Identifying the need for locally-observed wet bulb globe temperature across outdoor athletic venues for current and future climates in a desert environment

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Abstract

Exertional heat illness and stroke are serious concerns across youth and college sports programs. While some teams and governing bodies have adopted the wet bulb globe temperature (WBGT), few practitioners use measurements on the field of play; rather, they often rely on regionally modeled or estimated WBGT. However, urban development-induced heat and projected climate change increase exposure to heat. We examined WBGT levels between various athletic surfaces and regional weather stations under current and projected climates and in hot-humid and hot-dry weather regimes in the southwest U.S. in Tempe, Arizona. On-site sun-exposed WBGT data across five days (07:00–19:00 local time) in June (dry) and August (humid) were collected over five athletic surfaces: rubber, artificial turf, clay, grass, and asphalt. Weather station data were used to estimate regional WBGT (via the Liljegren model) and compared to on-site, observed WBGT. Finally, projected changes to WBGT were modeled under mid-century and late-century conditions. On-field WBGT observations were, on average, significantly higher than WBGT estimated from regional weather stations by 2.4 ± 2.5 °C, with mean on-field WBGT across both months of 28.5 ± 2.76 °C (versus 25.8 ± 3.21 °C regionally). However, between-athletic surface WBGT differences were largely insignificant. Significantly higher mean WBGTs occurred in August (30.1 ± 2.35 °C) versus June (26.9 ± 2.19 °C) across all venues; August conditions reached ‘limit activity’ or ‘cancellation’ thresholds for 6–8 h and 2–4 h of the day, respectively, for all sports venues. Climate projections show increased WBGTs across measurement locations, dependent on projection and period, with average August WBGT under the highest representative concentration pathway causing all-day activity cancellations. Practitioners are encouraged to use WBGT devices within the vicinity of the fields of play, yet should not rely on regional weather station estimations without corrections used. Heat concerns are expected to increase in the future, underlining the need for athlete monitoring, local cooling design strategies, and heat adaptation for safety.

1. Introduction and background

Exertional heat illness (EHI) and stroke (EHS) are concerns for health, performance, and safety across college and youth sports in the United States (U.S.). In youth sports, EHS is a leading cause of death, with American football players particularly vulnerable (Yard et al 2010, NCCSI 2020). Extreme heat may cause health and performance declines in athletes, may postpone events, cause athlete attrition (dropping out), and/or result in serious EHIs (Racinais et al 2015, Hosokawa and Vanos 2020, Graham et al 2021). The hot and dry U.S. desert southwest has experienced increasing temperatures over the last 20 years (NOAA 2021a) and rising numbers of heat-related mortality and EHI in athletes in recent years.
These trends, along with urban expansion, climate change, and population growth, warrant increased attention on outdoor human heat exposures (Georgescu et al 2013, Broadbent et al 2020) and the influence of the local urban climate (Martilli et al 2020), particularly during physical activity.

In college sports, EHI (e.g. nausea, vomiting, dizziness) is most common in American football players (75% of cases), followed by men’s (2.6%) and women’s soccer (3.4%), with most football EHI cases occurring in the preseason (Yeargin et al 2019). Kerr et al (2013) show that football players are 11 times more likely to sustain EHI than other athletes. More seriously, from 1960 to 2009, 127 known EHS cases in football resulted in death (Mueller and Colgate 2008). Such cases of EHS differ from classical heat stroke (more common in the general population) in that it usually occurs in young, healthy, and fit people during exercise (Leon and Bouchama 2015). It is important to note that EHI and EHS are entirely preventable with appropriate preparedness and care (e.g. Adams et al 2021, Miller et al 2021).

Given the vulnerability of youth and college athletes to EHI and EHS (Lopez and Jardine 2018), various heat adaptations and safety protocols are necessary to ensure safety before and during practice and competition (Casa et al 2015, Hosokawa et al 2019). These include (a) time-activity modification (based on activity modification guidelines), (b) clothing modification, (c) acclimatization, (d) hydration, (e) athlete monitoring and at-risk identification, and (f) emergency plans. Of these, appropriate actions for (a)–(d) require accurate on-site environmental monitoring (Hosokawa et al 2019). Consensus statements suggest wet bulb globe temperature (WBGT) measurements are required at the activity site throughout the event to assist practitioners in making appropriate decisions regarding clothing, duration, frequency of activity, and rest. However, the U.S. desert southwest states of Arizona, Colorado, Utah, California, and Nevada do not currently require exertional heat preparedness policies for high schools (KSI 2021). These life-saving policies include the use of on-site WBGT monitoring, an ice tub for cold-water immersion if EHS occurs, and an athletic trainer or a sports medicine professional on the field during competitions and training (KSI 2021). Please see section 2 for an overview of the WBGT measurements and equation.

The WBGT—a direct environmental measure—coupled with activity modification, has long been used in sports, occupational safety, and the military (Budd 2008). The WBGT has benefits in assessing overall heat exposure as it is simple to calculate or measure, and it integrates multiple weather variables. Yet, it also has important limitations, such as underestimating stress under conditions of limited evaporation, poor incorporation of clothing/adjustment factors, and challenges incorporating metabolic rate (Budd 2008, Alfano et al 2012, Grundstein and Vanos 2021). However, it is the preferred metric of use by both the American College of Sports Medicine (ACSM) and the National Athletic Trainers Association (NATA) (Armstrong et al 2007, Casa et al 2015) for activity or clothing modification, and is the primary tool suggested within these and other EHI/EHS consensus statements (e.g. Racinais et al 2015, Hosokawa et al 2021).

Coaches and trainers are advised to take measurements at their practice location with a WBGT meter to determine the safety of competition or practice on the field (Pryor et al 2017). Due to the cost of WBGT monitors, teams/schools may only use one sensor for multiple practices (over different fields) or may use regional estimates provided on smartphone apps or websites based on a weather station that is not co-located with the activity site (Grundstein and Cooper 2020, Tripp et al 2020). Critically, each surface type and urban microclimate may result in key differences in WBGT due to unique thermodynamic surface properties as well as impacts from distinct elements of the local built environment (e.g. structure or vegetation presence orientation can affect shading and wind). Surface moisture also affects air temperature (via evaporation or evapotranspiration) and local humidity. Thus, a calculated WBGT from a regional weather station is unlikely to reflect the microenvironments specific to each athletic surface; characterizing differences between regionally estimated and on-site WBGT values are essential to understand disparities and potentially create corrective factors for decision support and safety.

Few studies have attempted to determine the relationship between on-site WBGT and WBGT derived from regional weather station observations. Table 1 outlines the most recent studies in this space. While helpful, these studies have small sample sizes of one to a few days and short study periods, lack differing climate regimes, and often do not use simultaneous measurements at multiple test sites. These studies also have conflicting results. For example, Tripp et al (2020) found that a smartphone app (utilizing a local weather station) significantly overestimated the on-site WBGT in Florida on select days and practice times, while Pryor et al (2017) measured on-site WBGT across various athletic surfaces in Connecticut on varying days, finding significantly higher WBGT than those estimated by the National Weather Service (NWS). Conversely, in the humid climate of Athens, Georgia, Grundstein and Cooper (2020) found minimal differences among three athletic surfaces (grass, artificial turf, and asphalt), and thus that a single monitoring site was deemed representative of the three locations. These pilot studies serve as useful preliminary analyses that highlight the scarcity of longer-term, continuous, and concurrent
Table 1. Previous studies assessing differences in wet bulb globe temperature (WBGT) levels between venues with differing athletic surfaces and/or between such venues and WBGT estimates from regional weather stations.

| Location, purpose, and surfaces | No. of days | Time of year, day, and weather | Onsite WBGT measurement | WBGT model, methods, and access | Conclusions and notes |
|---------------------------------|-------------|--------------------------------|-------------------------|-------------------------------|------------------------|
| **Massachusetts**: Three locations along 23 km of the Boston marathon route compared to WBGT from commercial weather stations (over dirt, next to asphalt) (Chevront et al 2015) | 17 days | Meteorological summer (between spring and fall equinox) from 10:00 to 14:00 LST, collected data in 5 min intervals; compared the top of the hour interval to the forecasted values. **Conditions**: WBGT ranged from 5 °C to 35 °C; humid climate. | Three Kestrel 4400 Heat Stress Trackers, first tested in a heat chamber. | Compared onsite WBGT to the WBGT values from an online commercial system (Schneider Electric), which used meteorological data from two weather stations. | • Kestrel measurements taken simultaneously.  
• Concluded that one measurement along the route is sufficient for determining WBGT conditions for most of the route, yet significant misclassification existed when using weather stations (which mostly underestimate WBGT compared to on-site).  
• Use of regional stations may lead to serious health and social consequences. |
| **Connecticut**: Asynchronous comparisons of WBGT over ten athletic and to an ASOS station. Surfaces include rubber track (red and black), asphalt tennis court (blue and black), artificial turf, sand, clay, grass, water (Pryor et al 2017) | 18 days from 2012 to 2014 | May through September between 13:00 and 16:30 LST. **Conditions**: WBGT levels ranged from ~22 °C to 32 °C; humid climate. | Two Kestrel 4600 Heat Stress Tracker | NWS ASOS station via Liljegren et al (2008) model to calculate WBGT from weather stations. | • Asynchronous measurements due to only two sensors available; however, researchers found no significant difference in WBGT measured over athletic surfaces (WBGT$max$ difference of 1.29 °C).  
• WBGT from local weather stations underestimated the onsite WBGT; misclassification of heat category occurred in 45% of instances, which was worse as WBGT rises.  
• Use of regional stations may lead to serious health and social consequences. |

(Continued.)
| Location, purpose, and surfaces | No. of days | Time of year, day, and weather | Onsite WBGT measurement | WBGT model, methods, and access | Conclusions and notes |
|-------------------------------|-------------|--------------------------------|-------------------------|---------------------------------|-----------------------|
| **North-Central Florida:** Comparisons of onsite measured WBGT values to WBGT estimates from a smartphone Application using nearest weather station (Tripp et al 2020) | Three-month season | 1 August 2016–31 October 2016, 13 high schools (during football practice). WBGT values recorded at start and end of practice. Practices occurred before 10 am, 10–2 pm, and after 2 pm. **Conditions:** Generally warm and humid, WBGT levels ranged from 26.4 ± 3.2 °C. | Handheld device WBGT8758 Heat Index Monitor (General Tools and Instruments Co.) | Smartphone app (WeatherFX©, version 5), which uses the Australian Bureau of Meteorology (ABM) WBGT model with data from local NWS station based on phones GPS. | • WeatherFX© App did not accurately represent the onsite WBGT values, significantly overestimating the WBGT experienced on the field, likely due to use of ABM $s$WBGT equation. 
• Highest overestimates were midday and afternoon. |
| **Georgia:** Synchronous measurements over three surfaces—grass, artificial turf, hardcourt tennis (Grundstein and Cooper 2020) | Five days | July 2019, 10 min intervals from 9:00 am to 6:00 pm. **Conditions:** $T_{\text{max}}$ ranged from 30.3 °C to 32.6 °C; $T_{\text{dew}}$ ranged from 17.7 °C to 20.2 °C. Humid subtropical climate. | Three Kestrel 5400 heat stress trackers | Used a centrally located WeatherSTEM station but did not conduct comparisons to the weather station values. | • Data collected synchronously. 
• Minimal differences between surfaces. |

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1. ASOS: Automated Surface Observing System.
2. $s$WBGT = 0.567$T_d + 0.393e + 3.94$; $T_d$ = dry bulb air temperature, $e$ = vapor pressure. This approximation does not account for variations in the intensity of radiation or wind speed, yet assumes a *moderately high radiation level in light wind conditions.*
measurements of WBGT studies across multiple days, spatial and temporal scales, climate regimes, and surface types. Finally, to our knowledge, no study has used regional climate modeling (RCM) projections to characterize future changes in WBGT and the corresponding effect on heat stress in sport.

Accordingly, we examine differences in observed WBGT levels among various athletic surface environments against those derived from regional weather stations in both hot-humid and hot-dry weather regimes in Tempe, Arizona. We furthered this analysis to evaluate the effect of projected changes in regional climate, as simulated by an RCM accounting for increases in greenhouse gases and urban development (Krayenhoff et al. 2018) to ascertain the impact of future environmental change on projected heat stress. As part of this goal, we set out to achieve three objectives:

(a) Determine the differences in on-site WBGT levels between five distinct athletic venue surfaces (rubber, artificial turf, clay, grass, asphalt) across five full days (12 h d⁻¹) in June (dry) and August (humid).

(b) Examine potential differences, by month and time of day, between (a) the five on-site WBGT levels and (b) on-site versus modeled WBGT from regional weather stations.

(c) Assess the projected changes to regional heat stress risk based on WBGT modeled under contemporary, mid-century, and late-century conditions.

These differences across time and space were examined with respect to impacts on decision-making regarding activity modification (table 2).

2. Methods

This study was conducted in Tempe, Arizona (33.43, −111.94), located just east of Phoenix, AZ, USA in the Sonoran Desert. Field sites were located on the Arizona State University (ASU) campus (figure 1). The southwest U.S. is the warmest and sunniest region in the U.S. (Garfin et al. 2014). Higher air temperatures (Tₐ) and solar radiation may offset any attenuated heat risk from low humidity. Although an overall warmer climate allows athletes to achieve heat acclimatization earlier in the season, the sheer magnitude of extreme heat in the area (average summer daytime maximum Tₛ frequently exceeds 43 °C) keeps concerns for EHI and EHS high, particularly upon athlete return to campus in August for fall sports.

In collaboration with ASU’s Division I athletics program, various outdoor athletic venues were selected to monitor the on-site, near-surface microclimates on fully clear days (07:00 and 19:00 local standard time (LST)) in the summer of 2019 in June (five days) and August (five days). These periods were chosen to capture the hot/dry and clear part of the Arizona summer (June) and the hot/humid conditions (August; monsoon season), when moisture is drawn in from the Gulf of Mexico and the Gulf of California with prevailing winds from the south.

The outdoor WBGT is calculated as:

\[
WBGT = 0.7T_w + 0.2T_g + 0.1T_a
\]

where Tₐ is the dry-bulb temperature, Tₗ is the natural wet bulb temperature, and T₉ is the globe temperature, which accounts for the radiative load. Data obtained and used in WBGT analysis were obtained from (a) on-site simultaneous WBGT measurements with Kestrel Heat Stress Meter at each venue (section 2.1), (b) regional Arizona Meteorological Network (AZMET) weather stations (section 2.2), and (c) climate change projections (section 2.3).

2.1. Venue microclimates: in-situ data collection

WBGT measurements were concurrently collected over five athletic surfaces using factory-calibrated Kestrel 5400 Heat Stress Trackers (see figure 2(a) and supplemental material (available online at stacks.iop.org/ERL/16/124042/mmedia)). Kestrel 5400s collect Tₐ using a hermetically sealed external thermistor, relative humidity (RH) with a polymer capacitive external sensor, wind speed with a 1 inch diameter impeller anemometer and wind vane (also allows rotation for accurate wind speed readings), and T₉ using a thermistor within a 1 inch black powder-coated hollow copper globe. The device calculates natural wet bulb temperature (Tₗ), WBGT index (±0.7 °C error), and thermal work limit as relevant outputs. All data were collected at 1 min sampling intervals. Surface temperatures (Tₛₑ) were measured with Elekctiy Lasergrip 774 IR thermometers at 3 h intervals between 07:00 and 19:00 LST. These measurements are accurate within 2 °C.

The athletic surfaces were located within a 4 km (~3 mile) radius and maintained by Sun Devil Athletics (refer to figure 2). Surfaces include:

(a) Artificial turf field with natural infill (coconut husk, sand, and zeolite (Shaw Sports Turf 2021)) at the ASU football training center. Also called ‘Hydrochill,’ the artificial turf is meant to keep surfaces cooler than those with crumb rubber infill. This surface is a (1700 m²) training facility and on the north side of Sun Devil Football Stadium.

(b) Eight two-tone green asphalt tennis courts (6000 m²) (Whiteman Tennis Complex), with few buildings nearby.

(c) A light blue and tan rubber track at Sun Angel stadium directly north of the Whiteman Tennis Complex. The sensor was placed near the northeast over a large tan rubber area (~230 m²).
Table 2. 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 2020, modified from Armstrong et al 2007). Discretion (D), limit (L), and cancel (C) thresholds are used throughout the current manuscript for activity modification guidelines.

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

* Occurs when evaporative cooling is not supported by the environment, with other conditions (e.g. air temperature) impeding cooling; UCHS will cause a rise in $T_{core}$ without actions taken.

Figure 1. Locations of AZMET weather stations (Mesa, Desert Ridge, Phoenix Encanto, and Phoenix Greenway) and the on-site field locations.

for better surface homogeneity. The track was also close to a grass surface that was watered every afternoon ∼1330 h, which may increase humidity.

(d) Brown baseball clay surface (∼150 m²) at Phoenix Municipal Stadium, located approximately 3.2 km (2 miles) north of the ASU Tempe campus.

e) A natural grass surface (∼380 m²), also located at Phoenix Municipal Stadium.

The Kestrel Heat Stress Meters were placed over each surface on a tripod at 1.2 m height (47 inches), the approximate chest height of an athlete (Santee et al 1994, Pryor et al 2017). All locations were sun-exposed throughout the entire day (07:00–19:00 LST); however, minimal shading was present from low-lying fences and trees near the start and finish times in August. All sensors were placed at least 3.0 m from the edge of the given surface. These locations remained constant across the ten measurement days. Across the five days of collection in June, 4% of data were removed due to the device being blown over by the wind or incorrect set up by a volunteer. August data were 100% complete. To ensure consistency in the setup of the Kestrel devices, each research volunteer was provided a detailed guide and in-person training.
An additional field test was completed as there are some concerns that the Kestrel device may overestimate $T_a$ if the thermistor is directly exposed to the sun with low airflow (Kestrel 2016). Due to this concern, two Kestrel meters were placed in an open field $\sim1.22$ m (4 ft) from an AZMET weather station site (see section 2.2) on a golf course (Encanto) for a full clear, hot day and night in July (08:00–07:00 LST). Results are provided in the supplemental information. Notably, the wind vane attachment (figure 2(a)) allows the Kestrel device to constantly spin with the wind, altering the thermistor exposure to the sun and aligning the thermistor with the wind to prevent overestimates of the $T_a$. The average $T_a$ reading via the Kestrel device was $0.21^\circ C$ higher than that from the weather station and with a 2.3% higher relative humidity. In comparing the WBGT calculated from the AZMET data using the Liljegren model (see section 2.4) versus the measured WBGT by the Kestrel devices, the Kestrel WBGT was slightly higher ($1.2^\circ C$) across the daytime. This potential bias is considered in the results and discussion and outlined further in the supplemental material.

### 2.2. Regional meteorological data

To provide regional comparisons with on-site WBGT levels, weather station data were obtained from the AZMET data archive managed by the University of Arizona (The Arizona Meteorological Network 2020). The AZMET stations also monitor solar radiation and thus are more suitable than most airport weather stations. However, if a regional WBGT value is used by a sports team, it is likely derived from estimated solar radiation as most weather stations do not collect such data. AZMET data were downloaded from the four weather stations nearest to the ASU campus (see figure 1). All instrumentation at these locations is regularly maintained and monitored for accuracy, with data reported hourly as an average (The Arizona Meteorological Network 2020). Further information and overhead images are provided in the supplemental material. The data obtained from the four sites were used to model regional WBGT values (section 2.4).

### 2.3. Climate projection data

RCM projections based on dynamical downscaling using the Weather Research and Forecasting
(WRF) model were used in the Liljegren model to calculate future WBGT in Tempe for the given weeks in June and August. WRF model output was based on a continuous Control simulation centered on the conterminous U.S., representing the first decade of the current century (2000–2009). This simulation (i.e. Control) represents the start-of-century contemporary climate and was initialized and forced at the lateral boundaries with reanalysis data obtained from the European Centre for Medium-Range Weather Forecasting (ECMRWF 2009). Control simulation output was saved at 3 h intervals for the duration of the decadal period. Projections of future climate were provided for multiple representative concentration pathways (RCPs) that were used to drive WRF (see Krayenhoff et al. (2018) for further details on all WRF methodological aspects, including spin-up and parameterizations used).

In addition to accounting for increased concentration of greenhouse gases, these RCM simulations also account for projected growth (i.e. expansion and densification) of the built environment via the Integrated Climate and Land Use Scenarios (version 1.3.2) dataset (Bierwagen et al. 2010). These include: mid-century (2050–2059) simulations using the Community Earth Systems Model (CESM), as well as RCP4.5 and RCP8.5 end of century (2090–2099) simulations. In addition, one RCM simulation initialized and forced with CESM RCP8.5 for the end of century assumed heat mitigating ‘full adaptation’ (FA) measures (e.g. cool roofs, green roofs, trees, etc (Krayenhoff et al. 2018)). It is important to note that the CESM GCM has been shown to be among the top CMIP5 GCM performers when simulating global patterns of observed temperature and rainfall (Knutti et al. 2013). In addition, the Control (WRF) simulation has been evaluated extensively against station observations and gridded data products for both temperature and precipitation (Krayenhoff et al. 2018, Broadbent et al. 2020, Georgescu et al. 2021), ensuring that differences between projected and contemporary climate are based on skillful present-day simulations.

For all simulations, we retrieved the climate data at 3 h intervals from 7:00 to 19:00 LST for the given day of year and decadal period duration (e.g. averages from 2050 to 2059) from the grid cell encompassing Tempe, AZ. Complete methods describing RCM temperature output and model evaluation are outlined in Krayenhoff et al. (2018). The difference between the Control simulation and future projections was applied to the average AZMET or Kestrel observations by 3 h window and day of year to generate new projections that illustrate the effects of climate change. In sum, we utilize five RCM simulations (one contemporary and four future projections) to characterize projected climates.

2.4. Modeling WBGT with AZMET regional data and climate projections

Various methods exist to estimate the needed $T_a$ and $T_w$ for equation (1) from standard weather variables (e.g. see Lemke and Kjellstrom (2012)). Here, we used the Liljegren model (Liljegren et al. 2008) to calculate the WBGT from the AZMET regional weather station data (incoming horizontal radiation, $T_{air}$, wind-speed, RH) and using the climate projection data outlined in sections 2.2 and 2.3, respectively. The WBGT algorithm, the R package ‘HeatStress’ and command wbgt.liljegren (Casanueva 2017) require seven input variables, including air temperature (°C), dew point (°C), solar radiation (W m$^{-2}$), wind speed (ms$^{-1}$), latitude, longitude, and date, to generate the WBGT output. The Liljegren model was also used in nationwide WBGT climatology and heat stress studies by Grundstein et al. (2014) and Vanos and Grundstein (2020), with the former also assessing WBGT by time of day.

The Liljegren method was chosen because it is generally accurate across various conditions calculated hourly in outdoor sun-exposed conditions (Lemke and Kjellstrom 2012). It was used by Pryor et al. (2017) (see table 1) for similar field-type comparisons and has been implemented in prior EHI-related research using WBGT (e.g. Grundstein et al. 2015, Vanos and Grundstein 2020).

2.5. Analysis

We provide descriptive statistics of weather variables and WBGT by measurement location. Statistical comparisons of hourly WBGT between the nine locations (five venues and four AZMET locations) by month were determined using independent sample t-tests for each group based on surface type and month, with a significance level of $p = 0.05$. Each independent dataset had a high sample size with a normal distribution and homogeneous variance. Data were analyzed in SPSS (version 26; IBM Corp, Armonk, NY) and R (version 3.6.1).

3. Results

3.1. Weather conditions

The month of June captures the hot and dry portion of the summer in Arizona. As outlined in table 3, the mean daily $T_a$ across the four AZMET locations ranged from 29 °C to 36 °C ($T_{max} \sim 38.2$ °C–39.6 °C) with 12%–20% RH and low wind speeds ($\sim1.3$ ms$^{-1}$). These regional daily $T_a$ values on June study days were 5.4 °C lower than the $T_a$ averages measured over the athletic surfaces, which help explain lower on-site RH by $\sim4.5%$. During the August study period, the region experienced higher $T_a$ and RH ($T_{air} \sim 32.3$ °C–35.5 °C with $\sim24%$–30% RH). These mean daily regional $T_a$ values were, on average, 5.2 °C less than the $T_a$ over the athletic surfaces, which also had 5.8% lower RH (table 3).
Table 3. Summary of ambient environmental conditions at each study location (sports surface and AZMET station between 0700 and 1900 h), including average daily values of air temperature ($T_a$), maximum temperature ($T_{\text{max}}$), relative humidity (RH), wind speed ($v_w$), globe temperature ($T_g$), and solar radiation. Data are from five days between 18 and 27 June 2019, and five days between 7 and 14 August 2019. SD: standard deviation.

| Surface         | June | August       |          |          |          |          |          |          |          |          |          |          |          |
|-----------------|------|--------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|                 | $T_a$ ($^\circ$C) | $T_{\text{max}}$ ($^\circ$C) | RH (%)  | $v_w$ (ms$^{-1}$) | $T_{dC}$ (range) | SR (W m$^{-2}$) | $T_a$ ($^\circ$C) | $T_{\text{max}}$ ($^\circ$C) | RH (%)  | $v_w$ (ms$^{-1}$) | $T_{dC}$ ($^\circ$C) | SR (W m$^{-2}$) |
| Clay            | 36.3 ± 3.49 | 47.0         | 12 ± 4.4 | 1.3 ± 0.80 | 28.7–65.8       | —         | 38.7 ± 3.43 | 47.9         | 21 ± 9.0 | 1.2 ± 0.84 | 28.8–65.5       | —         |
| Grass           | 35.9 ± 3.05 | 44.1         | 13 ± 4.0 | 1.3 ± 0.90 | 23.2–38.4       | —         | 38.1 ± 3.21 | 49.7         | 22 ± 9.9 | 1.3 ± 0.96 | 25.4–41.5       | —         |
| Tennis          | 36.8 ± 3.64 | 47.6         | 12 ± 4.2 | 1.0 ± 0.71 | 32.8–69.4       | —         | 39.7 ± 3.57 | 49.3         | 19 ± 8.9 | 1.0 ± 0.83 | 34.3–70.8       | —         |
| Track           | 35.6 ± 3.44 | 43.2         | 14 ± 4.9 | 1.6 ± 0.91 | 31.7–67.1       | —         | 39.3 ± 3.30 | 48.3         | 22 ± 9.9 | 1.4 ± 0.9  | 33.4–71.9       | —         |
| Turf            | 36.4 ± 3.71 | 47.6         | 12 ± 7.4 | 1.2 ± 0.81 | 24.3–77.9       | —         | 39.1 ± 3.89 | 47.9         | 21 ± 12.4| 1.1 ± 0.83 | 25.2–68.1       | —         |
|                 | 34.2 ± 4.66 | 45.9 ± 2.09 | 12.6 ± 0.89 | 1.3 ± 0.22 | 28.1 ± 4.30       | —         | 39.0 ± 0.61 | 48.6 ± 0.83 | 21.0 ± 1.22| 1.2 ± 0.16 | 29.4 ± 4.3       | —         |

| AZMET stations | June | August       |          |          |          |          |          |          |          |          |          |          |          |
|-----------------|------|--------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|                 | $T_a$ ($^\circ$C) | $T_{\text{max}}$ ($^\circ$C) | RH (%)  | $v_w$ (ms$^{-1}$) | $T_{dC}$ (W m$^{-2}$) | $T_a$ ($^\circ$C) | $T_{\text{max}}$ ($^\circ$C) | RH (%)  | $v_w$ (ms$^{-1}$) | $T_{dC}$ ($^\circ$C) | SR (W m$^{-2}$) |
| Mesa            | 32.6 ± 4.82 | 39.6         | 13 ± 4.8 | 1.6 ± 0.71 | —         | 347 ± 380.6 | 35.5 ± 4.3 | 44.0 | 24 ± 10.9 | 1.4 ± 0.84 | —         | 307 ± 358.3       | —         |
| Desert Ridge    | 28.9 ± 5.63 | 37.0         | 20 ± 9.5 | 1.3 ± 0.87 | —         | 344 ± 388.9 | 32.3 ± 5.07 | 41.7 | 30 ± 13.4 | 1.2 ± 0.90 | —         | 308 ± 366.7       | —         |
| Phoenix Encanto | 31.1 ± 5.43 | 38.2         | 17 ± 8.6 | 1.3 ± 0.90 | —         | 344 ± 383.3 | 33.8 ± 5.27 | 43.2 | 29 ± 14.2 | 1.0 ± 0.85 | —         | 303 ± 361.1       | —         |
| Phoenix Greenway| 30.7 ± 5.37 | 38.3         | 17 ± 7.6 | 1.3 ± 0.88 | —         | 353 ± 388.9 | 33.9 ± 4.94 | 43.3 | 26 ± 11.5 | 1.1 ± 0.90 | —         | 309 ± 363.9       | —         |
|                 | 30.8 ± 1.52 | 38.3 ± 1.06 | 16.8 ± 2.87 | 1.4 ± 0.15 | —         | 347 ± 4.24 | 33.9 ± 1.31 | 43.1 ± 0.97 | 27.3 ± 2.73| 1.2 ± 0.17 | —         | 306 ± 2.63       | —         |

* Range of average values across five temporal periods for all days sampled in the given period.
Figure 3. Box plots of hourly WBGT levels across five full (7:00–19:00 LST) clear days in June and August. WBGT levels across five athletic surfaces and four regional weather stations are shown (DR: Desert Ridge). Each box indicates the median value (thick middle line), minimum and maximum (whiskers), as well as first and third quartile (box). Outliers from minimum are shown by filled circles. The average WBGT levels over the athletic surfaces (Clay, Grass, Tennis, Track, Turf) were significantly higher than from the AZMET stations, indicated by ‘∗∗’.

Figure 4. Time series of the average wet bulb globe temperature (WBGT) values (°C) observed at each location, including the AZMET weather stations (Wx) during the observation period in June 2019 and August 2019. Shaded areas represent 1 standard deviation (SD). Horizontal lines represent WBGT thresholds for cancellation (C = 32.3 °C), limiting activity (L = 30.1 °C), or use discretion (D = 29.7 °C) based on Armstrong et al. (2007) (see table 2).

The June study period was 1.1 °C warmer than the month’s climate average for Tempe (based on 1981–2010 averages), while the August study period was 2.5 °C warmer than average (National Weather Service 2020). Further, August 2019 was drier than normal, with a rainfall total of around 0.64 cm (0.25 in) compared to the normal of 2.54 cm (1 in), while June had the typical little-to-no rainfall (Selover 2019).

3.2. Regional versus on-site WBGT
Significantly lower WBGTs were found in June versus August across all athletic venues, with an average June WBGT of 26.9 ± 2.19 °C (maximum 31.1 °C) versus 30.1 ± 2.35 °C in August (maximum 34.1 °C) (p < 0.05) (see figure 3). For June and August combined, the WBGT was significantly lower at the AZMET sites (WBGT = 25.8 ± 3.21 °C) compared to on-site at the athletic venues (WBGT = 28.5 ± 2.76 °C). In June (August), the on-site WBGT was 2.4 °C (2.5 °C) higher than the AZMET WBGT average, both significant (p < 0.05). Compared to the AZMET group mean, all individual venue surfaces had significantly higher WBGT than the AZMET sites except for the natural grass surface in August.

The differences between the average WBGT above the five athletic surfaces and the AZMET site WBGT (i.e. the regional conditions) also varied by time-of-day (figure 4). Larger differences between on-site and regional WBGT are seen in June and in the morning hours (as shown by white space between groups in figure 4), resulting in ~3.9 °C higher on-site WBGT in the morning hours (before 10:00 LST),
converging throughout the afternoon between 10:00 and 15:00 LST (2.7 °C difference) and early evening hours (1.5 °C difference). Respective differences for August are 3.9 °C, 2.7 °C, and 0.9 °C. Hence, while the WBGT from regional stations had systematic differences from on-site venue averages, these differences lessen as the day progresses.

3.3. Between-surface comparisons
All venue microclimates had significantly higher WBGT levels in August than in June, with the greatest difference between the periods over the rubber track (+3.7 °C in August versus June). Between-surface in-month comparisons showed a significantly higher rubber track WBGT (30.6 °C) than grass (29.6 °C) in August (p < 0.05), with the artificial turf and tennis resulting in high WBGT values (daily averages of 30.1 °C and 30.2 °C, respectively), yet not significantly different than other surfaces (see figures 3 and 4 and supplemental material table 1).

Across both months and all sampling periods, the average T_dwc of grass was significantly lower than all other surfaces, averaging 34.3 °C in June and 31.1 °C in August (p < 0.05) (table 3). Overall, the highest mean T_dwc was recorded on the artificial turf surface in June (53.4 °C, reaching a maximum of 77.9 °C) (figure 5). Simultaneously, the grass surface reported 39.0 °C. In August, the highest T_dwc occurred on the clay, tennis, and track surfaces (48.0 °C, 54.8 °C, 53.1 °C, respectively). The slightly lowered artificial turf mean T_dwc in August (47.7 °C) may be due to the higher humidity levels allowing some moisture to be absorbed by the natural infill of the ‘cool turf’. These values did not differ significantly by month. See complete T_dwc data in the supplemental material. Thermal images on select sampling days are in figure 5. There was no significant difference in WBGT between the four AZMET sites in June or August.

3.4. Activity modification
Activity modification guidelines (cancel (C), limit (L), or discretionary (D) activity) were assessed based on the number of times, on average per day (12 h day from 07:00 to 19:00 LST), that the given thresholds (table 2) were reached using hourly WBGT data. In general, higher limits were reached in August, and regional weather station WBGT estimates considerably underestimated the need for safety measures. The WBGT values at each venue in June did not reach any cancel or limit activity modification, yet all venues reached a discretionary level for 4–6 h d^{-1} (or 33%–50% of the monitored 12 h of the day). None of the regional estimates of WBGT reached this discretionary threshold. However, in August, with higher T_a and RH present, all surface microclimates and regional stations reached a discretionary threshold (average 7–12 h d^{-1}, with the highest occurring over the track surface). Moreover, all venue microclimates reached the limit activity threshold (6–8 h (50%–67%) of the 12 h day), while all but grass reached a WBGT value that would constitute cancellation of practice or competition (the most serious heat stress modification) (figure 6). WBGT values over the track surface would require cancellation of practice for on average 4/12 h, or 25% of the day, in August. These cancellation thresholds were reached between approximately 11:00 and 15:00 LST (figure 4). Importantly, in August, 33%—or 4 of the 12 h d^{-1}—experienced WBGT values above the cancellation threshold for the track, tennis, and clay surfaces. Finally, almost the entire day (10 h (~83%) on clay, grass, tennis, and turf and 12 h (100%) on the track) crossed the discretion threshold of 27.9 °C.

3.5. Climate projections
RCM simulations calculating WBGT were applied to the athletic venue environmental conditions and the regional conditions based on the AZMET data. The contemporary scenario provides the lowest WBGT value (figure 7), with late-century RCP 8.5 projections for the regional conditions (CESM end-of-century and CESM FA end-of-century) reaching the currently experienced on-field WBGT values in June and August. Hence, the more extreme heat conditions experienced at the venue fields provide a glimpse into future regional WBGT. Mid-century CESM projections for RCP4.5 and RCP8.5 for on-field conditions show average daily WBGTs that range from 27.6 °C to 28.4 °C in June and 31.8 °C to 32.3 °C in August. Therefore, August conditions under RCP8.5 would, on average, be over the cancellation limit all day. Late-century conditions indicate that daily on-site WBGTs, on average, range from 30.0 °C to 30.2 °C in June and 33.4 °C to 33.8 °C in August. These projected August on-field WBGT values are 3.3 °C higher than contemporary on-field conditions and 5.6 °C higher than contemporary regional conditions based on AZMET sites.

4. Discussion
4.1. Current WBGTs
The current study examined WBGT values between various athletic surface microclimates and regional AZMET weather stations under current and projected climates in both hot-humid and hot-dry weather regimes in Tempe, AZ. Findings demonstrate significantly higher average WBGTs across all sites in August compared to June in 2019. However, within-month comparisons show predominantly insignificant differences in WBGT between the on-site venue measurements, yet significant differences between the on-site WBGT and regional AZMET WBGT estimates. These differences decrease throughout the day and can be explained by faster heating of surfaces and air temperatures at the urban venue sites in the morning compared to the AZMET sites, with overall heat levels
across the region reaching equilibrium late afternoon. Moreover, median August WBGTs on the sports fields were consistently over 30 °C, which is a concern for all players based on Cooper et al (2016) who showed that EHI among college football players increased noticeably with WBGT > 28 °C.

Our results align with Pryor et al (2017) over similar sports surfaces, with all on-site measurements...
Figure 6. Average number of hours per day spent above the three highest activity guideline thresholds (discretion, limit, cancel; see table 2) based on the wet-bulb globe temperature (WBGT) during the two study periods and 12 h of measurements per day, separated by athletic surface and AZMET regional weather station observed.

Figure 7. Box plots of average WBGT values for the AZMET Regional Weather Stations and the Kestrel Onsite Stations according to the five scenarios from Weather Research and Forecasting (WRF) climate projections for the months of June and August. Each box indicates the median value (thick middle line), minimum and maximum (whiskers), as well as first and third quartiles (box). Outliers from minimum are shown as filled circles.

presenting significantly higher WBGT values than regional. Pryor et al (2017) and Grundstein and Cooper (2020) similarly found no significant differences between the on-site venue WBGTs. Hence, while a WBGT sensor per field site is the optimal situation, repeated results in the literature (Cheuvront et al 2014, Pryor et al 2017, Grundstein and Cooper 2020) and current results show that the use of one or two WBGT stations on nearby sporting surfaces (e.g. on the same high school or university campus) can adequately represent all-venue conditions (as suggested in a recent consensus document by Hosokawa et al 2021). However, applying modeled WBGT from regional weather stations can significantly underestimate heat stress conditions for athletes, which may cause issues of spatial incongruence and heat safety misclassification for proper decision-making (e.g. Solís et al 2017). These findings are particularly important in the U.S. southwest, where Arizona, Colorado, Utah, California, and Nevada currently do not require exertional heat preparedness policies for high schools (KSI 2021). If an estimated or modeled regionally based WBGT is used, athletic trainers or researchers should first determine local corrective factors using a full season of data by time of day depending on the WBGT estimation model used. For example, Tripp et al (2020) found overestimations by the WeatherFX® phone application compared to on-site measurements due to the phone app model assumptions of a single radiation value and light winds (Meteorology A B O 2019).

Our study days tested in 2019 had conditions that differed slightly from the 30 year climatological average conditions for Tempe, AZ, with positive $T_a$ differences from normal (+1.1 °C and +2.5 °C for June and August, respectively (National Weather Service 2020)), which may be partially a result of choosing only clear study days. While August presented higher humidity than June, as expected, the humidity
remained lower than normal in the region for August due to a less active monsoon (Selover 2019).

The higher temperature and humidity in August, even with lower \( T_{\text{g}} \) and solar radiation, caused large windows of the day to reach activity modification thresholds, with most days under discretionary watches (at regional stations as well). All on-site WBGT values recorded would also require monitoring of hydration status, according to table 2. More concerning, all venues required limited activity across 50%–67% of the day, while select surfaces (clay, track, tennis surfaces) would have required cancelation of activities for 2–4 h of the day. While discretization was met in June at all venues, no limitation or cancelations were reached; thus, June sporting events and practices can occur more safely (if athletes are acclimatized) (Armstrong et al 2007). The daily time course of these threshold occurrences (figure 4) can support athletic trainer and coach decision-making on practice type, time, and location. Based on our results, August practices and competitions in Tempe, AZ, should try to ensure the following: fully acclimatized players with high fitness before full practices; adapting schedules for more intense, longer, and/or full equipment practices held in cooler portions of the day; playing on cooler surfaces (e.g. grass versus artificial turf) when possible (Hosokawa et al 2018). Future work is warranted to assess differences between on-site measurements with regional weather stations and new gridded WBGT forecasts (NOAA 2021b) for full seasons across various climates in the U.S. for optimal corrections specific to venue and climate.

4.2. Climate projections

The RCM simulations provide insight concerning future average climate conditions. In the current case study, they support the preparation of the sports community for outdoor play and microclimatic design improvements needed. Figure 7 shows that current WBGT conditions experienced, on average, at the venues in June and August (which was 2.5 °C WBGT over the regionally based WBGT) provide a glimpse into the future based on late-century RCP8.5 projections for regional conditions. These projections provide a range of potential futures and support proactive, rather than reactive, heat adaptations strategies that can be adopted by athletic facilities and personnel to limit future impacts on performance, health, and economics. The rising levels of heat projected in the future and the impacts of sporting events and outdoor work, in general, have been shown by others (Burke et al 2015, Smith et al 2016, Kenny et al 2020) with overall increasing challenges and economic considerations. These climate projections provide useful information to initiate preparation for the future to adapt microclimate and promote infrastructural, technological, and physiological adaptations according to IPCC recommendations to support health and performance (Smith et al 2014).

4.3. Venue microclimate differences and adaptation recommendations

The on-site WBGT measurements provide a starting point for researchers to understand heat stress experienced by athletes on the field of play and how it may impact physical activity, health, and performance. Microclimatic design modifications that can be made on-site can help reduce environmental parameters that cause WBGT thresholds to be reached, which can be particularly beneficial for already-hot locations. However, such modifications must consider the prevailing climatic conditions (e.g. sunny versus cloudy; humid versus dry; hot versus warm; prevailing winds) that affect WBGT.

Urban microclimate studies point to solar radiation changes via shading as the most important design consideration in the warm season driving thermal exposure of the general population (e.g. Middel et al 2021); however, sports fields have minimal, if any shading, and thus no measurements were taken in the shade. Moreover, shade is not generally a viable solution for decreasing heat load for sports played on an open field, apart from sidelines, which are typically used for breaks. For the non-shaded fields of play, the largest difference between the environments occurred in \( T_{\text{d}} \), with grass remaining significantly lower than all other surfaces, and the artificial surfaces (turf, rubber track, tennis court) presenting the highest \( T_{\text{d}} \). Similar work with full net radiation measurements in hot, dry climates support this finding (Hardin and Vanos 2018, Middel and Krayenhoff 2019), where hotter surfaces heat the air and emit longwave radiation towards any person on the surface.

Humidity levels also differed by site, which can be affected by evapotranspiration and local sources (e.g. nearby sprinklers). Further, watering surfaces (grass, concrete, or artificial turf) or the use of evaporative misters in dry climates are becoming more common for local cooling (e.g. Graham et al (2021) showed optimal body cooling in the heat by misting fans with windspeeds of 2.5 ms⁻¹), yet there are tradeoffs with water use to consider in a desert city (Snir et al 2016, Vanos et al 2021), and one must also be cognizant of humidity increases by time of year. High humidity and lack of wind flow can increase WBGT and cause oppressive conditions for athletes and can impede sweat evaporation, particularly with high clothing amount (Parsons 2014, Vanos and Grundstein 2020). Thus, ensuring that predominant wind flow directions are open, or using on-site fans during practice, is essential to maintain/increase evaporative efficiency (Ravanelli et al 2015). Further work is needed to test optimal local cool and personal pre and per-cooling strategies for athletics as cities warm due to urban growth and climate change.

A helpful example demonstrating microclimatic changes is presented using the artificial turf surface, ‘HydroChill’ by Shaw Sports. The artificial surface
works (i.e. attempts to stay cool) by evaporating moisture held in the natural infill and is stated to have the maximum benefit in the hottest part of the day (Shaw Sports Turf 2021). However, if there is no infill moisture, the temperatures will be similar to other plastic-based artificial turfs. Coaches or trainers must still irrigate the HydroChill turf, and the dry, sunny Arizona climate can quickly evaporate infill moisture. Extreme surface temperatures reached midday (see figure 5 and supplemental material) show a lack of moisture in the infill; however, personal communication with the athletic trainer confirms that the turf is generally watered by hand in morning hours ∼04:00 LST (hence, lower T_{skc}) for morning practices, and the field is generally not used for practice in the mid-day in the summer. The hot, dry climate supports enhanced evaporation (particularly with added wind flow), yet the available moisture would be evaporated quickly. Future work is warranted as teams adopt ‘cool turf’ for their grass fields to determine irrigation needs, heat levels, material lifespan, and tradeoffs (e.g. watering needs and maintenance for artificial turf versus natural grass).

4.4. Limitations

Important limitations exist in any field study. The current study was unable to control or account for the exact time of sprinkler use on or around select surfaces, yet we were able to record these occurrences based on daily viewings and communication with coaches or trainers to help explain specific results. The Kestrel devices are popular for use by athletics trainers and coaches because of their modest cost, durability, quick response time, ease of use for athletic trainers, and small size, yet may not provide as accurate WBGT estimate as higher cost portable monitors (Cooper et al 2017). There are also issues in the accuracy of the Liljegren model by time of day (e.g. morning low sun angles), yet they have been found to perform similarly to that of high-end sun-exposed WBGT measurements (Lemke and Kjellstrom 2012). The height at which windspeed was measured for the Kestrel was 1.2 m and the height of the AZMET regional weather stations is 3 m, which could be a partial reason for slightly lower WBGT values from the regional weather stations, yet insignificant compared to the effect on microclimates within the urban setting.

In addition, uncertainties associated with the RCM simulations exist. It is important to mention our approach makes use of a reanalysis product for the contemporary period and GCM data for future periods. We justify this decision by recognizing that meaningful impact assessment requires simulation of an accurate contemporary, or baseline/Control, climate, which is possible through use of reanalysis data that assimilates observations. Nevertheless, we do acknowledge the importance of future research that examines differences in impacts that result from RCM simulations using the approach used here, and the more traditional approach wherein the same GCM is used to initialize and drive a RCM for both a contemporary and future climate. Additional uncertainties associated with use of just one GCM, rather than a multi-model ensemble approach are also acknowledged. Finally, the arrival of CMIP6 data presents considerable additional opportunities associated with advances in large-scale climate modeling.

5. Conclusions

We examined ambient WBGT between various athletic surfaces (grass, artificial turf, rubber, clay, and asphalt) and regional weather stations under current and projected climates and in both hot-humid and hot-dry weather regimes in Tempe, Arizona in the summer of 2019. To the authors’ knowledge, this is the only study to (a) complete simultaneous, full-day comparisons of WBGT between five outdoor athletic venues and regional conditions, (b) complete these tests in oppressively hot conditions that span dry and humid conditions, and (c) utilize climate projections to estimate future on-site and regional WBGTs. Findings demonstrate that the use of regional WBGT estimates from weather stations significantly underestimate WBGT measurements at the outdoor sports fields, with August 2019 presenting much more oppressive conditions that result in considerable limited or cancelled activity versus June 2019. These findings support the positions of NATA and ACSM to use on-site observations of WBGT at athletic venues by athletic trainers, referees, umpires, team physicians, and/or coaches before/during any game or practice regardless of surface type. Our work demonstrates the increasing importance of urban heat mitigation and climate change mitigation efforts (Georgescu et al 2014) as well as a critical need for enhancing behavioral and physiological adaptations within sporting organizations across youth, college, and professional sports facing increasing levels of heat (Hosokawa et al 2019).

Data availability statement

The climate projections data that support this study can be found at https://doi.org/10.48349/ASU/3TYXZ1. Remaining WBGT data are available at https://erasms.com/UWIN/data/.

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**Conflict of interest**

The authors declare no competing interests.

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