Athletic Surfaces' Influence on the Thermal Environment: An Evaluation of Wet Bulb Globe Temperature in the Phoenix Metropolitan Area

by

Haven Guyer

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Arts

Approved April 2020 by the
Graduate Supervisory Committee:

Jennifer Vanos, Co-Chair
Matei Georgescu, Co-Chair
David Hondula

ARIZONA STATE UNIVERSITY

May 2020

ABSTRACT

Exertional heat stroke continues to be one of the leading causes of illness and death in sport in the United States, with an athlete's experienced microclimate varying by venue design and location. A limited number of studies have attempted to determine the relationship between observed wet bulb globe temperature (WBGT) and WBGT derived from regional weather station data. Moreover, only one study has quantified the relationship between regionally modeled and on-site measured WBGT over different athletic surfaces (natural grass, rubber track, and concrete tennis court). The current research expands on previous studies to examine how different athletic surfaces influence the thermal environment in the Phoenix Metropolitan Area using a combination of fieldwork, modeling, and statistical analysis. Meteorological data were collected from 0700–1900hr across 6 days in June and 5 days in August 2019 in Tempe, Arizona at various Sun Devil Athletics facilities. This research also explored the influence of surface temperatures on WBGT and the changes projected under a future warmer climate. Results indicate that based on American College of Sports Medicine guidelines practice would not be cancelled in June (WBGT≥32.3°C); however, in August, ~33% of practice time was lost across multiple surfaces. The second-tier recommendations (WBGT≥30.1°C) to limit intense exercise were reached an average of 7 hours each day for all surfaces in August. Further, WBGT was calculated using data from four Arizona Meteorological Network (AZMET) weather stations to provide regional WBGT values for comparison. The on-site (field/court) WBGT values were consistently higher than regional values and significantly different ($p<0.05$). Thus, using regionally-modeled WBGT data to guide activity or clothing modification for heat safety may lead to misclassification and unsafe conditions. Surface temperature measurements indicate a maximum temperature (170°F) occurring around solar noon, yet WBGT reached its highest level mid-afternoon and on the artificial turf surface (2–5PM). Climate projections show that WBGT values are expected to rise, further restricting the amount of practice and games than can take place outdoors during the afternoon. The findings from this study can be used to inform athletic trainers and coaches about the thermal environment through WBGT values on-field.

ACKNOWLEDGMENTS

First and foremost, I would like to thank my committee Dr. Jenni Vanos, Dr. Matei Georgescu, and Dr. David Hondula. I am so grateful for all of their support and guidance throughout this learning process. Thank you to Dr. Floris Wardenaar for being the liaison between Sun Devil Athletics and myself and helping me navigate conducting research within our athletics department. Thank you to Dr. Ash Broadbent for personally helping me with the climate projections. I am also grateful for each and every one of my volunteers that helped me out during data collection this past summer; Manny, Jenna, Alyssa, Ryan, Edward, Jamie, Jianni, and Claire this project absolutely would not have been possible without all of your help. I would also like to acknowledge my support system first in foremost Zee and Rebecca, thank you for helping me navigate my first experience with graduate school I never would've made it this far without your help. Second, thank you to my friends and family for all of the support. Finally, I would like to thank GPSA and Sundevil Athletics for funding my project. Each of these people were an absolutely integral part of completing my research, and it simply would not have been possible without them.

TABLE OF CONTENTS

CHAPTER Page

APPENDIX

LIST OF TABLES

Table Page

LIST OF FIGURES

LIST OF PHOTOS

CHAPTER 1

INTRODUCTION AND BACKGROUND

Heat stress is an important health challenge, particularly in the southwestern United States, and The State of Arizona experiences some of the highest rates of heat-related illness and death (Garfin et al., 2014). With air temperatures expected to rise in the southwest (Garfin et al., 2014) and given the vulnerability of youth, college, and professional athletes to extreme heat (Lopez & Jardine, 2018), various heat adaptations are required to prepare the sporting community to ensure that outdoor sports can still be performed when needed. Heat can also increase the risk of dehydration, reduce athletic performance (Casa et al., 2000), and result in practice schedules being changed or moved to indoor locations.

Currently, no state in the U.S. southwest (AZ, NM, CO, UT, CA, and NV) requires exertional heat preparedness policies for high schools (KSI, 2018). These life-saving policies include having an ice tub onside for cold-water immersion of players who are experiencing exertional heat stroke, using on-site wet bulb globe temperature (WBGT) monitoring, and having an athletic trainer or a sports medicine professional present on the field during competitions and training (KSI, 2018). Oppressively hot outdoor environments are particularly dangerous for humans. Heat related illness occurs when the body is not able to cool itself properly, which can ultimately lead to heat-related death. Exertional heat illness (EHI) differs from classical heat stroke in that it usually occurs in young, healthy, and fit people while they are exercising (Leon & Bouchama, 2015). People begin to experience the symptoms of heat *illness* when core temperature (T_{core}) begins to rise faster than the body can expel heat (Marshall, 2010), which indicates that strain is occurring in the body. The T_{core} threshold for exertional heat stroke (EHS) is >40°C (Armstrong et al., 2007). At this T_{core} value, contacting emergency services for medical assistance is recommended (Marshall, 2010) and *"cool first, transport second"* procedures should be followed (Belval et al., 2018), as waiting to cool could mean death or long-term organ damage. It is important to note that EHI and EHS are entirely preventable with appropriate preparedness yet remain a major issue with high environmental risks in the southwest (Garfin et al., 2014).

Environmental Considerations and Athletic Microclimates

Air temperature and relative humidity are important environmental risk factors for EHI (Armstrong et al., 2007; Marshall, 2010), yet windspeed and radiation are important considerations to the human heat balance (i.e., affecting radiative heat gain and evaporative or convective heat losses, respectively) (McGregor & Vanos, 2018). The location, surface materials, and design of a venue can also influence the micro-environment that athletes are experiencing. Different types of athletic surfaces have specific thermodynamic properties, which influence their surface temperature (and thus emitted infrared radiation towards an athlete), thermal admittance, and moisture level, all affecting the environment over the surface. The surface moisture can affect air temperature (via evapotranspiration) as well as localized humidity. The design of a venue also affects the microclimate through shading and shielding from the wind. Because of these design differences, there can be discrepancies in atmospheric conditions between a regional weather station and the local on-site conditions. The possible differences in the thermal and radiative environments can impact the levels of heat that athletes are exposed to during competition and training, potentially leading to a higher risk of heat-related illness (Pryor et al., 2017). Surface material influences and the design of a venue justifies why it is essential to take measurements at the actual location versus relying on a distant weather station or a forecast.

Current guidelines from the National Athletic Trainers' Association (NATA) note that high humidity can play a significant role in increasing the risk of heat-related illness when practicing outdoor sports (Casa et al., 2009). NATA recommends that temperature and humidity be monitored by athletic trainers or coaches to make localized adjustments to the activities planned for that time as needed (Binkley, Beckett, Casa, Kleiner, & Plummer, 2002; Yard et al., 2010). Humidity is less likely to be as important in heat related illness and death in the southwest due to its drier climate, yet the more humid monsoon season (mid-July–September) may factor into heat illness risks. Similarly, radiation plays a relatively more important role in hot, dry, and clear-sky climates such as Phoenix (Vanos & Grundstein, 2020). Understanding how meteorological components combine to increase the risk of heat exposure is imperative when developing mitigation strategies for a specific location. The southwestern United States is the warmest and sunniest region of the United States. The attenuated risk associated with humidity has the potential to be offset by increased risk from higher air temperatures and radiation common to this region.

Personal Risk Factors for Exertional Heat Illness

Three important intrinsic personal risk factors are 1) not being heat acclimatized, 2) high body mass, and 3) level of physical fitness (Fink, Brandom, & Torp, 2006; Howe

& Boden, 2007; Marshall, 2010; Shea, 2007). It is estimated that 9,000 high school athletes are treated for EHI every year across the US, with 88% of heat illness in football players occurring in August at the beginning of football season (Cooper et al., 2006; Kerr et al., 2013; Yard et al., 2010). Players also tend to have their lowest fitness as the season begins (Yard et al., 2010). Acclimatization is the gradual process of physiologically adapting to heat (Kim, 2016) and is critical to reducing the risk of EHI. A 14-day period is recommended for acclimatizing athletes to their local climate conditions by slowly increasing the duration, intensity, and frequency of practice, as well as the amount of protective gear worn (Binkley et al., 2002; Casa et al., 2009; Yard et al., 2010). Furthermore, not having adequate breaks to rest, wearing dark-colored clothing, and working at heightened metabolic loads during practice or competition have all also been noted as risk factors (Howe & Boden, 2007; Marshall, 2010). Those with anthropometric characteristics of low body height-to-width ratios and obesity have a lower tolerance for heat because they cannot cool their bodies as efficiently since body fat stores heat (Yard et al., 2010). For example, Yard et al. (2010) found that nearly 65% of football players who were victims of EHI were overweight or obese. Another study found that over 47% of football players are considered overweight or obese (Choate et al., 2007). Mitigating some of these risk factors is possible by improving guidelines and policies and encouraging enhanced safety measurements to be put in to place during practice and competition field.

Wet Bulb Globe Temperature History, Calculation, and Use

The WBGT is the measurement most often used in the military, occupational safety, and athletics to understand the meteorological factors that can influence a person's heat stress. The WBGT was first developed in 1945 by the United States Navy Bureau of Medicine and Surgery, following a spike in heat-related death and illness in military personnel, specifically in the marines and the army (Budd, 2008; Kopec, 1977). The WBGT is believed to most accurately represent heat stress compared to the Heat Index or air temperature alone because it takes into account the humidity, air temperature, wind speed, and radiative load (sunlight), yet limitations are present (Budd, 2008).

The WBGT is calculated in two ways depending on the location (indoor or outdoor; (Ramanathan & Belding, 1973)). For this study, only outdoor WBGT was used, calculated as:

$$\mathrm{W}BGT = 0.7T_w + 0.2T_g + 0.1T_d$$

where T_d (°C) is the dry bulb or ambient air temperature, T_w (°C) is the wet bulb temperature and is proportionate to relative humidity and wind speed, and T_g (°C) is the globe temperature, which accounts for the radiative load. The WBGT responds to wind and radiation, as well as humidity and temperature (Budd, 2008), which is a benefit of using the WBGT index over the heat index or temperature alone. Wind and radiation are important to human heat balance because they affect energy exchange between the body and the environment, such as evaporative cooling with wind. While the calculation can provide an estimation of WBGT for the region, it is not always reflective of the thermal environments over the individual athletic surfaces. Coaches and trainers are advised to be taking measurements of WBGT at their practice location to determine the safety of competition or practice on those fields (Pryor et al., 2017).

Wet Bulb Globe Temperature Guidelines

It is not common practice in athletics to take WBGT measurements at the location of the training or competition for sports. According to a survey by Luke et al. (2007) conducted in football programs across the United States, only around 7% of high school football coaches are using WBGT from their fields to determine if it is safe to conduct practice (2007). The cost and availability of the meteorological instrumentation are two of the main reasons for not taking observations on the field (Pryor et al., 2017). However, when on-site instrumentation is not available, practitioners and coaches are often using modeled WBGT derived from local weather station data (Pryor et al., 2017), which may cause issues of spatial incongruence and inappropriate decision making for safety and health (Solís et al., 2017).

Both the American College of Sports Medicine (ACSM) and the National Athletic Trainers Association (NATA) have important and similar positions on EHI and EHS in sports (Armstrong et al., 2007; Casa et al., 2015). General guidelines exist on the use of WBGT in sport and competition, which have evolved in their use since early creation for the military (Racinais et al., 2015). Table 1 displays the general guidelines in use in the U.S.

Table 1: The American College of Sports Medicine activity modification guidelines based on wet-bulb globe temperature (WBGT) for acclimatized, fit, low-risk athletes (Tripp et al., 2019, modified from Armstrong et al. 2007).

WBGT (°C)	**Activity modification or cancellation**
≤ 10	Normal Activity
10.1–18.3	Normal Activity
18.4–22.2	Normal Activity
22.3–25.6	Normal Activity. Monitor fluid intake
25.7–27.8	Normal Activity. Monitor fluid intake
27.9–30.0	Plan intense or prolonged exercise with discretion; watch at-risk individuals carefully
30.1–32.2	Limit intense exercise and total daily exposure to heat and humidity; watch for early signs and symptoms
>32.3	Cancel exercise; uncompensable heat stress (UCHS)[1] exists for all athletes

[1] occurs when evaporative cooling is not supported by the environment, with other conditions (e.g., air temperature) impeding cooling (Leon and Bouchama, 2015). UCHS will cause a rise in T_{core} without actions taken.

These WBGT guidelines are not adapted for obese, unfit individuals, or children; therefore, the given thresholds may be inappropriate guidelines for all athletes in all environments, and trainers can use more athletic-specific decisions as well. The climate of a location and the level of acclimatization of the players factors in to determining whether it is too dangerous to play. According to Grundstein et al. (2015), the country can be split in to three climatic zones. Much of the southern U.S. and all of Arizona is included in category three, which is the hottest on average. In this category, given the relatively high year-round temperatures, is it expected that in general, athletes should be more acclimatized and able to play at higher temperatures safely. Grundstein et al. (2015) outlined how practices should be modified depending on the category the location belongs to. Table 2 outlines the recommended WBGT guidelines for category 3. These climate-based guidelines are supported by Racinais et al. (2015) and Gonzalez (1995), who state that the WBGT does not accurately represent heat stress in hot environments with low humidity, and proposed changing how WBGT is used in hot and dry locations. Vanos and Grundstein (2020) further showed that the physiological heat loss potential in hot-dry environments is higher than hot-humid, further supporting these above notions.

Table 2: WBGT guidelines proposed for the 3rd category of the United States, outlined in Grundstein et al. (2015), which encompasses the majority of the southern United States and all of Arizona.

Wet-Bulb Globe Temperature in °C	Activity guidelines
<10.1	Normal activity
10.1–22.2	Normal activity
22.3–27.8	Normal activity, monitoring fluids
27.9–30.0	Plan intense or prolonged exercise with discretion
30.1–32.2	Limit intense Exercise and total daily exposure to heat and humidity
32.3	Cancel Exercise

Intellectual Merit

Heat illness is entirely preventable, yet is still a leading cause of death in high school athletes in the U.S. (Mueller & Cantu, 2008; Yard et al., 2010). Understanding how these occurrences can be prevented requires a deeper level of understanding about what is happening locally on the field during training/practice and competition. On-site WBGT measurements provide a starting point as researchers try to understand the heat experienced on the field and how it impacts physical activity and potential heat stress or strain.

A limited number of studies have attempted to determine the relationship between on-site WBGT and WBGT derived from regional observations obtained from local weather stations. Thus, the current research can substantially add to what is known concerning personally- or locally-experienced heat levels and the appropriateness of current approximations of heat. While certain studies have addressed these questions, they have small sample sizes, differing climates, and occur over minimal days of sampling. Cheuvront et al. (2014) compared WBGT measurements along the Boston marathon route to the local weather station. They determined that taking one measurement along the route would be sufficient for determining WBGT conditions for the entire route (Cheuvront et al., 2014). Tripp et al. (2019) conducted a study in north-central Florida, where they compared measured WBGT values to values from a smartphone app. Athletic trainers collected the measurements at the beginning and end of each varsity football practice from August 1st to October 31st (Tripp et al., 2019). The researchers found that the smartphone app did not accurately represent the measured WBGT values and significantly overestimated the on-site WBGT. Ultimately, they determined that the smartphone app would lead to being overly cautious, by two WBGT thresholds, and that the smartphone app is not ready for widespread use (Tripp et al., 2019).

Moreover, only one study (Pryor et al., 2017) has quantified the relationship between modeled WBGT and WBGT observed over different athletic surfaces, such as a natural grass football field, a rubber track and a concrete tennis court. The methodological approach undertaken relied on WBGT measurements taken at *different* times over ten different athletic surfaces and a comparison to measurements (and WBGT model) derived from the local National Weather Service (NWS) weather station. They used the Liljegren et al. (2008) model to calculate WBGT values at an NWS automated station. Their study timeline spanned 18 days over two years and was limited to periodic measurements between 1:00 PM and 4:30 PM. Among the key conclusions was a determination that discrepancies in the measurement on the field/court existed in comparison to the WBGT measurements derived from the NWS weather station. Such disagreement in the measurements has the potential to lead to situations of misclassified levels of heat, which can result in serious social consequences (Pryor et al., 2017). A limitation of their study was not using multiple weather stations and not taking simultaneous measurements across all surfaces to allow for direct comparison.

The aforementioned research serves as a useful template for similar analyses by the current study conducted in the Phoenix Metropolitan area, which frequently experiences summer air temperatures above 40°C and has a dry climate. Research specific to the Southwest on this topic is scarce. This gap provides researchers an opportunity to expand our knowledge.

Purpose, Objectives, Questions and Hypotheses

The purpose of this research is to critically review, measure, and analyze differences between various athletic surfaces and regional weather stations, and examine the effect of those differences on the safe usage of sporting venues, both under current conditions and future climate projections. The following objectives are addressed:

(1) To assess microclimate differences and WBGT values over various on-site athletic surfaces,

(2) To examine the differences between on-site WBGT measurements and regional WBGT approximations from AZMET regional weather stations,

(3) To determine the potential changes to regional heat stress risk between current, mid-century, and late-century WBGT estimates.

Specific research questions addressed throughout this thesis include: How are athletic surfaces impacting their local microclimates? Is there disagreement in the regional (AZMET station) WBGT and the observed WBGT that would lead to the misclassification of heat safety? What percentage of the practice day is lost based on WBGT observations at the athletic surfaces exceeding the ACSM activity modification guidelines? Can we derive a relationship between the AZMET regional weather station and on the field WBGT observations? Could the relationship between on-field observations and regional WBGT estimations guide future heat safety precautions?

Based on these questions, it is first hypothesized that the natural grass surface will provide the least stressful environment and show the most agreement with the AZMET regional weather stations, with artificial surfaces (rubber track, green concrete tennis court, or rubber track) expected to be the most thermally stressful due to the findings from Pryor et al. (2017). Second, it is hypothesized that heat stress risk will increase as the century progresses, and higher WBGT values will be observed.

CHAPTER 2

METHODS

Overview

This study was conducted in Tempe, Arizona (33.43, -111.94), which is located to the east of Phoenix, Arizona in the Sonoran Desert. Tempe is home to one of the largest public universities in the country, Arizona State University. This study leveraged research relationships with a division one athletics program to access venues and monitor the WBGT over various athletic surfaces, which required a combination of fieldwork, modeling, and statistical analysis. Three data types were used: 1) in situ field data collected using meteorological instrumentation; 2) regional weather station data over the same period; 3) Weather Research and Forecasting (WRF) regional climate projections. The field observations were conducted in the summer of 2019, with the first set of observations (six days) collected in June and the second set (five days) collected in August. The purpose of the June and August timeframe was to capture the hot/dry part of the Arizona summer (June) and the hot/humid conditions (August) experienced during the southwestern monsoon season.

Fieldwork & In Situ Data Collection

Measurements of WBGT were simultaneously collected over five athletic surfaces. These measurements were obtained using a Kestrel 5400 Heat Stress Tracker (see **Photo 1a**). The Kestrels collected several variables including air temperature using a hermetically-sealed external thermistor, relative humidity with a polymer capacitive external humidity sensor, wind speed with a 1-inch diameter impeller anemometer and a wind vane to allow rotation of the sensor for accurate wind speed readings, and globe temperature using a thermistor inside of a one-inch black powder-coated hollow copper globe. The device calculates natural wet bulb temperature, WBGT index, and heat index. The data were collected and stored every minute and downloaded each night after a full day of sampling. Per the manufacturer, Kestrels accurately report WBGT ± 0.7°C ("Kestrel Instruments," 2020). While measurements were being collected, a team of volunteers recorded the surface temperatures at each site at 3-hour intervals starting at 7 AM and ending at 7 PM MST. These measurements were taken using an Elekcity Lasergrip 774 infrared thermometer (see Photo 1b), which is accurate within 2°C ("Etekcity," n.d.). All devices used were calibrated in May of 2019 by the manufacturer to ensure accuracy.

Photo 1: (A) the Kestrel 5400 Heat Stress Tracker during data collection (Photo credit: Jamie Teran, and (B) the Etekcity Lasergrip 774 Infrared thermometer from the etekcity website ("Etekcity," n.d.).

Five distinct athletic surfaces were monitored, similar to those monitored by Pryor et al. (2017). All of the locations were within 3 miles (~ 4km) of each other and maintained by Sun Devil Athletics, as follows (see Figure 1):

- The football training center at Sun Devil Stadium: artificial turf field with natural infill made up of coconut husk, sand, and zeolite (Shaw Sports, 2020), also known as “cool turf” or “Hydrochill.” This surface was on the north side of Sun Devil Stadium and is used for practice purposes for the ASU football team. This surface is referred to as turf throughout the rest of the document.
- Whiteman Tennis Complex, consisting of eight two-tone green concrete tennis courts, is located to the west of Rural Rd on the north side of ASU’s Tempe campus.
- A light-blue rubber track at Sun Angel stadium directly north of the Whiteman Tennis Complex.
- Brown baseball clay and natural grass were monitored at Phoenix Municipal Stadium, which is located approximately 2 miles (3.2km) north of the Arizona State University Tempe campus.

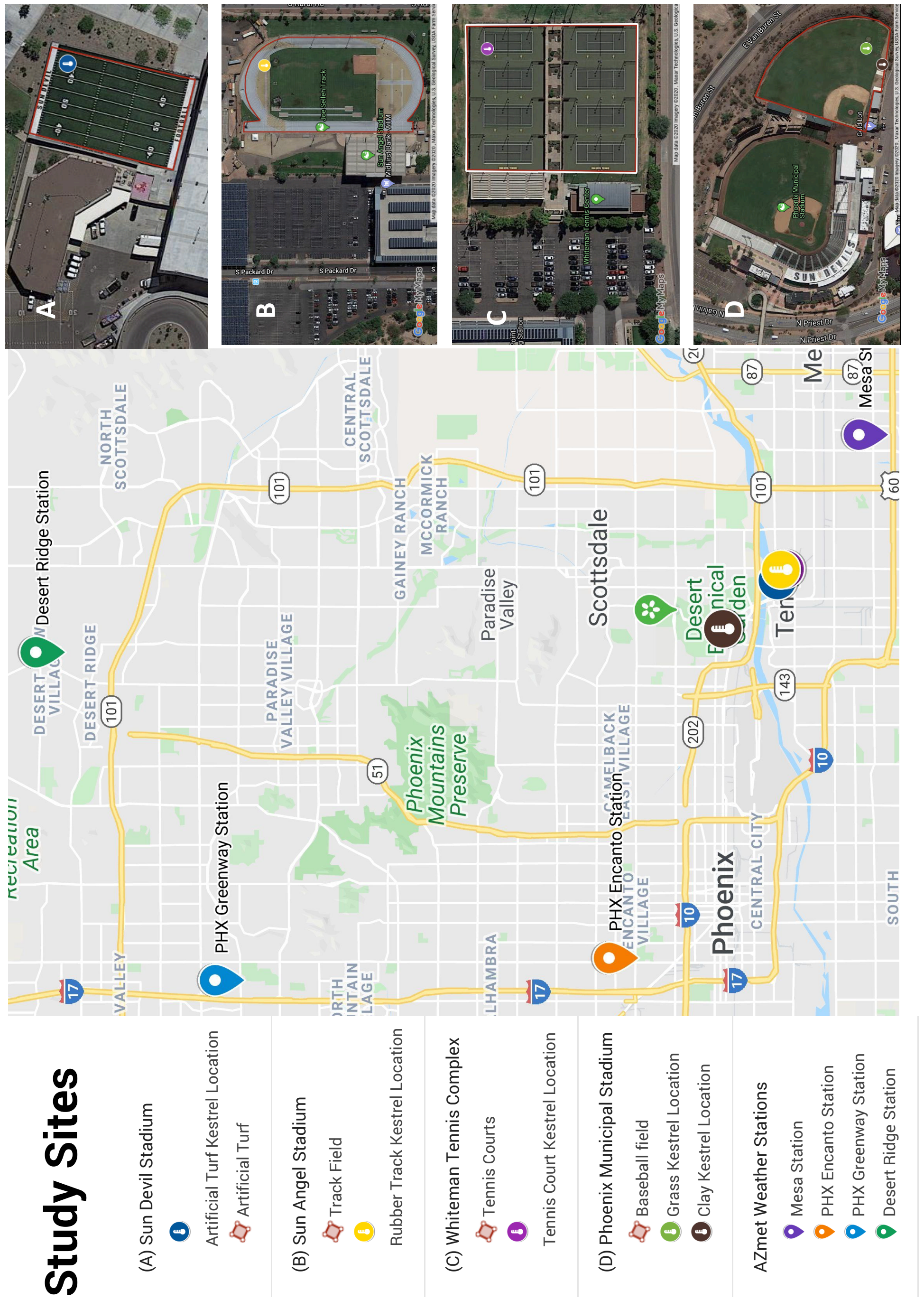


Figure 1- Map of the study location in relation to the four weather stations created using Google MyMaps ("Google MyMaps," 2020). (A) natural infill artificial turf surface at Sun Devil Stadium, (B) rubber track at Sun Angel Stadium, (C) two-tone green concrete tennis courts at Whiteman Tennis Complex, and (D) grass and clay surfaces at Phoenix Municipal Stadium. The teardrop shape symbols identify the AZMET regional weather stations that were used for this study and the exact Kestrel locations are identified using the multi-colored thermometer symbols.

For on-site measurements, a Kestrel heat stress meter was placed over each surface on a tripod at the height of 1.2 meters (47 inches), which represents the approximate chest height of an athlete (Pryor et al., 2017; Santee, Matthew, & Blanchard, 1994). The tripods were set in sun-exposed location and placed approximately 10 ft (3.05m) from the edge of the given surface to mitigate influence from surrounding surface-types. These locations remained the same each day. The measurements were collected for 12 hours each day (7 AM–7 PM), simultaneously across all surfaces to allow for direct comparisons. Data were only collected on clear sky days. Observations were collected for six days in June and five days in August. An extra data collection day was conducted in June to offset potential field measurement issues in the data collection process. In a couple of instances, the instruments were not set up correctly, had incorrect settings, or the device was blown over by the wind, in which case the data for those sections of time were removed from the data set (4.1% of the data). August data collection had minimal to no fieldwork issues. Shading on the instrument was avoided as much as possible, yet shading from low lying trees and fences was present during sunrise and sunset for most sensors. To ensure consistency, each research volunteer was provided a guide and in-person training on how to set up each station (included in Appendix A).

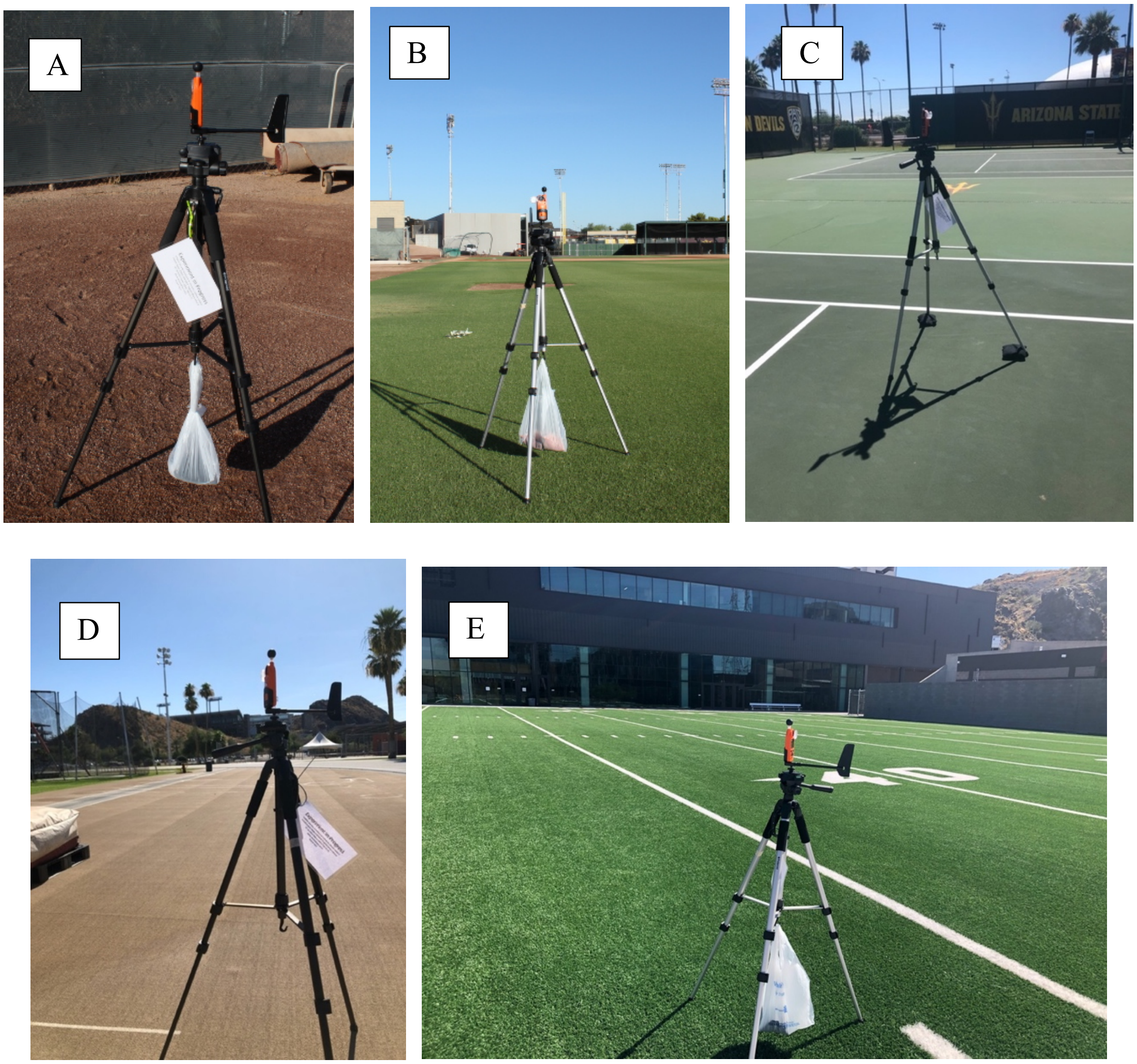


Photo 2A, B, C, and D: Are photographs of the Kestrel 5400 Heat Stress Trackers set up at each study location. 2A: Kestrel on the clay surface at Phoenix Municipal Stadium; 2B: Kestrel at Phoenix Municipal Stadium on the grass surface; 2: Kestrel at the two-tone, green, concrete tennis courts at Whiteman Tennis Complex; 2D: Kestrel over rubber track surface at Sun Angel Stadium; 3E: Kestrel over natural infill artificial turf surface at Sun Devil Stadium. All photos were taken by Haven Guyer or a research volunteer.

Regional Meteorological Data

To provide comparisons with on-site WBGT, regional (within the Phoenix Metropolitan area) weather station data were obtained from the AZMET (The Arizona

Meteorological Network) data archive managed by the University of Arizona (The Arizona Meteorological Network, 2020). The AZMET data are more suitable than NCEI stations because they measure solar radiation. Pryor et al. (2017) used NWS data for these comparisons; however, the NWS weather station in Phoenix, AZ does not measure solar radiation, which is an integral part of the calculation of WBGT. The National Solar Radiation Database; NSRBD used by Pryor et al. (2017) has a long time lag in the uploading of data, so these were not an option for the current study. AZMET data were downloaded from the four nearest weather station locations to the ASU campus (see Figure 1). These data are reported at the hourly frequency as an average. Per the AZMET website, all instrumentation at these locations are regularly maintained and monitored for accuracy (The Arizona Meteorological Network, n.d.). These data were used to model WBGT values (Section "Modeling WBGT With Regional Data and Climate Projections").

Climate Projection Data

Finally, climate projections provided by Dr. Ashley Broadbent and Dr. Matei Georgescu were also used to calculate future WBGT in Tempe for the given weeks in June and August. Projections were provided for multiple representative concentration pathways (RCPs) and global circulation models (GCMs) including; mid-century (2050–2059) simulations for Community Earth Systems Model (CESM) RCP4.5 and RCP8.5, and end of century (2090–2099) simulations for CESM RCP8.5 with heat mitigating adaptation measures (e.g., cool roofs, green roofs, trees, etc.) for the T2-City grid cell that encompasses Tempe, Arizona (Krayenhoff, Moustaoui, Broadbent, Gupta, & Georgescu, 2018). The projections provided are for mid-century (2050–2059) and end of the century (2090–2099) on a 3-hourly time scale (Krayenhoff et al., 2018).

Modeling WBGT With Regional Data and Climate Projections

As the WBGT is not a commonly reported variable by local news outlets or the National Weather Service, two parameters (T_g and T_w) must be calculated. The Liljegren model was used to calculate the WBGT from standard weather data from the AZMET regional weather stations and the climate projections (Liljegren et al., 2008). This method was chosen due to its use by Pryor et al. (2017), but also because it has been successfully used in many other research projects (Grundstein et al., 2015; Vanos & Grundstein, 2020). The Liljegren model was used to calculate WBGT for every weather station as well as to generate future projections for the middle of the century and the end (2050 and 2099). The WBGT algorithm, the R package HeatStress and command wbgt.liljegren (Casanueva, 2019), required 7 variables including Temperature (°C), dew point (°C), solar radiation (W m^{-2}), wind speed (ms^{-1}), latitude, longitude, and date, to generate the WBGT output.

Statistical Analysis

Descriptive statistics of weather variables and WBGT by study location were calculated. To statistically compare the AZMET regional weather station WBGT hourly values to the on-site WBGT values, hourly averages of on-site data were calculated. The AZMET regional weather stations also report their hourly temperature, radiation, and relative humidity values for the hour from 60 second samples (The Arizona

Meteorological Network, 2020). For direct statistical comparison of the WBGT by surface and with the AZMET WBGT, an ANOVA with a post hoc test was completed. From the data, several figures were generated to allow for graphical comparison. Data were analyzed using a combination of Microsoft Excel, SPSS (version 26; IBM Corp, Armonk, NY), and R (version 3.6.1).

CHAPTER 3

RESULTS

Weather Conditions

The month of June in Tempe captures the hot and dry part of the summer in Arizona.-In June, the average air temperature across the locations ranged from 29°C to 36°C, relative humidity between 12 and 20%, and all had low wind speeds (Table 3).

Table 3: Summary of ambient environmental conditions at each study location (sports surface and AZMET station), including air temperature, relative humidity, and wind speed. at each weather stations and on each surface type for June 18–27, 2019. T_{max} is the average maximum air temperature, and T_g is the average globe temperature.

Sensor	Mean Temperature ± Std. Dev (°C)	T_{max} (°C)	Relative Humidity (%)	Average wind speed (ms^{-1})	Radiation ($W\ m^{-2}$)	T_g (°C)
Clay	36.3±3.49	47	12.4±4.37	1.3±0.80	—	48.1±5.09
Grass	35.9±3.05	44.1	12.8±3.95	1.3±0.90	—	47.4±4.24
Tennis	36.8±3.64	47.6	12.1±4.19	1.0±0.71	—	48.3±4.74
Track	35.6±3.44	43.2	14.2±4.90	1.6±0.91	—	47.8±4.60
Turf	36.4±3.71	47.6	12.2±7.40	1.2±0.81	—	48±5.11
Mesa	32.6±4.82	39.6	13.3±4.82	1.6±0.71	347.2±380.56	—
Desert Ridge	28.9±5.63	37	20.4±9.45	1.3±0.87	344.4±388.89	—
Phoenix Encanto	31.1±5.43	38.2	17.2±8.57	1.3±0.90	344.4±383.34	—
Phoenix Greenway	30.7±5.37	38.3	16.9±7.61	1.3±0.88	352.8±388.89	—

In August, Arizona has higher levels of relative humidity and higher air temperature, with the study locations experiencing an average air temperature between 32°C and 40°C during the study dates, and relative humidity between 19% and 30% (Table 4).

Table 4: Summary of the ambient environmental conditions at each study location (sports surface and AZMET station), including air temperature, relative humidity, and wind speed. at each weather stations and on each surface type for August 7–14, 2019. T_{max} is the average maximum air temperature, and T_g is the average globe temperature.

Sensor	**Mean Temperature ± Std. Dev (°C)**	**T_{max} (°C)**	**Relative Humidity (%)**	**Average wind speed (ms^{-1})**	**Radiation ($W\ m^{-2}$)**	**Tg (°C)**
Clay	38.7±3.43	47.9	21.1±9.04	1.2±0.84	—	49.7±5.70
Grass	38.1±3.21	49.7	22.1±9.96	1.3±0.96	—	48.4±5.20
Tennis	39.7±3.57	49.3	19.2±8.94	1.0±0.83	—	48.4±5.20
Track	39.3±3.30	48.3	21.8±9.85	1.4±0.9	—	50.6±5.36
Turf	39.1±3.89	47.9	21.4±12.38	1.1±0.83	—	49.5±6.27
Mesa	35.5±4.3	44	23.7±10.91	1.4±0.84	307.2±358.34	—
Desert Ridge	32.3±5.07	41.7	29.9±13.37	1.2±0.90	307.8±366.67	—
Phoenix Encanto	33.8±5.27	43.2	28.6±14.16	1.0±0.85	302.8±361.11	—
Phoenix Greenway	33.9±4.94	43.3	25.5±11.50	1.1±0.90	309.2±363.89	—

When comparing the ambient weather conditions from the data collection campaign and the months of June and August as a whole to the long-term climate for the Phoenix area, it was found that the study period was 1.1°C warmer than climate normal for June, and 2.5°C warmer than an average August (“National Weather Service,” 2020). August 2019 was drier than average with a rainfall total of around 0.25 inches compared to the normal rainfall total for the month of 1.0 inch (Selover, 2019a). June was typical as far as rainfall goes, with little to no rainfall (Selover, 2019b).

Athletic Surface WBGT versus Regional Weather Station WBGT

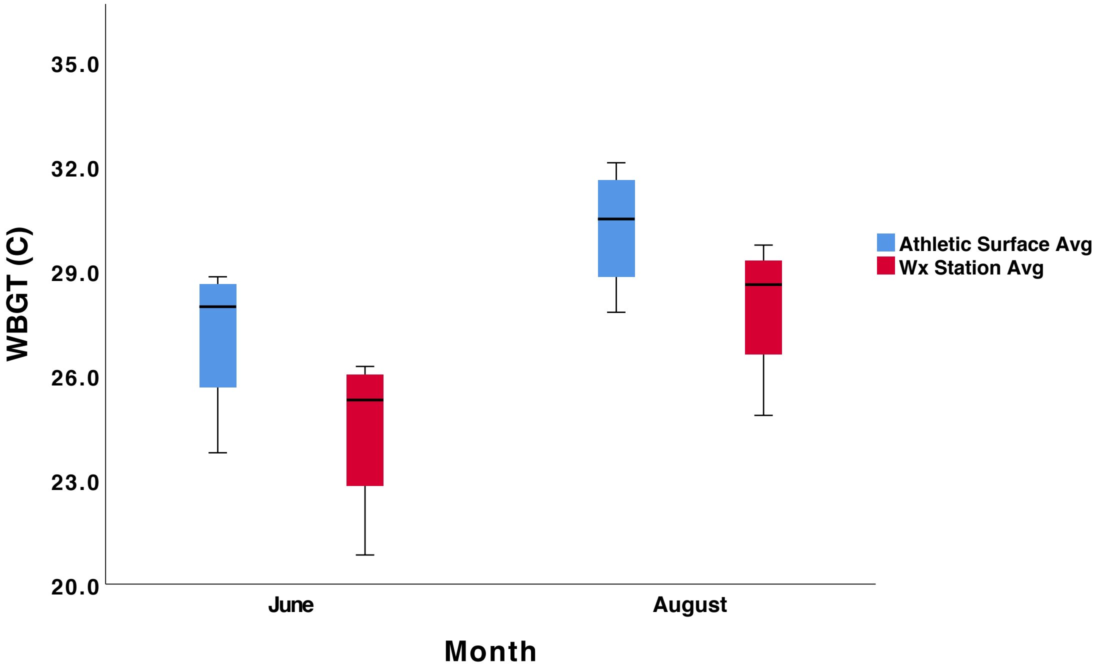


Figure 2: Boxplot of the average wet-bulb globe temperature (WBGT) values (in °C) by sensor type (athletic surfaces Kestrels ("Athletic Surface Avg") versus AZMET weather stations ("Wx Station Avg").

The difference between the average regional weather station WBGT and the on-site WBGT values in June was approximately 3°C higher over the athletic surfaces, while the August difference was approximately 1.5°C higher (Figure 2).

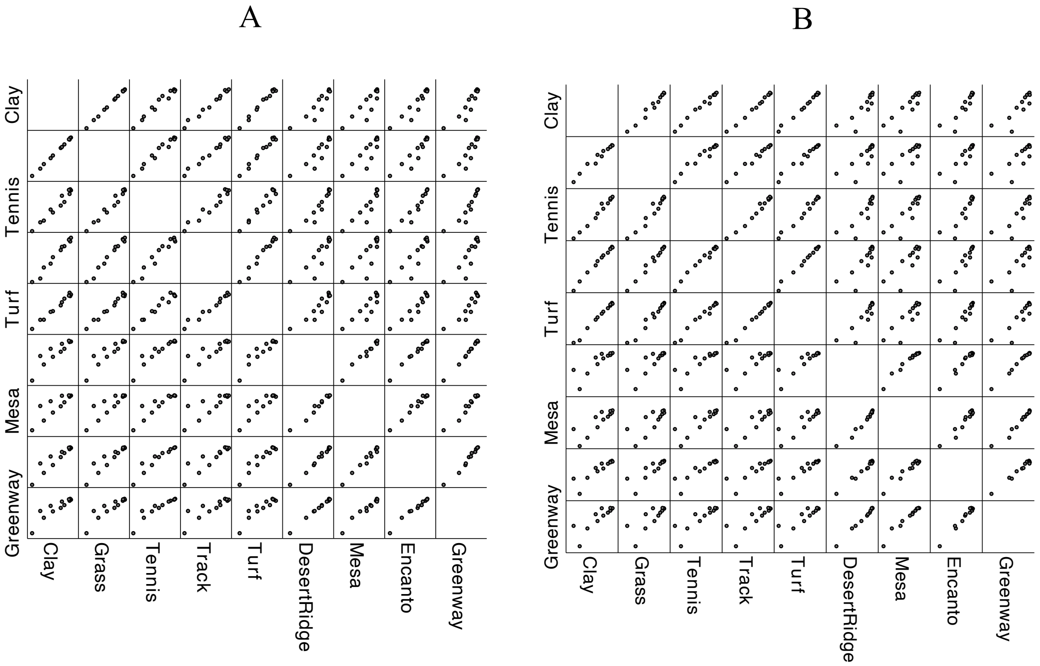


Figure 3: Correlation matrices of wet-bulb globe temperature (WBGT) values with regional weather stations and on-site observations in June (A) and August (B). Clay, grass, tennis, track and turf are the on-site observations and DesertRidge (Desert Ridge), Mesa, Encanto (Phoenix Encanto), and Greenway (Phoenix Greenway) are the AZMET regional weather stations.

Significant differences were in WBGT values between the on-site versus AZMET stations in August (F=5.237, $p<0.05$) and in June (F=5.038, $p<0.05$). Athletic surfaces had significantly higher WBGT than the weather station based on post-hoc tests except for the grass surface in August, which remained higher than the Mesa and Phoenix Encanto Stations, but not significantly different. Outputs for the ANOVA and post-hoc test for June and August can be found in Appendices B and C. All WBGT values on the athletic fields correlated significantly with WBGT at the AZMET weather stations at the 0.01 level based on a Pearson correlation (Figure 3).

Between Athletic Surface WBGT Comparisons

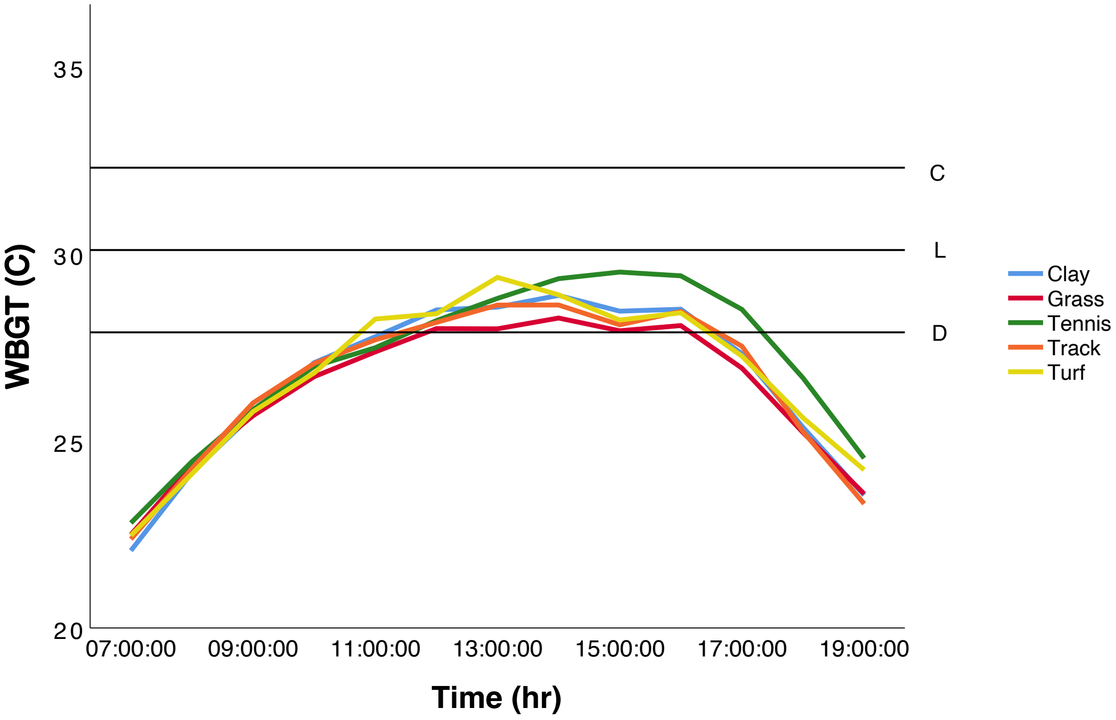


Figure 4: Timeseries of the average wet bulb globe temperature (WBGT) values (°C) observed over each athletic surface during the observation period in June 2019. 'C' represents the first tier WBGT guidelines that would require the cancellation of a practice or game at 32.3°C (see Table 1). 'L' represents the second tier WBGT threshold where athletic trainers and coaches should limit activity at 30.1°C. Finally, 'D' is used to represent the third-tier guideline were coaches and trainers would need to use discretion on planning activities for the day at 27.9°C.

In June, none of the surfaces reached a WBGT value that would constitute a cancellation (C) of practice or competition, nor did they reach the next lower limit that would recommend a limit to activity (L) (see Figure 4). However, all surfaces reached a WBGT that requires a decision (D) when determining if it is safe or appropriate for the team or individual to practice.

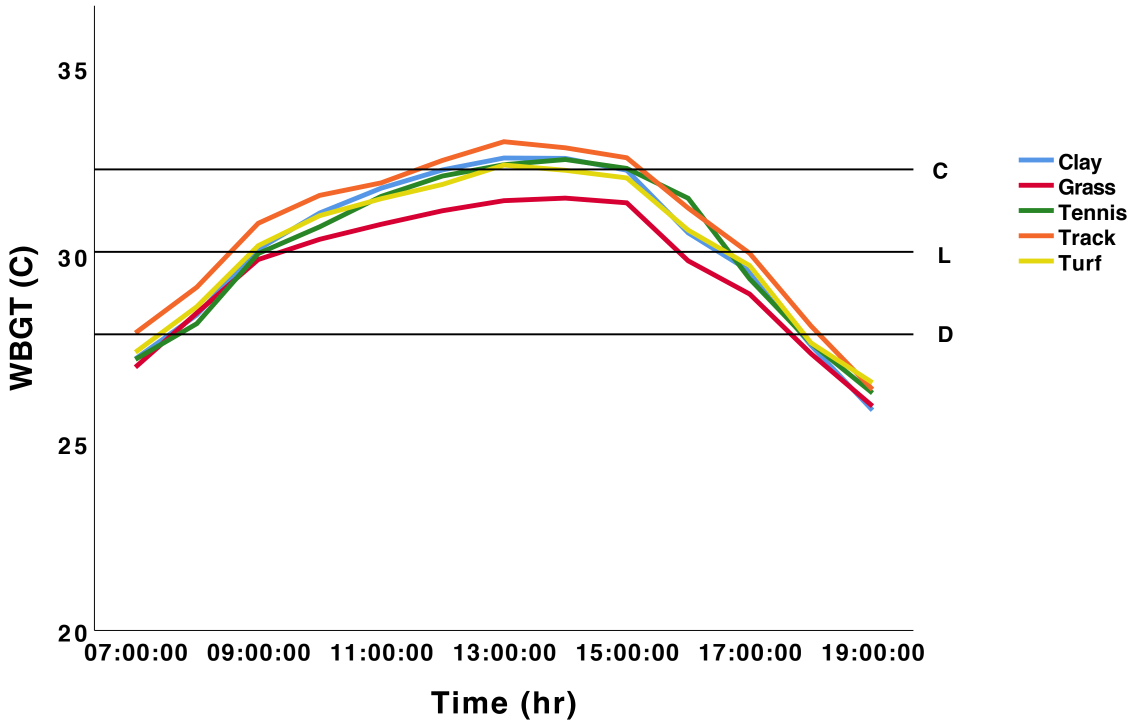


Figure 5: Timeseries of the average wet bulb globe temperature (WBGT) values (°C) observed over each athletic surface during the observation period in August 2019. 'C' represents the first tier WBGT guidelines that would require the cancellation of a practice or game at 32.3°C (see Table 1). 'L' represents the second tier WBGT threshold where athletic trainers and coaches should limit activity at 30.1°C. Finally, 'D' is used to represent the third-tier guideline were coaches and trainers would need to use discretion on planning activities for the day at 27.9°C.

In August, the environment over every surface but grass reached a WBGT value that would constitute a cancellation of practice or competition (the most serious heat stress modification) (Figure 5). These cancellation thresholds were reached between approximately 11 AM and 3 PM. All surfaces reached a WBGT that would recommend a limit in activity between 9 AM and 5 PM, which requires decision when determining if it is safe or appropriate for the team or individual to practice. Even though the WBGT profiles over the athletic surfaces differed, the average WBGT differences between surfaces for the study period were determined insignificant (p>0.05) by an ANOVA and post hoc test (Appendixes B and C).

Table 5: Average number of hours within the study period (i.e., 6 days in June and 5 days in August for 12 hours per day) over the three highest activity guideline thresholds for wet bulb globe temperature (WBGT), divided by athletic surface and AZMET regional weather station; DR=Desert Ridge, M=Mesa, PE=Phoenix Encanto, and PG=Phoenix Greenway.

	WBGT Threshold (°C)	**Clay**	**Grass**	**Tennis**	**Track**	**Turf**	**DR**	**M**	**PE**	**PG**
June	27.9	5	5	6	4	6	0	0	0	0
	30.1	0	0	0	0	0	0	0	0	0
	32.3	0	0	0	0	0	0	0	0	0
August	27.9	10	10	10	12	10	8	8	8	7
	30.1	8	6	7	8	8	0	1	1	0
	32.3	4	0	4	4	2	0	0	0	0

August presented conditions that caused a greater number of hours with WBGT above the activity modification thresholds compared to June (Table 5). In June, no surface exhibited WBGT values above the cancellation threshold (32.3°C) or the limit activity threshold (30.1°C), yet approximately 5 hours per day (~42%), on average, exhibited WBGT values above the discretion threshold (27.9°C). In August, approximately 33% of the observation period, 4 of the 12 hours per day, experienced WBGT levels above the cancellation threshold for the track, tennis, and clay surfaces. On average, only 17% of the day was lost on the artificial turf, and there were zero instances whereby the WBGT rose above the cancellation threshold over the grass surface. Finally, almost the entire day (10 hours (~83%) on clay, grass, tennis, and turf and 12 hours (100%) on the track) crossed the discretion threshold of 27.9°C.

Surface Temperatures Data

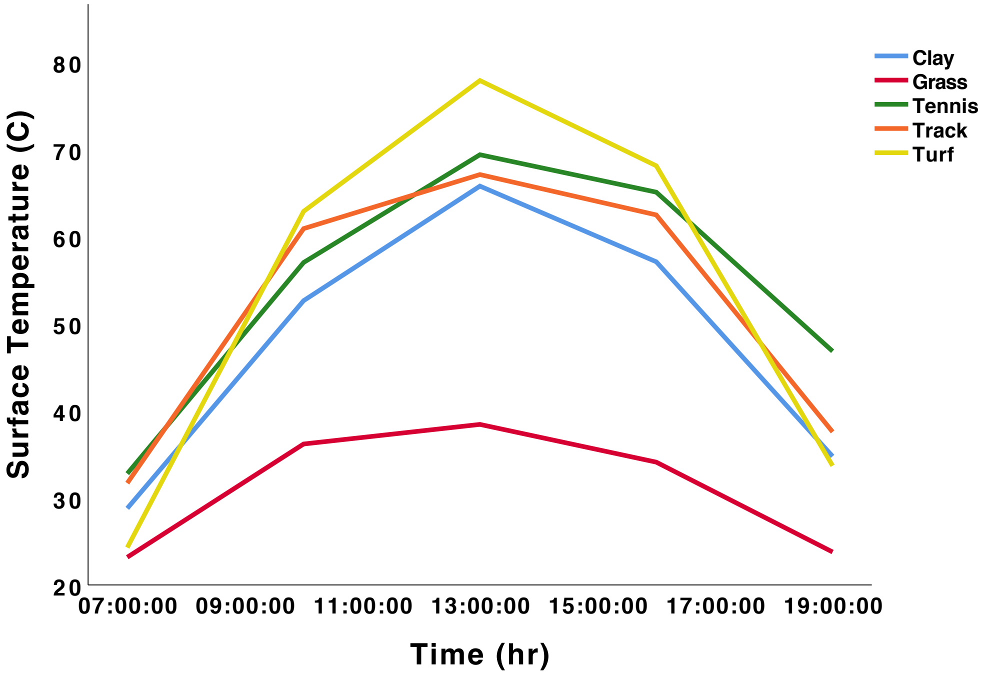


Figure 6: Timeseries of the average surface temperature (°C) observed over each athletic surface by time of day (hr) during the month of June. Measurements were taken at 7:00am, 10:00am, 1:00pm, 4:00pm, and 7:00pm MST. Each measurement was recorded within an hour of the specified time.

In June, the surface temperatures varied by surface (Figure 6), with the highest surface temperatures recorded on the natural infill artificial turf surface and the coolest temperatures recorded on the grass surface. The artificial turf surface reached a maximum of 83.5°C (182.2 °F), where the grass surface had an average maximum of 39°C (102°F) at the same time.

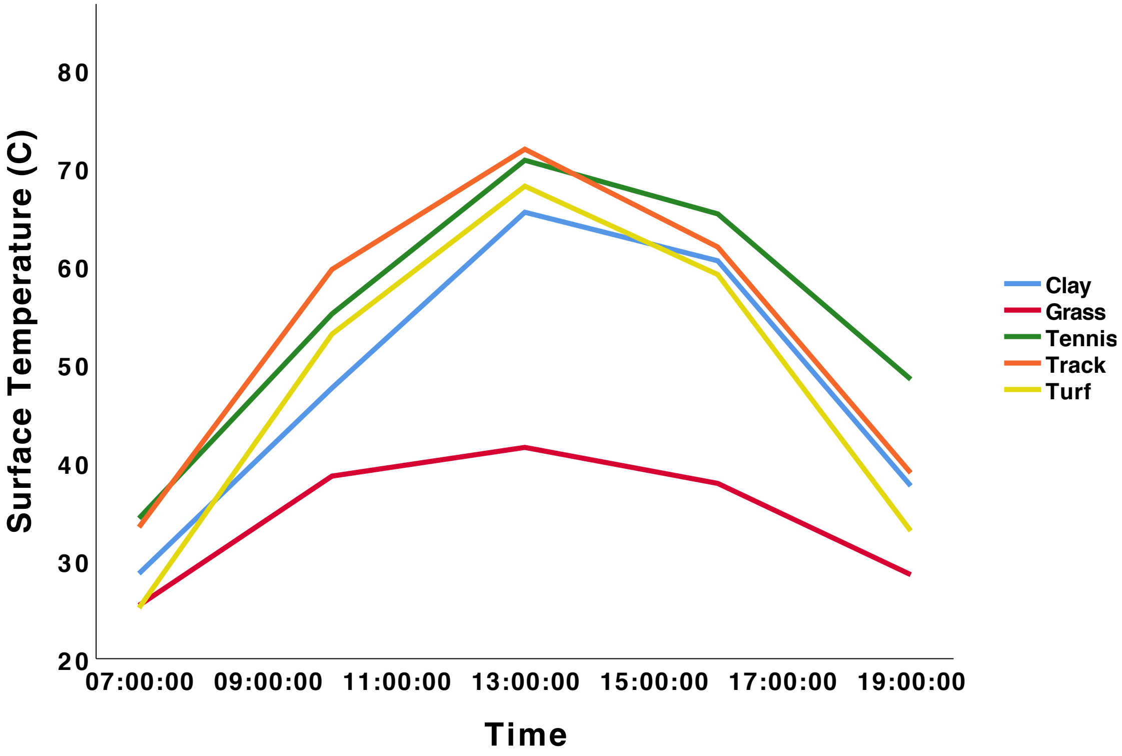


Figure 7: Timeseries of the average surface temperature (°C) observed over each athletic surface by time of day (hr) during the month of August. Measurements were taken at 7:00am, 10:00am, 1:00pm, 4:00pm, and 7:00pm MST. Each measurement was recorded within an hour of the specified time.

In August, the surface temperatures also varied by surface, with the coolest temperatures recorded on the grass surface (Figure 7). In August, the highest surface temperatures observed were not recorded on the turf surface, but rather a mix of the remaining four surface types. The average surface temperatures across all surfaces were similar in in both months, apart from the artificial turf, which was 9.8°C lower in August (77.9°C in June versus 68.1°C in August). The average surface temperature across all surfaces in June was 47.7°C, and August was 47.6°C, with an average difference of 0.11°C.

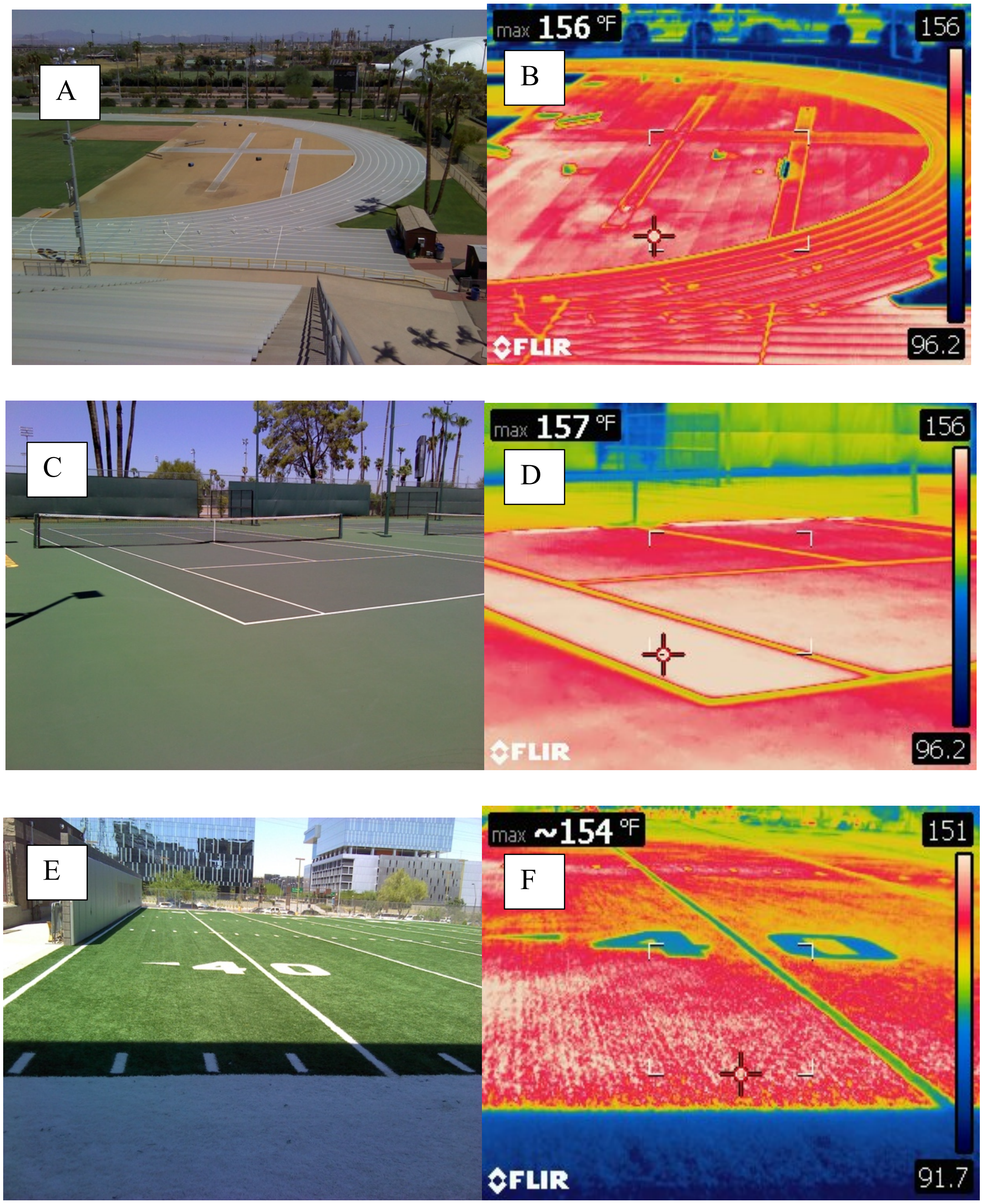


Photo 3A, B, C, D, E, and F: A series of infrared images and their associated regular image. The photographs are of the track surface (A and B), tennis surface (C and D), and turf surface (E and F) in August of 2019. (Photo Credit: Dr. Jennifer Vanos)

The maximum surface temperatures were consistently observed during the 1:00 PM observation period in August and June. The lowest average temperatures were always observed over the natural grass surface, with the highest surface temperatures changing from turf to track between June and August, respectively.

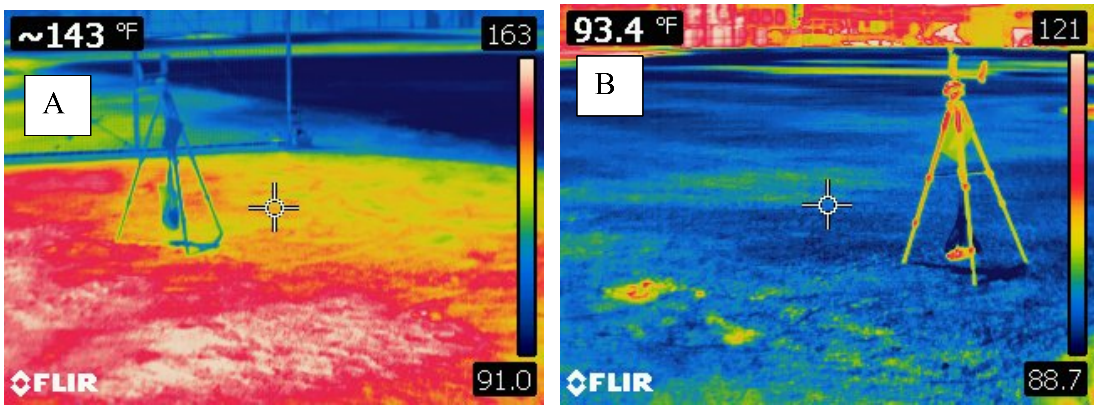


Photo 4A and B: Infrared images. Of the (A) clay and (B) grass surfaces at Phoenix Municipal Stadium in August of 2019. (Photo Credit: Dr. Jennifer Vanos)

Climate Projections

This study used four different regional climate projections from a Weather Research and Forecasting (WRF) model; Contemporary (2000–2010), Mid-Century RCP4.5 (2050–2057), Mid-Century RCP8.5 (2050–2057), and finally End of Century RCP8.5 Full Adaptation (2090–2099). With these climate projections, WBGT values were calculated using the Liljegren model and can be seen in Figure 8. Climate projections can provide useful information to jumpstart preparation for the future. While they are not perfect representations, they can provide a further understanding of what is to come. We can use this information to be proactive rather than reactive. Because climate models have an intrinsic bias, contemporary data was included to provide an understanding of the differences between today and contemporary data.

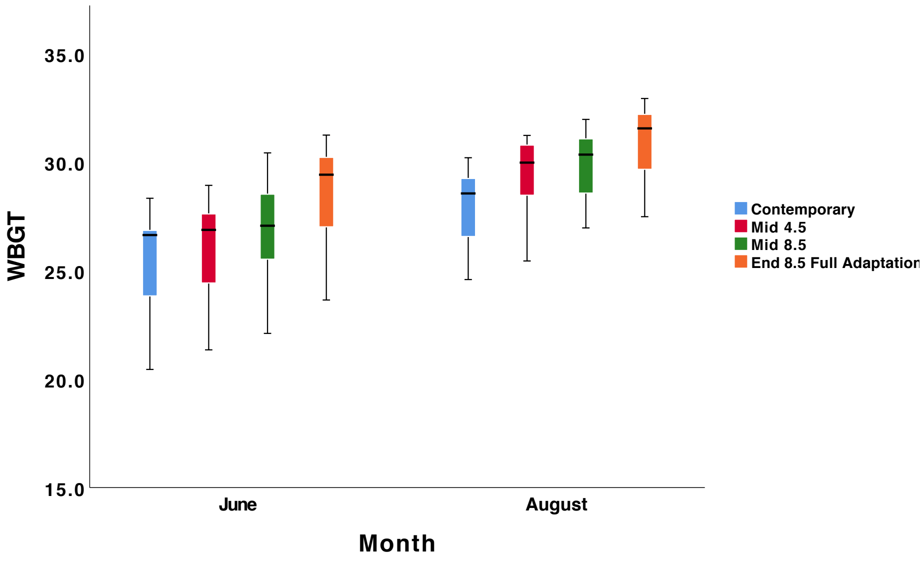


Figure 8: Average wet bulb globe temperature (WBGT) at 8:00am, 11:00am, 2:00pm and 5:00pm for all 4 scenarios from a Weather Research and Forecasting (WRF) regional climate projections (Krayenhoff et al., 2018).

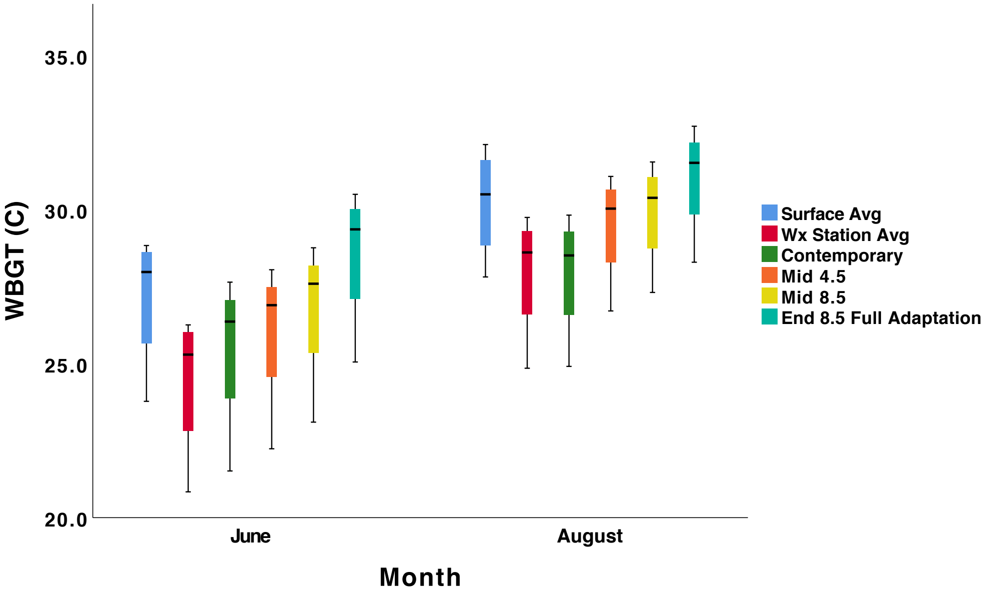


Figure 9: Average wet bulb globe temperature (WBGT) at 8:00am, 11:00am, 2:00pm and 5:00pm for all athletic surface (Surface Avg), all weather stations (Wx Station Avg) and 4 scenarios from a Weather Research and Forecasting (WRF) regional climate projections (Krayenhoff et al., 2018).

The contemporary scenario shows the coolest WBGT values (Figure 8) and increased from there, with the final scenario, RCP 8.5 Full Adaptation, having an average WBGT 2.9°C higher than the contemporary. The average WBGT observed over the different athletic surfaces was higher by about 2°C in June and 3°C in August, with an average mean difference of 2.5°C between the contemporary data and the average on-site WBGT at the athletic surfaces. The average weather station WBGT in June was cooler than the contemporary data by approximately 1°C, which was similar in August. In light of the difference between the contemporary climate data and the weather stations in June, further comparisons were done with the weather stations individually instead of as an average (Figure 10). The contemporary data was most similar to the Mesa AZMET regional weather station, but warmer by 1–2°C than all stations in June. In August the contemporary was similar, within 1°C, to all of the AZMET regional weather stations.

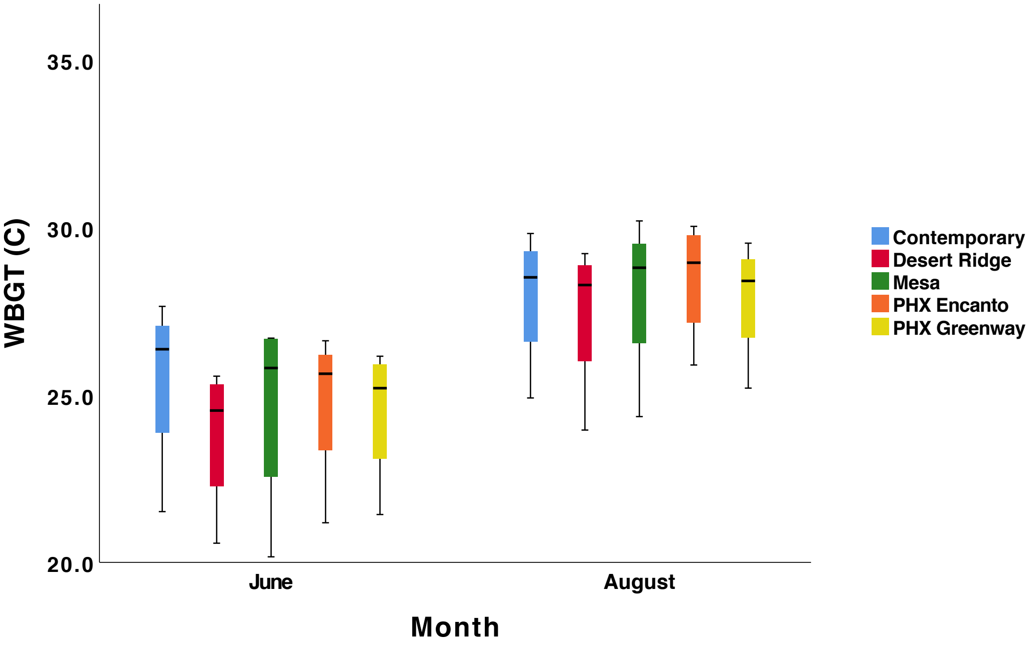


Figure 10: Average wet bulb globe temperature (WBGT) (°C) of the contemporary climate model and the weather station individually.

CHAPTER 4

DISCUSSION AND CONCLUSION

Weather Conditions

The study was designed to capture two different weather types experienced in the Sonoran Desert during the summer months. The first being the hot, dry part of the summer in June (Table 3), with low relative humidity and high air temperature. These June conditions are relatively hotter and drier than in August (Table 4); however, average solar radiation was lower in June. These increases in relative humidity and air temperature were very apparent in the enhanced WBGT values in August, which is discussed below. The increase in humidity occurs because the Sonoran Desert sees the effects of the southwestern monsoon, which draws in moisture from the Gulf of Mexico and the Gulf of California as prevailing winds come from the south. In June, prevailing winds come from the west, which flows over a cool ocean, a mountain range, and desert, allowing minimal moisture to reach Arizona. High humidity levels play an important role in heat stress and thus the WBGT calculation and results. As shown in the time series of the average WBGT over each surface for June and August (Figures 3 and 4), there is an increase in WBGT across all athletic surfaces in August, with much more dangerous heat stress conditions reached for athletes. However, even with air temperatures reaching 39°C at times in June, the WBGT threshold to cancel is never reached. This failure to meet the threshold is likely caused by the emphasis that the WBGT equation places on moisture, which is something Arizona noticeably lacks in June. Compared to the typical climate of Phoenix, June and August were both warmer than average (“National Weather

Service," 2020). June 2019 precipitation was normal, but in August 2019, precipitation was unusually dry (Selover, 2019b, 2019a).

Athletic Surfaces versus Weather Stations

This project had a similar goal to Pryor et al. (2017) and Tripp et al. (2019) but used different approaches, timeline, and tested different climate types within the northeast and southeast, respectively. These studies evaluated the relationship between on-site WBGT and a modeled WBGT from a regional weather station. The current study, modeling WBGT from four regional weather stations, were similar to results of Pryor et al. (2017) over similar surfaces, with all on-site stations presenting significantly higher WBGT levels. These differences thus may cause significant discrepancies in the understanding and potentially decision making given the on-field/on-court microclimate situations if users use regional weather station models, which are often used by coaches or trainers as a substitute for on-site measurements (Pryor et al., 2017; Tripp et al., 2019). This discrepancy could lead to potentially dangerous situations for athletes of all ages. These discrepancies (on-site versus regional WBGT levels) decrease between June to August. This decrease in the difference between the AZMET regional weather station WBGT values and the on-site WBGT observations could partially be explained by the increase in humidity experienced in this region in August. However, these findings also lead to more questions concerning the cause for these variations between June and August that should be explored in future work. For example, could this difference be explained by the emphasis that the WBGT equation places on moisture? Are the calculations in August more accurate because there is an increase in moisture in Arizona? To gain a better understanding of why there is such a difference between the on-site WBGT and the modeled WBGT, more fieldwork is currently being planned for the summer of 2020. Part of the difference between the regional weather station WBGT in the on-site WBGT could be attributed to the different equipment that was used, as well as model error. The Kestrel device was used to collect and model WBGT on-site, while the AZMET regional weather station data and the Liljegren model were used to model a regional WBGT value, thus there could be some disagreement between the two methods leading to a more substantial discrepancy than anticipated. The height at which windspeed was measured for the Kestrel was 1.2m and the height of the AZMET regional weather stations is 3m. This difference in height might provide some insight to why there is a difference between the WBGT values observed at the athletic surfaces compared to the regional weather stations. Pryor et al. (2017), Tripp et al. (2019), and Cheuvront et al. (2014) all found that modeled WBGT measurements did not serve as an accurate proxy for on-site measurements. These researchers also noticed a greater difference between weather station data and on-site measurements from synthetic surfaces, which is consistent with the findings of the current study.

Between Athletic Surfaces

There was a stark difference between June and August based on the number of hours that the WBGT values above each surface met and surpassed a certain WBGT threshold that would modify activity (Table 5). When comparing the WBGT values observed above the surfaces in June, they are more similar across the different surface types. Further, in June the conditions over each surface never reach the “cancellation” threshold (32.3°C) or the “limit physical activity” threshold (30.1°C) provided by ACSM (Armstrong et al., 2007). However, the WBGT over every athletic surface surpasses the threshold that advises athletic trainers and coaches to use discretion when determining activities for that practice or competition. Finally, every surface exceeded the “discretion” threshold and the “limit activity” threshold, all surfaces other than grass also cross into the “cancellation” zone. In some cases, a third of the practice day (7 AM to 7 PM) is lost due to the cancellation. This is important because the weather stations did not cross the cancelation threshold, and if the on-field decision-making is based on regional weather station, athletes could be put at unnecessary risk of EHI and EHS.

When comparing the location of the clay and grass surface to the other athletic surface, it is important to mention that they are in a low density area, which also might contribute to them being slightly cooler. The track and tennis courts are both located in a more urbanized area on the west side of a major road in Tempe. This setting could contribute to the higher air temperatures and thus WBGT values observed at these venues. The tennis court is also surrounded by a chain-link and mesh fence, which may reduce airflow over the surface. However, the track surface is largely unobstructed on the south and west sides. On the east side of the track surface, there is a large section of stadium seating for spectators, while the northeast corner is directly next to a concrete baseball stadium, both of these structures could impede wind, but it is unclear exactly how much. The artificial turf surface is located on the north side of Sun Devil Stadium and the east side of Hayden Butte, which could be shielding some wind from the surface. A combination of more frequent watering and adding fans could allow for some cooling. Evaporative cooling may play a part in allowing the natural grass surface to stay cooler throughout the day and thus not reach such high WBGT levels above the grass. These findings are consistent with the hypothesis that the natural grass surface would prove to have the lowest WBGT values observed and similar to the findings of Pryor et al. (2017).

Surface Temperatures

The surface temperatures are essential to thermal comfort because the infrared radiation emitted from the athletic surfaces can be felt by athletes while playing on them. There were vast differences in the surface temperatures observed, for example the artificial turf surface has an average peak of over 77°C at 1:00 PM, where the grass has an average peak of around 39°C at the same time in June. Hardin and Vanos (2018) also discovered that a grass surface is more thermally comfortable than an artificial turf surface or tennis court. Even though the surface temperatures varied from surface to surface, the WBGT values observed were not significantly different which indicates that surface temperature may not have as much influence when compared to ambient conditions such as wind, humidity, air temperature, and incoming solar radiation, which are all essential components of the WBGT value observed.

The surface temperatures can have an impact on the athlete's heat stress potential, which is reflected in the WBGT values observed, yet there is a lag in the peak surface temperature and the peak WBGT values from maximum surface temperature to maximum WBGT. Of the WBGT values, the grass surface has the lowest and least stressful WBGT values as well as the lowest surface temperatures (Photos 3 and 4). Many of these findings demonstrate that the use of grass when possible, can both decrease heat stress and improve thermal comfort, which Hardin and Vanos (2018) also found, yet there are important tradeoffs to consider with water use in a desert city (Snir, Pearlmutter, & Erell, 2016).

Climate Projections

The use of climate projections can provide some insight about what the future may look like. In this case it can help us better prepare the sports community to continue to play sports outdoors during the warmest parts of the day in the Phoenix Metropolitan area. Climate projection data was obtained for each of the future scenarios using the same dates in June and August as the in-situ data collections for 2050–2057 in the mid-century projections and 2090–2099 for the end of century projections. Through these climate projections, the expected rise in WBGT values is visualized through the end of the century (Figure 7) allowing the opportunity to incorporate adaptations to athletic facilities now. The most interesting discovery with the climate projections is of the average WBGT observed across the athletic surfaces is in line with the mid-century RCP 4.5 projections, not the contemporary projections. This difference indicates that the on-site measurements have the potential to measure above the projected WBGT values and thus give a sense of what future average regional conditions could be like. With this increase in WBGT in the future, hosting games and practices outdoors will become increasingly challenging, and adaptations will have to be made. Adaptations could include changing practice times and locations. They could also include adaptations to the facilities (i.e., Sun Devil Stadium, Whiteman Tennis Complex, or Phoenix Municipal Stadium) such as changing the types of materials used, the design of the structure to optimize cooling, and updating watering schedules of certain surface types to increase evaporative cooling.

Comparison to Prior Research

Pryor et al. (2017) took measurements across 18 days over two years. These were also “pinpoint” measurements, not 12-hour observations over multiple days, as conducted in the current study. A further limitation of the Pryor et al. (2017) study is that they only compared to one regional NWS weather station, yet the current study compared to four regional weather stations.

Tripp et al. (2019) also focused their study on the sport of football during the end of summer and beginning of fall in Florida, which is important for football season. They investigated how a mobile app compared to on-site measurements. To do so, they used different equipment to capture the on-site measurements and compared them to a mobile app that uses the Australian Bureau of Meteorology (ABM) method to calculate WBGT values from the closest National Weather Service station (Tripp et al. 2019). The ABM method uses a set radiation value and assumes light wind (Australian Bureau of Meteorology, 2019), which could contribute to the overestimation Tripp et al. (2019) observed during the study.

Finally, the largest and most significant difference in these studies is the geographical location in which they were conducted. Pryor et al. (2017) conducted their study in the northeastern United States, and Tripp et al. (2019) was in Florida. None of the previously mentioned studies addressed surface temperatures or climate projections. A novel part of this research is that fills a large gap in the literature where WBGT values have not been studied as closely in the arid environment of the southwest.

Implications

This study explored the influence of the structural design and materials used in athletic settings on the thermal environment of an athlete, specifically focusing on different athletic surface types. This study also examined how these different microclimates may lead to a mismatch between on-site WBGT values and WBGT values modeled from regional weather stations, the latter of which may be used by an athletic coach or trainer as a substitute for on-site measurement. While the difference experienced across surface types was not significant in itself, the difference between all surface types and the modeled WBGT value was. These findings support the positions of NATA (Casa et al., 2009) and ACSM (Armstrong et al., 2007) for monitoring on-site WBGT as crucial for accurate athlete heat exposure. This research can be used by athletic trainers, referees, umpires, team physicians, and coaches for decision-making at game time, and also by policymakers when setting rules and regulations for heat safety in athletics in Arizona to protect health and save lives. This research can help inform policy in heat safety in the southwest in athletics at all levels, but especially in youth sports, vulnerable groups who cannot advocate for themselves, and/or those with higher physiological vulnerabilities and are (often unknowingly) more susceptible to heat illness, long-term complications of EHS, or death. It can also inform how venues are built in the future to optimize cooling and reduce heat stress. Summer 2019 data and climate projections can also support future decision making for new outdoor facility types by Sun Devil Athletics and supports the use of grass surfaces to keep players cooler (when possible), as well as the use of shade on the sidelines when possible to provide cooling. The artificial turf, although titled "cool turf," remained the hottest throughout the study due to the infill not being moist and drying out quickly (particularly in June).

Limitations and Future Research

Limitations of this research include the timeline and number of surfaces monitored. A future study could expand on the months included and add additional surfaces such as a crumb rubber turf, water, and surfaces of different colors to expand upon the current findings and those of Pryor et al. (2017).

There are also portions of missing information with respect to the exact timing and amount of water that was used on various surfaces throughout the study. The turf surface was watered in the early morning hours (~4:00 AM) prior to set up, but duration and amount are unknown. The track was close to a grass surface that was watered every afternoon around 1:30 PM. Facilities managers for the 'cool turf' can thus be made aware of the extreme temperatures over the turf and that watering the surface is needed for it to perform optimally, as outlined by the manufacturers ("Shaw Sports," 2020). However, added moisture can also increase humidity above the surface (increasing WBGT), which would create more oppressive conditions unless wind flow was present or added (via fans on the field). A future study should assess the watering and air flow needs per area of the 'cool turf' versus watering needs for natural grass as a cost-benefit analysis for watering and maintenance costs for both current use and any future implementation.

Future work will also be completed to observe the difference in WBGT values using multiple instruments over the same surface type to further explore the difference in the on-site and modeled WBGT values. The results of this study are more applicable to athletic surfaces located in the southwestern United States due to the unique climate experienced in the Sonoran Desert. However, the findings of this study support the positions of NATA and ACSM for taking on-site observations of WBGT before/during any game or practice regardless of surface type. The differences between the WBGT values observed over the different surface types, and the modeled values using regional weather station data do show that relying only on weather station data has the potential to lead to heat safety misclassification and potentially dangerous situations.

REFERENCES

Armstrong, L. E., Casa, D. J., Millard-Stafford, M., Moran, D. S., Pyne, S. W., & Roberts, W. O. (2007). Exertional heat illness during training and competition. *Medicine & Science in Sports & Exercise*, *39*(3), 556–572. https://doi.org/10.1249/MSS.0b013e31802fa199

Belval, L. N., Casa, D. J., Adams, W. M., Chiampas, G. T., Holschen, J. C., Hosokawa, Y., … Lemieux, R. S. (2018). Consensus statement-prehospital care of exertional heat stroke. *Prehospital Emergency Care*, *22*(3), 392–397.

Binkley, H. M., Beckett, J., Casa, D. J., Kleiner, D. M., & Plummer, P. E. (2002). National Athletic Trainers' Association position statement: exertional heat illnesses. *Journal of Athletic Training*, *37*(3), 329.

Budd, G. M. (2008). Wet-bulb globe temperature (WBGT)—its history and its limitations. *Journal of Science and Medicine in Sport*, *11*(1), 20–32.

Casa, D. J., Armstrong, L. E., Hillman, S. K., Montain, S. J., Reiff, R. V, Rich, B. S. E., … Stone, J. A. (2000). National Athletic Trainers' Association position statement: fluid replacement for athletes. *Journal of Athletic Training*, *35*(2), 212.

Casa, D. J., Csillan, D., Participants, I.-A. T. F., Armstrong, L. E., Baker, L. B., Bergeron, M. F., … Eichner, E. R. (2009). Preseason heat-acclimatization guidelines for secondary school athletics. *Journal of Athletic Training*, *44*(3), 332–333.

Casa, D. J., DeMartini, J. K., Bergeron, M. F., Csillan, D., Eichner, E. R., Lopez, R. M., … Sawka, M. N. (2015). National Athletic Trainers' Association position statement: exertional heat illnesses. *Journal of Athletic Training*, *50*(9), 986–1000.

Casanueva, A. (2019). HeatStress: Calculate heat stress indices. R package version 1.0.7.

Cheuvront, S. N., Caruso, E. M., Heavens, K. R., Karis, A. J., Santee, W. R., Troyanos, C., & d'Hemecourt, P. (2014). Effect of WBGT Measurement Location on Heat Stress Category Classification: 715 Board# 130 May 28, 200 PM-330 PM. *Medicine & Science in Sports & Exercise*, *46*(5S), 185.

Choate, N., Forster, C., Almquist, J., Olsen, C., & Poth, M. (2007). The prevalence of overweight in participants in high school extramural sports. *Journal of Adolescent Health*, *40*(3), 283–285.

Cooper Jr, E. R., Ferrara, M. S., & Broglio, S. P. (2006). Exertional heat illness and environmental conditions during a single football season in the southeast. *Journal of Athletic Training*, *41*(3), 332.

Etekcity. (n.d.). Retrieved from https://www.etekcity.com/product/100022

Fink, E., Brandom, B. W., & Torp, K. D. (2006). Heatstroke in the super-sized athlete. *Pediatric Emergency Care*, *22*(7), 510–513.

Garfin, G., Jardine, A., Merideth, R., Black, M., Leroy, S., Franco, G., … Waskom, R. (2014). Southwest. *Climate Change Impacts in the United States*, 462–486. https://doi.org/10.7930/J08G8HMN.On

Gonzalez, R. R. (1995). Biophysics of heat exchange and clothing: applications to sports physiology. *Med Exerc Nutr Health*, *4*(2), 3.

Google MyMaps. (n.d.). Retrieved from https://www.google.com/maps/d/u/0/edit?mid=1IjZR_cmuUG4bMyPBRiVbG-KW2hRue7sA&ll=33.537714061829774%2C-111.9876597&z=11

Grundstein, A., Williams, C., Phan, M., & Cooper, E. (2015). Regional heat safety thresholds for athletics in the contiguous United States. *Applied Geography*, *56*, 55–60.

Hardin, A. W., & Vanos, J. K. (2018). The influence of surface type on the absorbed radiation by a human under hot, dry conditions. *International Journal of Biometeorology*, *62*(1), 43–56.

Howe, A. S., & Boden, B. P. (2007). Heat-related illness in athletes. *The American Journal of Sports Medicine*, *35*(8), 1384–1395.

Kerr, Z. Y., Casa, D. J., Marshall, S. W., & Comstock, R. D. (2013). Epidemiology of exertional heat illness among US high school athletes. *American Journal of Preventive Medicine*, *44*(1), 8–14.

Kestrel Instruments. (n.d.). Retrieved from https://kestrelinstruments.com/category-kestrel-advanced/kestrel-5400-heat-stress-tracker-pro

Kim, E. J. (2016). The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment, by US Global Change Research Program: (2016). Washington, DC: Author. 312 pages. Available online at https://health2016. globalchange. gov/downloads. Taylor & Francis.

Kopec, R. J. (1977). Response of the wet-bulb-globe-thermometer heat stress index to selected land use surfaces. *Southeastern Geographer*, *17*(2), 133–145.

Krayenhoff, E. S., Moustaoui, M., Broadbent, A. M., Gupta, V., & Georgescu, M. (2018). Diurnal interaction between urban expansion, climate change and adaptation in US cities. *Nature Climate Change*, *8*(12), 1097–1103.

Leon, L. R., & Bouchama, A. (2015). Heat stroke: Compr Physiol, v. 5.

Liljegren, J. C., Carhart, R. A., Lawday, P., Tschopp, S., & Sharp, R. (2008). Modeling the wet bulb globe temperature using standard meteorological measurements. *Journal of Occupational and Environmental Hygiene*, *5*(10), 645–655.

Lopez, R. M., & Jardine, J. F. (2018). Exertional heat illnesses. In *Sport and Physical Activity in the Heat* (pp. 313–329). Springer.

Luke, A. C., Bergeron, M. F., & Roberts, W. O. (2007). Heat injury prevention practices in high school football. *Clinical Journal of Sport Medicine*, *17*(6), 488–493.

Marshall, S. W. (2010). Heat injury in youth sport. *British Journal of Sports Medicine*, *44*(1), 8–12.

McGregor, G. R., & Vanos, J. K. (2018). Heat: a primer for public health researchers. *Public Health*, *161*, 138–146.

Meteorology, A. B. O. (2019). Thermal stress approximation. Bureau of Meteorology. Retrieved from http://www.bom.gov.au/info/thermal_stress/approximation

Mueller, F. O., & Cantu, R. C. (2008). Catastrophic sports injury research. Twenty-Fifth annual report: Fall 1982 to Spring 2007. *National Center for Catastrophic Injury Research Website. Http://Www. Unc. Edu/Depts/Nccsi/. Accessed August*, *19*.

National Weather Service. (2020). Retrieved April 21, 2020, from https://w2.weather.gov/climate/xmacis.php?wfo=psr

Pryor, J. L., Pryor, R. R., Grundstein, A., & Casa, D. J. (2017). The Heat Strain of Various Athletic Surfaces: A Comparison Between Observed and Modeled Wet-Bulb Globe Temperatures. *Journal of Athletic Training*, *52*(11), 1056–1064.

Racinais, S., Alonso, J. M., Coutts, A. J., Flouris, A. D., Girard, O., González-Alonso, J., … Périard, J. D. (2015). Consensus recommendations on training and competing in the heat. *British Journal of Sports Medicine*, *49*(18), 1164–1173. https://doi.org/10.1136/bjsports-2015-094915

Ramanathan, N. L., & Belding, H. S. (1973). Physiological evaluation of the WBGT index for occupational heat stress. *American Industrial Hygiene Association Journal*, *34*(9), 375–383.

Santee, W. R., Matthew, W. T., & Blanchard, L. A. (1994). Effects of meteorological parameters on adequate evaluation of the thermal environment. *Journal of Thermal Biology*, *19*(3), 187–198.

Selover, N. J. (2019a). Summary of Conditions for August 2019. Retrieved April 21, 2020, from https://static.sustainability.asu.edu/sosMS-uploads/sites/26/2019/09/AzClimSumAug2019.pdf

Selover, N. J. (2019b). Summary of Conditions for June 2019. Retrieved April 21, 2020, from https://static.sustainability.asu.edu/sosMS-uploads/sites/26/2019/07/AzClimSumJun2019.pdf

Shaw Sports. (n.d.). Retrieved from https://www.shawsportsturf.com/hydrochill/

Shea, K. M. (2007). Global Climate Change and Children9s Health. *Pediatrics*, *120*(5), e1359–e1367.

Snir, K., Pearlmutter, D., & Erell, E. (2016). The moderating effect of water-efficient ground cover vegetation on pedestrian thermal stress. *Landscape and Urban Planning*, *152*, 1–12.

Solís, P., Vanos, J. K., & Forbis, R. E. (2017). The decision-making/accountability spatial incongruence problem for research linking environmental science and policy. *Geographical Review*, *107*(4), 680–704.

State High School Sports Safety Policies | Korey Stringer Institute. (2018). Retrieved November 5, 2018, from https://ksi.uconn.edu/high-school-state-policies-2018/

The Arizona Meteorological Network. (n.d.). AZMET Data. Retrieved from https://cals.arizona.edu/azmet/az-data.htm

Tripp, B., Vincent, H. K., Bruner, M., & Smith, M. S. (2019). Comparison of wet bulb globe temperature measured on-site vs estimated and the impact on activity modification in high school football. *International Journal of Biometeorology*. https://doi.org/10.1007/s00484-019-01847-2

Vanos, J.K., Grundstein, A. (2020) Variations in athlete heat loss potential between hot-dry and warm-humid environments at equivalent WBGT thresholds. *Journal of Athletic Training*. *In press.* DOI: 10.4085/1062-6050-313-19

Yard, E. E., Gilchrist, J., Haileyesus, T., Murphy, M., Collins, C., McIlvain, N., & Comstock, R. D. (2010). Heat illness among high school athletes—United States, 2005–2009. *Journal of Safety Research*, *41*(6), 471–474. https://doi.org/10.1016/j.jsr.2010.09.001

APPENDIX A

GUYER ATHLETIC SURFACE HEAT STUDY VOLUNTEER GUIDE

Guyer Athletic Surface Heat Study Volunteer Guide

Haven Guyer
(480) XXX-XXX
Email here @gmail.com, Email here @asu.edu

Hopefully this guide will clearly explain your responsibilities as a volunteer on my project and be a resource for most of the questions that may arise.

This kit is specific to the facility you have been assigned. Some facilities, such as Phoenix Muni, will have multiple surfaces (natural grass, and clay) that I am interested in obtaining measurements for. In each kit there should be tripods & kestrels, an infrared thermometer gun, a tape measure, a sheet to record surface temp measurements, pens, batteries, and tripod weights (bean bags or equivalent).

You will be responsible for setting up and checking on the Kestrels and obtaining surface temperature measurements throughout the day. We will meet at 6:30 am in the parking lot that is in front of the track stadium on each data collection day to distribute supplies. This lot is permit parking only. If you want to park over on this side of campus without a lot 59 pass then you will have to pay to park in the Packard Garage, or if you have a pass for a different garage, you can park north of Rio Salado in that section of lot 59. The third option is to reach out to parking and transit for special permission to park south or Rio. I will be in a white Chevy Cruze. I will have cold Powerade's and Water as well as granola bars for you.

Photo credit: Google Maps

To set up the tripod to have to flip out the latches on the bottom of each legs and extend them until the top of the tripod is 47 inches from the ground. Make sure to lock the latches.

Unlocked Locked

Photo Credit: Haven Guyer

The top of the tripod should be perfectly level, there are green bubble levels on most of the tripods. If there is not a level on the tripod, I will have included one in the kit. Make sure the bubble on the level is as close to the middle as possible. You will also have to add weights to the tripods to prevent them from tipping over. There are hooks at the bottom of the tripod and I will provide you with a plastic bag and something to put in the bag to weigh it down. You can simply hang the bag on the hook.

Photo Credit: Haven Guyer

Next, you will assemble the kestrel and wind vane. The kestrel needs to be set up/on for ten minutes before the data collection begins so it has time to adjust to the outdoor setting.

To put the kestrel and wind vane together follow these steps below;

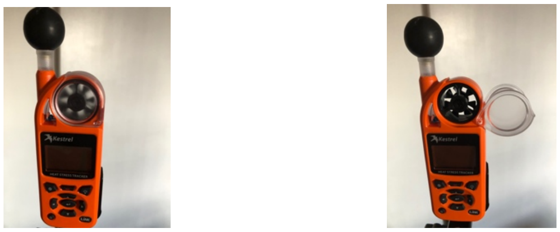
1. You should have 5 pieces in your kit. Note that the Kestrel may already be set in its mount.
    a. Kestrel
    b. Kestrel mount
    c. Wind vane mount
    d. Wind vain pole
    e. Wind vane tail

Photo Credit: Haven Guyer

2. You will then attach the pieces in the order listed above. *Important note-the longer side of the wind vane tail will be on top.
3. Then you will attach this to the screw mount on top of the tripod.

Photo Credit: Haven Guyer

4. Turn the Kestrel on using the button in the bottom left corner.
5. Once the kestrel is assembled and set up there are three major things to check
    a. The window to the propeller should be open



Closed Open

Photo Credit: Haven Guyer

    b. The Auto-shutdown should be switched off. This is very important. If this is not off, then the kestrel will not collect the measurement that I need.
        i. Press the settings button (the gear in the top left corner)-scroll down to display-hit enter-Auto shutdown should be the top one-toggle to the left until auto shutdown says off.
    c. Bluetooth should be switched on.
        i. This is the first thing under settings.

You will need to download the Kestrel LINK app (not the ballistics one) on your phone. It is FREE. This will allow you to connect the device(s) that you are in charge of. EVERY time that you check on the device you should toggle over to the manage, then manage logs, then export data and email (email address) me the data logs. PLEASE DO NOT clear the data on the devices. I will do that every evening after I do a final download of all the data. When you send the data to me it is a backup in case the device malfunctions. Please indicate the surface and facility in the subject line of the email.

Not only will you be collecting data from the Kestrel, but you will also be taking surface temperature measurements. Surface temperature measurements are as easy as point and shoot. You will have a sperate data sheet to note the time and temperature of the surface.

IR Thermometer
Photo Credit: Haven Guyer

This leads to the question of how often you should be out there checking on the device. I need surface temperature measurements for 7am, 1pm and 7pm. You should check on the kestrel a few more times during the day. A good guideline would be 7am, 10am, 1pm, 4pm, 7pm. Don't stress if these times are not working for you, there is some flexibility to this, but try to follow this schedule. I can also arrange to be at your location to take measurements when you're not able.

We will also be at the mercy of the monsoon. Sunlight is important to for my project, so if we do experience rain or dense cloud cover, we will have to take down the Kestrels and be done for the day. Bad weather days will have to be rescheduled, so let's hope for good weather and no mistakes in set up to get the data collected in a timely manner. I will be watching the sky vigilantly and will send a text to volunteers if we need to break everything down in a hurry due to rain or haboobs.

If there are any issues with the devices, please let me know as soon as you know about them. My number is at the top of this handout. Finally, please be aware that it is going to be hot out there. Stay hydrated and wear light colored, lose fitting clothes, hats, sunglasses and sun block.

APPENDIX B

JUNE ANOVA OUTPUT

ANOVA
WBGT

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	231.295	8	28.912	5.237	.000
Within Groups	590.666	107	5.520		
Total	821.961	115			

Post Hoc Test

Multiple Comparisons

Dependent Variable: WBGT

LSD

		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
(I) Surface	(J) Surface				Lower Bound	Upper Bound
Clay	Grass	0.256	0.922	0.782	-1.571	2.083
	Tennis	-0.507	0.922	0.584	-2.334	1.320
	Track	0.170	0.941	0.857	-1.695	2.035
	Turf	-0.144	0.922	0.876	-1.971	1.683
	Desert Ridge	3.404*	0.922	0.000	1.577	5.231
	Mesa	2.495*	0.922	0.008	0.668	4.322
	PHX Encanto	2.317*	0.922	0.013	0.490	4.144
	PHX Greenway	2.608*	0.922	0.006	0.781	4.435
Grass	Clay	-0.256	0.922	0.782	-2.083	1.571
	Tennis	-0.763	0.922	0.410	-2.590	1.064
	Track	-0.086	0.941	0.927	-1.951	1.779
	Turf	-0.400	0.922	0.665	-2.227	1.427
	Desert Ridge	3.148*	0.922	0.001	1.321	4.975
	Mesa	2.239*	0.922	0.017	0.412	4.066
	PHX Encanto	2.061*	0.922	0.027	0.234	3.888
	PHX Greenway	2.352*	0.922	0.012	0.525	4.179
Tennis	Clay	0.507	0.922	0.584	-1.320	2.334
	Grass	0.763	0.922	0.410	-1.064	2.590
	Track	0.677	0.941	0.473	-1.188	2.541
	Turf	0.362	0.922	0.695	-1.464	2.189
	Desert Ridge	3.910*	0.922	0.000	2.083	5.737
	Mesa	3.002*	0.922	0.002	1.175	4.829
	PHX Encanto	2.823*	0.922	0.003	0.996	4.650
	PHX Greenway	3.115*	0.922	0.001	1.288	4.942

Track	Clay	-0.170	0.941	0.857	-2.035	1.695
	Grass	0.086	0.941	0.927	-1.779	1.951
	Tennis	-0.677	0.941	0.473	-2.541	1.188
	Turf	-0.314	0.941	0.739	-2.179	1.550
	Desert Ridge	3.234*	0.941	0.001	1.369	5.098
	Mesa	2.325*	0.941	0.015	0.461	4.190
	PHX Encanto	2.147*	0.941	0.024	0.282	4.011
	PHX Greenway	2.438*	0.941	0.011	0.574	4.303
Turf	Clay	0.144	0.922	0.876	-1.683	1.971
	Grass	0.400	0.922	0.665	-1.427	2.227
	Tennis	-0.362	0.922	0.695	-2.189	1.464
	Track	0.314	0.941	0.739	-1.550	2.179
	Desert Ridge	3.548*	0.922	0.000	1.721	5.375
	Mesa	2.639*	0.922	0.005	0.812	4.466
	PHX Encanto	2.461*	0.922	0.009	0.634	4.288
	PHX Greenway	2.752*	0.922	0.003	0.926	4.579
Desert Ridge	Clay	-3.404*	0.922	0.000	-5.231	-1.577
	Grass	-3.148*	0.922	0.001	-4.975	-1.321
	Tennis	-3.910*	0.922	0.000	-5.737	-2.083
	Track	-3.234*	0.941	0.001	-5.098	-1.369
	Turf	-3.548*	0.922	0.000	-5.375	-1.721
	Mesa	-0.908	0.922	0.326	-2.735	0.918
	PHX Encanto	-1.087	0.922	0.241	-2.914	0.740
	PHX Greenway	-0.795	0.922	0.390	-2.622	1.031
Mesa	Clay	-2.495*	0.922	0.008	-4.322	-0.668
	Grass	-2.239*	0.922	0.017	-4.066	-0.412
	Tennis	-3.002*	0.922	0.002	-4.829	-1.175
	Track	-2.325*	0.941	0.015	-4.190	-0.461
	Turf	-2.639*	0.922	0.005	-4.466	-0.812
	Desert Ridge	0.908	0.922	0.326	-0.918	2.735
	PHX Encanto	-0.178	0.922	0.847	-2.005	1.648
	PHX Greenway	0.113	0.922	0.903	-1.714	1.940
PHX Encanto	Clay	-2.317*	0.922	0.013	-4.144	-0.490
	Grass	-2.061*	0.922	0.027	-3.888	-0.234
	Tennis	-2.823*	0.922	0.003	-4.650	-0.996
	Track	-2.147*	0.941	0.024	-4.011	-0.282
	Turf	-2.461*	0.922	0.009	-4.288	-0.634

	Desert Ridge	1.087	0.922	0.241	-0.740	2.914
	Mesa	0.178	0.922	0.847	-1.648	2.005
	PHX Greenway	0.292	0.922	0.752	-1.535	2.118
PHX Greenway	Clay	-2.608*	0.922	0.006	-4.435	-0.781
	Grass	-2.352*	0.922	0.012	-4.179	-0.525
	Tennis	-3.115*	0.922	0.001	-4.942	-1.288
	Track	-2.438*	0.941	0.011	-4.303	-0.574
	Turf	-2.752*	0.922	0.003	-4.579	-0.926
	Desert Ridge	0.795	0.922	0.390	-1.031	2.622
	Mesa	-0.113	0.922	0.903	-1.940	1.714
	PHX Encanto	-0.292	0.922	0.752	-2.118	1.535

*. The mean difference is significant at the 0.05 level.

APPENDIX C

AUGUST ANOVA OUTPUT

ANOVA
WBGT

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	197.784	8	24.723	5.038	.000
Within Groups	529.968	108	4.907		
Total	727.752	116			

Post Hoc Test

Multiple Comparisons

Dependent Variable: WBGT

LSD

					95% Confidence Interval	
(I) Surface	(J) Surface	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
Clay	Grass	0.595	0.869	0.495	-1.127	2.317
	Tennis	0.003	0.869	0.997	-1.719	1.725
	Track	-0.481	0.869	0.581	-2.203	1.241
	Turf	-0.005	0.869	0.995	-1.728	1.717
	Desert Ridge	3.049*	0.869	0.001	1.327	4.772
	Mesa	2.260*	0.869	0.011	0.538	3.982
	PHX Encanto	2.184*	0.869	0.013	0.462	3.906
	PHX Greenway	2.687*	0.869	0.003	0.965	4.410
Grass	Clay	-0.595	0.869	0.495	-2.317	1.127
	Tennis	-0.592	0.869	0.497	-2.314	1.130
	Track	-1.076	0.869	0.218	-2.798	0.647
	Turf	-0.600	0.869	0.491	-2.322	1.122
	Desert Ridge	2.455*	0.869	0.006	0.733	4.177
	Mesa	1.665	0.869	0.058	-0.057	3.388
	PHX Encanto	1.589	0.869	0.070	-0.133	3.311
	PHX Greenway	2.093*	0.869	0.018	0.370	3.815
Tennis	Clay	-0.003	0.869	0.997	-1.725	1.719
	Grass	0.592	0.869	0.497	-1.130	2.314
	Track	-0.484	0.869	0.579	-2.206	1.239
	Turf	-0.008	0.869	0.993	-1.730	1.714
	Desert Ridge	3.047*	0.869	0.001	1.324	4.769
	Mesa	2.257*	0.869	0.011	0.535	3.980
	PHX Encanto	2.181*	0.869	0.014	0.459	3.903
	PHX Greenway	2.685*	0.869	0.003	0.962	4.407
Track	Clay	0.481	0.869	0.581	-1.241	2.203

	Grass	1.076	0.869	0.218	-0.647	2.798
	Tennis	0.484	0.869	0.579	-1.239	2.206
	Turf	0.476	0.869	0.585	-1.247	2.198
	Desert Ridge	3.530*	0.869	0.000	1.808	5.253
	Mesa	2.741*	0.869	0.002	1.019	4.463
	PHX Encanto	2.665*	0.869	0.003	0.943	4.387
	PHX Greenway	3.168*	0.869	0.000	1.446	4.891
Turf	Clay	0.005	0.869	0.995	-1.717	1.728
	Grass	0.600	0.869	0.491	-1.122	2.322
	Tennis	0.008	0.869	0.993	-1.714	1.730
	Track	-0.476	0.869	0.585	-2.198	1.247
	Desert Ridge	3.055*	0.869	0.001	1.333	4.777
	Mesa	2.265*	0.869	0.010	0.543	3.988
	PHX Encanto	2.189*	0.869	0.013	0.467	3.911
	PHX Greenway	2.693*	0.869	0.002	0.970	4.415
Desert Ridge	Clay	-3.050*	0.869	0.001	-4.772	-1.327
	Grass	-2.455*	0.869	0.006	-4.177	-0.733
	Tennis	-3.047*	0.869	0.001	-4.769	-1.324
	Track	-3.530*	0.869	0.000	-5.253	-1.808
	Turf	-3.055*	0.869	0.001	-4.777	-1.333
	Mesa	-0.789	0.869	0.366	-2.512	0.933
	PHX Encanto	-0.866	0.869	0.321	-2.588	0.857
	PHX Greenway	-0.362	0.869	0.678	-2.084	1.360
Mesa	Clay	-2.260*	0.869	0.011	-3.982	-0.538
	Grass	-1.665	0.869	0.058	-3.388	0.057
	Tennis	-2.257*	0.869	0.011	-3.980	-0.535
	Track	-2.741*	0.869	0.002	-4.463	-1.019
	Turf	-2.265*	0.869	0.010	-3.988	-0.543
	Desert Ridge	0.789	0.869	0.366	-0.933	2.512
	PHX Encanto	-0.076	0.869	0.930	-1.798	1.646
	PHX Greenway	0.427	0.869	0.624	-1.295	2.150
PHX Encanto	Clay	-2.184*	0.869	0.013	-3.906	-0.462
	Grass	-1.589	0.869	0.070	-3.311	0.133
	Tennis	-2.181*	0.869	0.014	-3.903	-0.459
	Track	-2.665*	0.869	0.003	-4.387	-0.943
	Turf	-2.189*	0.869	0.013	-3.911	-0.467
	Desert Ridge	0.866	0.869	0.321	-0.857	2.588

	Mesa	0.076	0.869	0.930	-1.646	1.798
	PHX Greenway	0.503	0.869	0.563	-1.219	2.226
PHX Greenway	Clay	-2.687*	0.869	0.003	-4.410	-0.965
	Grass	-2.093*	0.869	0.018	-3.815	-0.370
	Tennis	-2.685*	0.869	0.003	-4.407	-0.962
	Track	-3.168*	0.869	0.000	-4.891	-1.446
	Turf	-2.693*	0.869	0.002	-4.415	-0.970
	Desert Ridge	0.362	0.869	0.678	-1.360	2.084
	Mesa	-0.427	0.869	0.624	-2.150	1.295
	PHX Encanto	-0.503	0.869	0.563	-2.226	1.219

*. The mean difference is significant at the 0.05 level.