01$) (Figure 15A) and between the daily mean WBGT_{app} and WBGT_{ins} indices ($r=0.52$, $P=0.02$) (Figure 15B). The correlation between the daily maximum WBGT_{app} and

WBGT_{ins} indices was weak and marginally insignificant ($r=0.45$, $0.3 < r < 0.5$, $P=0.05$) (Figure 15C).

Table 4. Correlation parameters between WBGT_{ins} and WBGT_{app} indices by month

Month	Hourly Mean			Daily Mean			Daily Max		
	n	r	P-value	n	r	P-value	n	r	P-value
March	80	0.83	<0.01*	8	0.87	<0.01*	8	0.85	<0.01*
April	120	0.96	<0.01*	12	0.98	<0.01*	12	0.97	<0.01*
May	175	0.84	<0.01*	18	0.90	<0.01*	18	0.85	<0.01*
June	178	0.85	<0.01*	18	0.92	<0.01*	18	0.71	<0.01*
July	177	0.63	<0.01*	19	0.52	0.02*	19	0.45	0.05
August	60	0.89	<0.01*	6	0.95	<0.01*	6	0.83	0.04*

**Statistically significant correlation ($P<0.05$)*

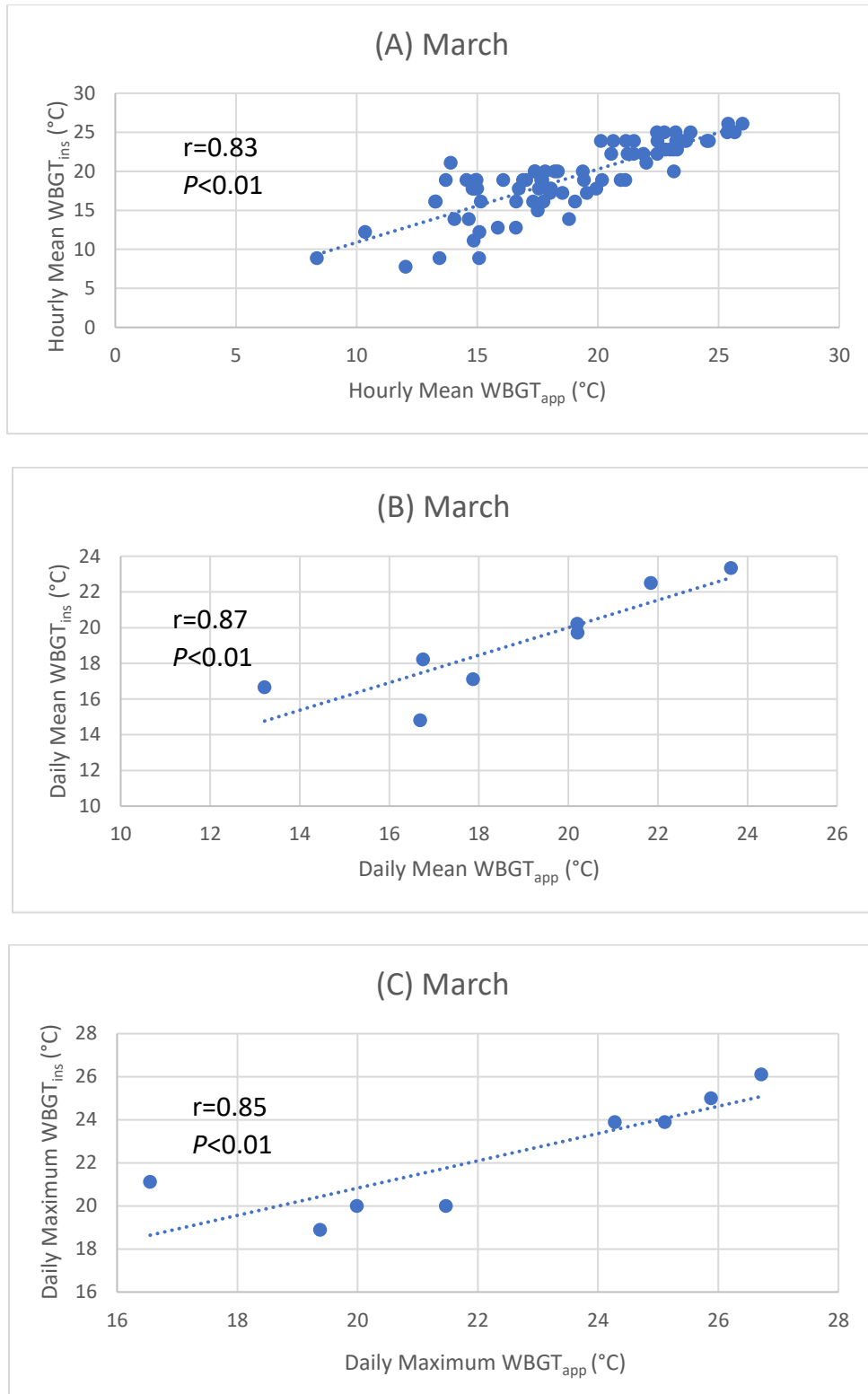


Figure 11. Monthly correlation for March between (A) hourly mean, (B) daily mean and (C) daily maximum (WBGT_{ins} (°C) and WBGT_{app} (°C))

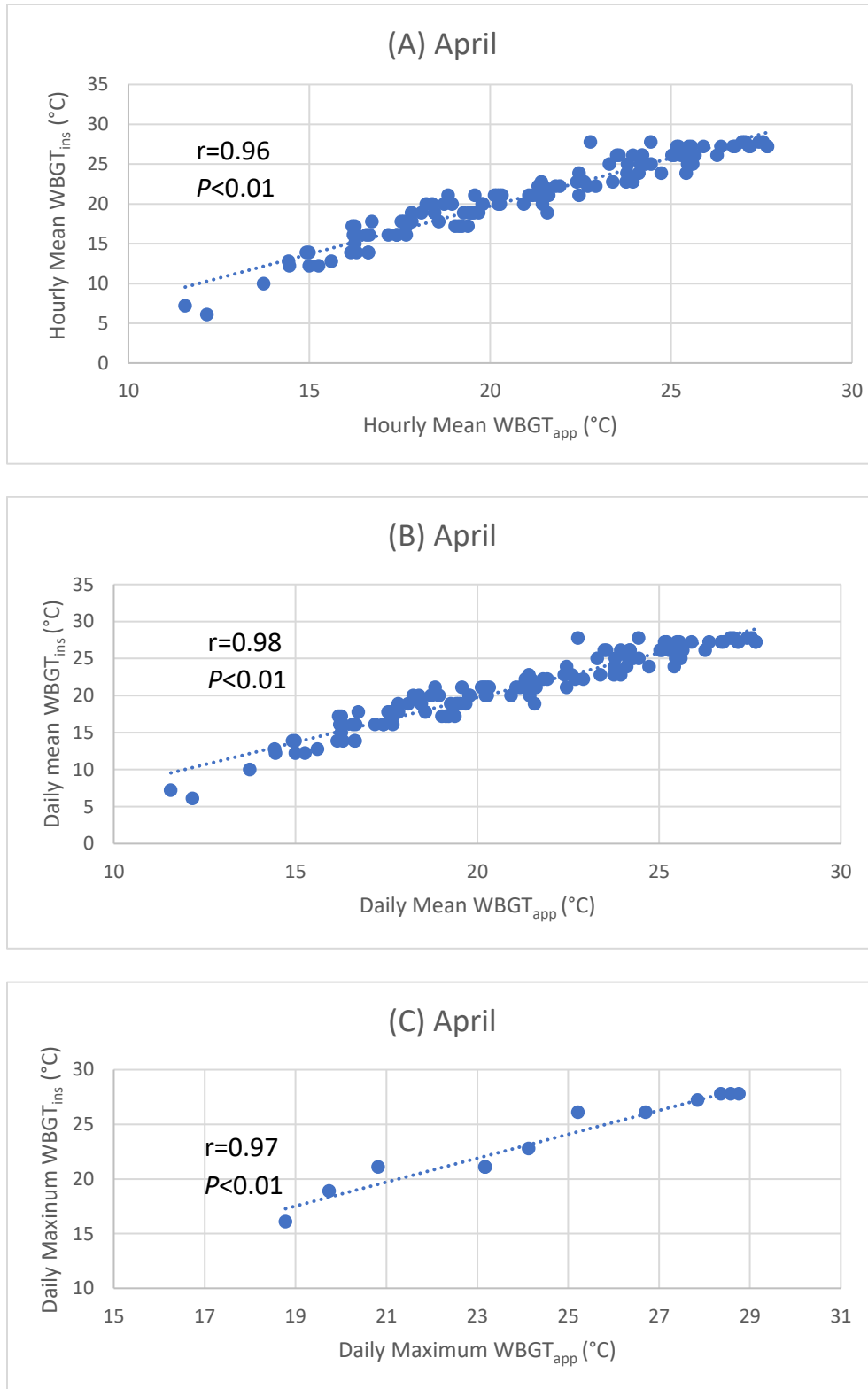


Figure 12. Monthly correlation for April between (A) hourly mean, (B) daily mean and (C) daily maximum (WBGT_{ins} (°C) and WBGT_{app} (°C))

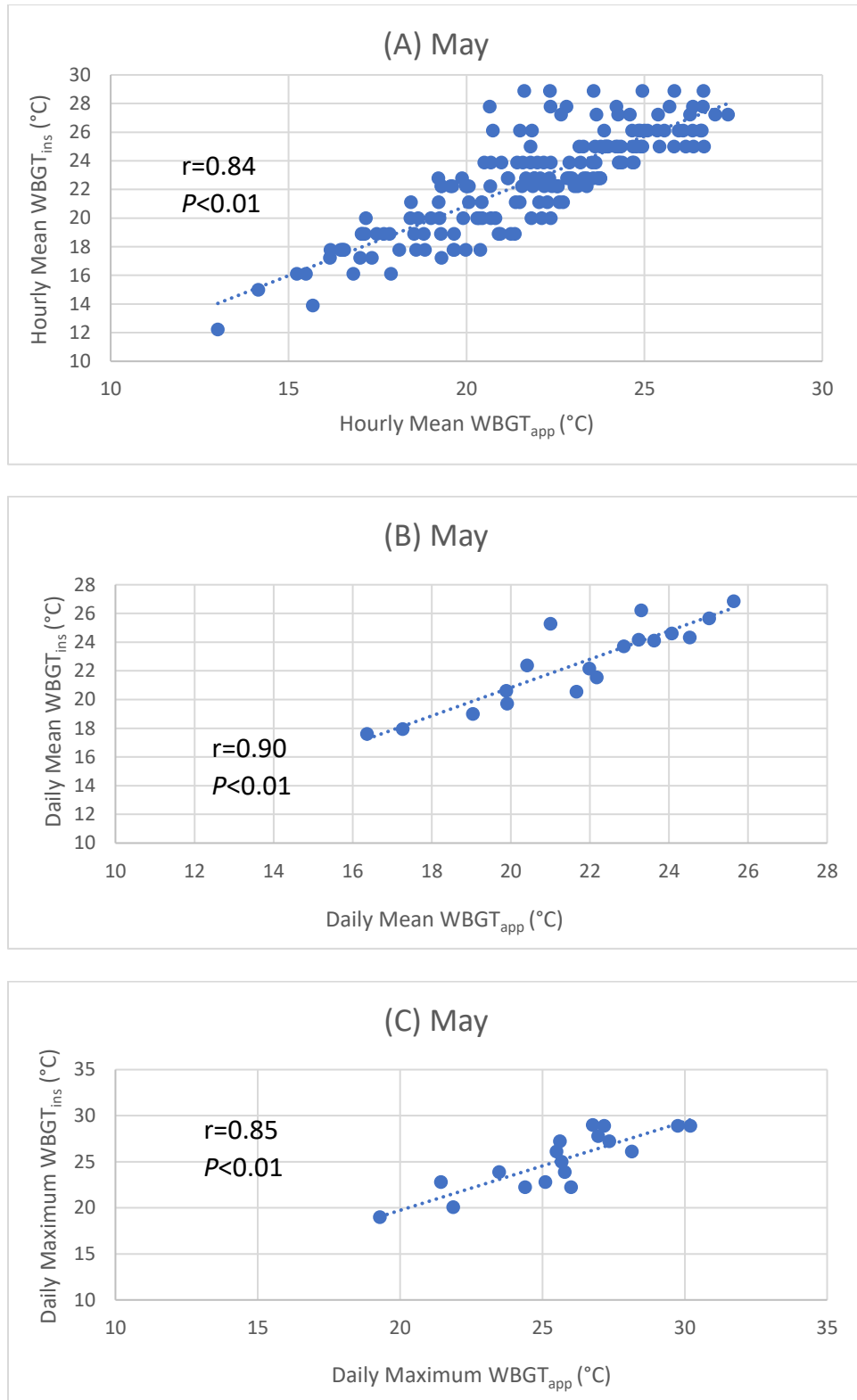


Figure 13. Monthly correlation for May between (A) hourly mean, (B) daily mean and (C) daily maximum (WBGT_{ins} (°C) and WBGT_{app} (°C))

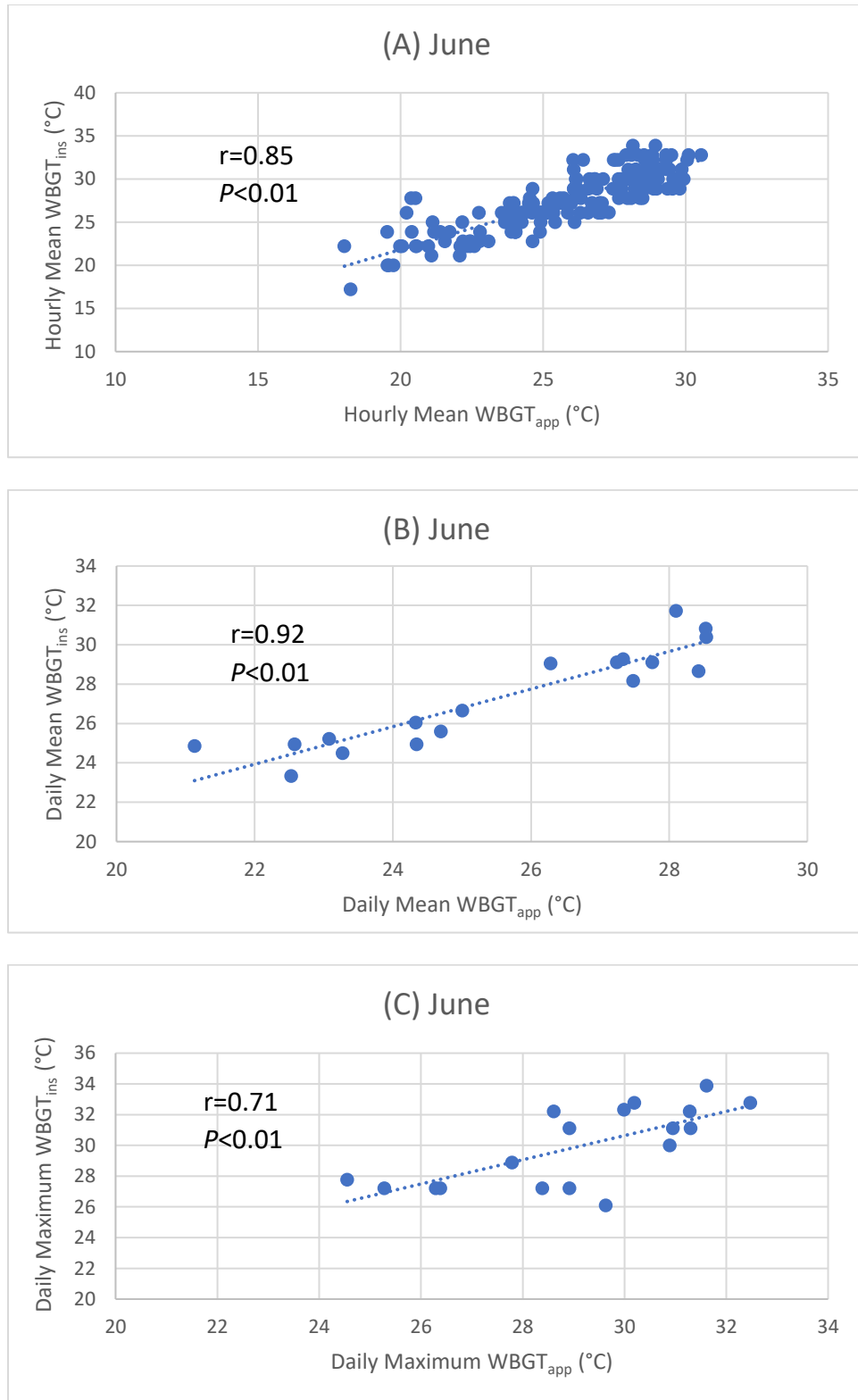


Figure 14. Monthly correlation for June between (A) hourly mean, (B) daily mean and (C) daily maximum (WBGT_{ins} (°C) and WBGT_{app} (°C))

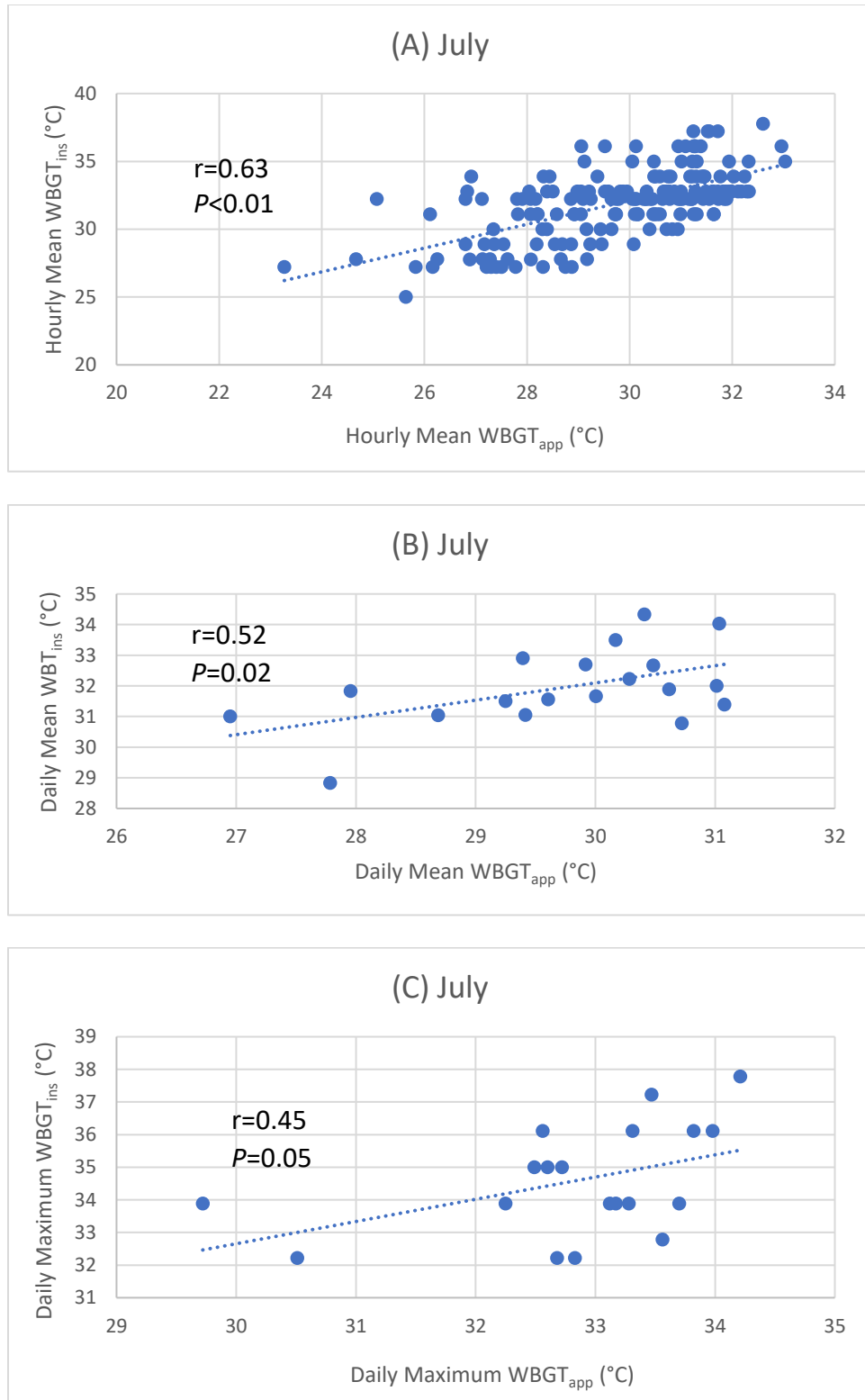


Figure 15. Monthly correlation for July between (A) hourly mean, (B) daily mean and (C) daily maximum WBGT_{ins} (°C) and WBGT_{app} (°C)

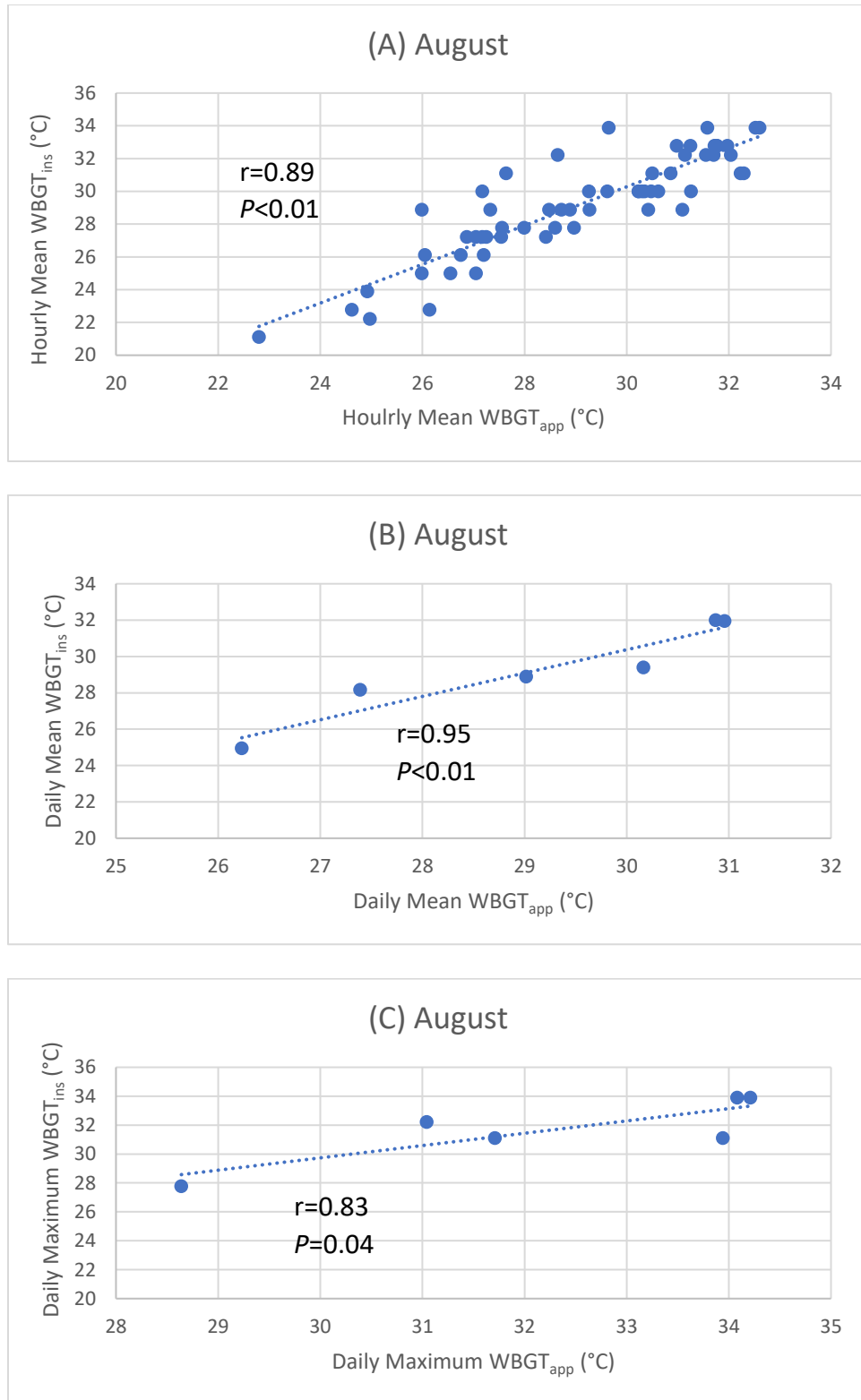


Figure 16. Monthly correlation for August between (A) hourly mean, (B) daily mean and (C) daily maximum (WBGT_{ins} (°C) and WBGT_{app} (°C))

Comparison of WBGT_{ins} vs. WBGT_{app} indices by WBGT range

Table 5 summarizes the comparison data between the WBGT_{ins} and WBGT_{app} indices' hourly mean, daily mean and daily maximum by WBGT range. For WBGT indices <15.00°C, the hourly mean WBGT_{app} index (13.9 ± 4.2 °C, n=26) was not significantly different ($t(50)=-0.35$, $P=0.73$) from the hourly mean WBGT_{ins} index (13.6 ± 1.6 °C, n=26). The daily mean WBGT_{app} index (13.2°C, n=1) cannot be statistically compared to the daily mean WBGT_{ins} index (16.7°C, n=1) since there is only 1 data point. No daily maximum WBGT_{app} or WBGT_{ins} index was measured <15.00°C.

For WBGT range of 15.00-19.99 °C, the hourly mean (18.0 ± 2.5 °C, n=129), daily mean (17.7 ± 2.0 °C, n=13) and daily maximum (18.6 ± 1.5 °C, n=5) WBGT_{app} indices were not significantly different ($t(256)=-0.29$, $P=0.78$; $t(24)=0.21$, $P=0.83$; $t(9)=-0.47$, $P=0.65$) from the hourly mean (17.9 ± 1.4 °C, n=120), daily mean (17.8 ± 1.4 °C, n=13) and daily maximum (19.0 ± 1.2 °C, n=6) WBGT_{ins} indices (Table 5).

For WBGT range of 20.00-24.99 °C, the hourly mean WBGT_{app} index (23.7 ± 2.3 °C, n=244) was significantly higher ($t(486)=-5.50$, $P<0.01$) than the hourly mean WBGT_{ins} index (22.7 ± 1.4 °C, n=244). The daily mean WBGT_{app} index (23.5 ± 1.9 °C, n=28) was significantly higher, but marginally, ($t(54)=-1.99$, $P=0.05$) than the daily mean WBGT_{ins} index (22.6 ± 1.4 °C, n=28). The daily maximum WBGT_{app} index (22.4 ± 2.2 °C, n=11) was not significantly different ($t(20)=0.70$, $P=0.50$) from the daily maximum WBGT_{ins} index (20.0 ± 1.4 °C, n=11) (Table 5).

For WBGT range of 25.00-29.99 °C, the hourly mean (29.0 ± 2.5 °C, n=265) and daily mean (29.3 ± 2.3 °C, n=26) WBGT_{app} indices were significantly higher ($t(528)=-8.53$, $P<0.01$; $t(50)=-83.12$, $P<0.01$) than the hourly mean (27.5 ± 1.4 °C, n=265) and daily mean (27.6 ± 1.5 °C, n=26) WBGT_{ins} indices. The daily max WBGT_{app} index (27.3 ± 2.5 °C, n=33) was not

significantly different ($t(64)=0.01$, $P=0.99$) than the daily max WBGT_{ins} index (27.3 ± 1.5 °C, $n=33$) (Table 5).

For WBGT indices $>30.00^{\circ}\text{C}$, the hourly mean (32.8 ± 1.9 °C, $n=126$) was significantly higher ($t(250)=9.06$, $P=0.01$) than the hourly mean WBGT_{ins} index (31.1 ± 0.7 °C, $n=126$). Similarly, the daily mean (32.1 ± 1.3 °C, $n=13$) and daily maximum (33.5 ± 1.2 °C, $n=26$) WBGT_{app} indices were significantly higher ($t(24)=-4.05$, $P<0.01$; $t(60)=-2.22$, $P=0.03$) than the daily mean ($30.6 \pm 0.4^{\circ}\text{C}$, $n=13$) and daily maximum (32.5 ± 1.2 °C, $n=26$) WBGT_{ins} indices (Table 5).

Table 5. Comparison of hourly mean, daily mean, and daily maximum between WBGT_{ins} and WBGT_{app} indices by WBGT range for all the Month.

WBGT _{ins} range (°C)	n	WBGT _{ins} (°C)	WBGT _{app} (°C)	t	df	P-value
Hourly Mean						
<15.00	26	13.6 ± 1.6	13.9 ± 4.2	-0.35	50	0.73
15.00-19.99	129	17.9 ± 1.4	18.0 ± 2.5	-0.29	256	0.78
20.0-24.99	244	22.7 ± 1.4	23.7 ± 2.3	-5.50	486	<0.01*
25.00-29.99	265	27.5 ± 1.4	29.0 ± 2.5	-8.54	528	<0.01*
≥30.00	126	31.1 ± 0.7	32.8 ± 1.9	-9.06	250	0.01*
Daily Mean						
<15.00	1	13.2	16.7	N/A	N/A	N/A
15.00-19.99	13	17.8 ± 1.4	17.7 ± 2.0	0.21	24	0.83
20.0-24.99	28	22.6 ± 1.4	23.5 ± 1.9	-1.99	54	0.05
25.00-29.99	26	27.6 ± 1.5	29.3 ± 2.3	-3.13	50	<0.01*
≥30.00	13	30.6 ± 0.4	32.1 ± 1.3	-4.05	24	<0.01*
Daily Maximum						
<15.00	0	-	-	-	-	-
15.00-19.99	6	19.0 ± 1.2	19.0 ± 1.7	-0.05	10	0.96
20.0-24.99	11	23.0 ± 1.4	22.4 ± 2.2	0.70	20	0.50
25.00-29.99	33	27.3 ± 1.5	27.3 ± 2.5	0.01	64	0.99
≥30.00	26	32.5 ± 1.2	33.5 ± 2.1	-2.22	60	0.03*

*Statistically significant difference ($P < 0.05$)

Correlation between WBGT_{ins} vs. WBGT_{app} indices by WBGT range

Table 6 summarizes the correlation data between the WBGT_{ins} and WBGT_{app} indices' hourly mean, daily mean and daily maximum by WBGT range. For WBGT indices <15.0°C, there was a moderate, positive correlation between the hourly mean WBGT_{app} and WBGT_{ins} indices ($r=0.57$, $P<0.01$) (Figure 17).

For WBGT indices ranging from 15.00-19.99 °C, there was a moderate, positive correlation between the hourly mean WBGT_{app} and WBGT_{ins} indices ($r=0.68$, $P<0.01$) (Figure 18A) and a strong, positive correlation between the daily mean WBGT_{app} and WBGT_{ins} indices ($r=0.83$, $P<0.01$) (Figure 18B). However, there was no correlation between the daily maximum WBGT_{app} and WBGT_{ins} indices ($P=0.49$) (Figure 18C).

For WBGT indices ranging from 20.00-24.99 °C, there was a moderate, positive correlation between the hourly mean WBGT_{app} and WBGT_{ins} indices ($r=0.55$, $P<0.01$) (Figure 19A) and between the daily maximum WBGT_{app} and WBGT_{ins} indices ($r=0.64$, $P=0.04$) (Figure 19C). There was a strong, positive correlation between the daily mean WBGT_{app} and WBGT_{ins} indices ($r=0.71$, $P<0.01$) (Figure 19B).

Similarly, for WBGT indices ranging from 25.00-29.99 °C, there was a moderate, positive correlation between the hourly mean WBGT_{app} and WBGT_{ins} indices ($r=0.66$, $P<0.01$) (Figure 20A) and between the daily maximum WBGT_{app} and WBGT_{ins} indices ($r=0.69$, $P<0.01$) (Figure 20C). There was a strong, positive correlation between the daily mean WBGT_{app} and WBGT_{ins} indices ($r=0.85$, $P<0.01$) (Figure 20B).

For WBGT indices >30.00°C, there was a weak, positive correlation between the hourly mean WBGT_{app} and WBGT_{ins} indices ($r=0.36$, $P<0.01$) (Figure 21A), no correlation between the daily mean WBGT_{app} and WBGT_{ins} indices ($r=0.09$, $P=0.78$) (Figure 21 B), and a moderate,

positive correlation between the daily maximum WBGT_{app} and WBGT_{ins} indices ($r=0.64$, $P<0.01$) (Figure 21C).

Table 6. Correlation parameters between WBGT_{ins} and WBGT_{app} indices by WBGT range for all months

WBGT Range (°C)	Hourly Mean			Daily Mean			Daily Max		
	n	r	P-value	n	r	P-value	n	r	P-value
< 15.00	26	0.57	<0.01*	N/A	N/A	N/A	N/A	N/A	N/A
15.00-19.99	129	0.68	<0.01*	13	0.83	<0.01*	6	-0.35	0.49
20.00-24.99	244	0.55	<0.01*	28	0.71	<0.01*	11	0.64	0.04*
25.00-29.99	265	0.66	<0.01*	26	0.85	<0.01*	33	0.69	<0.01*
≥ 30.00	126	0.36	<0.01*	13	0.09	0.78	31	0.64	<0.01*

*Statistically significant correlation ($P<0.05$)

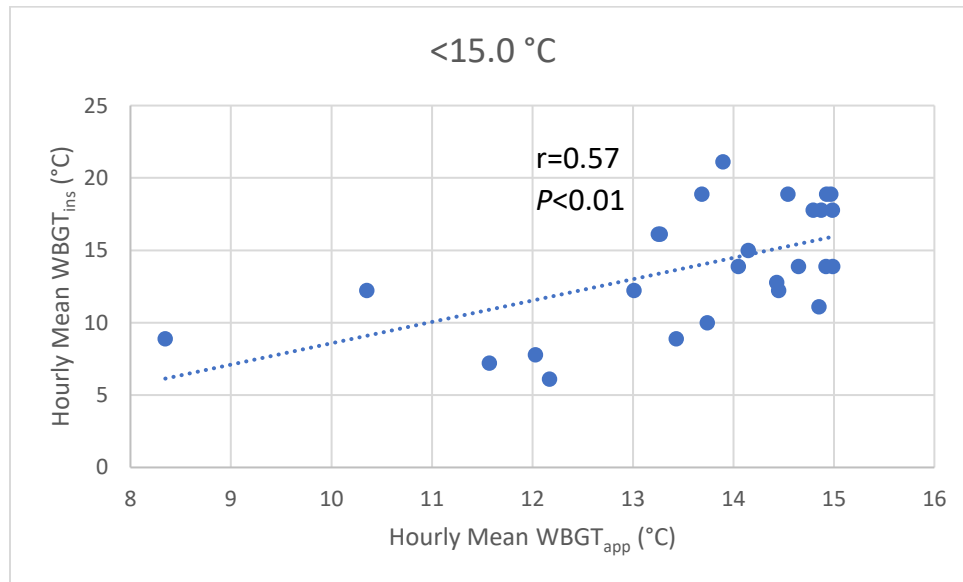


Figure 17. Correlation between hourly mean WBGT_{ins} (°C) and WBGT_{app} (°C) for WBGT indices <15.00°C

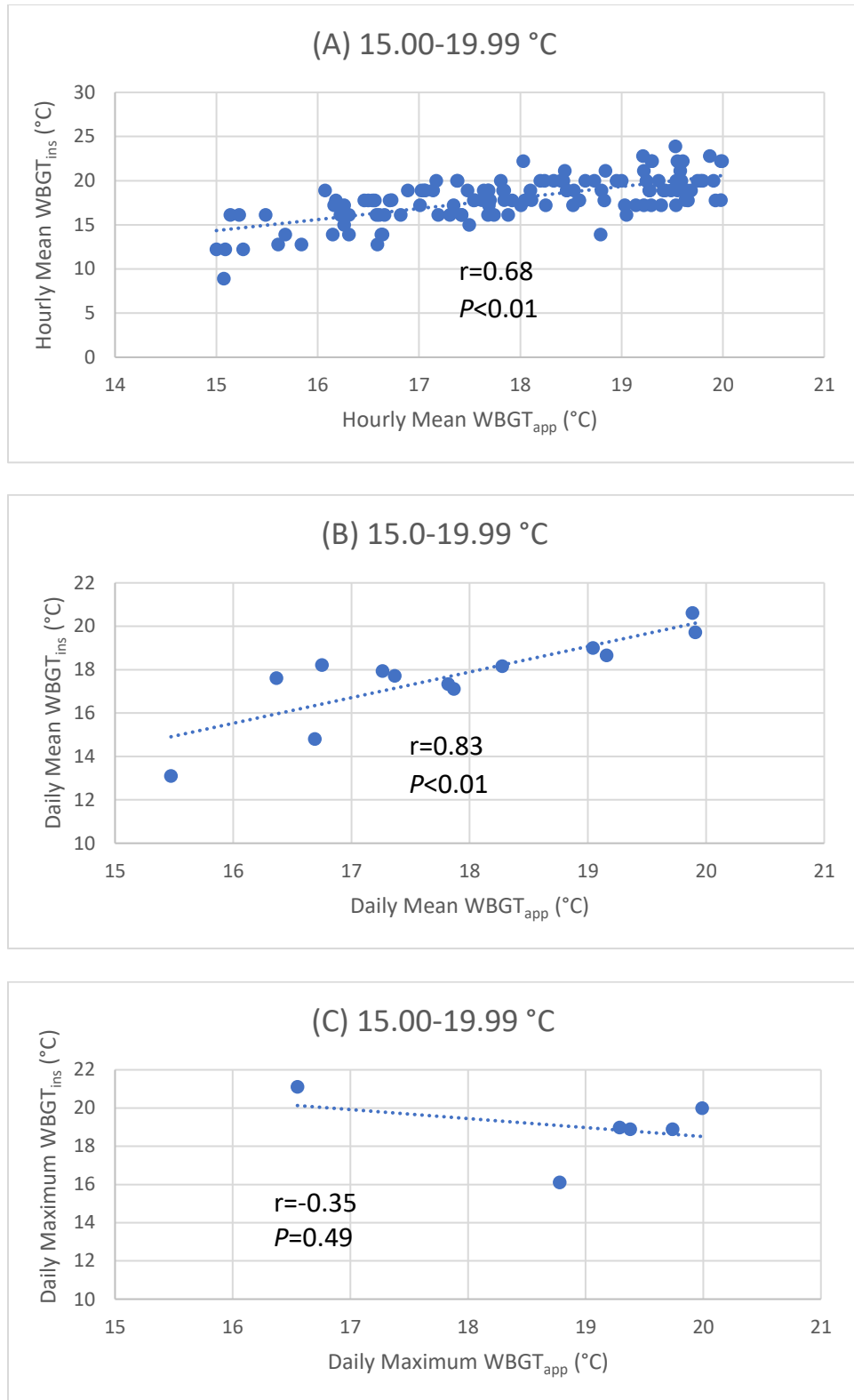


Figure 18. Correlation between hourly mean WBGT_{ins} (°C) and WBGT_{app} (°C) for WBGT indices ranging from 15.00-19.99°C

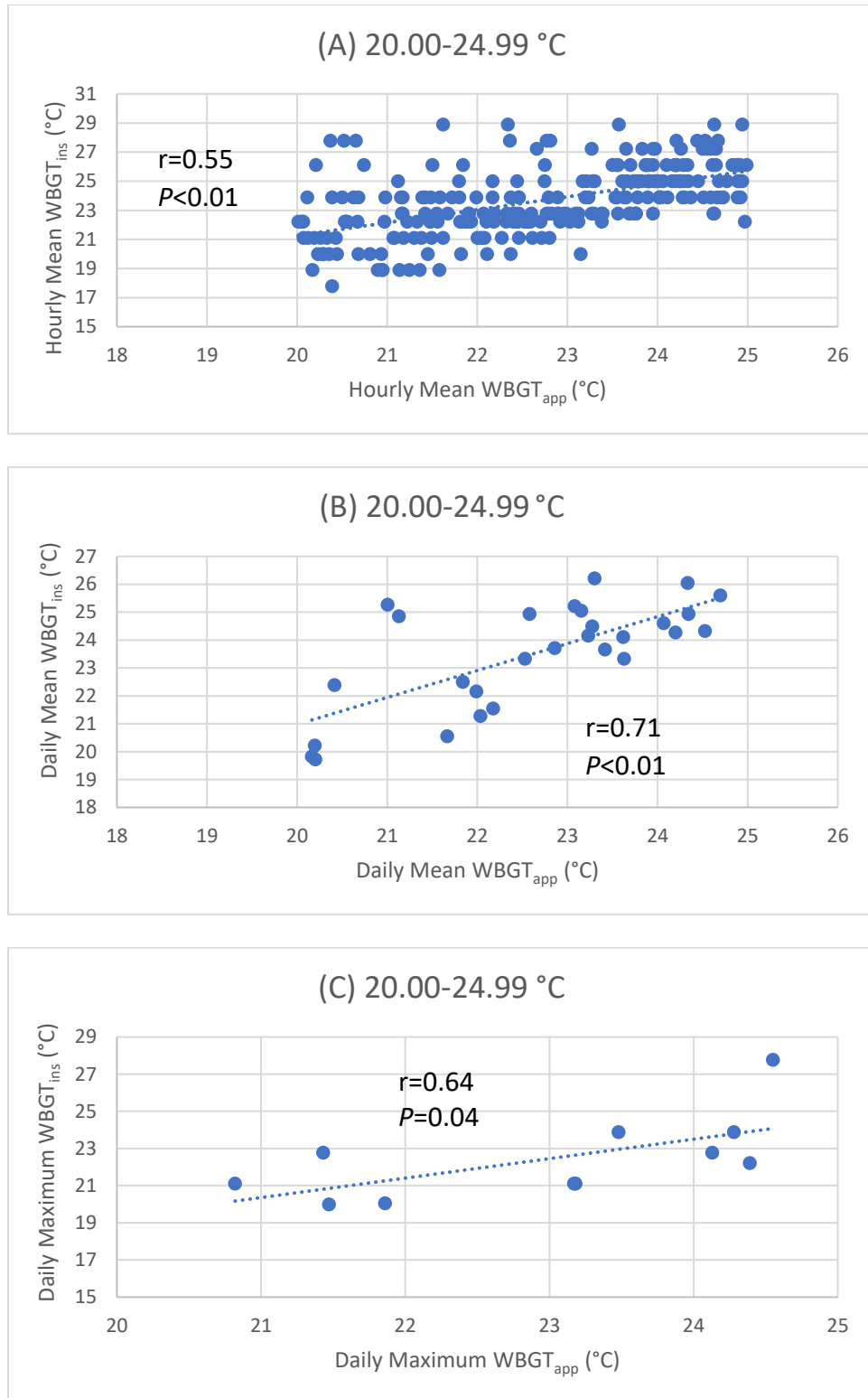


Figure 19. Correlation between hourly mean WBGT_{ins} (°C) and WBGT_{app} (°C) for WBGT indices ranging from 20.00-24.99°C

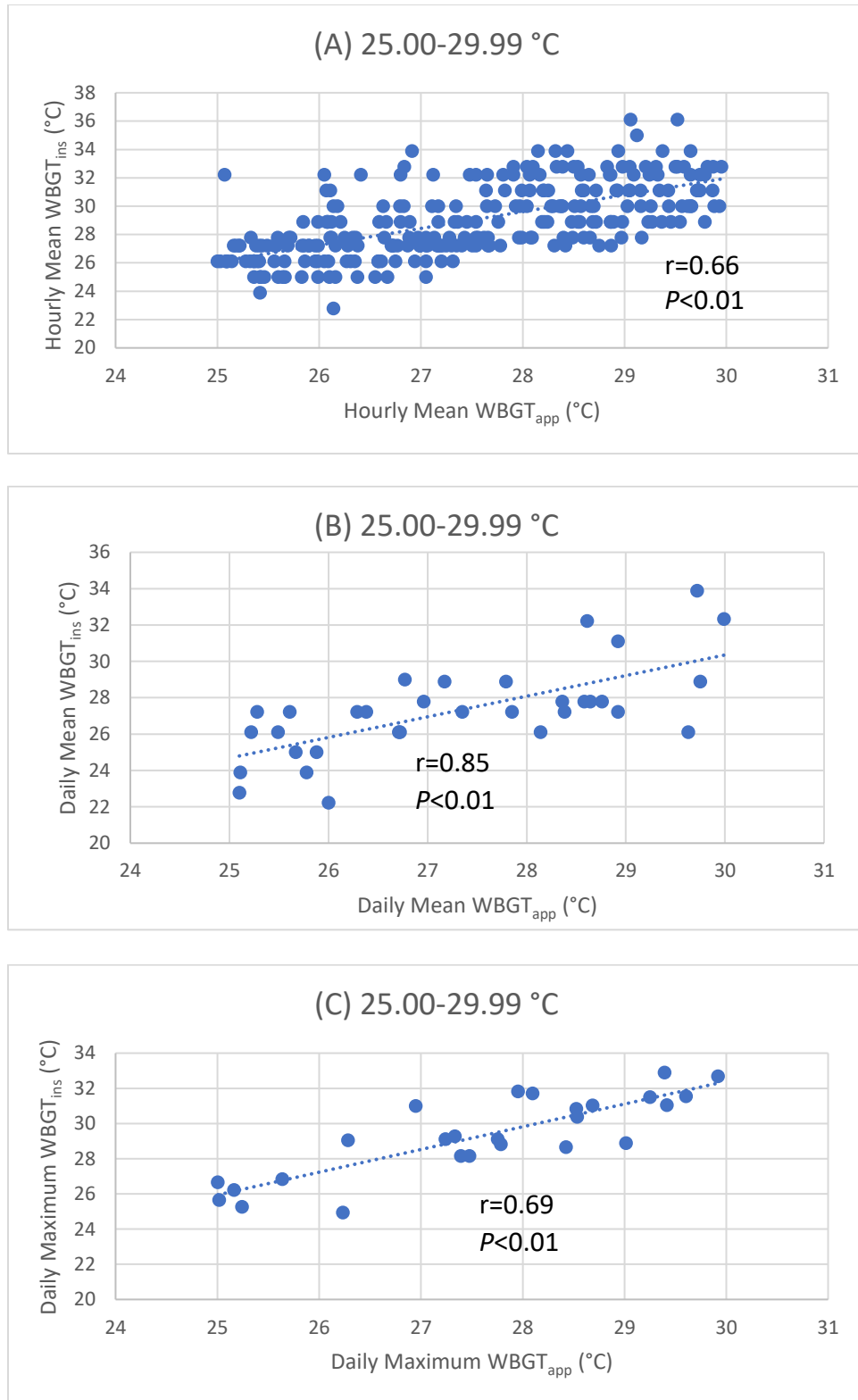


Figure 20. Correlation between hourly mean WBGT_{ins} (°C) and WBGT_{app} (°C) for WBGT indices ranging from 25.00-29.99°C

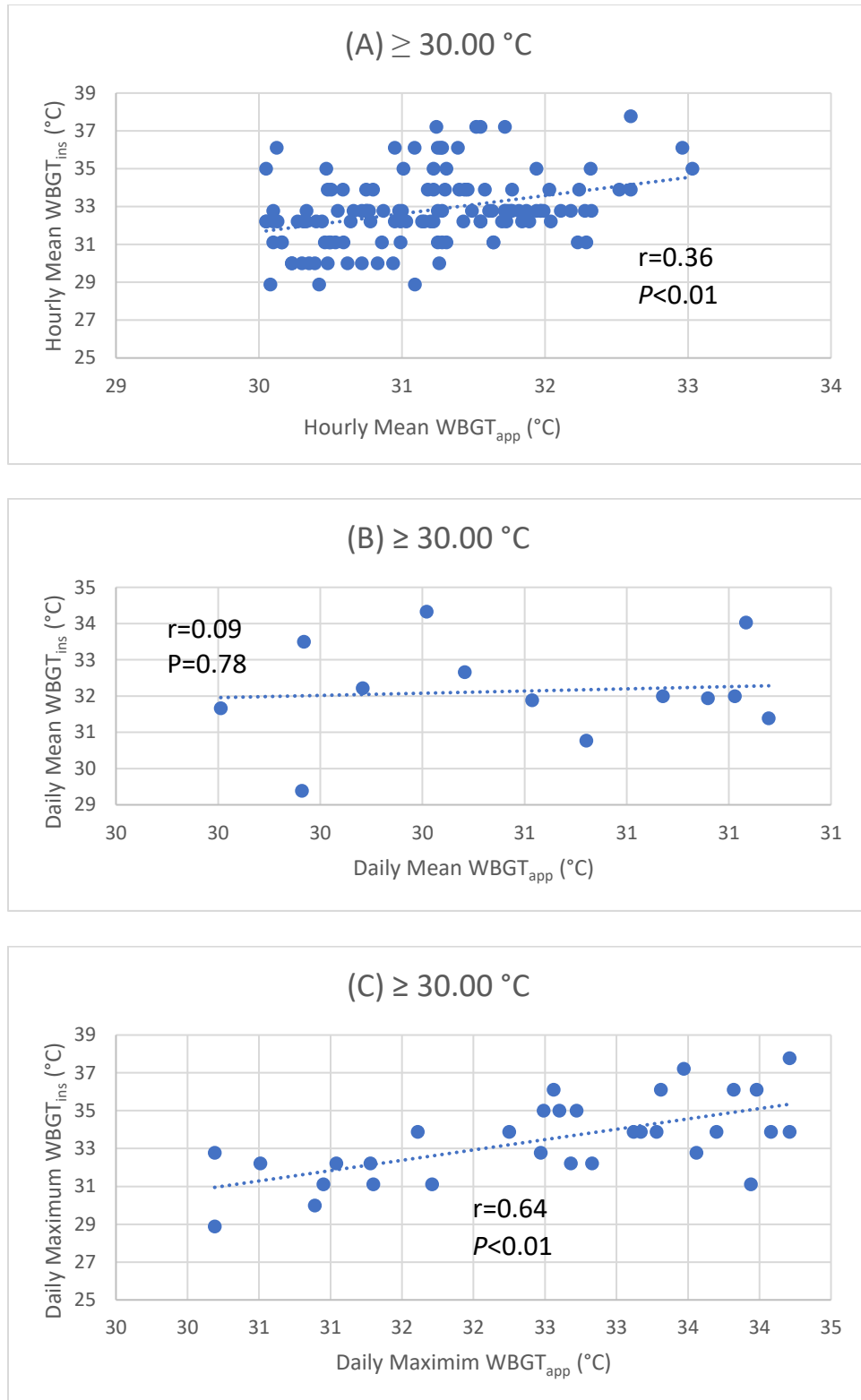


Figure 21. Correlation between hourly mean WBGT_{ins} ($^{\circ}\text{C}$) and WBGT_{app} ($^{\circ}\text{C}$) for WBGT indices $>30.00\text{ }^{\circ}\text{C}$

Comparison between WBGT_{ins} and WBGT_{app} heat stress risks

Hourly mean WBGT_{ins} indices (n = 791) were assigned to a heat stress risk level depending on the workload category and had been paired to their corresponding hourly mean WBGT_{app} indices, which were automatically assigned to a heat stress risk level by the app. Figure 20 shows the percentage of each risk level category assigned for WBGT_{ins} and WBGT_{app} indices by workload. “Minimal risk” was the most common assigned risk level for WBGT_{ins} indices under light, moderate, heavy, and all workloads combined (73.1%, 51.2%, 38.9%, and 54.4%, respectively), and for WBGT_{app} indices under light, moderate, and all workloads (65.7%, 39.6%, and 44.8%, respectively). “Extreme risk” was the most common risk level for WBGT_{app} indices under heavy workload (39.3%), followed by “minimal risk” (29.1%) and “low risk” (17.1%). Comparing the three workload types, either by WBGT_{ins} or WBGT_{app} indices, the percentages for the least severe risk level (i.e., minimal risk) decreased (e.g., from 73.1% to 38.9% for WBGT_{ins}; from 65.7% to 29.1% for WBGT_{app}) as the workload severity increased. In contrast, the percentages for the most severe risk level (i.e., extreme risk) increased (e.g., from 7.8% to 34.6% for WBGT_{ins}; from 23.5% to 39.3% for WBGT_{app}) as the workload severity increased, which is due to the increasing stringency of the TLV associated with the increasing workload. Such increasing trend with increasing workload was also observed for “low risk” assignments (e.g., from 0.6% to 7.2% for WBGT_{ins}; from 0.0% to 17.1% for WBGT_{app}). The decreasing percentage of “minimal risk” assignments with increasing workload was both observed in WBGT_{ins} or WBGT_{app} indices, but these percentages tend to be higher for WBGT_{ins} compared to WBGT_{app} indices (e.g., 73.1% for WBGT_{ins} vs. 65.7% for WBGT_{app} under light workload). Moreover, the increasing percentage of “extreme risk” assignments with increasing workload was also both observed in WBGT_{ins} or WBGT_{app} indices, but these percentages tend to be higher for WBGT_{app} compared to WBGT_{ins} indices (e.g., 7.8% for WBGT_{ins} vs. 23.5% for WBGT_{app} under light workload). No

particular trend was observed for “moderate risk” and “high risk” percentages as the workload increased.



Figure 22. Percentage of assigned heat stress risk level (n = 791) for WBGT_{ins} and WBGT_{app} indices by workload

The reliability of the app prototype in assessing heat stress risk was determined by comparing the WBGT_{app}-based risk levels to the WBGT_{ins}-based risk levels as the “gold standard”. Figure 21 shows the percentage of hourly WBGT_{ins}-based risk level assignments that had the same hourly WBGT_{app}-based risk level assignment by workload. Among the WBGT_{ins}-based “minimal risk” assignments under the “light workload” assumption (n = 578), 87.5% were also assigned as “minimal risk” by the app, while the remaining 12.5% were assigned higher risk levels (6.4% as moderate risk, 6.1% as extreme risk). This made the app more conservative and more protective when assigning risks for “minimal risk” conditions. As the workload increased, the percentage of

“minimal risk” assignments by the app decreased from 87.5–73.1% for light to very heavy workloads (Figure 23A). Among the WBGT-based “low risk” assignments under the “light workload” assumption ($n = 5$), 0.0% were also identified as “low risk” by the app, while 40.0% were assigned higher risk levels (20.0% as moderate risk, 20.0% as extreme risk) and 60.0% were assigned a lower risk level of “minimal,” making the app less conservative (i.e., less protective) for this “low risk” scenario. Under moderate workload, 27.3% of the WBGT-based “low risk” assignments ($n = 22$) were also assigned by the app as “low risk. As the workload increased from moderate to very heavy, the percentage of “low risk” assignments by the app increased to 62.3%, demonstrating the best accuracy in risk assignment. Moreover, the increase in workload from light to very heavy also decreased the percentage of lower risk assignments of “minimal” (Figure 23B).

Among the WBGT-based “moderate risk” assignments under the “light workload” ($n = 91$), 36.3% were also identified as “moderate risk” by the app, while 51.6% were assigned a higher risk level of “extreme” and 12.1% were assigned to a lower risk level of “minimal”, making the app even more conservative for “moderate risk” conditions. Moreover, as the workload increased, the percentage of “moderate risk” assignments by the app decreased. The worst-case scenario was found under heavy workload wherein 26.4% of the WBGT-based “moderate risk” assignments ($n = 106$) were assigned the same risk level by the app, while 40.6% were assigned to higher risk levels and 33.0% were assigned to lower risk levels (Figure 23C). The best-case scenario was found under moderate workload wherein 56.1% the WBGT-based “moderate risk” assignments ($n = 139$) were assigned the same risk level by the app (Figure 23C).

Among the WBGT-based “high risk” assignments under light ($n = 55$) and moderate ($n = 3$), 0.0% were identified as “high risk” by the app while majority (78.2% and 66.7%, respectively) were assigned to a higher risk level of “extreme”. Under heavy workload ($n = 46$), the app

correctly identified 21.7% as “high risk”. This distribution indicates that the app assigned a majority of the WBGT-based “high-risk” assignments to extreme risk levels, with a decrease in such percentages in overestimation as the workload increased (Figure 23D).

Regarding the WBGT-based “extreme-risk” assignments, under “light workload” (n = 62), a majority (96.8%) were also identified as “extreme risk” by the app, with a small percentage (3.2%) identified as "moderate risk," indicating close alignment between the app and the WBGT_{ins}-based assessments. For “moderate workload” (n = 222), 95% were correctly categorized as “extreme risk”, while 5% were assigned to a lower risk level of "moderate risk" by the app. Under “heavy workload” (n = 274), the app correctly classified 93.1% as “extreme risk”, while the rest were assigned to lower risk levels (5.8% as high risk, 0.7% as moderate risk and 0.4% as low risk”. This pattern shows that the app performs best in identifying “extreme risk” conditions regardless of the workload (Figure 23E).

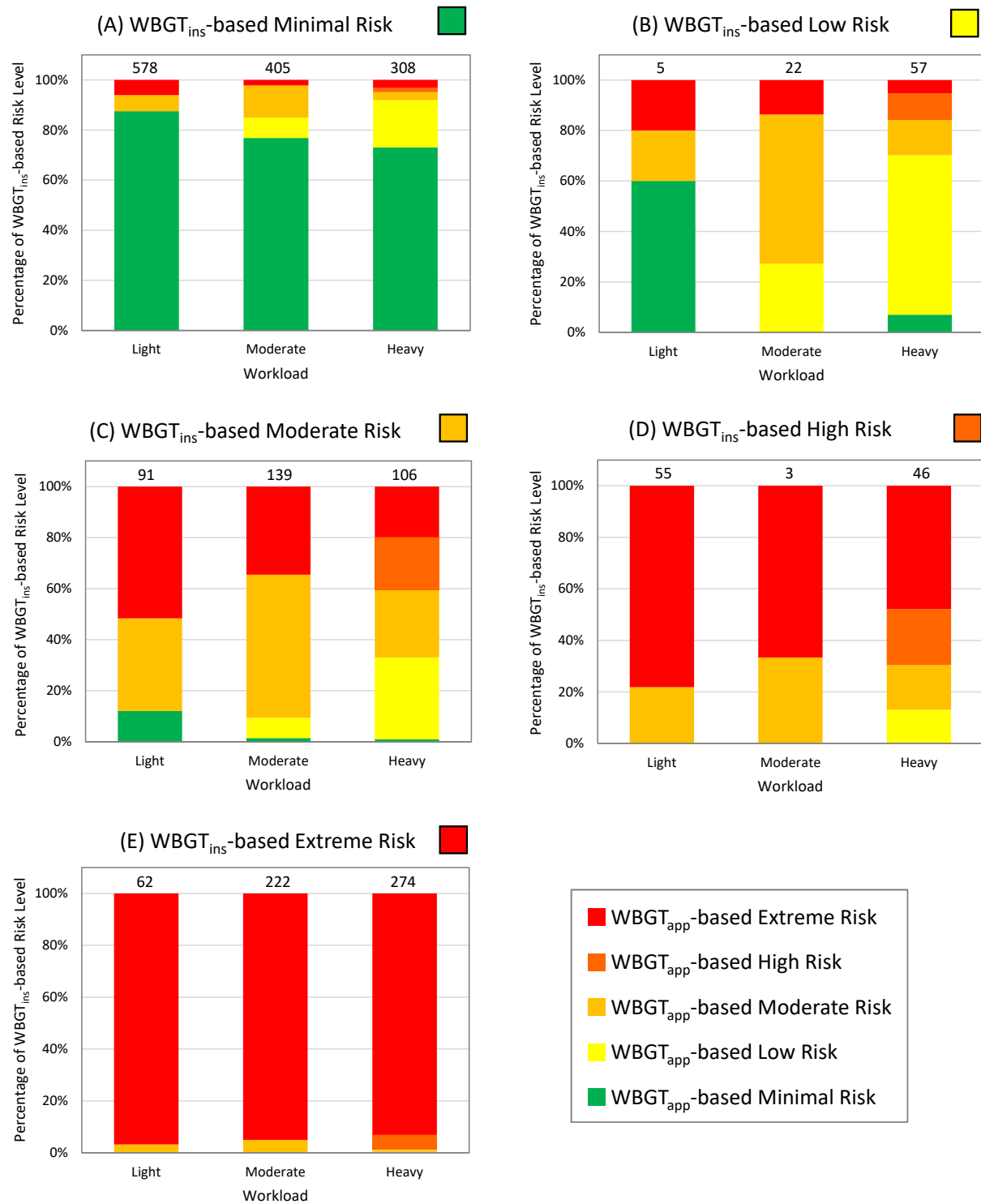


Figure 23. Percentage of hourly WBGT_{ins}-based risk level assignments with the same hourly WBGT_{app}-based risk level assignment by workload

CHAPTER VIII. DISCUSSION

Results from this study show excessive heat exposures during the summer months of June to August 2023, as demonstrated by high percentages of heat stress levels exceeding both the TLVs and action limits for occupational heat exposure. This finding was particularly important when the workload was either moderate or heavy since TLV exceedance increases as the workload increases. Results also showed that the action limits for moderate and heavy workloads were exceeded during almost all months monitored during the study although at varying magnitude. While March had the lowest heat exposure, action limits were still exceeded when workload was classified as heavy. July showed the highest heat stress levels and this finding was supported by other studies. A study by Nakamura et al. (2022) that analyzed trends in ambulance dispatches related to heat illness from 2010 to 2019 found significant differences in WBGT across months. The average maximum WBGT was highest in July ($28.4 \pm 2.7^{\circ}\text{C}$) and August ($29.3 \pm 2.5^{\circ}\text{C}$), supporting the observation of increased heat stress risk during these months (Nakamura et al., 2022). Another study examined the changes in heat stress indices in an outdoor environment over 15 years and found that the highest average WBGT index occurred consistently in July ($37.22 \pm 0.43^{\circ}\text{C}$) (Ghalhari et al., 2020). Lastly, a study noted that in July and August, the WBGT is projected to increase by 3.2°C across three cities, which highlights the trend of higher WBGT readings during these peak summer months (Nassiri et al., 2020). There is a need for heightened preventive measures as workloads increase, including more frequent rest breaks, adequate hydration, and potentially the use of personal cooling devices or modified work schedules.

Data on TLV and action limit indicates the WBGT_{app} generally shows a higher index than the WBGT_{ins} , which could indicate a difference in sensitivity and/or calibration between the two methods. This means that the app is likely responding more strongly to environmental conditions

compared to the monitor which is considered the accurate standard in this study. Both detection methods demonstrate an increasing trend of heat stress potential during the summer months from June to August, reflecting expected seasonal temperature increases for outdoor workers. The WBGT_{app} tends to exceed TLVs and action limits more frequently, especially for heavy workloads. The highest risk period for heat stress here was July, aligning with peak summer temperatures. These findings are similar to those in the Dillane and Balanay (2020) study also carried out in eastern NC, which demonstrates that July recorded the highest daily mean WBGT index (31.8 °C) and had one of the highest TLV exceedances at any workload. Given the significantly higher readings from the WBGT_{app} and its tendency to exceed TLVs, caution is recommended when using the app for heat stress monitoring. The app can serve as an early warning system, especially since it tends to predict higher heat stress levels. The discrepancy between the WBGT_{ins} and WBGT_{app} suggests that the app prototype may be more sensitive to certain environmental conditions which includes radiant heat, ambient temperature, and humidity, or that its algorithmic adjustment or software tuning differs from the traditional monitor, potentially leading to overestimation of heat stress risk. If the app consistently overestimates risk, it may lead to a psychological impact where users become overly cautious, which may lead to implementing more stringent heat stress prevention measures than necessary. This could include more frequent breaks, reduced working or playing hours in hot conditions, or the use of additional cooling facilities. On the other hand, such overestimation may result to app users disregarding the app's warnings due to perceived inaccuracies. This may impact compliance with safety protocols and potentially put individuals at risk in situations where the heat stress is genuinely high. The WBGT_{app}, with its strong correlation to the traditional monitor, can be tentatively recommended for preliminary assessment of heat

stress risk, especially in resource-limited occupational settings where traditional monitoring devices might not be available.

In March and April 2023, the app showed high reliability in providing accurate heat stress advisories. The similarity in the monthly averages of hourly mean, daily mean, and daily maximum indices between the app and the monitor during these months suggests that the app was more reliable when temperatures were relatively cooler. The month of May presented a mixed scenario. While the app's daily mean and maximum indices were similar to the monitor's in May, the hourly mean was significantly higher. This indicates that the app's reliability starts to decrease as temperatures rise, particularly for hourly measurements. June and July show a marked decrease in the app's reliability. In these months, the app consistently recorded higher values than the monitor for hourly and daily mean indices, pointing to its reduced accuracy in hotter conditions. In August, the app's performance improved, showing no significant difference in all indices compared to the monitor. This suggests that as the peak summer heat started to decline, the app became more reliable again. The app's reliability varied significantly across the year, exhibiting greater accuracy in relatively cooler months compared to peak summer months. These results are expected to vary, depending on geographic location of app usage and should be evaluated further.

For WBGT_{ins} indices below 15.00°C and 15.00-19.99°C, the app demonstrated high reliability. In these cooler WBGT_{ins} ranges, the differences in measurements between the app and monitor were not significant, indicating that the app performs well in cooler environments. As the temperature rose to the moderate range of 20.00-24.99°C, the app began to show some discrepancies, particularly in the hourly and daily mean measurements, where it recorded slightly higher temperatures than the monitor. However, the daily maximum measurements remained closely aligned with the monitor, suggesting the app retains some reliability for peak temperature

readings in this range. In the warmer WBGT_{ins} ranges of 25.00-29.99°C and above 30.00°C, the app's reliability decreased. It consistently recorded higher temperatures than the monitor across all measures (hourly mean, daily mean, and daily maximum). This trend indicates that the app was less reliable in hotter environments under the conditions of this study. In summary, the app was more reliable at lower temperatures, showing close agreement with the monitor's readings. As the temperature increased, the app's accuracy decreased, particularly in higher temperature ranges where it tended to overestimate the WBGT compared to the monitor.

In the months of March, April, May, June, and August, positive correlation across all measures (hourly mean, daily mean, and daily maximum) indicated a high degree of consistency between the app and the monitor. This strong correlation suggests that the app is a reliable tool for estimating WBGT in these months under the conditions of this study in eastern NC. Further assessments are needed to evaluate the app in different geographic locations during the summer months. Users and decision-makers can trust the app's readings for activities such as planning outdoor work, sports events, or assessing heat stress risks. More work should be done in the future to evaluate the extent to which outdoor worker behavior changes in relation to app recommendations. Moderate (for hourly mean and daily mean) and weak (for daily maximum) correlations observed in July indicate a decline in the app's reliability during these months. In practical terms, this means that during July, users should be more cautious in relying solely on the app for critical decisions related to heat stress or outdoor activities. The reduced correlation could be due to various factors, such as higher temperatures or overestimated solar radiation affecting the app algorithm's calculations. For months where we found correlations between the app and monitor, users can have greater confidence in using the app for various purposes, including occupational health and safety, sports training, and public health advisories. However, in months

like July, where the correlation weakened, reliance on the app could lead to overestimation of heat stress risks and implementation of more-than-necessary preventive measures. In the cooler WBGT_{ins} range (<15.0°C and 15.00-19.99°C), the app showed moderate positive correlations with the monitor for the hourly mean. This suggests that while the app was somewhat consistent with the monitor in cooler environments, there were noticeable differences in readings. For the range of 15.00-19.99°C, the daily mean showed a strong correlation between the app and monitor; however, no correlation was observed for the daily maximum, highlighting a specific limitation in capturing peak temperatures in this range. The moderate correlation in cooler ranges indicates that the app is a reasonable tool for general temperature assessments. In warmer ranges (20.00-24.99°C and 25.00-29.99 °C), the app showed a mix of moderate and strong correlations across different measures. The daily mean often showed a strong positive correlation, suggesting better consistency for average temperatures compared to peak or hourly measurements. The variability in correlation strength at warmer temperatures suggests that although the app serves as a useful tool for general assessments, its reliability decreases for specific conditions, particularly in monitoring peak temperature scenarios. Users should be cautious in relying on the app for critical decision-making in environments with warmer temperatures. At high WBGT_{ins} (>30.00°C), the correlation between the app and monitor became weak here, particularly for the hourly and daily mean temperatures. This indicates a significant divergence between the app and the monitor in extreme heat conditions observed in eastern NC during summer 2023. The weak correlation in high temperatures raises concerns about the app's reliability in extreme heat. This has significant implications for safety, especially in outdoor occupational settings where accurate heat stress management is essential. Users should be wary of using the app as a sole source for heat stress monitoring in such conditions and might need to rely on more accurate, specialized equipment WBGT monitor and WBGT app.

The correlation data across WBGT ranges suggests that the app's reliability varies with WBGT indices. It is more consistent with the monitor at lower and moderate temperatures, particularly for average temperature readings, but its reliability decreases significantly in higher temperature ranges.

One potential reason for the app's overestimation of the WBGT index is the value of the solar irradiance used by the app's algorithm. The current algorithm estimates the WBGT from calculated solar irradiance in direct sunlight (i.e., assuming no clouds and a clear sky) using the date, time, and location (i.e., latitude, and longitude). This may explain why the $WBGT_{app}$ is higher than the $WBGT_{ins}$, especially since the estimated solar irradiance is highest in July. To demonstrate, given some constant parameters (i.e., time: 14:00; latitude: 35.6°; longitude: 77.4°), the calculated solar irradiance was 625 W/m² on March 1st, 804 W/m² on May 1st, and 844 W/m² on July 1 (highest). The findings indicate there is a need to adjust the app's algorithm to improve its estimation of WBGT index in hot conditions. Such algorithm adjustment may involve the use of more accurate values for solar irradiation. However, despite the app's overestimation of the WBGT index, the app may still provide sufficient worker protection against heat stress given its more conservative advice on heat exposure.

Overall, data suggest the $WBGT_{app}$ has potential as a tool for monitoring heat stress. Correlation between app and monitor readings under some conditions is promising, but the tendency of the app to predict higher heat stress levels calls for a cautious approach to its deployment in work environments. The WBGT app prototype potentially paves the way to heat stress tools that have the advantage of convenience due to their easier accessibility from portable personal devices. The proliferation of smartphones and tablets allows many users to readily access apps, making it easier to stay informed about potential heat stress risks. Compared to WBGT

monitors, apps tend to be much more affordable. Given these advantages, WBGT apps may be considered as promising tools for occupational heat stress prevention.

Strengths of the Study

A key strength of the study is its extended monitoring period from March to August 2023. This timeframe allowed for a more detailed analysis of heat stress patterns over varying seasonal conditions not limited to the peak summer period. This is the first study evaluating a heat stress app estimating the WBGT index, hence breaking new ground in applying technology to environmental heat stress monitoring. This is important given the increasing reliance on technological solutions for environmental assessment and the need for tools that can provide accurate, real-time data on potentially hazardous conditions like heat stress. This study provides the strengths and limitations of the WBGT app as a promising alternative tool for occupational heat stress prevention, which consequently will be useful in improving the app's algorithm for use in a mobile app in the future.

Limitations of the Study

The app prototype may have limitations in providing accurate WBGT indices due to estimated parameters used in the app's algorithm (e.g., solar irradiance). Moreover, an app prototype that is designed to sense environmental conditions may face challenges in accurately performing its intended function due to the variability in hardware among different smartphones. This is a significant concern in the development of mobile applications that rely on a device's sensors, as smartphones vary widely in terms of the quality and sensitivity of their built-in hardware like cameras, microphones, global positioning systems (GPS), accelerometers, and other sensors. An app that relies on a phone's GPS to provide location-based services could perform differently on various devices, depending on the accuracy of their GPS hardware. When an app

relies on a smartphone's hardware to sense environmental conditions, the developers must account for a wide range of hardware capabilities and limitations. This can be a challenge, especially for apps intended for a broad user base with various phone models.

Another limitation is the study was conducted at only one monitoring site in eastern North Carolina. This limited geographical coverage might restrict the generalizability of the findings to other regions with different weather conditions and geography. To address this limitation and enhance the study's applicability, future research should be conducted in other states or regions with differing weather conditions and geographical features. This expansion would allow for a comparison of how various climatic and topographical factors influence the effectiveness and accuracy of the heat stress app. For instance, conducting the study in areas with extreme weather conditions, like arid deserts or humid tropical regions, could provide insights into the app's reliability under different environmental stressors. Additionally, assessing the app's performance in varied geographical settings, such as urban versus rural areas, and mountainous regions versus plains, could reveal important data about its adaptability and utility in diverse contexts. Implementing a multi-site study design would validate the initial findings and contribute to a more holistic understanding of heat stress patterns across different environmental settings. Also, the WBGT app prototype can be used for outdoor workers.

CHAPTER IX. CONCLUSION

Outdoor workers in eastern NC, , are at significant risk of HRI due to exposure to heat stress, as evidenced by the exceedances of both the TLVs and action limits across various workload categories. This risk is accentuated for those engaged in moderate to heavy workloads, where the percentage of WBGT indices surpassing both TLVs and action limits is markedly higher compared to light workloads. July was the period with the highest risk in this study, showcasing extreme exceedance percentages that suggest almost all workers, regardless of workload intensity, would face dangerous levels of heat stress. Differences in risk levels between the monitoring methods (i.e., WBGT_{ins} and WBGT_{app}) also underscores the variability in assessing heat exposure risks but consistently points towards a risk of HRI across all work categories. It is evident that workers are at substantial risk of HRI, showing the urgent need for enhanced monitoring, preventive measures, and adaptation strategies to mitigate heat stress impacts in the workplace.

The comparison of WBGT values between the WBGT_{ins} and the WBGT_{app} indices reveals notable differences across various conditions and timeframes. While both methods generally followed similar daily patterns, with WBGT values rising to their peak midday and decreasing towards the end, the WBGT_{app} indices consistently reported higher temperatures than the WBGT_{ins} across the monitoring period. Both methods can be useful for monitoring heat stress, but the differences between them should be considered when making decisions on exposure prevention and risk mitigation based on the measurements. Given its tendency to overestimate risk, the app still shows promise in heat stress risk assessment as it shows to be more conservative in protecting workers from heat exposure.

The correlation data between the WBGT_{ins} and the WBGT_{app} indices across different months and WBGT ranges demonstrate generally strong positive correlations for hourly mean,

daily mean, and daily maximum values, particularly in cooler to moderate temperature ranges. These strong correlations indicate a reliable agreement between the two measurement methods under most conditions, suggesting that both tools can be used interchangeably for monitoring heat stress in environments with WBGT indices below 30.00°C.

Here, the app correctly identified 73–88% of minimal risk conditions, depending on workload classification. The app was most reliable in identifying extreme-risk conditions at 97%, 95%, and 93% for light, moderate, and heavy workloads, respectively, demonstrating its capability of protecting workers, particularly for more severe heat stress risk conditions.

Given the percentage of reliability of the app depending on workload type, the use of the WBGT app prototype to assess heat stress risk in the groundskeeping occupation in an eastern North Carolina university setting is appropriate. The performance of the app in assessing risk was demonstrated to be protective of the workers, particularly for all workloads, which is likely performed by groundkeepers. This app is portable, readily accessible, and reliable and can be used by groundkeepers and other similar outdoor workers.

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APPENDIX A: HEAT STRESS MONITORING PROTOCOL

Equipment needed for assembly/disassembly:

- QUESTemp 34 Thermal Environment Monitor
- Tripod
- Distilled Water
- Extra Battery (9V)

Morning Assembly:

1. Assemble the tripod.
 - a. Remove from bag.
 - b. Extend the top part of the tripod legs to their full extent (~3 ft). Make sure that the legs are properly locked in place.
2. Remove the heat stress monitor from its case.
3. Mount the heat stress monitor to the tripod.
 - a. Remove the quick-release plate at the top of the tripod by sliding it off while holding down the red plate release button.
 - b. Attach the quick-release plate to the heat stress monitor by screwing it in to the bottom of the monitor. Hand tighten only.
 - c. Replace the quick-release plate with the monitor attached to the tripod.
 - d. Turn the quick-release plate lock lever on the opposite side of the tripod from the red plate release button to ensure the quick-release plate will no longer move.
 - e. Make sure that the monitor is leveled.
4. Turn the monitor ON.
 - a. Hold down the I/O Enter button.
 - b. When it first comes on, the battery voltage will be displayed. Check to ensure the battery voltage is at least 6.4V. If not, replace the battery before data logging.
 - c. Using the arrow keys, scroll down to SETUP and hit the I/O Enter button. Scroll through to ensure the list looks as follows:
 - i. Celsius - English
 - ii. Time - hour:min:sec
 - iii. DATE - dd-month-yy
 - iv. Log Rate - 1 min
 - v. Heat Index
5. If one of the parameters is incorrect, click the I/O Enter button until it is corrected. Once finished, click the Run Stop button to return to the main menu. Fill the wet bulb thermometer reservoir with distilled water. Moisten the wick and ensure that it is clean. Replace the wick if discolored.
6. Allow the sensors to stabilize to a new environment for 10 minutes.
7. Once it is stabilized, press the Run Stop button to begin logging data. A small asterisk will appear in the bottom right hand corner to indicate data is being logged.
8. Do not stand close to the monitor during the sampling to prevent blocking radiant heat or airflow.

Evening Disassembly:

1. Press the Run Stop button to stop logging data. The asterisk in the bottom right hand corner will disappear to indicate data is no longer being logged.
2. Hold down the I/O Enter button to return to the main menu. A countdown will occur in the bottom right hand corner to indicate 3 seconds until you will be returned to the main menu.
3. Hold down the I/O Enter button again to turn off the heat stress monitor. Again, a countdown will occur in the bottom right hand corner to indicate 3 seconds until the monitor will turn off.
4. Remove the heat stress monitor from the tripod by following step 3a-d under “Morning Assembly” in reverse order.
5. Empty the wet bulb thermometer reservoir of distilled water. Discard used distilled water. Do not pour it back into the bottle of clean distilled water.
6. Replace the heat stress monitor in its case.
7. Disassemble the tripod and return it to its case.

Equipment Needed for Downloading Data:

- Laptop (should have “heat stress monitoring project” on a white piece of paper taped to the left top hand corner of the screen) & laptop charger
- Heat stress monitor
- Black AMP cable in heat stress monitor case (QUEST:054-715)
- Black USB cable (B_USA_151black)

Downloading Data from the Heat Stress Monitor to the Laptop:

1. Connect the laptop to the charger, and log into the laptop (should have “heat stress monitoring project” on a white piece of paper taped to the left top hand corner of the screen). Once logged in, open the detection management software on the desktop.
 - a. Click download on the main window that opens.
 - b. Ensure ‘heat stress’ is highlighted in the top panel on the left-hand side of the window and QT-34 is highlighted in the bottom panel on the same side of the window.
2. Connect the two black cables to each other. Connect the black AMP cable to the heat stress monitor on the left-hand side where it says “data.” Connect the black USB cable to the laptop. The monitor will come on automatically once the USB cable is connected to the laptop.
3. Click download on the software window. A new window will open once the data has finished downloading showing the link to the data. Double click on this to open the data in a new window.
4. In the Add Panel section on the left-hand side of the window, double click ‘Logged Data Table.’
 - a. Click ‘Select All’ in the new window that opens and then close this window.
 - b. Click the save (blue floppy disk icon) button on the new table that appeared in the main window to save the data. Save the file as a .xls file, name it as the day’s date, and save it to the ‘Heat Stress Data’ folder on the desktop.
5. Click on the Instrument Communications tab on the software window. Click clear instrument. Click yes to clear the memory.
6. Exit the detection management software by clicking the red x in the top right-hand corner.
7. Hold down the I/O Enter button for three seconds (you’ll see a 3 second countdown in the bottom right hand corner) to turn the monitor off.
8. Unplug the cord and replace all parts properly back into the case.
9. Return the equipment back to the lab to their proper places.

APPENDIX B: WET BULB GLOBE TEMPERATURE (WBGT) APP PROTOCOL

Equipment needed for accessibility:

- Laptop/ Mobile Phone or Desktop Computer
- Internet

Steps to Access Temperature on WBGT App:

1. Get access to a web browser on a phone, laptop or desktop computer.
2. Launch the WBGT application screen. The following four icons will show: Temperature, Heat Alert, Resources, and About (Figure 1).
3. Click the **Temperature** icon.
4. Enter the zip code '**27858**' and click the submit button.
5. The 'temperature output' (current weather) page (Figure 2) will display the following:
 - a. Current weather: current ambient temperature (i.e., middle data in big text) in °F, humidity in %, and heat index in °F
 - b. Weather forecast: forecasted temperature in °F for the next 12 hours

Steps to Access Heat Alert on WBGT App:

1. Get access to a web browser on a phone, laptop or desktop computer.
2. Launch the WBGT application screen. The following four icons will show: Temperature, Heat Alert, Resources, and About (Figure 1).
3. Click the **Heat Alert** icon.
4. Enter the zip code "**27858**", select **light** workload, and click the submit button.
5. The 'WBGT out' (current heat stress) page (Figure 3) will display the following:
 - a. Current weather: current heat stress risk level (minimal to extreme), ambient temperature in °F, WBGT index in °F

- b. Weather forecast: forecasted temperature in °F, WBGT index in °F, and the associated WBGT risk level for the next 12 hours
6. Take a screenshot of the app output at the start of every hour of the monitored day from 8:00 AM to 5:00 PM.
7. Record the following on the research data sheet:
 - a. Current ambient temp (°F)
 - b. Current WBGT index (°F)
 - c. Current heat stress risk level (minimal to extreme)
8. Click **Heat Alert** icon (!) at the bottom. Enter the zip code, select **moderate** workload, and click the submit button. Repeat steps 5-7.
9. Click **Heat Alert** icon (!) at the bottom. Enter the zip code, select **heavy** workload, and click the submit button. Repeat steps 5-7.



Figure 1. Launch screen

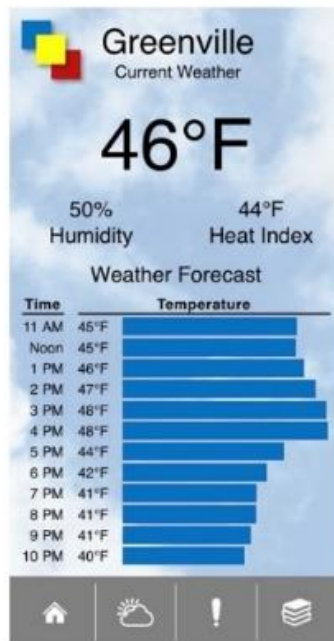


Figure 2. Temperature output



Figure 3. WBGT output

APPENDIX C: STATISTICAL OUTPUT FOR INDEPENDENT SAMPLES T-TESTS

C1. Independent Samples T-test: Overall Hourly Mean

Group Statistics										
		Method	N	Mean	Std. Deviation	Std. Error Mean				
Hourly mean WBGT	App		790	25.6638	5.74948	.20456				
	Monitor		790	24.5802	4.87189	.17333				

Independent Samples Test										
		Levene's Test for Equality of Variances			t-test for Equality of Means					
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower Upper
Hourly mean WBGT	Equal variances assumed	18.450	<.001	4.042	1578	<.001	<.001	1.08367	.26812	.55776 1.60958
	Equal variances not assumed			4.042	1536.606	<.001	<.001	1.08367	.26812	.55775 1.60959

C2. Independent Samples T-test: Overall Daily Mean

Group Statistics										
		Method	N	Mean	Std. Deviation	Std. Error Mean				
Daily_Mean_WBGT	App		81	25.7340	5.26639	.58515				
	Monitor		81	24.6158	4.56672	.50741				

Independent Samples Test										
		Levene's Test for Equality of Variances			t-test for Equality of Means					
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower Upper
Daily_Mean_WBGT	Equal variances assumed	1.769	.185	1.444	160	.075	.151	1.11815	.77452	-.41144 2.64774
	Equal variances not assumed			1.444	156.855	.075	.151	1.11815	.77452	-.41168 2.64797

C3. Independent Samples T-test: Overall Daily Maximum

Group Statistics										
		Method	N	Mean	Std. Deviation	Std. Error Mean				
Daily_Max_WBGT	App		81	28.3995	5.20923	.57880				
	Monitor		81	28.1005	4.42295	.49144				

Independent Samples Test										
		Levene's Test for Equality of Variances			t-test for Equality of Means					
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower Upper
Daily_Max_WBGT	Equal variances assumed	2.729	.101	.394	160	.347	.694	.29901	.75929	-1.20052 1.79854
	Equal variances not assumed			.394	155.899	.347	.694	.29901	.75929	-1.20082 1.79884

C4. Independent Samples T-test: Hourly Mean WBGT for March

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Hourly_mean_WBGT	App	80	19.1254	4.38399	.49014
	Monitor	80	18.7766	3.87652	.43341

Independent Samples Test											
		Levene's Test for Equality of Variances		t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Hourly_mean_WBGT	Equal variances assumed	.232	.631	.533	158	.297	.595	.34875	.65428	-.94352	1.64102
	Equal variances not assumed			.533	155.668	.297	.595	.34875	.65428	-.94367	1.64117

C5. Independent Samples T-test: Hourly Mean WBGT for April

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Hourly_Mean_WBGT	App	120	20.8840	4.89717	.44705
	Monitor	120	20.9552	3.89621	.35567

Independent Samples Test											
		Levene's Test for Equality of Variances		t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Hourly_Mean_WBGT	Equal variances assumed	4.717	.031	-.125	238	.450	.901	-.07125	.57128	-1.19665	1.05415
	Equal variances not assumed			-.125	226.556	.450	.901	-.07125	.57128	-1.19694	1.05444

C6. Independent Samples T-test: Hourly Mean WBGT for May

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Hourly_Mean_WBGT	App	175	22.6129	3.44178	.26017
	Monitor	175	21.8103	2.96765	.22433

Independent Samples Test											
		Levene's Test for Equality of Variances		t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Hourly_Mean_WBGT	Equal variances assumed	3.502	.062	2.336	348	.010	.020	.80257	.34353	.12691	1.47824
	Equal variances not assumed			2.336	340.625	.010	.020	.80257	.34353	.12686	1.47829

C7. Independent Samples T-test: Hourly Mean WBGT for June

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Hourly_mean_WBGT	App	178	27.3875	3.28748	.24641
	Monitor	178	25.6415	2.84857	.21351

Independent Samples Test											
		Levene's Test for Equality of Variances		t-test for Equality of Means							
		F	Sig.	t	df	Significance One-Sided p	Significance Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
Hourly_mean_WBGT	Equal variances assumed	2.634	.106	5.355	354	<.001	<.001	1.74596	.32604	1.10473	2.38718
	Equal variances not assumed			5.355	346.971	<.001	<.001	1.74596	.32604	1.10469	2.38722

C8. Independent Samples T-test: Hourly Mean WBGT for July

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Hourly_mean_WBGT	App	177	31.9365	2.50572	.18834
	Monitor	177	29.7981	1.80344	.13555

Independent Samples Test											
		Levene's Test for Equality of Variances		t-test for Equality of Means							
		F	Sig.	t	df	Significance One-Sided p	Significance Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
Hourly_mean_WBGT	Equal variances assumed	9.310	.002	9.215	352	<.001	<.001	2.13836	.23205	1.68198	2.59474
	Equal variances not assumed			9.215	319.763	<.001	<.001	2.13836	.23205	1.68182	2.59490

C9. Independent Samples T-test: Hourly Mean WBGT for August

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Hourly_mean_WBGT	App	60	29.2223	3.15323	.40708
	Monitor	60	29.1052	2.36601	.30545

Independent Samples Test											
		Levene's Test for Equality of Variances		t-test for Equality of Means							
		F	Sig.	t	df	Significance One-Sided p	Significance Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
Hourly_mean_WBGT	Equal variances assumed	3.093	.081	.230	118	.409	.818	.11717	.50893	-.89066	1.12500
	Equal variances not assumed			.230	109.445	.409	.818	.11717	.50893	-.89148	1.12581

C10. Independent Samples T-test: Daily Mean WGBT for March

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Daily_monthly_mean_WB GT	App		8	19.0725	2.93085	1.03621					
	Monitor		8	18.7988	3.32218	1.17457					

Independent Samples Test											
		Levene's Test for Equality of Variances				t-test for Equality of Means				95% Confidence Interval of the Difference	
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
Daily_monthly_mean_WB GT	Equal variances assumed	.141	.713	.175	14	.432	.864	.27375	1.56632	-3.08566	3.63316
	Equal variances not assumed			.175	13.786	.432	.864	.27375	1.56632	-3.09057	3.63807

C11. Independent Samples T-test: Daily Mean WGBT for April

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Daily_monthly_mean_WB GT	App		12	20.8850	4.05803	1.17145					
	Monitor		12	20.9550	3.33574	.96294					

Independent Samples Test											
		Levene's Test for Equality of Variances				t-test for Equality of Means				95% Confidence Interval of the Difference	
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
Daily_monthly_mean_WB GT	Equal variances assumed	.536	.472	-.046	22	.482	.964	-.07000	1.51643	-3.21488	3.07488
	Equal variances not assumed			-.046	21.206	.482	.964	-.07000	1.51643	-3.22173	3.08173

C12. Independent Samples T-test: Daily Mean WGBT for May

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Daily_monthly_mean_WB GT	App		18	22.5856	2.84886	.67148					
	Monitor		18	21.7772	2.59107	.61072					

Independent Samples Test											
		Levene's Test for Equality of Variances				t-test for Equality of Means				95% Confidence Interval of the Difference	
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
Daily_monthly_mean_WB GT	Equal variances assumed	.492	.488	.891	34	.190	.379	.80833	.90767	-1.03628	2.65295
	Equal variances not assumed			.891	33.699	.190	.379	.80833	.90767	-1.03689	2.65355

C13. Independent Samples T-test: Daily Mean WGBT for June

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Daily_monthly_mean_WB GT	App	18	27.3594	2.51462	.59270
	Monitor	18	25.5917	2.43150	.57311

Independent Samples Test											
		Levene's Test for Equality of Variances		t-test for Equality of Means							
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
Daily_monthly_mean_WB GT	Equal variances assumed	.059	.809	2.144	34	.020	.039	1.76778	.82447	.09225	3.44330
	Equal variances not assumed			2.144	33.962	.020	.039	1.76778	.82447	.09218	3.44337

C14. Independent Samples T-test: Daily Mean WGBT for July

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Daily_monthly_mean_WB GT	App	19	31.9421	1.26582	.29040
	Monitor	19	29.7247	1.17290	.26908

Independent Samples Test											
		Levene's Test for Equality of Variances		t-test for Equality of Means							
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
Daily_monthly_mean_WB GT	Equal variances assumed	.001	.981	5.601	36	<.001	<.001	2.21737	.39590	1.41445	3.02029
	Equal variances not assumed			5.601	35.793	<.001	<.001	2.21737	.39590	1.41428	3.02045

C15. Independent Samples T-test: Daily Mean WGBT for August

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Daily_monthly_mean_WB GT	App	6	29.2233	2.63590	1.07610
	Monitor	6	29.1033	1.94346	.79341

Independent Samples Test											
		Levene's Test for Equality of Variances		t-test for Equality of Means							
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
Daily_monthly_mean_WB GT	Equal variances assumed	.186	.676	.090	10	.465	.930	.12000	1.33698	-2.85897	3.09897
	Equal variances not assumed			.090	9.196	.465	.930	.12000	1.33698	-2.89464	3.13464

C16. Independent Samples T-test: Daily Maximum WGBT for March

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Daily_monthly_max_WBGT	App	8	22.3613	2.68478	.94921
	Monitor	8	22.4225	3.61866	1.27939

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
Daily_monthly_max_WBGT	Equal variances assumed	1.304	.273	-.038	14	.485	.970	-.06125	1.59306	-3.47803	3.35553
	Equal variances not assumed			-.038	12.914	.485	.970	-.06125	1.59306	-3.50518	3.38268

C17. Independent Samples T-test: Daily Maximum WGBT for April

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Daily_monthly_max_WBGT	App	12	23.6575	3.99590	1.15352
	Monitor	12	24.6083	3.55150	1.02523

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
Daily_monthly_max_WBGT	Equal variances assumed	.520	.479	-.616	22	.272	.544	-.95083	1.54327	-4.15139	2.24972
	Equal variances not assumed			-.616	21.701	.272	.544	-.95083	1.54327	-4.15394	2.25228

C18. Independent Samples T-test: Daily Maximum WGBT for May

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Daliy_month_max_WBGT	App	18	25.1072	3.15725	.74417
	Monitor	18	25.5794	2.77691	.65452

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
Daliy_month_max_WBGT	Equal variances assumed	1.429	.240	-.476	34	.318	.637	-.47222	.99106	-2.48629	1.54185
	Equal variances not assumed			-.476	33.455	.318	.637	-.47222	.99106	-2.48750	1.54306

C19. Independent Samples T-test: Daily Maximum WGBT for June

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Daily_monthly_max_WGBT	App	18	29.9128	2.53642	.59784
	Monitor	18	29.0794	2.29139	.54009

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
Daily_monthly_max_WGBT	Equal variances assumed	1.237	.274	1.034	34	.154	.308	.83333	.80567	-.80399	2.47066
	Equal variances not assumed			1.034	33.655	.154	.308	.83333	.80567	-.80461	2.47127

C20. Independent Samples T-test: Daily Maximum WGBT for July

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Daily_monthly_max_WGBT	App	19	34.5905	1.66509	.38200
	Monitor	19	32.8411	1.11064	.25480

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
Daily_monthly_max_WGBT	Equal variances assumed	5.326	.027	3.810	36	<.001	<.001	1.74947	.45918	.81821	2.68073
	Equal variances not assumed			3.810	31.370	<.001	<.001	1.74947	.45918	.81342	2.68553

C21. Independent Samples T-test: Daily Maximum WGBT for August

Group Statistics					
	Method	N	Mean	Std. Deviation	Std. Error Mean
Daily_monthly_max_WGBT	App	6	31.6667	2.27678	.92949
	Monitor	6	32.2700	2.22854	.90980

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
Daily_monthly_max_WGBT	Equal variances assumed	.041	.844	-.464	10	.326	.653	-.60333	1.30065	-3.50136	2.29469
	Equal variances not assumed			-.464	9.995	.326	.653	-.60333	1.30065	-3.50154	2.29487

C22. Independent Samples T-test: Hourly Mean WBGT for WBGT >15.00°C

Group Statistics

	Method	N	Mean	Std. Deviation	Std. Error Mean
Hourly_ave_WBGT	Monitor	26	13.6285	1.61497	.31672
	App	26	13.9319	4.16354	.81654

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						95% Confidence Interval of the Difference	
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
Hourly_ave_WBGT	Equal variances assumed	19.230	<.001	-.346	50	.365	.730	-.30346	.87581	-2.06258	1.45566
	Equal variances not assumed			-.346	32.356	.366	.731	-.30346	.87581	-2.08666	1.47974

C23. Independent Samples T-test: Hourly Mean WBGT for WBGT 15.00-19.99 °C

Group Statistics

	Method	N	Mean	Std. Deviation	Std. Error Mean
Hourly_ave_WBGT	Monitor	129	17.9302	1.36197	.11992
	App	129	18.0019	2.50432	.22049

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						95% Confidence Interval of the Difference	
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
Hourly_ave_WBGT	Equal variances assumed	21.461	<.001	-.286	256	.388	.775	-.07171	.25099	-.56598	.42257
	Equal variances not assumed			-.286	197.627	.388	.775	-.07171	.25099	-.56667	.42326

C24. Independent Samples T-test: Hourly Mean WBGT for WBGT 20.00-24.99 °C

Group Statistics

	Method	N	Mean	Std. Deviation	Std. Error Mean
Hourly_ave_WBGT	Monitor	244	22.7250	1.43504	.09187
	App	244	23.6818	2.30997	.14788

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						95% Confidence Interval of the Difference	
		F	Sig.	t	df	Significance One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
Hourly_ave_WBGT	Equal variances assumed	39.578	<.001	-5.496	486	<.001	<.001	-.95680	.17409	-1.29887	-.61473
	Equal variances not assumed			-5.496	406.249	<.001	<.001	-.95680	.17409	-1.29904	-.61457

C25. Independent Samples T-test: Hourly Mean WBGT for WBGT 25.00-29.99 °C

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Hourly_ave_WBGT	Monitor		265	27.4668	1.40265	.08616					
	App		265	28.9830	2.52844	.15532					

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Hourly_ave_WBGT	Equal variances assumed	87.759	<.001	-8.536	528	<.001	<.001	-1.51619	.17762	-1.86512	-1.16726
	Equal variances not assumed			-8.536	412.433	<.001	<.001	-1.51619	.17762	-1.86534	-1.16704

C26. Independent Samples T-test: Hourly Mean WBGT for WBGT >30.00°C

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Hourly_ave_WBGT	Monitor		126	31.1698	.70518	.06282					
	App		126	32.7866	1.87383	.16693					

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Hourly_ave_WBGT	Equal variances assumed	42.434	<.001	-9.064	250	<.001	<.001	-1.61675	.17836	-1.96803	-1.26546
	Equal variances not assumed			-9.064	159.709	<.001	<.001	-1.61675	.17836	-1.96900	-1.26449

C27. Independent Samples T-test: Daily Mean WBGT for WBGT >15.00°C

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Daily_ave_WBGT	Monitor		1	13.2100	.	.					
	App		1	16.6700	.	.					

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Daily_ave_WBGT	Equal variances assumed	.	.	.	0	.	.	-3.46000	.	.	.
	Equal variances not assumed			.	.	.	.	-3.46000	.	.	.

C28. Independent Samples T-test: Daily Mean WGBT for WGBT 15.00-19.99 °C

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Daily_ave_WGBT	Monitor		13	17.8369	1.37569	.38155					
	App		13	17.6954	1.95160	.54128					

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Daily_ave_WGBT	Equal variances assumed	.230	.636	.214	24	.416	.833	.14154	.66224	-1.22525	1.50833
	Equal variances not assumed			.214	21.564	.416	.833	.14154	.66224	-1.23347	1.51655

C29. Independent Samples T-test: Daily Mean WGBT for WGBT 20.00-24.99 °C

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Daily_ave_WGBT	Monitor		28	22.6304	1.39919	.26442					
	App		28	23.5168	1.89826	.35874					

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Daily_ave_WGBT	Equal variances assumed	2.644	.110	-1.989	54	.026	.052	-.88643	.44566	-1.77992	.00706
	Equal variances not assumed			-1.989	49.652	.026	.052	-.88643	.44566	-1.78172	.00886

C30. Independent Samples T-test: Daily Mean WGBT for WGBT 25.00-29.99 °C

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Daily_ave_WGBT	Monitor		26	27.5900	1.51992	.29808					
	App		26	29.2865	2.31073	.45317					

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Daily_ave_WGBT	Equal variances assumed	4.384	.041	-3.128	50	.001	.003	-1.69654	.54242	-2.78602	-.60706
	Equal variances not assumed			-3.128	43.222	.002	.003	-1.69654	.54242	-2.79027	-.60281

C31. Independent Samples T-test: Daily Mean WGBT for WGBT >30.00°C

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Daily_ave_WBGT	Monitor		13	30.6000	.37419	.10378					
	App		13	32.1400	1.31778	.36549					

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Daily_ave_WBGT	Equal variances assumed	5.841	.024	-4.053	24	<.001	<.001	-1.54000	.37993	-2.32415	-.75585
	Equal variances not assumed			-4.053	13.923	<.001	.001	-1.54000	.37993	-2.35530	-.72470

C32. Independent Samples T-test: Daily Maximum WGBT for WGBT 15.00-19.99 °C

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Daily_max_WBGT	Monitor		6	18.9550	1.24860	.50974					
	App		6	18.9983	1.66304	.67893					

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Daily_max_WBGT	Equal variances assumed	.088	.772	-.051	10	.480	.960	-.04333	.84899	-1.93500	1.84833
	Equal variances not assumed			-.051	9.278	.480	.960	-.04333	.84899	-1.95515	1.86849

C33. Independent Samples T-test: Daily Maximum WGBT for WGBT 20.00-24.99 °C

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Daily_max_WBGT	Monitor		11	22.9782	1.35625	.40893					
	App		11	22.4300	2.23436	.67369					

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Daily_max_WBGT	Equal variances assumed	1.033	.322	.696	20	.247	.495	.54818	.78808	-1.09573	2.19209
	Equal variances not assumed			.696	16.488	.248	.496	.54818	.78808	-1.11847	2.21483

C34. Independent Samples T-test: Daily Maximum WGBT for WGBT 25.00-29.99 °C

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Daily_max_WGBT	Monitor		33	27.3191	1.54512	.26897					
	App		33	27.3124	2.54742	.44345					

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Daily_max_WGBT	Equal variances assumed	1.460	.231	.013	64	.495	.990	.00667	.51864	-1.02945	1.04278
	Equal variances not assumed			.013	52.738	.495	.990	.00667	.51864	-1.03372	1.04706

C35. Independent Samples T-test: Daily Maximum WGBT for WGBT >30.00°C

Group Statistics											
		Method	N	Mean	Std. Deviation	Std. Error Mean					
Daily_max_WGBT	Monitor		31	32.5200	1.24245	.22315					
	App		31	33.4945	2.10926	.37883					

Independent Samples Test											
Levene's Test for Equality of Variances				t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Daily_max_WGBT	Equal variances assumed	6.926	.011	-2.216	60	.015	.030	-.97452	.43967	-1.85399	-.09504
	Equal variances not assumed			-2.216	48.582	.016	.031	-.97452	.43967	-1.85826	-.09077

APPENDIX D: STATISTICAL OUTPUT FOR PEARSON CORRELATION TESTS

D1. Pearson Correlation Test: Overall Hourly Mean WBGT

Descriptive Statistics

	Mean	Std. Deviation	N
WBGT_M	24.5802	4.87189	790
WBGT_A	25.6638	5.74948	790

Correlations

		WBGT_M	WBGT_A
WBGT_M	Pearson Correlation	1	.940**
	Sig. (2-tailed)		<.001
	N	790	790
WBGT_A	Pearson Correlation	.940**	1
	Sig. (2-tailed)	<.001	
	N	790	790

** . Correlation is significant at the 0.01 level (2-tailed).

D2. Pearson Correlation Test: Overall Daily Mean WBGT

Descriptive Statistics

	Mean	Std. Deviation	N
Daily Mean WBGT M	24.6158	4.56672	81
Daily Mean WBGT A	25.7340	5.26639	81

Correlations

		Daily Mean WBGT M	Daily Mean WBGT A
Daily Mean WBGT M	Pearson Correlation	1	.967**
	Sig. (2-tailed)		<.001
	N	81	81
Daily Mean WBGT A	Pearson Correlation	.967**	1
	Sig. (2-tailed)	<.001	
	N	81	81

** . Correlation is significant at the 0.01 level (2-tailed).

D3. Pearson Correlation Test: Overall Daily Maximum Mean WBGT

Descriptive Statistics

	Mean	Std. Deviation	N
Daily Max WBGT M	28.10	4.423	81
Daily Max WBGT A	28.40	5.209	81

Correlations

		Daily Max WBGT M	Daily Max WBGT A
Daily Max WBGT M	Pearson Correlation	1	.939**
	Sig. (2-tailed)		<.001
	N	81	81
Daily Max WBGT A	Pearson Correlation	.939**	1
	Sig. (2-tailed)	<.001	
	N	81	81

** . Correlation is significant at the 0.01 level (2-tailed).

D4. Pearson Correlation Test: Hourly Mean WBGT for March

Descriptive Statistics

	Mean	Std. Deviation	N
WBGT_M	18.7766	3.87652	80
WBGT_A	19.1254	4.38399	80

Correlations

		WBGT_M	WBGT_A
WBGT_M	Pearson Correlation	1	.831**
	Sig. (2-tailed)		<.001
	N	80	80
WBGT_A	Pearson Correlation	.831**	1
	Sig. (2-tailed)	<.001	
	N	80	80

** . Correlation is significant at the 0.01 level (2-tailed).

D5. Pearson Correlation Test: Hourly Mean WGBT for April

Descriptive Statistics

	Mean	Std. Deviation	N
WGBT_M	20.9553	3.89621	120
WGBT_A	20.8840	4.89717	120

Correlations

		WGBT_M	WGBT_A
WGBT_M	Pearson Correlation	1	.961**
	Sig. (2-tailed)		<.001
	N	120	120
WGBT_A	Pearson Correlation	.961**	1
	Sig. (2-tailed)	<.001	
	N	120	120

** . Correlation is significant at the 0.01 level (2-tailed).

D6. Pearson Correlation Test: Hourly Mean WGBT for May

Descriptive Statistics

	Mean	Std. Deviation	N
WGBT_M	21.8103	2.96765	175
WGBT_A	22.6129	3.44178	175

Correlations

		WGBT_M	WGBT_A
WGBT_M	Pearson Correlation	1	.840**
	Sig. (2-tailed)		<.001
	N	175	175
WGBT_A	Pearson Correlation	.840**	1
	Sig. (2-tailed)	<.001	
	N	175	175

** . Correlation is significant at the 0.01 level (2-tailed).

D7. Pearson Correlation Test: Hourly Mean WGBT for June

Descriptive Statistics

	Mean	Std. Deviation	N
WGBT_M	25.6415	2.84857	178
WGBT_A	27.3875	3.28748	178

Correlations

		WGBT_M	WGBT_A
WGBT_M	Pearson Correlation	1	.852**
	Sig. (2-tailed)		<.001
	N	178	178
WGBT_A	Pearson Correlation	.852**	1
	Sig. (2-tailed)	<.001	
	N	178	178

** Correlation is significant at the 0.01 level (2-tailed).

D8. Pearson Correlation Test: Hourly Mean WGBT for July

Descriptive Statistics

	Mean	Std. Deviation	N
WGBT_M	29.7981	1.80344	177
WGBT_A	31.9365	2.50572	177

Correlations

		WGBT_M	WGBT_A
WGBT_M	Pearson Correlation	1	.631**
	Sig. (2-tailed)		<.001
	N	177	177
WGBT_A	Pearson Correlation	.631**	1
	Sig. (2-tailed)	<.001	
	N	177	177

** Correlation is significant at the 0.01 level (2-tailed).

D9. Pearson Correlation Test: Hourly Mean WGBT for August**Descriptive Statistics**

	Mean	Std. Deviation	N
WGBT_M	29.1052	2.36601	60
WGBT_A	29.2223	3.15323	60

Correlations

		WGBT_M	WGBT_A
WGBT_M	Pearson Correlation	1	.888**
	Sig. (2-tailed)		<.001
	N	60	60
WGBT_A	Pearson Correlation	.888**	1
	Sig. (2-tailed)	<.001	
	N	60	60

** . Correlation is significant at the 0.01 level (2-tailed).

D10. Pearson Correlation Test: Daily Mean WGBT for March**Descriptive Statistics**

	Mean	Std. Deviation	N
Daily_Ave_WBGT_M	18.7988	3.32218	8
Daily_Ave_WBGT_A	19.0725	2.93085	8

Correlations

		Daily_Ave_WBGT_M	Daily_Ave_WBGT_A
Daily_Ave_WBGT_M	Pearson Correlation	1	.873**
	Sig. (2-tailed)		.005
	N	8	8
Daily_Ave_WBGT_A	Pearson Correlation	.873**	1
	Sig. (2-tailed)	.005	
	N	8	8

** . Correlation is significant at the 0.01 level (2-tailed).

D11. Pearson Correlation Test: Daily Mean WBGT for April

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_Ave_WBGT_M	20.9550	3.33574	12
Daily_Ave_WBGT_A	20.8850	4.05803	12

Correlations

		Daily_Ave_WB GT_M	Daily_Ave_WB GT_A
Daily_Ave_WBGT_M	Pearson Correlation	1	.980**
	Sig. (2-tailed)		<.001
	N	12	12
Daily_Ave_WBGT_A	Pearson Correlation	.980**	1
	Sig. (2-tailed)	<.001	
	N	12	12

** . Correlation is significant at the 0.01 level (2-tailed).

D12. Pearson Correlation Test: Daily Mean WBGT for May

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_Ave_WBGT_M	21.7772	2.59107	18
Daily_Ave_WBGT_A	22.5856	2.84886	18

Correlations

		Daily_Ave_WB GT_M	Daily_Ave_WB GT_A
Daily_Ave_WBGT_M	Pearson Correlation	1	.896**
	Sig. (2-tailed)		<.001
	N	18	18
Daily_Ave_WBGT_A	Pearson Correlation	.896**	1
	Sig. (2-tailed)	<.001	
	N	18	18

** . Correlation is significant at the 0.01 level (2-tailed).

D13. Pearson Correlation Test: Daily Mean WBGT for June

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_Ave_WBGT_M	25.5917	2.43150	18
Daily_Ave_WBGT_A	27.3594	2.51462	18

Correlations

		Daily_Ave_WB GT_M	Daily_Ave_WB GT_A
Daily_Ave_WBGT_M	Pearson Correlation	1	.923**
	Sig. (2-tailed)		<.001
	N	18	18
Daily_Ave_WBGT_A	Pearson Correlation	.923**	1
	Sig. (2-tailed)	<.001	
	N	18	18

** . Correlation is significant at the 0.01 level (2-tailed).

D14. Pearson Correlation Test: Daily Mean WBGT for July

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_Ave_WBGT_M	29.7247	1.17290	19
Daily_Ave_WBGT_A	31.9421	1.26582	19

Correlations

		Daily_Ave_WB GT_M	Daily_Ave_WB GT_A
Daily_Ave_WBGT_M	Pearson Correlation	1	.522*
	Sig. (2-tailed)		.022
	N	19	19
Daily_Ave_WBGT_A	Pearson Correlation	.522*	1
	Sig. (2-tailed)	.022	
	N	19	19

*. Correlation is significant at the 0.05 level (2-tailed).

D15. Pearson Correlation Test: Daily Mean WBGT for August

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_Ave_WBGT_M	29.1033	1.94346	6
Daily_Ave_WBGT_A	29.2233	2.63590	6

Correlations

		Daily_Ave_WBGT_M	Daily_Ave_WBGT_A
Daily_Ave_WBGT_M	Pearson Correlation	1	.948**
	Sig. (2-tailed)		.004
	N	6	6
Daily_Ave_WBGT_A	Pearson Correlation	.948**	1
	Sig. (2-tailed)	.004	
	N	6	6

** . Correlation is significant at the 0.01 level (2-tailed).

D16. Pearson Correlation Test: Daily Maximum WBGT for March

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_Max_WBGT_M	22.4225	3.61866	8
Daily_Max_WBGT_A	22.3613	2.68478	8

Correlations

		Daily_Max_WBGT_M	Daily_Max_WBGT_A
Daily_Max_WBGT_M	Pearson Correlation	1	.854**
	Sig. (2-tailed)		.007
	N	8	8
Daily_Max_WBGT_A	Pearson Correlation	.854**	1
	Sig. (2-tailed)	.007	
	N	8	8

** . Correlation is significant at the 0.01 level (2-tailed).

D17. Pearson Correlation Test: Daily Maximum WGBT for April

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_Max_WBGT_M	24.6083	3.55150	12
Daily_Max_WBGT_A	23.6575	3.99590	12

Correlations

		Daily_Max_WBGT_M	Daily_Max_WBGT_A
Daily_Max_WBGT_M	Pearson Correlation	1	.972**
	Sig. (2-tailed)		<.001
	N	12	12
Daily_Max_WBGT_A	Pearson Correlation	.972**	1
	Sig. (2-tailed)	<.001	
	N	12	12

** . Correlation is significant at the 0.01 level (2-tailed).

D18. Pearson Correlation Test: Daily Maximum WGBT for May

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_Max_WBGT_M	25.5794	2.77691	18
Daily_Max_WBGT_A	25.1072	3.15725	18

Correlations

		Daily_Max_WBGT_M	Daily_Max_WBGT_A
Daily_Max_WBGT_M	Pearson Correlation	1	.848**
	Sig. (2-tailed)		<.001
	N	18	18
Daily_Max_WBGT_A	Pearson Correlation	.848**	1
	Sig. (2-tailed)	<.001	
	N	18	18

** . Correlation is significant at the 0.01 level (2-tailed).

D19. Pearson Correlation Test: Daily Maximum WGBT for June

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_Max_WBGT_M	29.0794	2.29139	18
Daily_Max_WBGT_A	29.9128	2.53642	18

Correlations

		Daily_Max_WBGT_M	Daily_Max_WBGT_A
Daily_Max_WBGT_M	Pearson Correlation	1	.711**
	Sig. (2-tailed)		<.001
	N	18	18
Daily_Max_WBGT_A	Pearson Correlation	.711**	1
	Sig. (2-tailed)	<.001	
	N	18	18

** . Correlation is significant at the 0.01 level (2-tailed).

D20. Pearson Correlation Test: Daily Maximum WGBT for July

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_Max_WBGT_M	32.8411	1.11064	19
Daily_Max_WBGT_A	34.5905	1.66509	19

Correlations

		Daily_Max_WBGT_M	Daily_Max_WBGT_A
Daily_Max_WBGT_M	Pearson Correlation	1	.454
	Sig. (2-tailed)		.051
	N	19	19
Daily_Max_WBGT_A	Pearson Correlation	.454	1
	Sig. (2-tailed)	.051	
	N	19	19

D21. Pearson Correlation Test: Daily Maximum WBGT for August

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_Max_WBGT_M	32.2700	2.22854	6
Daily_Max_WBGT_A	31.6667	2.27678	6

Correlations

		Daily_Max_WBGT_M	Daily_Max_WBGT_A
Daily_Max_WBGT_M	Pearson Correlation	1	.834 [*]
	Sig. (2-tailed)		.039
	N	6	6
Daily_Max_WBGT_A	Pearson Correlation	.834 [*]	1
	Sig. (2-tailed)	.039	
	N	6	6

*. Correlation is significant at the 0.05 level (2-tailed).

D22. Pearson Correlation Test: Hourly Mean WBGT for WBGT >15.00°C

Descriptive Statistics

	Mean	Std. Deviation	N
WBGT_M	13.6285	1.61497	26
WBGT_A	13.9319	4.16354	26

Correlations

		WBGT_M	WBGT_A
WBGT_M	Pearson Correlation	1	.573 ^{**}
	Sig. (2-tailed)		.002
	N	26	26
WBGT_A	Pearson Correlation	.573 ^{**}	1
	Sig. (2-tailed)	.002	
	N	26	26

** Correlation is significant at the 0.01 level (2-tailed).

D23. Pearson Correlation Test: Hourly Mean WGBT for WGBT 15.00-19.99 °C

Descriptive Statistics

	Mean	Std. Deviation	N
WGBT_M	17.9302	1.36197	129
WGBT_A	18.0019	2.50432	129

Correlations

		WGBT_M	WGBT_A
WGBT_M	Pearson Correlation	1	.679**
	Sig. (2-tailed)		<.001
	N	129	129
WGBT_A	Pearson Correlation	.679**	1
	Sig. (2-tailed)	<.001	
	N	129	129

** . Correlation is significant at the 0.01 level (2-tailed).

D24. Pearson Correlation Test: Hourly Mean WGBT for WGBT 20.00-24.99 °C

Descriptive Statistics

	Mean	Std. Deviation	N
WGBT_M	22.7250	1.43504	244
WGBT_A	23.6818	2.30997	244

Correlations

		WGBT_M	WGBT_A
WGBT_M	Pearson Correlation	1	.552**
	Sig. (2-tailed)		<.001
	N	244	244
WGBT_A	Pearson Correlation	.552**	1
	Sig. (2-tailed)	<.001	
	N	244	244

** . Correlation is significant at the 0.01 level (2-tailed).

D25. Pearson Correlation Test: Hourly Mean WGBT for WGBT 25.00-29.99 °C**Descriptive Statistics**

	Mean	Std. Deviation	N
WGBT_M	27.4668	1.40265	265
WGBT_A	28.9830	2.52844	265

Correlations

		WGBT_M	WGBT_A
WGBT_M	Pearson Correlation	1	.655**
	Sig. (2-tailed)		<.001
	N	265	265
WGBT_A	Pearson Correlation	.655**	1
	Sig. (2-tailed)	<.001	
	N	265	265

** . Correlation is significant at the 0.01 level (2-tailed).

D26. Pearson Correlation Test: Hourly Mean WGBT for WGBT >30.00°C**Descriptive Statistics**

	Mean	Std. Deviation	N
WGBT_M	31.1698	.70518	126
WGBT_A	32.7866	1.87383	126

Correlations

		WGBT_M	WGBT_A
WGBT_M	Pearson Correlation	1	.360**
	Sig. (2-tailed)		<.001
	N	126	126
WGBT_A	Pearson Correlation	.360**	1
	Sig. (2-tailed)	<.001	
	N	126	126

** . Correlation is significant at the 0.01 level (2-tailed).

D27. Pearson Correlation Test: Daily Mean WBGT for WBGT >15.00°C

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_ave_WBGT_M	13.2100	.	1
Daily_ave_WBGT_A	16.6700	.	1

Correlations

		Daily_ave_WBGT_M	Daily_ave_WBGT_A
Daily_ave_WBGT_M	Pearson Correlation	. ^a	. ^a
	Sig. (2-tailed)	.	.
	N	1	1
Daily_ave_WBGT_A	Pearson Correlation	. ^a	. ^a
	Sig. (2-tailed)	.	.
	N	1	1

a. Cannot be computed because at least one of the variables is constant.

D28. Pearson Correlation Test: Daily Mean WBGT for WBGT 15.00-19.99 °C

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_ave_WBGT_M	17.8369	1.37569	13
Daily_ave_WBGT_A	17.6954	1.95160	13

Correlations

		Daily_ave_WBGT_M	Daily_ave_WBGT_A
Daily_ave_WBGT_M	Pearson Correlation	1	.832 ^{**}
	Sig. (2-tailed)		<.001
	N	13	13
Daily_ave_WBGT_A	Pearson Correlation	.832 ^{**}	1
	Sig. (2-tailed)	<.001	
	N	13	13

^{**}. Correlation is significant at the 0.01 level (2-tailed).

D29. Pearson Correlation Test: Daily Mean WBGT for WBGT 20.00-24.99 °C**Descriptive Statistics**

	Mean	Std. Deviation	N
Daily_ave_WBGT_M	22.6304	1.39919	28
Daily_ave_WBGT_A	23.5168	1.89826	28

Correlations

		Daily_ave_WBGT_M	Daily_ave_WBGT_A
Daily_ave_WBGT_M	Pearson Correlation	1	.712**
	Sig. (2-tailed)		<.001
	N	28	28
Daily_ave_WBGT_A	Pearson Correlation	.712**	1
	Sig. (2-tailed)	<.001	
	N	28	28

** . Correlation is significant at the 0.01 level (2-tailed).

D30. Pearson Correlation Test: Daily Mean WBGT for WBGT 25.00-29.99 °C**Descriptive Statistics**

	Mean	Std. Deviation	N
Daily_ave_WBGT_M	27.5900	1.51992	26
Daily_ave_WBGT_A	29.2865	2.31073	26

Correlations

		Daily_ave_WBGT_M	Daily_ave_WBGT_A
Daily_ave_WBGT_M	Pearson Correlation	1	.849**
	Sig. (2-tailed)		<.001
	N	26	26
Daily_ave_WBGT_A	Pearson Correlation	.849**	1
	Sig. (2-tailed)	<.001	
	N	26	26

** . Correlation is significant at the 0.01 level (2-tailed).

D31. Pearson Correlation Test: Daily Mean WBGT for WBGT >30.00°C

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_ave_WBGT_M	30.6000	.37419	13
Daily_ave_WBGT_A	32.1400	1.31778	13

Correlations

		Daily_ave_WBGT_M	Daily_ave_WBGT_A
Daily_ave_WBGT_M	Pearson Correlation	1	.088
	Sig. (2-tailed)		.776
	N	13	13
Daily_ave_WBGT_A	Pearson Correlation	.088	1
	Sig. (2-tailed)	.776	
	N	13	13

D32. Pearson Correlation Test: Daily Maximum WBGT for WBGT 15.00-19.99 °C

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_ave_WBGT_M	18.9550	1.24860	6
Daily_ave_WBGT_A	18.9983	1.66304	6

Correlations

		Daily_ave_WBGT_M	Daily_ave_WBGT_A
Daily_ave_WBGT_M	Pearson Correlation	1	-.354
	Sig. (2-tailed)		.492
	N	6	6
Daily_ave_WBGT_A	Pearson Correlation	-.354	1
	Sig. (2-tailed)	.492	
	N	6	6

D33. Pearson Correlation Test: Daily Maximum WBGT for WBGT 20.00-24.99 °C

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_max_WBGT_M	22.9782	1.35625	11
Daily_max_WBGT_A	22.4300	2.23436	11

Correlations

		Daily_max_WBGT_M	Daily_max_WBGT_A
Daily_max_WBGT_M	Pearson Correlation	1	.635*
	Sig. (2-tailed)		.036
	N	11	11
Daily_max_WBGT_A	Pearson Correlation	.635*	1
	Sig. (2-tailed)	.036	
	N	11	11

*. Correlation is significant at the 0.05 level (2-tailed).

D34. Pearson Correlation Test: Daily Maximum WBGT for WBGT 25.00-29.99 °C

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_max_WBGT_M	27.3191	1.54512	33
Daily_max_WBGT_A	27.3124	2.54742	33

Correlations

		Daily_max_WBGT_M	Daily_max_WBGT_A
Daily_max_WBGT_M	Pearson Correlation	1	.688**
	Sig. (2-tailed)		<.001
	N	33	33
Daily_max_WBGT_A	Pearson Correlation	.688**	1
	Sig. (2-tailed)	<.001	
	N	33	33

** . Correlation is significant at the 0.01 level (2-tailed).

D35. Pearson Correlation Test: Daily Maximum WGBT for WGBT >30.00°C

Descriptive Statistics

	Mean	Std. Deviation	N
Daily_max_WGBT_M	32.5200	1.24245	31
Daily_max_WGBT_A	33.4945	2.10926	31

Correlations

		Daily_max_WB GT_M	Daily_max_WB GT_A
Daily_max_WGBT_M	Pearson Correlation	1	.644**
	Sig. (2-tailed)		<.001
	N	31	31
Daily_max_WGBT_A	Pearson Correlation	.644**	1
	Sig. (2-tailed)	<.001	
	N	31	31

** . Correlation is significant at the 0.01 level (2-tailed).