Improvements in Estimating Wet-Bulb Globe Temperature (WBGT) Using Full-Scale Measurement Platform Observations

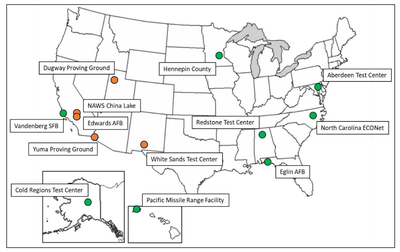
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Overview: The Range Commanders Council Meteorology Group (RCC-MG) conducted a campaign in May-October 2021 to collect observations of WBGT-related variables at 13 different locations in the United States covering several different climate regions using sensors compliant with ISO Document 7243 (2017) specifications. This set of observations, the most extensive known in which all three components of WBGT are measured, was used to assess algorithms most frequently implemented for estimating black globe temperature, natural wet-bulb temperature, and the resultant WBGT. Given the assessment results and further analysis of the measured data, algorithms with improved estimations were developed that can be applied at any location with requisite standard meteorological variables.

Data Collection

- Measurements taken at 4 ft AGL except three locations at 2 m AGL. Data quality control completed on one- or five-minute average data. Fifteen-minute averages then determined at 0, 15, 30, and 45 minutes past the hour.



2021 WBGT data campaign participants. Green (orange) dots represent moist (dry) locations.

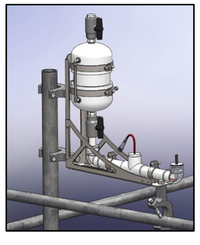
Black Globe: Campbell Scientific BLACKGLOBE-L with CS109 probe

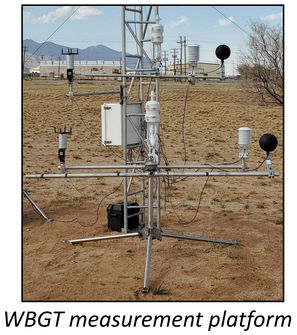
Probe is vertically oriented and centered in the globe, which is different than the standard installation in the sensor manual with the probe in the lower half of the globe and angled off the vertical that produces notably lower temperatures (Thomas 2024).



Natural Wet-Bulb: Custom fixture with Atlas Scientific PT-1000 probe

Designed by Vandenberg SFB Training Device Development and Engineering Center. Incorporates design features of several custom sensors used at U.S. Army test ranges and commercial heat stress sensors.





WBGT measurement platform at White Sands Missile Range

Black Globe Estimate

Lil	Liljegren et al. (2008) Equation 17
Dim315	Dimiceli and Piltz (2011) with h = 0.315
Dim228	Dimiceli and Piltz (2011) with h_{day} = 0.228, h_{night} = 0
Dim207	Dimiceli and Piltz (2011) with h_{day} = 0.207, h_{night} = 0
Dim167L	Dimiceli and Piltz (2011) with h_{day} = 0.167, h_{night} = 0 and the variable B with heat gain terms like Liljegren et al. (2008)

**For Dimiceli models: Surface albedo = 0.20, direct beam fraction from Liljegren et al. (2008) with maximum 0.75, minimum wind 1 m s^{-1}.

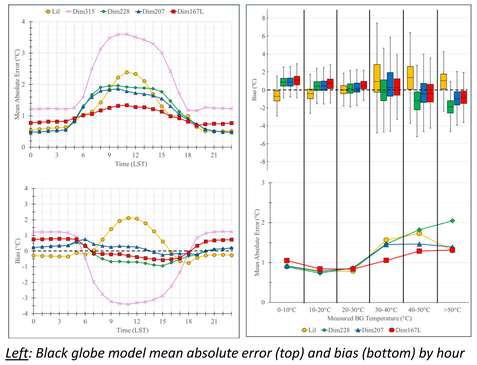
- Convective heat transfer coefficient (h) has major role in black globe temperature estimation. Improved algorithms (Dim207 and Dim167L) have constant h that minimizes MAE and maximizes the number of estimations with errors of ±2°C.
- Heat balance equations in Liljegren and Dimiceli are slightly different though contain the same general energy loss and gain elements. Heat gain terms in Liljegren can be substituted in for the same terms in variable B from Dimiceli, as is done for Dim167L.

Original variable B in Dimiceli and Piltz (2011)

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

Variable B from Dimiceli and Piltz (2011) with heat gain terms from Liljegren et al. (2008)

$$B = S\left(\frac{f_{db}}{4\sigma\cos(\theta)} + \left(\frac{1-f_{db}+\alpha_{sfc}}{2\sigma}\right)\right) + \frac{1}{2}(1+\varepsilon_a)T_a^4$$



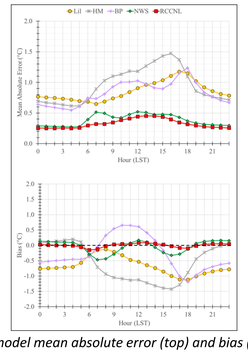
Left: Black globe model mean absolute error (top) and bias (bottom) by hour
Right: Black globe model bias (top) and mean absolute error (bottom) by measured black globe temperature bins

- Dim315 had worst results with MAE up to 3.5°C with negative mean bias during daytime.
- Liljegren MAE peaked ~2.4°C midday with positive mean bias during daytime (maximum ~2°C).
- Dim228 and Dim207 MAE smaller than Liljegren at 09-13 LST with mean bias near zero.
- Dim167L MAE near or lower than Liljegren during daytime with peak MAE ~1°C less than Liljegren.
- For BG temperature >30°C, Liljegren has general high bias and larger error spread while Dimiceli methods have slight low bias that increases with increasing BG temperature.
- Dim167L has the lowest MAE overall when BG temperature >30°C.

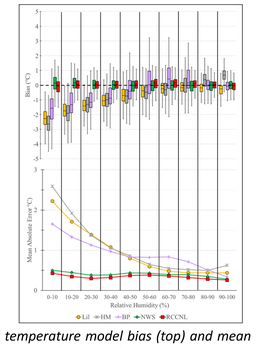
Natural Wet-Bulb Estimate

Lil	Liljegren et al. (2008) Equation 9
HM	Hunter and Minyard (1999): $T_{nwb} = T_w + 0.00117S - 0.233u + 1.072$ (°C)
BP	Bernard and Pourmoghani (1999) Equations 1 and 2
NWS	Boyer (2022) using 15 May-15 Jun 2021 data from six RCC ranges: $T_{nwb} = T_w + 0.001651S - 0.09555u + 0.13235T_{wd} + 0.20249$ (°C)
RCCNL	"RCC Method" with nonlinear coefficients using training subset of 2021 campaign data: $T_{nwb} = T_w + [(-3 \times 10^{-6} S^2 + 0.0046S + 0.135T_{wd}) / u^{0.15}] - 0.0443$ (°C)

- Including wet-bulb depression greatly improves a regression algorithm for estimating natural wet-bulb temperature. Further improvement is achieved when nonlinear expressions are used.



Natural wet-bulb model mean absolute error (top) and bias (bottom) by hour



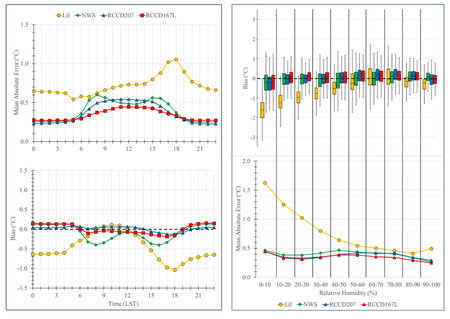
Natural wet-bulb temperature model bias (top) and mean absolute error (bottom) by measured relative humidity bins

- Relatively large MAE in Liljegren, HM, and BP, especially in afternoon (near or exceeds 1°C). Liljegren and HM have substantial low bias throughout the day while BP has slight warm bias from mid-morning through mid-afternoon.
- NWS and RCCNL MAE in 0.3-0.5°C range, about 0.5-1.0°C lower than other models. RCCNL has slightly lower MAE than NWS.
- Large low bias and MAE in Liljegren, HM, and BP driven by poor performance in low relative humidity conditions (MAE >1°C when RH <40% and increases with decreasing RH).
- NWS and RCCNL have lower MAE across all RH levels compared to other models with RCCNL offering slightly better results than NWS.

WBGT Estimate

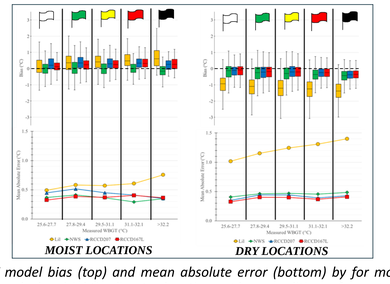
WBGT Method	*Black Globe*	*Natural Wet-Bulb*
Lil	Lil	Lil
NWS	Dim228	NWS
RCCD207	Dim207	RCCNL
RCCD167L	Dim167L	RCCNL

- Liljegren (Lil) used in many peer-reviewed studies and U.S. OSHA WBGT calculator; NWS closely follows method used in U.S. National Weather Service NDFD and NBM; RCCD207 and RCCD167L use algorithms with improved estimations of black globe and natural wet-bulb temperature.



Left: WBGT model mean absolute error (top) and bias (bottom) by hour
Right: WBGT model bias (top) and mean absolute error (bottom) by measured relative humidity bins

- NWS, RCCD207, and RCCD167L have MAE lower than Liljegren with largest difference afternoon through night.
- Mean bias near zero for all models from near sunrise to mid-afternoon. Liljegren becomes increasingly biased low late afternoon and early evening before leveling off near -0.5°C at night.
- Liljegren MAE >1°C starting in 20-30% RH range.
- RCCD167L has slightly lower MAE and slightly less range in errors for almost all RH conditions.



WBGT model bias (top) and mean absolute error (bottom) by for moist (left) and dry (right) climate locations. Flag conditions from Army Technical Bulletin Medical 507 (2022).

- At dangerous heat levels, Liljegren has slight high bias and MAE of 0.5-0.7°C at moist locations and substantial low bias and MAE of 1.0-1.5°C at dry locations. Other models have smaller mean bias (±0.3°C) and MAE (<0.5°C) with RCCD167L performing best for most flag conditions.

Estimate Implementation

- Mesonets with requisite temperature, humidity, wind speed, solar radiation observations can easily calculate estimated WBGT.
- Desire for real-time WBGT estimations increasing given growing use in heat assessment, notably in the U.S. NWS. Estimates would be valued by those involved in heat-related decision support services and would give greater visibility to this metric.
- Important to disclose methods used for estimations given algorithm sensitivities to several variables and potential algorithm biases.
- Psychrometric wet-bulb temperature (T_w) is crucial in estimating natural wet-bulb temperature. Direct T_w calculations, such as Stull (2011), have limitations and biases that can produce non-negligible differences from iterative methods, such as one used for WBGT estimations in the U.S. NWS NDFD. Differences between Stull and NWS NDFD T_w become progressively more positive (or less negative) with lower pressure as shown by differences at Aberdeen Test Center (sea level) versus White Sands Missile Range (1270 m MSL).

Average Difference between Stull and NWS NDFD T_w (°C) at Aberdeen Proving Ground, MD

Relative Humidity (%) \ Air Temperature (°C)	<10	10-15	15-20	20-25	25-30	30-35	35-40	>40
<10								
10-20								
20-30				0.13				
30-40			-0.11	0.16	0.25	0.43		
40-50		-0.25	-0.11	0.09	0.26	0.42		
50-60		-0.31	-0.14	0.02	0.16	0.29		
60-70		-0.33	-0.20	-0.05	0.08	0.18		
70-80		-0.30	-0.20	-0.08	0.02	0.10		
80-90	-0.27	-0.25	-0.15	-0.07	-0.01	0.05		
>90	-0.17	-0.13	-0.07	-0.02	0.00			

Average Difference between Stull and NWS NDFD T_w (°C) at White Sands Missile Range, NM

Relative Humidity (%) \ Air Temperature (°C)	<10	10-15	15-20	20-25	25-30	30-35	35-40	>40
<10			0.30	0.24	0.32	0.50	0.75	1.02
10-20		0.48	0.52	0.59	0.80	1.01	1.18	
20-30	0.30	0.40	0.58	0.76	0.96	1.19	1.32	
30-40	0.26	0.30	0.47	0.65	0.87	1.04	1.25	
40-50		0.20	0.31	0.50	0.67	0.83		
50-60		-0.01	0.17	0.34	0.47			
60-70		-0.09	0.04	0.18	0.28			
70-80		-0.16	-0.04	0.05				
80-90		-0.15	-0.06	-0.01				
>90	-0.15	-0.11	-0.04	-0.02				

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