Range Commanders Council
Meteorology Group

WP-23-001

FINDING IMPROVEMENTS IN THE MEASUREMENT AND ESTIMATION OF WET-BULB GLOBE TEMPERATURE

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Preface

The wet-bulb globe temperature (WBGT) index is the standard measure of heat stress for the DoD. Several published studies have addressed measuring and estimating the WBGT, but these studies have been plagued by data sets that are too small and/or are biased due to geographical influences and sensor differences. This paper outlines the campaign undertaken by the Range Commanders Council Meteorology Group to fill these deficiencies by taking observations of WBGT-related variables over several months in 2021 at several climatic sites using a standard set of instrumentation. The WBGT measurement platform development, data collection procedures, data quality control results, and suggestions for future WBGT estimation algorithm development are highlighted. The results from this campaign will serve as the foundation for improving estimations of WBGT using standard meteorological variables.

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Acronyms

AFB	Air Force Base
AGL	above ground level
ATC	Aberdeen Test Center
BG	black globe
CRTC	Cold Regions Test Center
CS	Campbell Scientific
DPG	Dugway Proving Ground
LST	Local Standard Time
MG	Meteorology Group
NBM	National Blend of Models
NDFD	National Digital Forecast Database
NWB	natural wet-bulb
NWS	National Weather Service
PMRF	Pacific Missile Range Facility
RCC	Range Commanders Council
RTC	Redstone Test Center
SFB	Space Force Base
TDDEC	Training Device Design and Engineering Center
UTC	Universal Coordinated Time
WBGT	wet-bulb globe temperature
WSTC	White Sands Test Center

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1. Introduction

Heat stress is a substantial concern to the DoD in operational and testing environments. In April 2022, the DoD Defense Health Agency stated that over 12,000 heat-related illnesses occurred within active component service members in 2017-2021, with the threat continuing to be "a significant and persistent threat to both the health of U.S. military members and the effectiveness of military operations."[1] In an effort during the 1950s to reduce heat-related casualties at Marine Corps training bases across the southeastern United States, Yaglou and Minard[2] developed a heat stress index called the wet-bulb globe temperature (WBGT). This index accounts for the effects of temperature, humidity, wind, and intensity of solar radiation on the human body. The WBGT is calculated using Equation 1.

$$WBGT = 0.1T_a + 0.2T_g + 0.7T_{nwb} \qquad \text{Equation 1}$$

where T_a is the air temperature
T_g is the black globe (BG) temperature (the temperature in the middle of a six-inch copper sphere painted matte black)
T_{nwb} is the natural wet-bulb (NWB) temperature (temperature of a thermometer fitted with a wetted wick and aspirated naturally)

Figure 1 shows an early setup to measure WBGT using mercury-in-glass thermometers.[3] These platforms were cumbersome to deploy and challenging to maintain, but the measured data were very beneficial. Electronic sensors began to replace mercury-in-glass thermometers in the 1980s and portable WBGT units were developed in the 1990s.

[1] Defense Health Agency. "Update: Heat illness, active component, U.S. Armed Forces, 2021." In *Medical Surveillance Monthly Report*, vol. 29, no. 4, pp. 8-14. April 2022.
[2] Yaglou, C. P. and D. Minard. *Prevention of heat casualties at Marine Corps Training Centers*. Office of Naval Research Physiology Branch report, 48 pp. 31 May 1956. Retrieved 25 May 2023. Available at https://apps.dtic.mil/sti/pdfs/AD0099920.pdf.
[3] Departments of the Army and the Air Force. "Heat Stress Control and Heat Casualty Management." TB MED 507/AFPAM 48-152. 7 March 2003. Superseded by TB MED 507, 12 April 2022. Retrieved 25 May 2023. Available at https://apps.dtic.mil/sti/pdfs/ADA433236.pdf.

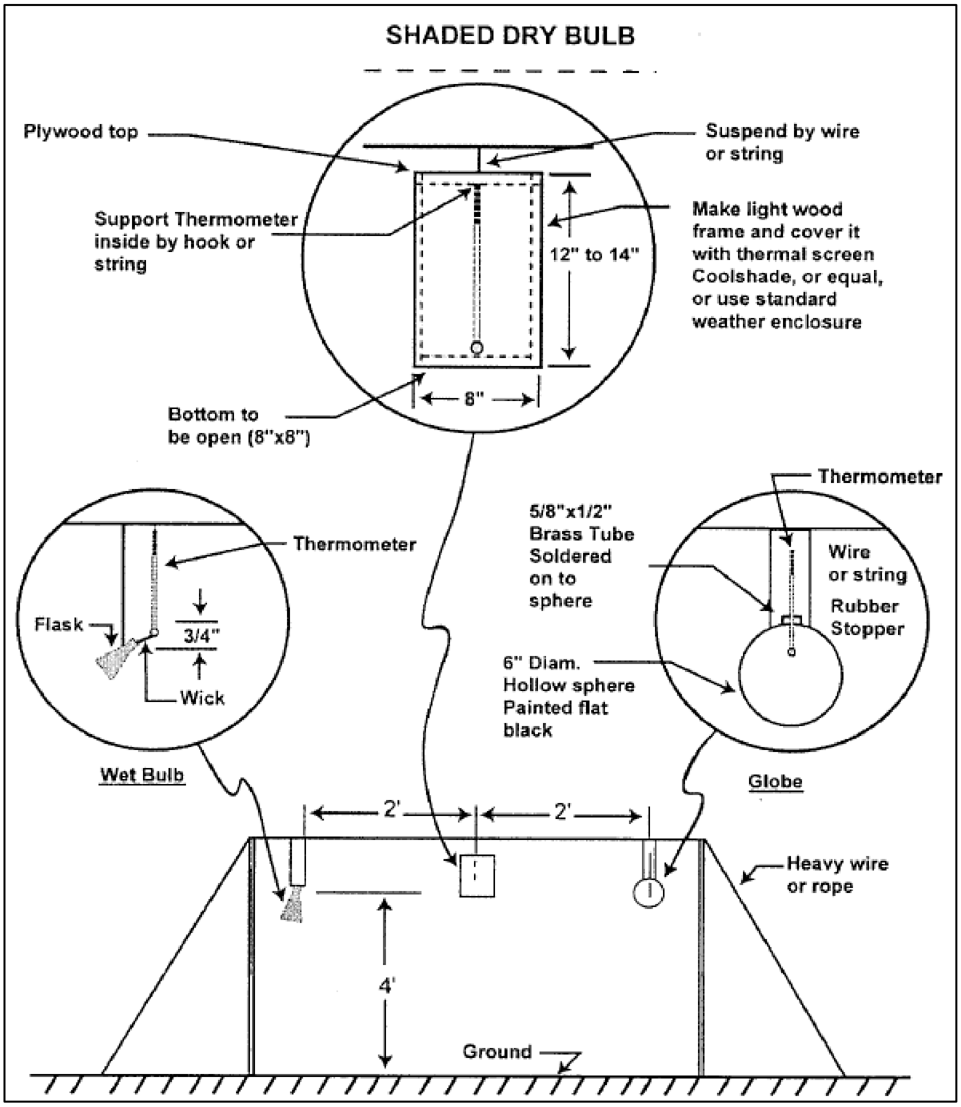

Figure 1. Early WBGT Measurement Platform

The WBGT is the DoD standard for assessing heat stress and formulating work-rest guidelines (Air Force 2022, Army 2022, Navy 2009 listed in Appendix A). Table 1 shows guidelines for WBGT heat categories by work level based on heat production rate.

Table 1. Work-rest and Fluid Replacement Guidelines by WBGT Heat Category

		Easy Work (250 W)		Moderate Work (400 W)		Heavy Work (600 W)		Very Heavy Work (800 W)	
Heat Category	WBGT Index (°F)	Work-Rest	Water Intake (qt/hr)	Work-Rest	Water Intake (qt/hr)	Work-Rest	Water Intake (qt/hr)	Work-Rest	Water Intake (qt/hr)
1 (white)	78-81.9	No limit	0.5	No limit	0.75	40/20	0.75	20/40	1
2 (green)	82-84.9	No limit	0.5	No limit	0.75	30/30	1	15/45	1
3 (yellow)	85-87.9	No limit	0.5	No limit	0.75	30/30	1	10/50	1
4 (red)	88-89.9	No limit	0.75	50/10	0.75	20/40	1	10/50	1

5 (black)	> 90	No limit	1	20/40	1	15/45	1	10/50	1
Examples of Work		• Weapon maintenance • Marksmanship training • Drill and ceremony		• Patrolling with 30-pound load • Low and high crawl • Dig defensive position		• Patrolling with 45-pound load • Four-person litter carry (180 pounds) • Jogging 4 mph		• Two-person little carry (150 pounds) • Move under direct fire • Obstacle course	

Measurements of WBGT are typically taken by bioenvironmental or biomedical personnel at DoD installations, although several Army test ranges have routinely measured WBGT since the 1990s. Given the challenges to move and maintain instruments traditionally used for measuring WBGT, smaller and more portable monitors are now being accepted for WBGT measurements (Air Force 2022, Army 2022, Navy 2009). Some questions remain about the quality of measurements from these portable units as estimations of NWB temperature and six-inch BG temperature need to be made with many of these monitors. The WBGT has been incorporated into the Occupational Safety and Health Association heat stress assessment[4] and is becoming more popular with state high school activities associations. The United States National Weather Service (NWS) introduced WBGT as an operational product in its National Digital Forecast Database (NDFD), the official gridded weather forecast data, and the National Blend of Models (NBM), which serves as a baseline for the NWS's 7-day public weather forecast products.

Decades of research have been conducted on the WBGT and its application to heat stress assessment. Given the challenges of measuring the WBGT, multiple efforts have been made to estimate the index and its components using standard meteorological variables,[5,6,7,8,9,10] including by the Range Commanders Council (RCC) Meteorology Group (MG). NASA Dryden and Dugway Proving Ground (DPG) conducted studies in the mid- to late 2000s and developed approximations specific to those locations. Similar work was also done in the mid-2010s at Eglin Air Force Base (AFB) and Aberdeen Test Center (ATC). Additionally, a closer look at measuring WBGT started in 2017 at White Sands Test Center (WSTC). Results from these efforts revealed the need for WBGT data collection across several different climate regions using the same or similar sensors over an extended period that would serve as a foundation for developing algorithms to estimate BG and NWB temperature for calculation of WBGT that may

[4] Department of Labor. "National Emphasis Program – Outdoor and Indoor Heat-Related Hazards." CPL 03-00-024. 8 April 2022. May be superseded by update. Retrieved 17 July 2023. Available at https://www.osha.gov/sites/default/files/enforcement/directives/CPL_03-00-024.pdf.
[5] Hunter, C. and C. Minyard. "Estimating Wet Bulb Globe Temperature Using Standard Meteorological Measurements." WSRC-MS-99-00757 2.7. Paper presented during the 2nd Conference on Environmental Applications, Long Beach, CA, 13-7 January 2000.
[6] Turco, S. H. N. et al. "Estimating Black Globe Temperature Based on Meteorological Data." Paper presented during Livestock Environment VIII, Iguassu Falls, Brazil, 31 August-4 September 2008.
[7] Liljegren, James et al. "Modeling the Wet Bulb Globe Temperature Using Standard Meteorological Measurements." In *J. Occup. Environ. Hyg.*, vol. 5, pp. 645-655. 4 August 2008.
[8] Gallagher, F. and M. B. Curtis. "An evaluation of several wet bulb globe temperature algorithms at Dugway Proving Ground." Paper presented during the 15th Symposium on Meteorological Observations and Instrumentation, Atlanta, GA, 16-21 January 2010.
[9] Dimiceli, V. E. and S. F. Piltz. "Estimation of black globe temperature for calculation of the WBGT Index." National Weather Service internal technical paper. Retrieved 25 May 2023. Available at https://www.weather.gov/media/tsa/pdf/WBGTpaper2.pdf.
[10] Biggar, D. G. et al. "Development of a Wet Bulb Globe Temperature approximation equation from..." Paper presented during the Ninth Conference on Environment and Health, Austin, TX., 8-10 January 2018.

be applied in all regions. To fill this need, the MG initiated a formal data collection campaign in 2021. Data were collected from 11 RCC ranges and 2 outside organizations over different climate regions (Figure 2).

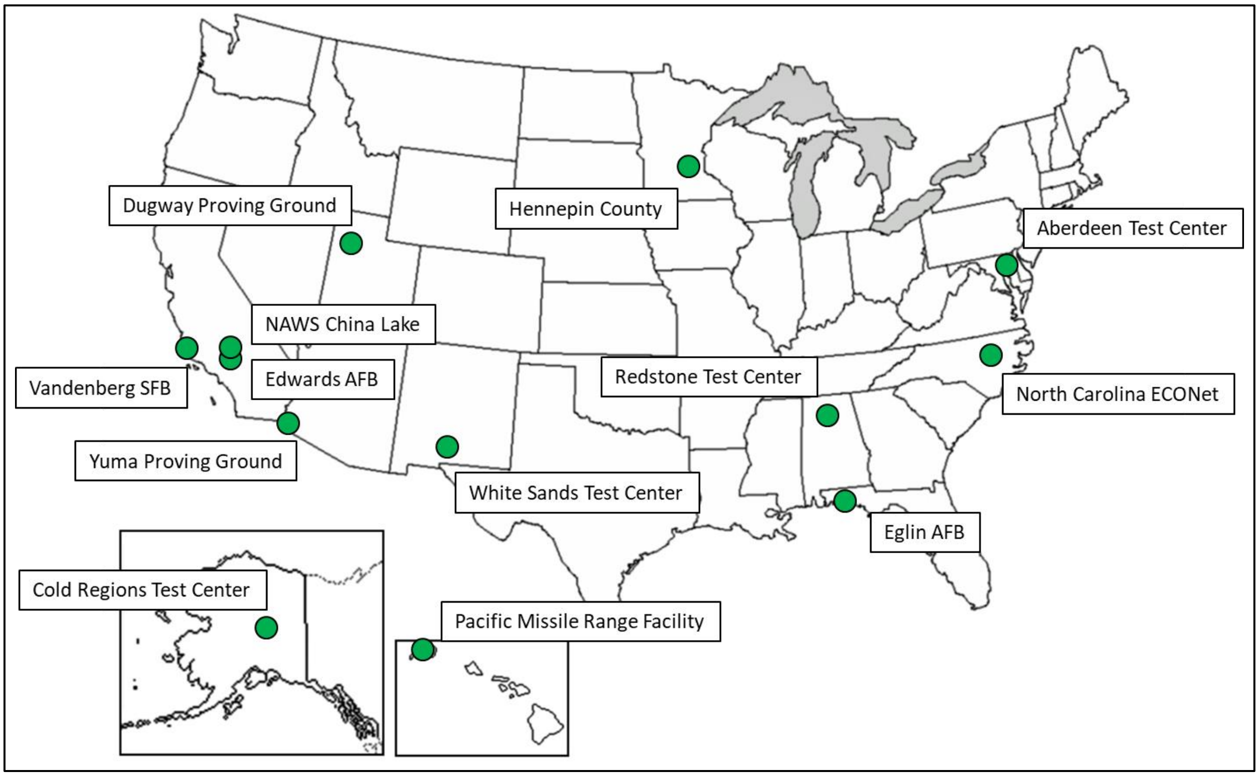

Figure 2. WBGT Data Collection Campaign Participants in 2021

This paper covers details in WBGT measurement platform development and the data collection campaign conducted in 2021. Section 2 describes the platform development and data collection procedures. Section 3 covers results of data quality control, including comparisons of measured data with existing WBGT estimation algorithms used by the NWS and the MG. Section 4 provides suggestions for future algorithm development and other areas of study using the 2021 campaign dataset. Section 5 gives conclusions to this study's findings.

2. Platform development and data collection procedures

Measurement of BG and NWB temperature is very sensitive to the composition and design of the sensor. A variety of platforms have been used since the WBGT's inception with non-standard sensors used to measure the WBGT's components. Alfano et al.[11] stated the NWB temperature is sensitive to wick tightness, capillarity, and other minute details. The BG temperature can be impacted by elements like composition, size of the globe, and paint color. Uniformity in sensor setup was needed to obtain a set of reliable data that can be comparable

[11] Alfano, F., J. Malchaire, B. Palella, and G. Riccio. "WBGT index revised after 60 years of use." *Ann Occup Hyd.*, vol. 58 issue 8, pp. 955-970. October 2014.

between locations. The MG used the International Organization for Standardization (ISO) Document 7243[12] as the guide for sensor selection and configuration.

2.1 BG temperature

ISO 7243 states that measurement of the BG should be done at the center of a six-inch copper sphere painted matte black. The temperature within such a sphere matches closely with the mean radiant temperature, which is the thermal measure for radiative balance between a human and its environment. For the MG campaign, the BLACKGLOBE-L manufactured by Campbell Scientific (CS) was chosen. One concern of the BLACKGLOBE-L was the positioning of the temperature sensor within the globe. The installation instructions provided by CS result in the probe positioning on the lower half of the globe and slightly angled off vertical, which is not an ISO 7243-compliant configuration (measurement at the center of the globe). Several tests of temperature probe orientation were conducted at WSTC in late 2020 and early 2021 to examine differences in BG temperature solely from sensor positioning. Tests were done using a CS109 temperature probe from CS as well as the PT-1000 temperature sensor from Atlas Scientific.

A test was conducted in November 2020 to compare BG temperatures measured by a CS109 probe in a standard installation configuration in one BLACKGLOBE-L and three thermocouples positioned near the edges and center of a second BLACKGLOBE-L. Figure 3 shows the approximate axis along which the CS109 prove lies in standard installation (transparent white rectangle) along with positioning of the thermocouples along the same axis (space between yellow dots). Considerable differences in temperatures can be found between the various positions within the globe, as evident in Figure 4. Testing on 19 November 2020 showed the temperature difference between the CS109 probe and the thermocouple in the middle of the globe ranged from 1 to 3 °C during the daytime, suggestive of the cool bias when using the standard CS installation method due to the CS109 probe being in the lower half and shade side of the globe.

[12] International Organization for Standardization. *Ergonomics of the thermal environment – Assessment of heat stress using WBGT (wet bulb globe temperature)*. IS 7243:2017. August 2017. Maybe superseded by update. Available for purchase from https://www.iso.org/standard/67188.html.

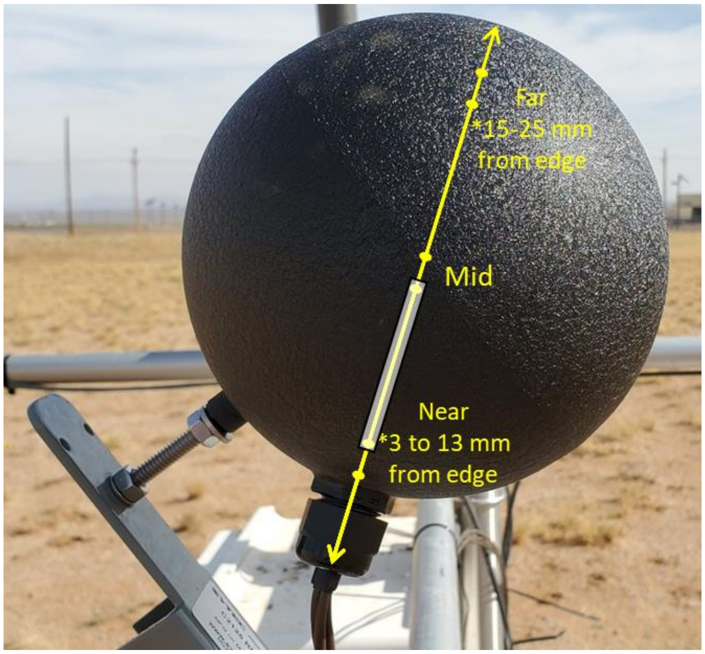

Figure 3. Sensor Locations Inside the BLACKGLOBE-L for Testing During November 2020

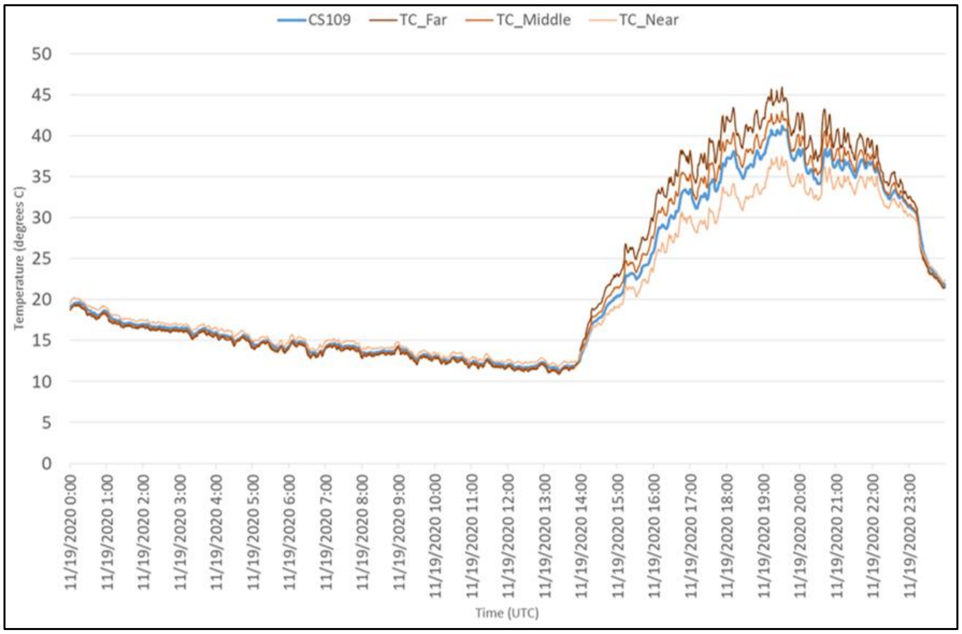

Figure 4. BG Temperature Measurements on 19 November 2020

A second test of probe orientation inside the BLACKGLOBE-L in January 2021 involved having the cable gland on the globe pointed straight down and comparing the temperature measured by the CS109 in the lower and center parts of the globe versus a PT-1000 centered in an adjacent globe (Figure 5). When positioned in the lower part of the globe (i.e., the "standard" installation location of the globe), the CS109 measured on average up to 1.5 °C lower than the PT-1000. When the CS109 was positioned in the center of the globe, the CS109 and PT-1000 differences were nearly zero. This test showed once again that a bias is present when a probe is not centered in the globe.

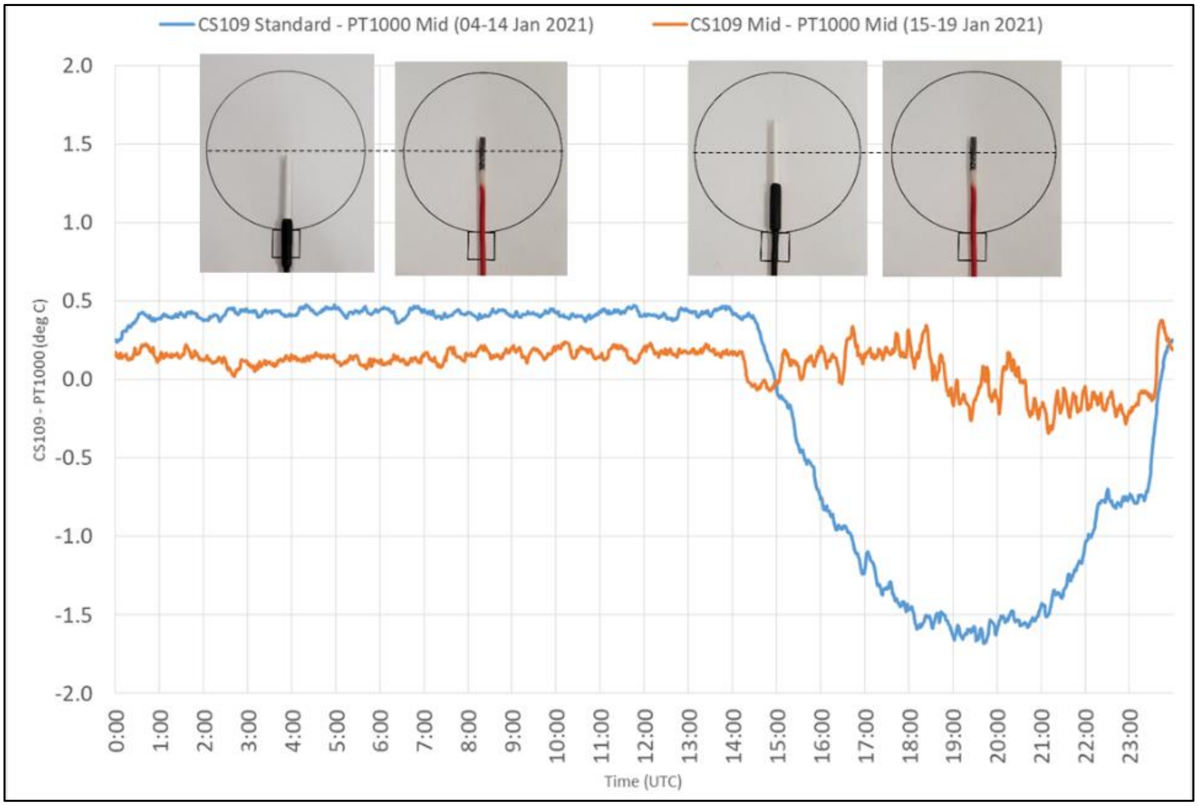

Figure 5. Average Difference in BG Temperature (C) Measured by CS109 and PT-1000 Probes during January 2021 Tests

Another test was conducted 04-19 February 2021 to examine the influence of the probe angle on globe temperature measurements (Figure 6). During the daytime hours, the average BG temperature from CS109 probes angled off vertical was lower than the temperature from a CS109 probe oriented vertically and centered in the globe with a greater difference occurring with the probe at 35° versus 20° off vertical. The large positive difference between the angled probes and the vertical probe between 2300 and 0030 Universal Coordinated Time (UTC) was a result of a shadow on the BG with the vertical probe.

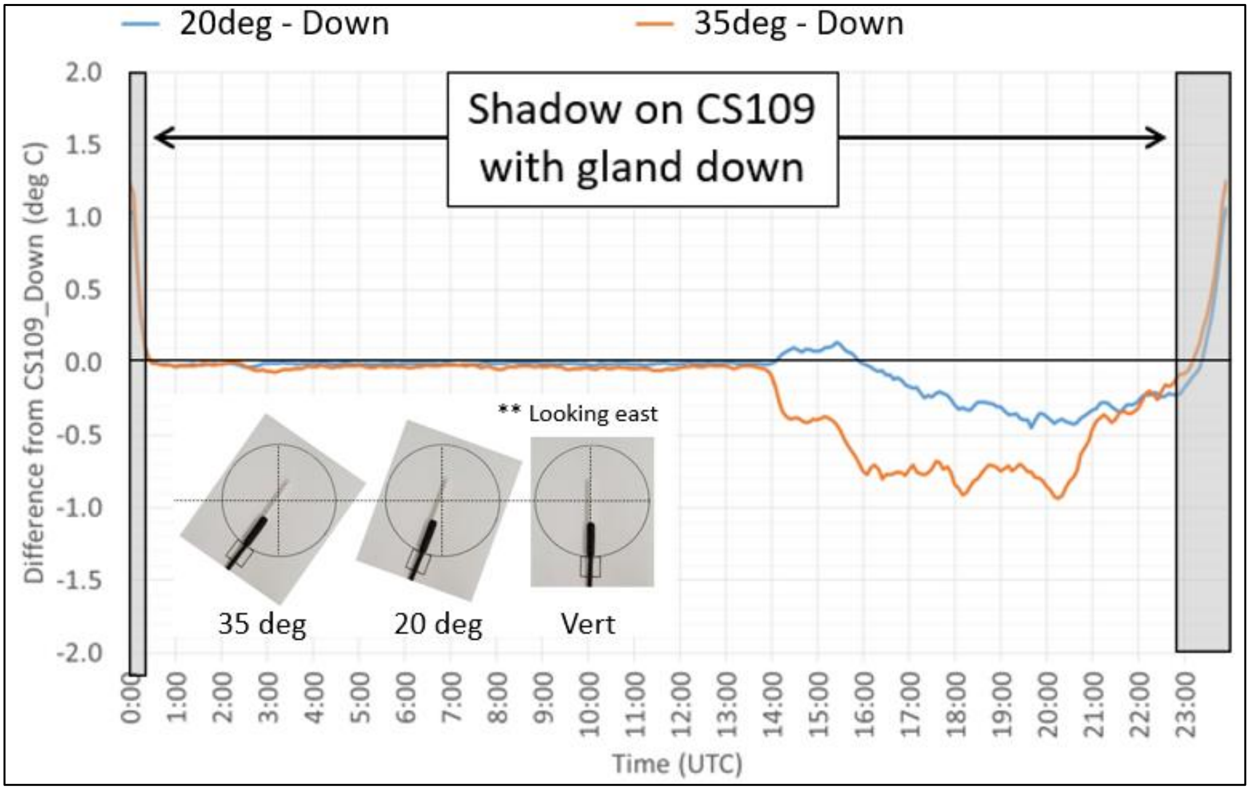

Figure 6. Average BG Temperature Difference (°C) between Different Probe Orientations

These tests demonstrated that the positioning of the temperature probe can have a considerable influence on measurement of BG temperature. The installation of the probe into the BLACKGLOBE-L as described in the CS manual will introduce a cool bias to BG temperature measurements with the probe in the lower part of the globe and at an angle slightly off vertical. This bias can be large enough to have a one-heat category impact on the WBGT index, particularly on days with full sun and light wind. The CS109 probe should be vertical and inserted about 130 mm from the cable gland opening (Figure 7) to ensure the best BG temperature measurement for heat stress assessment. The widened portion of the cable needs to be extended about 40 mm to allow for a tight fit of the cable into the cable gland with the probe farther into the globe. This extension can be done using black electrical tape.

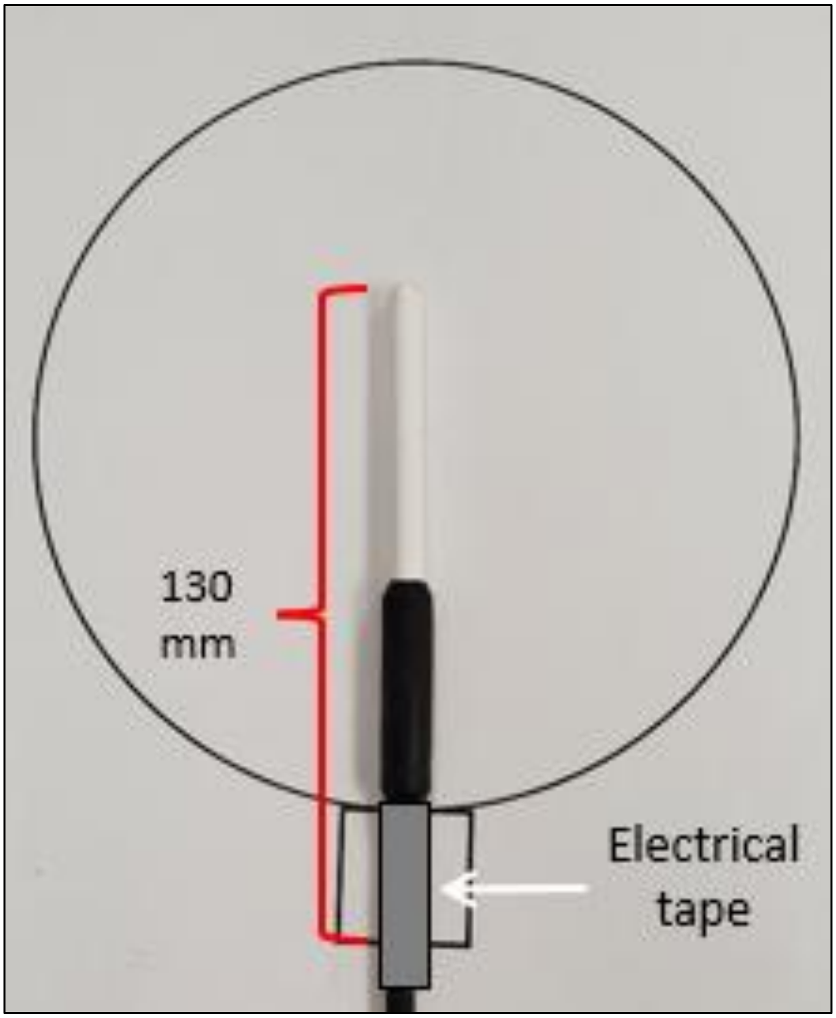

Figure 7. Ideal Position of the CS109 Probe within the BLACKGLOBE-L

2.2 NWB Temperature

The NWB temperature can be a challenge to measure given the high level of maintenance required for filling the water reservoir and replacing wicks that cover the temperature sensor. Early platforms for WBGT measurements like in Figure 1 used glass flasks as the water reservoirs. Army test ranges constructed reservoirs starting in the 1990s using polyvinyl chloride (PVC) pipe endcaps pressed together with a temperature probe inserted through the reservoir. In very dry environments, these endcap reservoirs needed to be refilled every one to two days. Experiments with PVC reservoirs having larger horizontal and vertical extent have been done at DPG, ATC, Redstone Test Center (RTC), and Edwards AFB since 2017 with some success. With a need for an NWB fixture requiring less observation and maintenance, the MG consulted with the Training Device Design and Engineering Center (TDDEC) at Vandenberg Space Force Base (SFB) to design and manufacture the apparatus. Prototype units were provided to Edwards AFB and RTC in summer 2020 for testing with operational units manufactured in early 2021. The fixture (Figure 8) has a large water reservoir with controlled water flow into a horizontal pipe. An Atlas Scientific PT-1000 probe, compliant with the ISO 7243 standard for sensing length and diameter, is inserted into the center portion of the horizontal pipe and emerges from the end of the pipe. The brackets on the fixture allow for installation on a crossbar or vertical pipe. Each participant was provided a Bayonet Neill-Concelman female connector, a 0.1% 1000-Ohm resistor, and 10 feet of connection wire to connect the PT-1000 temperature probe to a CS datalogger. A supply of 3/8-inch diameter wicks from Pepperell (model 735) cut six inches in length that fit over the PT-1000 probe was also provided. Participants were provided instructions on probe and wick positioning to avoid exposure issues with water in the horizontal pipe and sunlight. As shown in Figure 9, the bottom of the PT-1000 sensing element (darker area inside the wick) should be about 1/4 to 1/2 inch above the horizontal tube cap. In addition, the end of the wick should extend 3/16 inch above the end of the sensing element and folded over or tied off to avoid exposure of the top of the sensing element.

Figure 8. Schematic of the TDDEC's NWB Temperature Fixture

Figure 9. Desired Position of PT-1000 Temperature Probe and Wick

2.3 Platform Setup

Consistency in instrumentation type and layout was pursued for the WBGT data collection campaign. Every location measured the following meteorological variables: air temperature, relative humidity, atmospheric pressure, wind speed, incoming solar radiation, BG temperature, and NWB temperature. Differences in available sensors and mounting platforms did not allow for identical layouts at every location (Table 2), though all participants used the BLACKGLOBE-L and TDDEC NWB fixture.

Table 2. Sensors Used for Data Collection

Location	Temperature/Humidity	Wind	Solar Radiation	Pressure
Aberdeen Test Center	Campbell Scientific HydroVUE10	RM Young 05103	Eppley PSP	Vaisala PT330
China Lake	MetOne AIO 1	MetOne AIO 1	OTT Hydromet CMP3	MetOne AIO 1
Cold Regions Test Center (CRTC)	RM Young 41382VC	RM Young 05103	Apogee SP-230	Vaisala PTB110
Dugway Proving Ground	Vaisala HMP155	RM Young 05103	Li-COR LI-200R	Vaisala PTB110
Edwards AFB	MetOne 083E	RM Young 86000	OTT Hydromet CMP6	Vaisala PTB101B
Eglin AFB	Vaisala HMP155A	RM Young 86000	Li-COR LI-200R	Vaisala PTB110
Hennepin County	Campbell Scientific EE181	RM Young 05103	Campbell Scientific CS320	Campbell Scientific CS100
North Carolina ECONet	Campbell Scientific HydroVUE10	RM Young 05103	Apogee SP-110	Campbell Scientific CS100
Pacific Missile Range Facility (PMRF)	Rotronics HC2-S3	RM Young 86004	Li-COR LI-200R	Vaisala PTB110
Redstone Test Center	Campbell Scientific CS215	RM Young 05103	OTT Hydromet CMP3	Campbell Scientific CS100
Vandenberg SFB	MetOne 083E	RM Young 86000	Li-COR LI-200R	Vaisala PTB101B
White Sands Test Center	Rotronics HC2-S3	RM Young 86004	Li-COR LI-200R	Vaisala PTB110
Yuma Proving Ground	Vaisala HMP100	RM Young 86000	Eppley PSP	Vaisala PTB110

Shadow-sensitive sensors (BG, NWB, and solar radiation) were to be installed on the south side of the platform without obstruction from other sensors or mounting hardware. Distilled water for the NWB fixture was suggested to be left outside at ambient air temperature, as water temperature can impact readings. All measurements were to be taken at the same level. The preferred measurement height was 4 ft above ground level (AGL), which corresponds to human mid-torso level and provides the best assessment for heat stress effects on the human body. Two locations collected data at 2 m AGL, which is the standard surface level for meteorological measurements and weather model output. Several locations measured WBGT at both 4 ft and 2 m AGL (Figure 10).

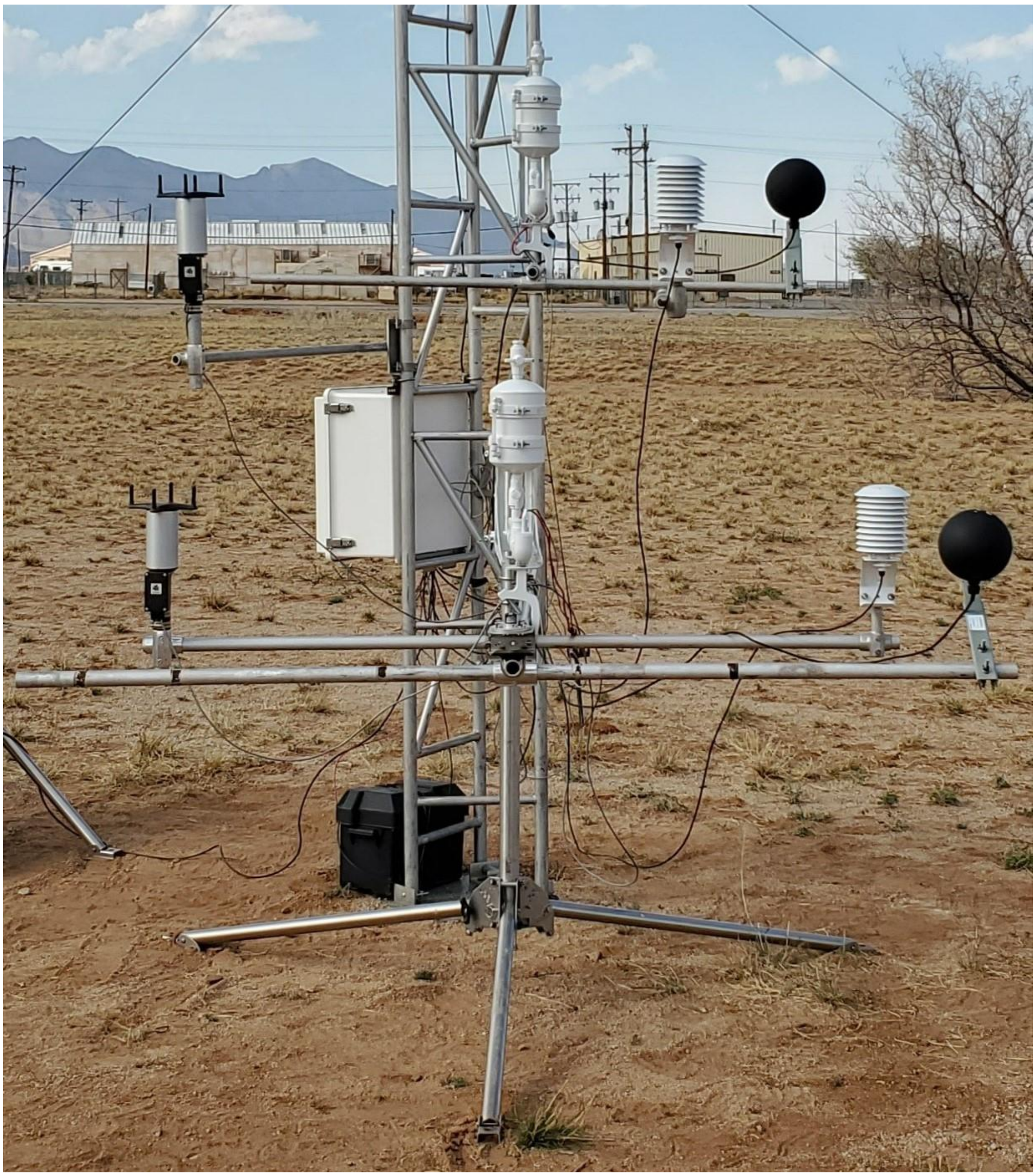

Figure 10. WBGT Platform at WSTC in 2021

2.4 Data Collection and Quality Control Procedures

Campaign participants collected one-minute and five-minute average observations within the 15 May-15 October 2021 period. Routine visits to the WBGT platform were recommended during the campaign, especially to check the NWB fixture water reservoir level and wick condition. Campaign participants kept a log of maintenance visits, providing notes on wick changes and condition, water fills, platform condition, and other observations that could impact measurements. Data were collected on CS dataloggers and saved as plain text files in comma-separated value format. Data collected included time of observation, latitude and longitude of the platform, incoming solar radiation, air temperature, relative humidity, atmospheric pressure, wind speed, BG temperature, NWB temperature, and WBGT.

Formal quality control of campaign data was completed on only the one-minute average data. Around 2,200,000 one-minute records were available from participants (Table 3). Quality control was initially completed using a Microsoft Excel file with embedded Visual Basic for Application (VBA) macros for data display and evaluation that was developed by personnel at Edwards AFB and WSTC. Gross checks of data were completed using the sorting and graphing options available in Excel. The Excel file was limited to processing 32,767 records at one time as coding was done on a 32-bit system. To overcome this limitation plus process data more quickly, staff at WSTC translated the calculations code from VBA to Python. Staff at Eglin AFB provided Python code for quality control checks that was added to the calculations code. These checks were used to alert data analysts of potential issues with data; no changes were made to raw data or to any quality control flags previously set. Each participant's data were processed separately to capture the proper value ranges of basic meteorological variables for the quality control checks. Additional manual inspection of data was done to capture questionable data not detected by the quality control checks or were resulting from the influence of rainfall extending beyond the baseline 30-minute period after last report of accumulating rainfall. Further details on quality control checks, adjustments of parameters for calculations, and Python tool output can be found in Appendix A.

Table 3. Breakdown of One-minute Weather Observations by Participant

Participant	Period of Record	Total One-Min Obs	One-Min Obs Passing Base MET, Mx, & Rain QC	Percentage One-Min Obs Passing Base MET, Mx, and Rain QC
Aberdeen	5/15/2021 - 10/1/2021	200,786	186,042	92.7%
China Lake	5/15/2021 - 10/15/2021	221,735	206,617	93.2%
Cold Regions	5/20/2021 - 9/20/2021	175,188	152,139	86.8%
Dugway	6/11/2021 - 10/11/2021	169,772	157,266	92.6%
Edwards	5/17/2021 - 10/15/2021	216,796	215,337	99.3%
Eglin	7/6/2021 - 10/15/2021	145,796	128,027	87.8%
Hennepin County	6/10/2021 - 9/27/2021	157,680	142,283	90.2%
NC ECONet	5/15/2021 - 10/15/2021	221,752	207,769	93.7%
PMRF	7/8/2021 - 8/1/2021	34,737	32,994	95.0%
Redstone	5/15/2021 - 10/15/2021	0 (43,562 5-Min)	0 (38,820 5-Min)	0.0% (89.1%)
Vandenberg	5/15/2021 - 10/15/2021	221,760	211,898	95.6%
White Sands	5/15/2021 - 10/15/2021	221,629	213,761	96.4%
Yuma	5/15/2021 - 10/15/2021	221,339	219,339	99.0%
TOTAL		**2,208,970**	**2,073,472**	**93.9%**

About 94% of total one-minute observations from all participants passed base meteorological variable, maintenance, and rainfall quality control checks (Table 3). Rainfall accounted for the vast majority of flagged observations. The dataset covers a wide spectrum of temperature and humidity conditions with a broad normal distribution of temperature centered around 25 °C and a bimodal distribution of relative humidity with peaks at 20-30% and 80-90% (Table 4). The number of observations collected in this campaign far exceeds any other known dataset with simultaneous measurements of all three components of the WBGT equation.

Table 4. Percentage of Observations by Air Temperature and Relative Humidity (Blue – Relative Maximum, Red – Relative Minimum)

		Air Temperature (°C)										
Relative Humidity (%)		LT 0	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	GT 40	Total
	<10	0.00	0.00	0.00	0.00	0.03	0.91	1.28	1.36	2.07	1.33	6.98
	10-20	0.00	0.00	0.03	0.12	0.45	1.21	2.45	3.63	2.63	1.05	11.57
	20-30	0.00	0.04	0.11	0.48	1.25	2.48	3.12	2.08	1.02	0.59	11.17
	30-40	0.01	0.04	0.19	0.72	1.56	2.28	2.16	1.49	0.65	0.01	9.11
	40-50	0.01	0.08	0.25	0.71	1.37	1.96	2.02	1.16	0.08	0.00	7.64
	50-60	0.01	0.07	0.23	0.69	1.41	1.87	2.07	1.28	0.00	0.00	7.63
	60-70	0.00	0.06	0.22	0.81	1.71	2.34	2.46	1.21	0.00	0.00	8.81
	70-80	0.00	0.09	0.30	1.07	2.75	2.81	2.86	0.33	0.00	0.00	10.21
	80-90	0.01	0.13	0.54	1.72	2.72	3.67	2.36	0.01	0.00	0.00	11.16
	>90	0.06	0.30	1.22	5.72	2.64	5.17	0.63	0.00	0.00	0.00	15.74
	Total	0.10	0.81	3.09	12.04	15.89	24.70	21.41	12.55	6.45	2.98	

3. BG and NWB Data Evaluation and Analysis

The integrity of measured BG and NWB temperature data needs to be evaluated prior to the development of any new estimation algorithms. After passing quality control, the data were compared to estimations from a modified version of an algorithm developed by Dimiceli and Piltz (heareafter referred to as the Dimiceli model) for BG temperature and a multiple linear regression equation developed by WSTC for NWB temperature. From these comparisons, potential systematic issues in measured data or weaknesses in the estimation methods may be detected.

3.1 BG temperature

Equation 2 shows the Dimiceli model.

$$T_g = \frac{B + CT_a + 768000}{C + 256000} \qquad \text{Equation 2}$$

where

$$B = S\left(\frac{f_{db}}{4\sigma \cos(z)} + \left(\frac{1 + \alpha_{sfc}}{\sigma}\right) f_{dif} + (\varepsilon_a) T_a^4\right.$$

$$C = \frac{hu^{0.58}}{\varepsilon\sigma}$$

T_g = globe temperature (°C)
T_a = air temperature (°C)

S = incoming solar radiation (W m^{-2})
f_{db}, f_{dif} = direct beam and diffuse radiation fraction (from 0 to 1)
z = sun zenith angle (degrees)
σ = Stefan-Boltzmann constant
α_{sfc} = surface albedo
ε_a = thermal emissivity of the air
h = convective heat transfer coefficient
ε = BG emissivity
u = wind speed (meters per hour)

Direct beam radiation fraction (f_{db}) was calculated using Equation 13 from Liljegren et al. with diffuse beam radiation (f_{dif}) equal to $1 - f_{db}$. The surface albedo (α_{sfc}) was set to 0.25 for all sites as it approximates the average albedo at data collection sites. The thermal emissivity (ε_a) equals $0.575e_a^{(1/7)}$ where e_a is the water vapor pressure (hPa), while the globe emissivity (ε) is 0.95. The convective heat transfer coefficient (h) was set to 0.228 during the day and 0 at night (with day/night differentiation set at 87° zenith angle). This value was based on analysis of computed heat transfer coefficient values using measured BG temperature data collected at five Army test ranges between 2014 and 2018. This coefficient value differs from the 0.315 value used in the Dimiceli model, which was found to give estimated BG temperatures much lower than measured data.

The following figures show the average difference between the measured and Dimiceli model BG temperature by hour for each data collection location. For the nighttime hours, the measured temperature was generally a little lower than the model temperature (ranging from −0.1 to −0.7 °C). During the daytime, the measured versus model BG temperature difference was generally ±1 °C for moist climate locations (Figure 11, Figure 12) while larger positive differences (up to 3 °C) were present at most dry climate locations (Figure 13). The dry climate locations showed slightly positive differences early in the nighttime period but eventually became negative like the moist climate locations.

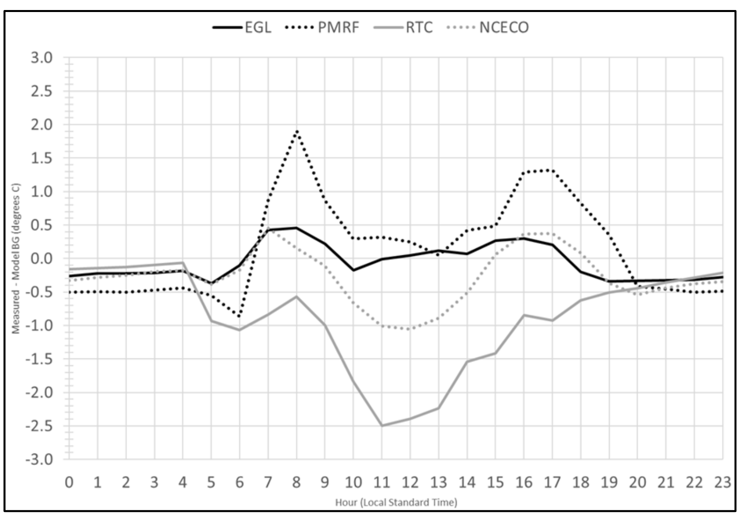

Figure 11. Southern Locations with Moist Climate

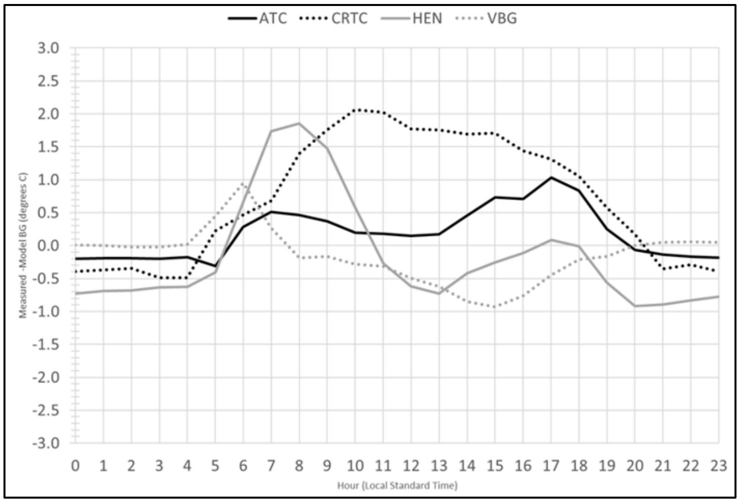

Figure 12. Northern Locations with Moist Climate

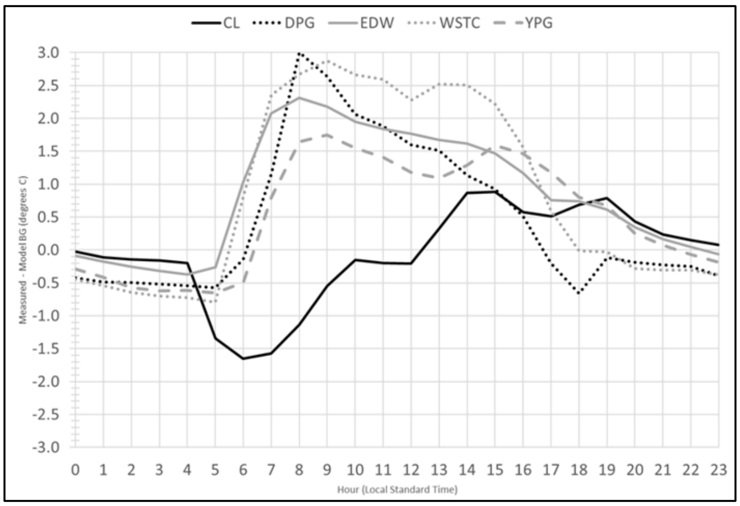

Figure 13. Locations with Dry Climate

The larger difference with dry climate locations is tied to the difference between the constant convective heat transfer coefficient in the Dimiceli model (0.228) and the lower average and median values derived from calculated heat transfer coefficient values (orange-shaded rows in Table 5). On the other hand, the Dimiceli model coefficient value is much closer to calculated values at most climate locations (green-shaded rows in Table 5), thus the lesser difference between measured and model-derived BG temperatures.

Table 5. Heat Transfer Coefficient Values

Location	Average	Median
Aberdeen Test Center	0.213	0.191
China Lake	0.190	0.171
CRTC	0.203	0.172
Dugway Proving Ground	0.177	0.154
Edwards AFB	0.141	0.138

Eglin AFB	0.220	0.185
Hennepin County	0.227	0.203
North Carolina ECONet	0.235	0.204
PMRF	0.196	0.175
Redstone Test Center	0.275	0.238
Vandenberg SFB	0.221	0.198
White Sands Test Center	0.152	0.129
Yuma Proving Ground	0.144	0.128

A few locations presented differences between measured and Dimiceli model BG temperature that did not match up with locations with similar environments. RTC (Figure 11) and China Lake (Figure 13) had measured BG temperatures well below that from the Dimiceli model while Hennepin County's measured BG temperatures were well above model BG temperatures during the morning hours (Figure 12). Pictures of platforms and participant accounts from each location revealed that the temperature probe was not installed in the BLACKGLOBE-L in the vertical position and centered in the globe, thus leading to biases in the measured BG temperature. Shadowing of the globe at China Lake during the morning is also suspected based on positioning of the Met One All-In-One sensor just above the level and to the west of the globe. The biases also appear in the average and median convective heat transfer coefficient values for these locations (Table 5) with RTC and China Lake having values considerably higher than locations with similar climate. The overall average convective heat transfer coefficient value at Hennepin County is not much different than locations with similar climate (Table 5). However, comparison of values by hour with the North Carolina ECONet site (Figure 14) reveals considerably lower coefficients in the morning at Hennepin County compared to the afternoon as well as throughout all hours at the North Carolina ECONet. This difference in heat coefficient is the result of the BG cable gland being positioned at a slight angle away from vertical and towards the east, thus exposing the bottom part of the temperature probe to more direct sunlight in the morning that led to much higher-than-modeled BG temperature (Figure 12). The PMRF (Figure 11) and CRTC (Figure 12) also showed substantial differences between measured and model BG temperature that warranted further investigation. Platform pictures showed the probe in the BG was installed as requested. Hourly average heat transfer coefficient values (Figure 15) for both locations are considerably lower than the 0.228 constant value used in the Dimiceli model, thus accounting for the larger measured versus model difference.

Figure 14. Average Convective Heat Transfer Coefficient – Hennepin County and North Carolina ECONet

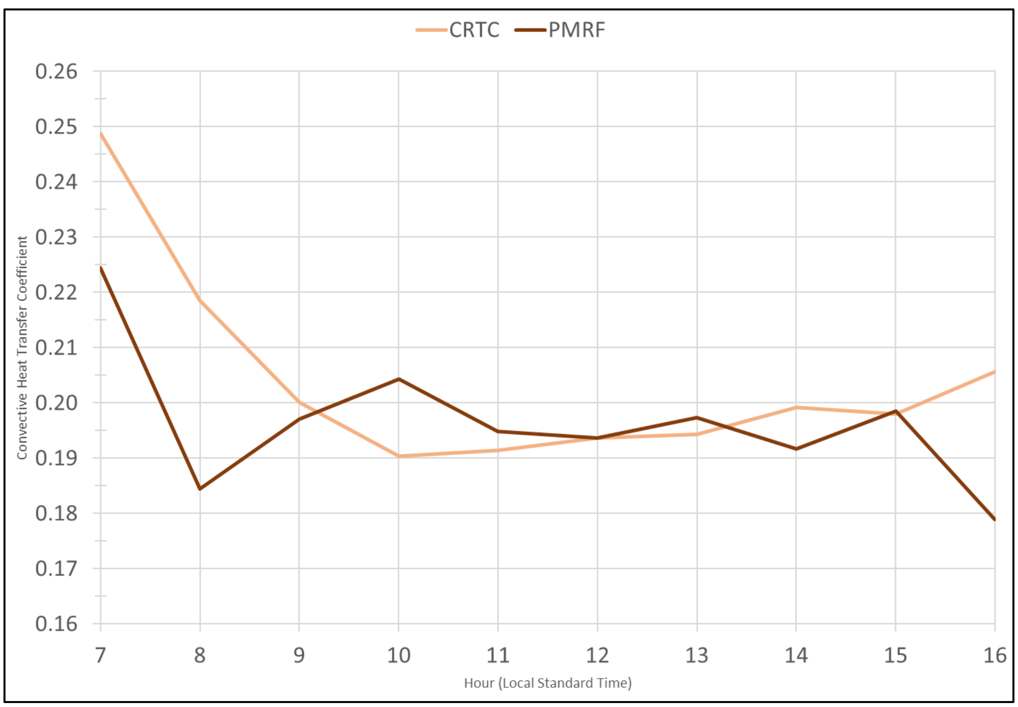

Figure 15. Average Convective Heat Transfer Coefficient – PMRF and CRTC

Sensor lag should be taken into consideration when assessing differences between measured and modeled data. The availability of one-minute average data from the MG campaign allowed for such an evaluation of the BLACKGLOBE-L. This lag was best revealed when examining the response of BG temperature to sudden changes in solar radiation while all other weather elements that may impact BG temperature stayed nearly constant. One such case comes from ATC on 15 July 2021 (Figure 16) where changes in BG temperature lag behind changes in solar radiation by three to four minutes. This lag time was consistent across all locations and probes used (CS109 or PT-1000). This lag time can impact model verification statistics and algorithm development, a concern that will be addressed in Section 4.

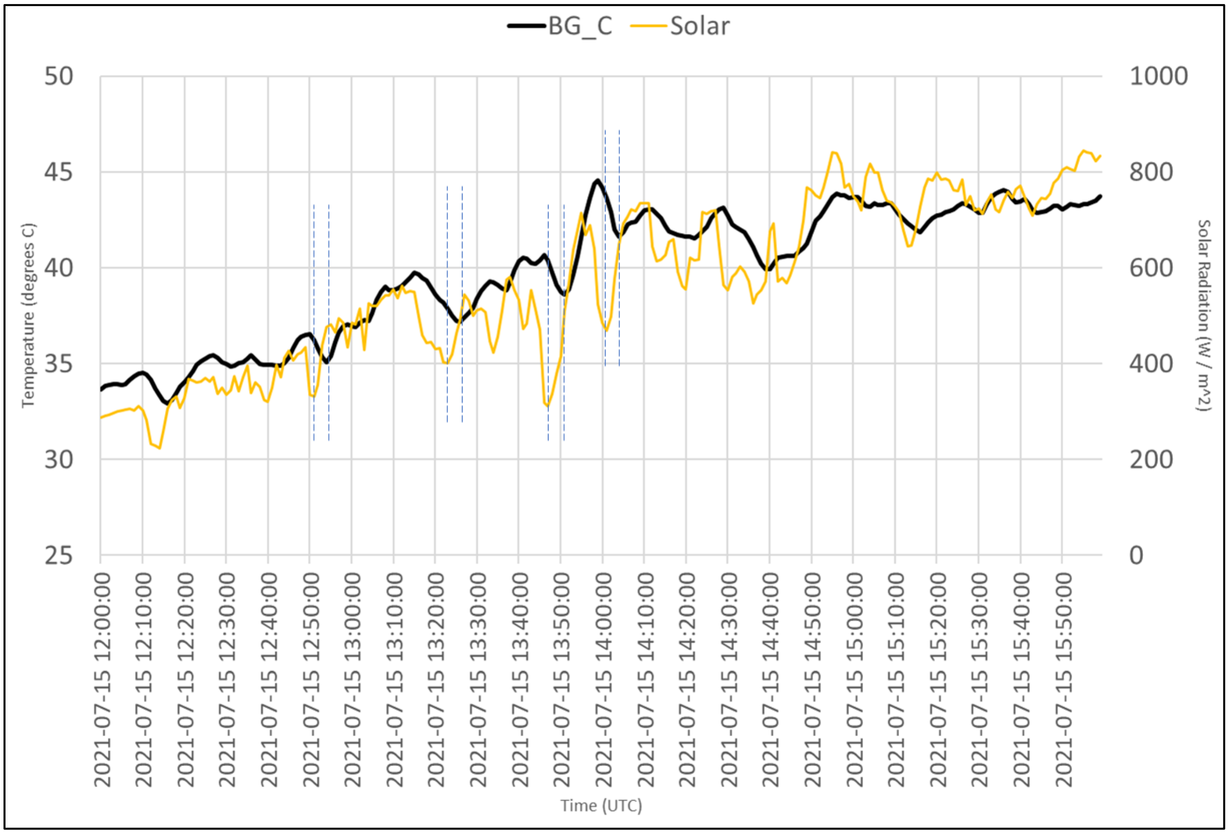

Figure 16. Measured BG Temperature and Incoming Solar Radiation

3.2 NWB Temperature

During the experimental period of generating WBGT products, the NWS used the multiple linear regression equation found in Hunter and Minyard to estimate the NWB temperature. The equation was built by regressing incoming solar radiation and wind speed on the difference between the natural and psychrometric wet-bulb temperatures. The algorithm was derived from a small dataset (15-minute observations during a four- to six-hour period from 0900-1500L over nine days spanning May-July 1999) at one location (interior South Carolina). Work at WSTC showed a substantial cold bias in the Hunter and Minyard model in low relative humidity environments (less than 40%), a condition seen commonly at several RCC ranges. Results from a series of controlled indoor and outdoor tests at WSTC in late 2020 and early 2021 suggested that adding effects of heat transfer between the air and the wick on the temperature sensor would improve the estimate of NWB temperature compared to observations. The heat transfer effect can be accounted for using the wet-bulb depression (T_{wd}), which is the difference between the air temperature and psychrometric wet-bulb temperature. Tests of a multiple linear regression equation that included solar radiation, wind speed, and wet-bulb depression using data from spring to fall 2020 at five RCC ranges showed no substantial bias across all relative humidity conditions. Some concern was raised over different types of NWB fixtures used in the 2020 dataset that could introduce biases to the algorithm. A new model shown in Equation 3 (hereafter the RCC NWB model) was derived using data from 15 May to 15 June 2021 collected at China Lake, CRTC, the North Carolina ECONet, Vandenberg SFB, WSTC, and Yuma Proving Ground where the NWB fixture from Vandenberg TDDEC was used.

$$T_{nwb} = T_w + 0.001651S - 0.09555u + 0.13235T_{wd} + 0.20249 \qquad \text{Equation 3}$$

Where T_{nwb} is the NWB temperature (°C)
T_w is the psychrometric wet-bulb temperature (°C)
S is incoming solar radiation (W m^{-2})
u is wind speed (m s^{-1})
T_{wd} is the wet-bulb depression (°C).

As of February 2023, this expression is being used by the NWS in its calculation of WBGT for its NDFD grids and the NBM version 4.1.

The average difference between the measured NWB temperature and the RCC NWB model is within ±0.7 °C throughout the day for most locations (Figure 17, Figure 18, and Figure 19). These same locations also have a wavy trend in the measured versus model differences over the course of the daytime. This trend plus examination of the heat balance equation for a wick on a temperature probe (such as in Liljegren et al.) give evidence of non-linear effects of variables on the NWB temperature, particularly from solar radiation and wind speed. Outliers from this wave trend were found at RTC (Figure 18) as well as China Lake and DPG (Figure 19), giving rise to uncertainty in the accuracy of the NWB measurements at those locations.

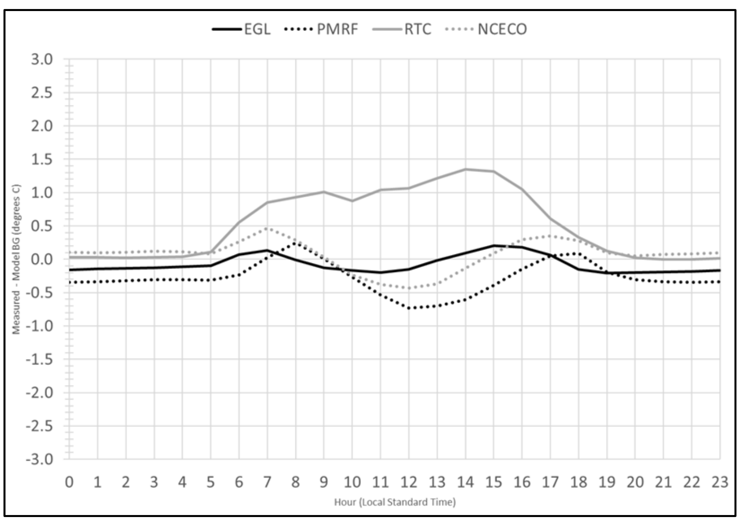

Figure 17. Difference between Measured and Modeled NWB - Southern Locations with Moist Climate

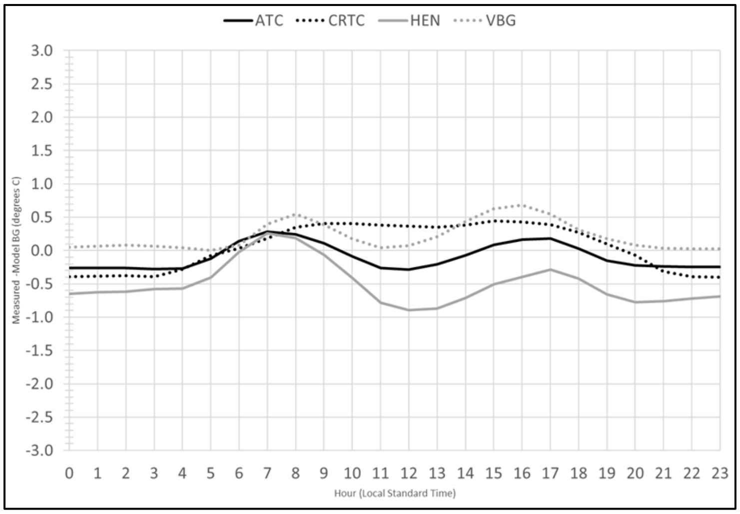

Figure 18. Difference between Measured and Modeled NWB - Northern Locations with Moist Climate

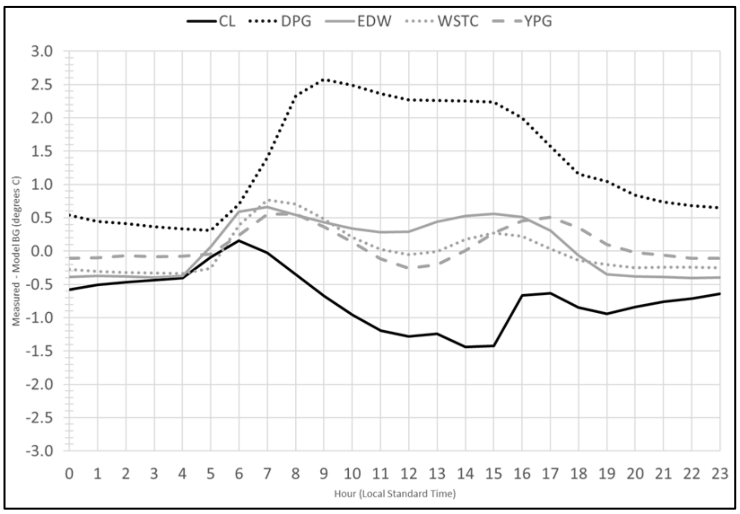

Figure 19. Difference between Measured and Modeled NWB - Locations with Dry Climate

Accuracy issues at RTC and China Lake may be connected to a large step change in NWB temperature that occurred when the wick was changed. At RTC the change was a step increase of approximately 0.8 °C on 11 August 2021, while at China Lake the change was a step decrease of approximately 0.7 °C on 11 June 2021. These step changes were maintained through the rest of the data collection period. Figure 20 and Figure 21 show the substantial difference in the average measured versus RCC model NWB temperature from before and after the step change at RTC and China Lake (the gap in data at China Lake during 14 LST and 15 LST hours was due to erroneous solar radiation data). Similar step changes had been noted at times at other data collection locations, though the influence or frequency of that change is not apparent in the measured versus model difference data at those locations. A closer examination of changes in NWB temperatures after wick replacement will be needed at all sites prior to finalizing datasets for algorithm development.

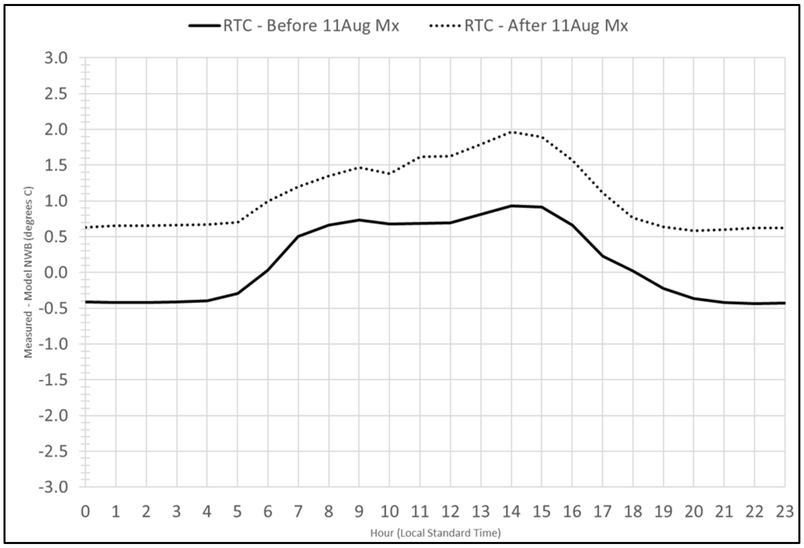

Figure 20. Average Difference of Measured and RCC Model NWB Temperature - Redstone

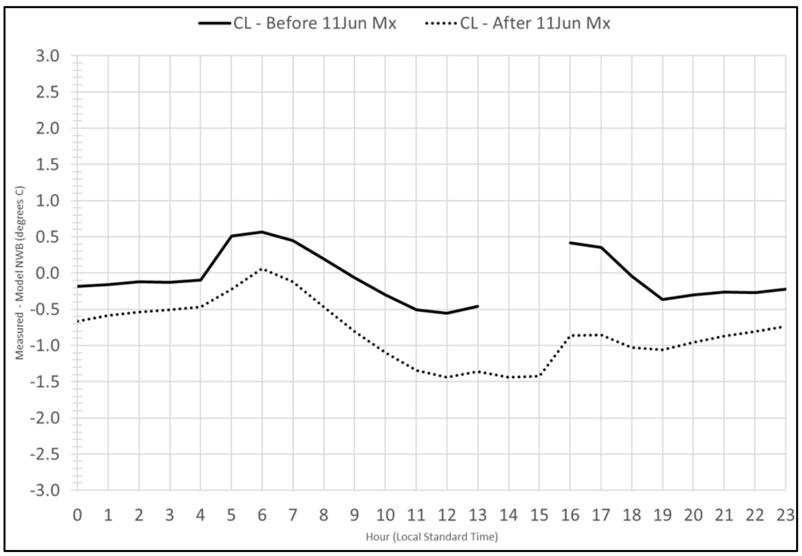

Figure 21. Average Difference of Measured and RCC Model NWB Temperature – China Lake

Reasons for the measured NWB temperature being substantially higher than the RCC NWB model temperature at DPG are not known at the time of this paper's publication. The issue occurred with TDDEC NWB fixtures at both 4 ft and 2 m, though it was not present with the DPG-built NWB sensor at 2 m that was operating on a platform very near where the TDDEC fixtures were positioned (Figure 22). Discussion with DPG staff suggests the sensing portion of the PT-1000 probe may have been positioned too close to the opening in the cap on the horizontal tube, thus exposing the sensor to possible radiative heat off the cap and/or the warmer water in the reservoir. Adjustments will be made to probe positioning by DPG staff in 2023 to test this conjecture. In addition to providing information on assessing the TDDEC fixtures, the DPG-built NWB fixture showed that the NWB estimation in Equation 3 is sound, as the trend in measured versus model NWB temperature difference followed a similar pattern as seen with TDDEC fixtures at other data collection locations with measured-versus-model difference within ±0.7 °C.

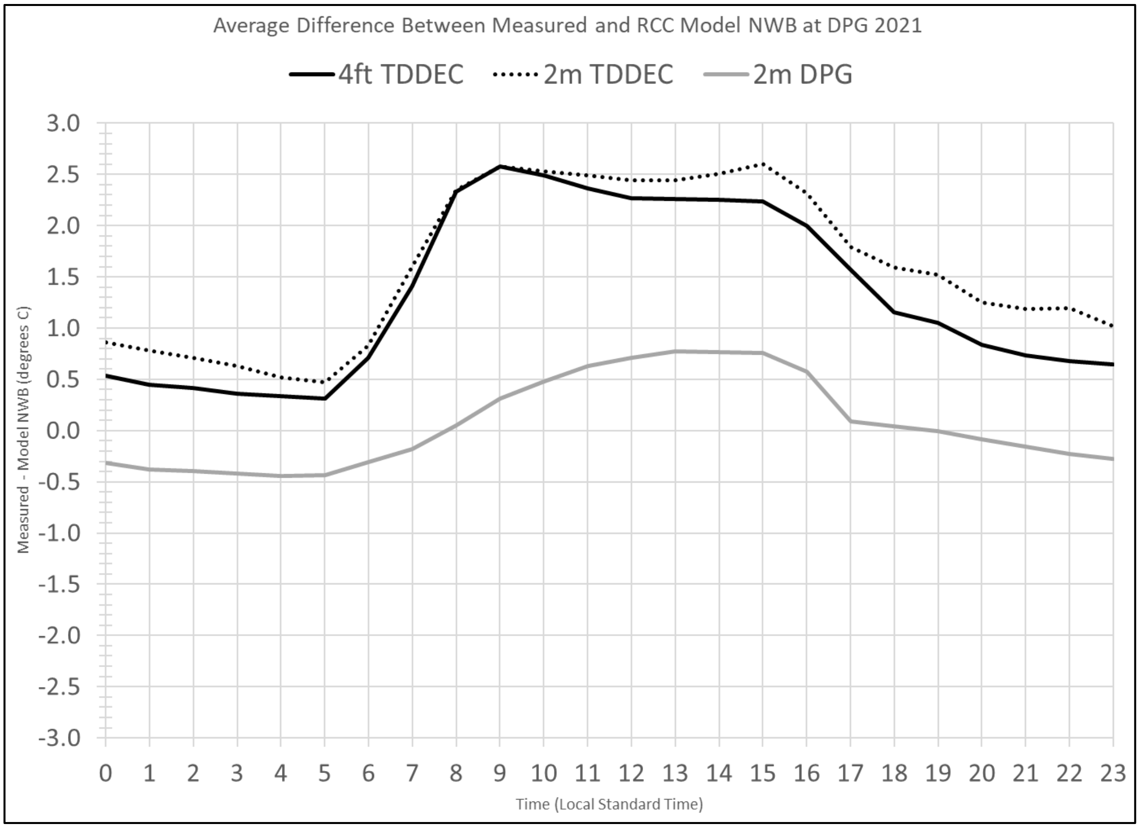

Figure 22. Average Difference of Measured and RCC Model NWB Temperature – Dugway

4. Suggestions for Estimation Algorithm Development and Future Work

Results in Section 3 show that the Dimiceli BG and RCC NWB estimation algorithms compare quite well with measured data, though there is room for improvement. The use of a constant convective heat transfer coefficient in the Dimiceli BG model can result in substantial differences between model and observed data. Improvement in the model may be possible using the expression provided in Dimiceli et al.[13] where the coefficient varies as a function of incoming solar radiation and the cosine of the zenith angle: $h = a\,(S^b)\,[\cos(z)]^c$ where S is the incoming solar radiation (W m^{-2}), z is the zenith angle (degrees), and a, b, and c are empirically derived coefficients from measured data. Coefficient values were not revealed in Dimiceli et al., but values were derived using BG data from five Army test ranges in the 2014-2018 period (a = 13.833, b = −0.61678, c = 0.784093) for testing of the Dimiceli model with varying heat transfer coefficient using 2021 campaign data. A substantial improvement in the Dimiceli model occurred when the varying heat transfer coefficient was used (dashed lines in Figure 23) versus the constant 0.228 value (solid lines in Figure 23) during the daytime. Globes used by the Army test ranges in the five-year period varied in wall thickness, exterior covering, and temperature sensors, leading to some uncertainty in the soundness of the measured BG data used for coefficient derivation. New coefficients using data from the BLACKGLOBE-L units at 2021

[13] Dimiceli, V. E., S. F. Piltz, and S. A. Amburn. "Estimation of black globe temperature for the calculation of the wet bulb globe temperature index." In Proceedings of the World Congress on Engineering and Computer Science 2011 Vol II, San Francisco, CA.

data collection locations will be determined in future work. An additional term in the expression for the heat coefficient that accounts for humidity may also be considered.

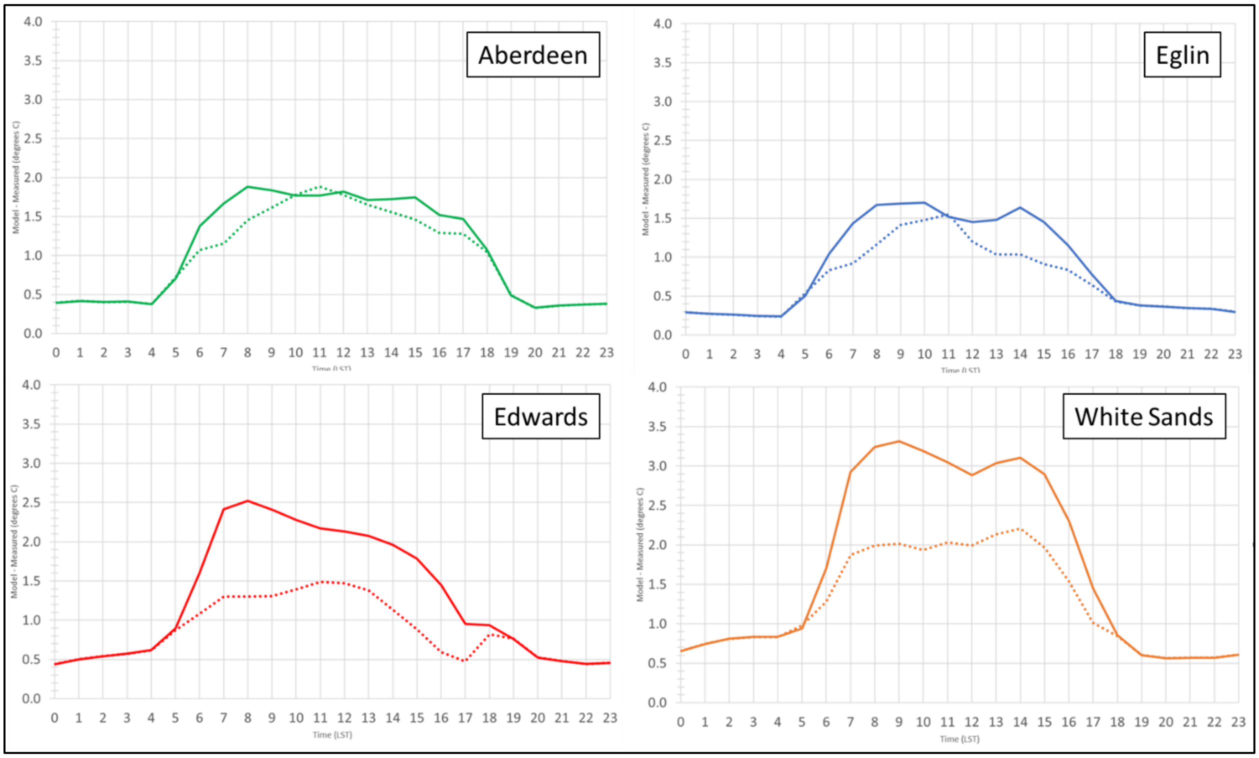

Figure 23 Average Difference between Dimiceli Model and Measured BG Temperature (°C) using Varying and Constant Heat Transfer Coefficients

The approximate three-minute lag in BG temperature from the BLACKGLOBE-L can have impacts on model verification and development. Measured data averaged over 15 minutes may be used for future data evaluation and algorithm development to temper the effects of this lag as well as smooth out noisiness in BG data. The use of 15-minute average data (dashed lines in Figure 24) results in a further reduction in Dimiceli model mean absolute error compared to the one-minute average data (solid lines in Figure 24) when a varying convective heat transfer coefficient value is used. Sensor lag for the NWB temperature is generally less than one minute, so use of 15-minute versus one-minute data should have little impact on RCC NWB model performance.

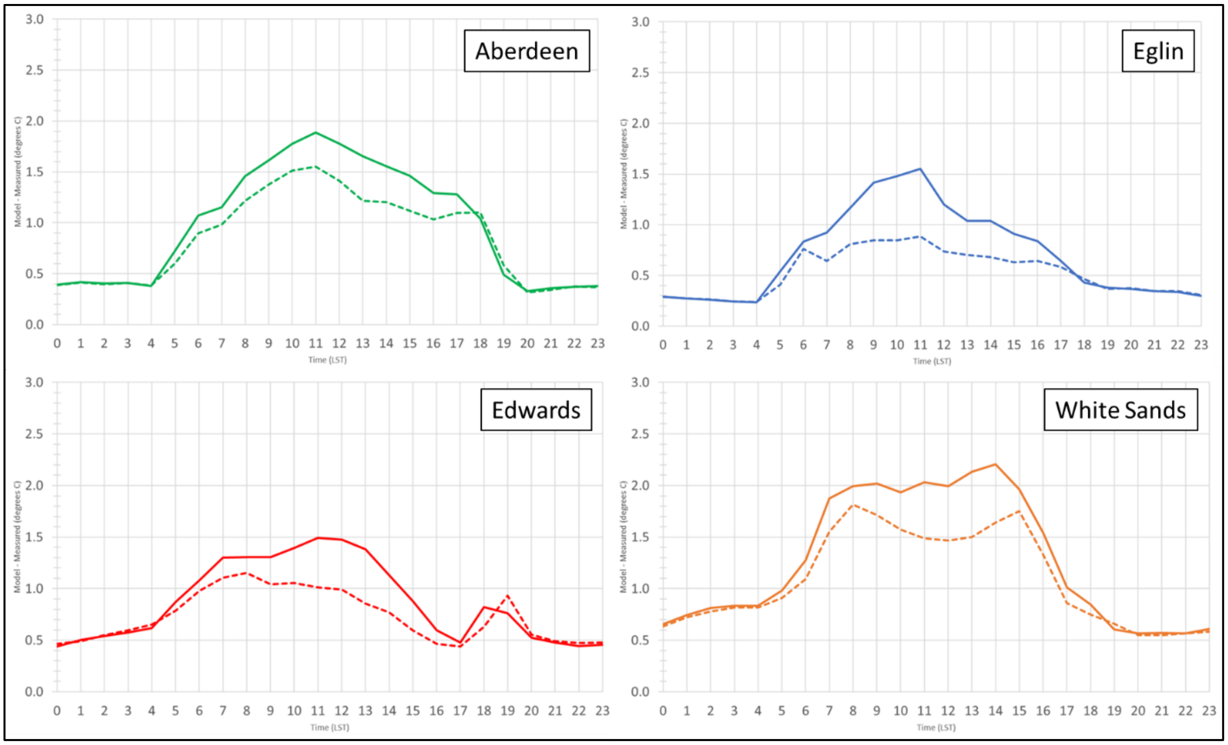

Figure 24. Average Difference between Dimiceli Model and Measured BG Temperature (°C) Using 1-Minute and 15-Minute Average Data

The Dimiceli BG and RCC NWB models examined in this paper as well as many other estimation algorithms for WBGT-related variables depend on solar radiation values. Many locations with a need for WBGT data do not have measured solar radiation available. Approximations for solar radiation can be made, such as: using maximum expected solar radiation modulated by cloud cover as done for the NWS NDFD grids; or incorporating a constant solar radiation value based on cloud coverage and type as done by an application developed by the Army Research Laboratory.[14] Initial investigation is underway on the feasibility of deriving solar radiation from light sensor data at locations with Automated Surface Observing System and Fixed Meteorological Equipment platforms.[15] Algorithms without solar radiation as an input (either measured or estimated) will be investigated in future work. Sun angle as a replacement for solar radiation has been examined by Eglin AFB with some success. Given solar radiation is a key driver in WBGT, it may be challenging to get acceptable results from algorithms based solely from air temperature, relative humidity, and wind.

Several other topics may be pursued by the MG in future work on WBGT. Five campaign participants collected data at 4 ft and 2 m AGL simultaneously, providing an opportunity to compare base meteorological and WBGT-related variables at those two levels and explore the differences on WBGT measurements. The 2-m data may also be used as a possible validation dataset for future algorithms. Measured data from the campaign can also be utilized for evaluation of WBGT-related estimation algorithms already in the peer-reviewed literature.

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[14] David Sauter. "A wet-bulb globe temperature validation study using standard meteorological inputs and modeled solar irradiance." *J. Operational Meteor*., vol. 1, pp. 215-225. 13 November 2013.
[15] P. Harvey, Edwards AFB, 2023, personal communication

Sensitivity of current algorithms to changes in parameters such as the convective heat transfer coefficient and surface albedo may be explored. Many DoD facilities use portable heat stress monitors for the assessment of WBGT. Edwards AFB collected data from a TSI QUESTemp 44 monitor alongside its standard WBGT platforms during the 2021 data collection campaign with a future goal of evaluating data quality of the monitor. Many complexities and uncertainties in measuring WBGT can be addressed in future work, including taking temperature measurements inside globes of different diameter to assess equations that convert temperatures inside smaller globes to an equivalent six-inch globe temperature; comparing the BG temperature from a standard BLACKGLOBE-L installation versus the MG project “probe centered” installation over a longer time period; and examining the use of a temperature probe different than the PT-1000, a sensor that seems prone to step changes in temperature readings after wick changes.

5. Conclusion

The DoD uses WBGT as its benchmark for heat stress assessment. A need exists for universal, easy-to-use WBGT estimation algorithms based on standard meteorological measurements that give acceptable results for all locations. Current estimation algorithms for WBGT and its components are either too complicated or can be improved. The improvement of algorithms requires a large set of observed WBGT-related variables measured at as many climatic regions as possible over an extended period using a standard set of instrumentation. The MG fulfills that requirement with an extensive set of data collected during 2021 at 11 MG member ranges and 2 outside organizations. Many intricacies in taking WBGT measurements were revealed during the campaign with Malchaire’s[16] statement of results being notably influenced by seemingly insignificant design factors coming to light during data collection. With a high-quality observational dataset now in place, work can proceed towards the development of algorithms applicable to all locations with quickly calculated and reasonably accurate solutions using standard meteorological variable data from weather observations and models as input.

[16] J. B. Malchaire. “Evaluation of natural wet bulb and wet bulb thermometers.” *Ann. Occup Hyg.*, vol. 19, issue 3-4, pp. 251-258. December 1976.

Appendix A

WBGT Data Quality Control and Calculation Tool

Quality Control Checks and Data Adjustments for Calculations

Staff from WSTC, Edwards AFB, and Eglin AFB contributed to the creation of software in Python containing quality control checks for measured air temperature, humidity, wind, pressure, incoming solar radiation, BG temperature, and NWB temperature as well as calculations of WBGT-related variables. Software can be made available upon request through the MG Chair. Below are the criteria used for data quality control checks.

- Air temperature/pressure/BG temperature/NWB temperature that is more than three standard deviations from the mean (out-of-range check)
- Relative humidity < 0% or > 100%
- Measured NWB temperature is more than ±1°C from the RCC NWB model
- NWB temperature > Air temperature
- NWB temperature < Psychrometric wet-bulb temperature
- BG temperature < 90% of air temperature when solar radiation < 100 W m^{-2}
- BG temperature < air temperature when solar radiation > 100 W m^{-2}
- Difference between BG and air temperature < 1 °C when solar radiation > 100 W m^{-2}

Flags for maintenance were set from start of maintenance to 30 minutes after completion of maintenance as indicated in participant logs. Rainfall flags were set for times spanning from 30 minutes prior to the first report of accumulating rainfall to 30 minutes after last report of accumulating rainfall at the platform (if available) or the closest observation location with rainfall accumulation data (e.g., nearby range observation site, surface weather observing systems at nearby airports).

Adjustments or maximum/minimum thresholds were applied to select variables to avoid numerical instability in some calculations (e.g., division by zero errors). The adjustments were made only within the calculation; no changes were made to the original input data that is reproduced in the output data. Below are the adjustments/thresholds.

- All incoming solar radiation values < 0.5 W m^{-2} set to 0
- Wind speed of 0 set to 0.01 m s^{-1}
- Wind speed thresholds
    - NWS BG (with constant convective heat transfer coefficient), RCC BG (with variable convective heat transfer coefficient), Hunter and Minyard NWB, convective heat transfer coefficient from Dimiceli: Minimum 1.78816 m s^{-1} (4 mph)
    - Liljegren BG and NWB: Minimum 0.13 m s^{-1}

  - All forms of Universal Thermal Climate Index (UTCI): Minimum 0.5 m s^{-1}; maximum 17 m s^{-1}
  - RCC NWB: Minimum 0.01 m s^{-1}
- Relative humidity > 100% set to 100%
- Direct beam radiation fraction (f_{db}) > 0.75 set to 0.75

Python Tool Input and Output

The Python tool requires a plain text file in comma-separated format as input with parameters in the following order and format/units.

Date (mm/dd/yyyy hh:mm or yyyy-mm-dd hh:mm); UTC)
Latitude (degrees; north is positive, south is negative)
Longitude (degrees; east is positive, west is negatave)
Solar radiation (Wm^{-2})
Air temperature (°C)
Relative humidity (%)
Station pressure (hPa)
Wind speed (ms^{-1})
Measured BG temperature (°C)
Measured NWB temperature (°C)
Measured WBGT (°C)°

The output from the software is a Microsoft Excel (.xlsx) format file with the parameters listed below (column header list first). Note that the first 11 parameters are the same as those in the input file.

Date: Date and time (UTC)
Lat: Latitude (degrees)
Lon: Longitude
Solar: Incoming solar radiation (Wm^{-2})
Temp_C: Air temperature (°C)
RH: Relative humidity (%)
Pres: Station pressure (hPa)
WS_mps: Wind speed (ms^{-1})
BG_C: Measured BG temperature (°C)
NWB_C: Measured NWB temperature (°C)
WBGT_C: Measured WBGT (°C)
BG_Lil_C: BG temperature from Liljegren et al. model (°C)
BG_Dim_C: BG temperature from Dimiceli model using a constant convective heat transfer coefficient (°C)
BG_RCC_C: BG temperature from Dimiceli model using a variable convective heat transfer coefficient (°C)
NWB_Lil_C: NWB temperature from Liljegren et al. model (°C)
NWB_HM_C: NWB temperature from Hunter and Minyard (°C)
NWB_RCC_C: NWB temperature from RCC MG regression equation (Eq. 3) (°C)
WBGT_Lil_C: WBGT using BG_Lil_G and NWB_Lil_C (°C)

WBGT_NWS_C: WBGT using BG_Dim_C and NWB_HM_C (°C)
WBGT_RCC_C: WBGT using BG_RCC_C and NWB_RCC_C (°C)
UTCI_Lil_C: Universal Thermal Climate Index value using BG_Lil_C (°C)
UTCI_Dim_C: Universal Thermal Climate Index value using BG_Dim_C (°C)
UTCI_RCC_C: Universal Thermal Climate Index value using BG_RCC_C (°C)
UTCI_MEAS_C: Universal Thermal Climate Index value using measured BG temperature (°C)
Tw_Lil_C: Psychrometric wet-bulb temperature using Liljegren et al. code (°C)
Tw_NWS_C: Psychrometric wet-bulb temperature using iterative method used in the National Weather Service National Digital Forecast Database (°C)
Tw_Sad_C: Psychrometric wet-bulb temperature using Sadeghi et al.[17] (°C)
Td_Lil_C: Dew point temperature from Liljegren et al. code (°C)
HeatIndex_NWS_C: Heat index from NWS NDFD code (from Rothfusz)[18]
BG_Lil-Meas_C: Difference between BG_Lil_C and measured BG temperature (°C)
BG_Dim-Meas_C: Difference between BG_Dim_C and measured BG temperature (°C)
BG_RCC-Meas_C: Difference between BG_RCC_C and measured BG temperature (°C)
NWB_Lil-Meas_C: Difference between NWB_Lil_C and measured NWB temperature (°C)
NWB_HM-Meas_C: Difference between NWB_HM_C and measured NWB temperature (°C)
NWB_RCC-Meas_C: Difference between NWB_RCC_C and measured NWB temperature (°C)
Dir Beam Fract: Direct Beam Fraction from Liljegren et al. code
Liljegren_h: Convective heat transfer coefficient for BG from Liljegren et al.
Dimiceli_h: Convective heat transfer coefficient for BG using measured BG temperature from Dimiceli and Piltz (2011)
RCC Dimiceli h: Convective heat transfer coefficient for BG using Dimiceli et al. multiple power regression using coefficients from 2014-2018 Army test range data
Cosine_Zen_Ang: Cosine of the zenith angle
Sun_Angle: Sun angle (°)

Below are the values of select variables used in BG and NWB temperature estimation algorithms.

BG_Lil_C: As defined in Liljegren et al.
BG_Dim_C: From Dimiceli and Piltz with the following adjustments:

- Surface albedo = 0.25
- Globe albedo = 0.05
- Globe emissivity = 0.95
- Convective heat coefficient (h) = 0.228 during day, 0 during night (change when zenith angle > 87°)
- If wind speed < 1.78816 ms^{-1} (4 mph), then wind speed = 1.78816 ms^{-1} (4 mph)
- Direct beam radiation (fdb) from Liljegren et al. and capped at 0.75.

BG_RCC_C: Same as BG_Dim_C except the convective heat coefficient (h) equals 13.833 $(S^{-0.61678})\ [\cos(z)]^{0.784093}$ where S is solar radiation ($W\ m^{-2}$), and z is zenith angle

[17] Sadeghi, H., R. Peters, D. Cobos, H. Loescher, and C. Campbell. "Direct Calculation of Thermodynamic Wet-Bulb Temperature as a Function of Pressure and Elevation." *J. Atmos. Ocean. Technology*, vol 30 issue 8, pp. 1757-1765. January 2013.
[18] L. P. Rothfusz. "The Heat Index "Equation" (or, More than You Ever Wanted to Know About Heat Index)." Tech Attachment SR 90-23. 1 July 1990. Retrieved 6 June 2023. Available at https://www.weather.gov/media/ffc/ta_htindx.PDF.

NWB_Lil_C: As defined in Liljegren et al.
NWB_HM_C: As defined in Hunter and Minyard. The psychrometric wet-bulb (T_w) is from the iterative method used in the NWS NDFD.
NWB_RCC_C: $T_{nwb} = T_w + 0.001651S – 0.09555u + 0.13235 (T_{wd}) + 0.20249$ (°C) where T_w is the psychrometric wet-bulb using the iterative method in the NWS NDFD code, S is solar radiation (W m^{-2}), u is wind speed (m s^{-1}), and T_{wd} is wet-bulb depression.

Appendix B

Citations

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Biggar, D. G., P. B. Homan, T. A. Russ, K. D. Burris, and M. D. Scott. "Development of a Wet Bulb Globe Temperature approximation equation from standard meteorological variables and implementation of an automated heat stress condition display at the Eglin Range." Paper presented during the Ninth Conference on Environment and Health, Austin, TX., 8-10 January 2018.

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