Industrial Health 2013, **51**, 79–85

Original Article

Empirical Approach to Outdoor WBGT from Meteorological Data and Performance of Two Different Instrument Designs

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Received September 22, 2012 and accepted November 16, 2012

Abstract. The wet bulb globe temperature index (WBGT) is a common method to assess the environmental contribution to heat stress as part of an occupational exposure assessment. The two purposes of this study were (1) to compare empirical relationships of some meteorological conditions to WBGT, and (2) to evaluate a smaller globe and alternative method to assess natural wet bulb using a relative humidity sensor. Data were collected in six West-central Florida locations over multiple days for a total of 14 measurement days. Multiple linear regression was used to explore relationships relevant to the two purposes. It was clear that estimating WBGT directly from meteorological data or through estimates of the components of WBGT can be accomplished with a 95% confidence of ± 2°C-WBGT. The 50 mm globe size is a reasonable approximation of the standard size (150 mm). The relative humidity method of the waterless natural wet bulb provides a very good estimation of natural wet bulb temperature. The determination of WBGT from the electronic instruments (small globe with or without the relative humidity method) provided a good estimate of the WBGT.

Key words: WBGT, Wet bulb globe temperature, Meteorological data, Instruments

Introduction

The wet bulb globe temperature index (WBGT) is a common method to assess the environmental contribution to heat stress as part of an occupational exposure assessment[1, 2]. Lemke and Kjellstrom recently reviewed a range of rational and empirical approaches to predict WBGT from meteorological data[3]. There is utility in being able to predict outdoor WBGT from meteorological data for climate modeling[3] and real-time monitoring for heat stress management[4]. For general areas (e.g., agriculture and road maintenance) as well as fixed locations that vary with ambient conditions, surrogate measures based on actual or projected meteorological data may be helpful to predict the local WBGT.

Another facet of WBGT monitoring is the variety of instruments. The standard instrumentation for assessing WBGT uses three thermometers[5]. One is a shielded dry bulb temperature, a second has a wetted wick with a water reservoir for natural wet bulb, and a third thermometer is placed in a 150 mm copper globe. Many manufacturers are now making instruments with smaller globes and electronic sensors with digital readouts. These facilitate the calculation of WBGT and data collection. One variation of the electronic sensors is the measurement of relative humidity instead of natural wet bulb.

One purpose of the current paper is to examine the relationships between some meteorological conditions (dry bulb temperature, dew point temperature, water vapor pressure, and psychrometric wet bulb temperature) and components of the WBGT (namely, dry bulb, natural wet bulb and globe temperatures). The second purpose is to

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compare a smaller globe and alternative method to assess natural wet bulb using a relative humidity sensor.

Methods

WBGT Instrumentation

A standard WBGT configuration was set up using three individual thermometers for dry bulb, wet bulb and globe temperature. Using a tripod stand, one mercury-in-glass thermometer was suspended with an aluminum foil shield to measure dry bulb temperature. A second thermometer was inserted into a 150 mm globe to measure globe temperature. For natural wet bulb temperature, the third thermometer was suspended and a wick placed over the bulb. The wick was kept moist throughout the data collection period by adding water to a sponge ring above the bulb.

The Metrosonics hs-3700 (see Technical Note) was an example of a commercial electronic instrument. It consisted of electronic unit with thermal resistive temperature sensors for dry bulb, natural wet bulb, and globe temperatures. The smaller globe had a 50 mm diameter. For this device, there was no correction for globe size. An alternative instrument was the Metrosonics hs-3900 (see Technical Note), which was developed for the US Navy and general use. The Metrosonics hs-3900 substituted a relative humidity sensor for the natural wet bulb sensor. Natural wet bulb was computed in two steps. First the water vapor pressure was calculated as

$$P_v = (RH/100)(0.6107\ e^{(17.27*Tdb)/(Tdb+237.3)})$$

Then, the psychrometric wet bulb was estimated from

$$T_{nwb} = 0.0376 + 5.79P_v + (0.388–0.0465P_v)T_{db} + 1.0$$

The temperature sensors in the instruments (individual mercury-in-glass thermometers and Metrosonincs hs-3700) were calibrated against a calibration thermometer (0.1°C increments) using a warm water bath. The Metrosonics hs-3900 was factory calibrated.

Data collection

Data were collected in six locations in West-central Florida, and in five of the locations over multiple days (2 or 3) for a total of 14 measurement days in the period from October 1999 to January 2000. One day of data was collected on a farm (6 readings) and open parks represented three other locations (about 210 readings). Two locations were residential developments (about 70 readings). The hs-3900 data were collected later in the effort with about 185 readings across most locations.

The instrument clusters were placed in close proximity. The globes of the instrumentation packages were located about 130 cm above the ground. Environmental measurements were performed after instrument stabilization and were typically recorded every 15 min during the hottest part of the day (10:00 to 15:00).

Weather service data

Meteorological data (dry bulb [$T_{db\text{-}Met}$] and dew point [$T_{dp\text{-}Met}$] temperatures) were obtained from the nearest National Oceanic and Atmospheric Administration (NOAA) station (Tampa International Airport or St. Petersburg/Clearwater Airport) for the day of the site measurement. Since NOAA data were reported hourly and site data were recorded every 15 min, NOAA data were interpolated linearly to match the measured site data.

It was necessary to compute the water vapor pressure ($P_{v\text{-}Met}$) and psychrometric wet bulb ($T_{pwb\text{-}Met}$) from the dry bulb and dew point temperatures. This was done using an iterative method (GoalSeek in Microsoft® Excel®) by comparing alternative methods to compute water vapor pressure (P_v). From the dew point, $P_{v\text{-}Met}$ was computed from

$$P_{v\text{-}Met} = 0.6107\ e^{(17.27*Tdp\text{-}Met)/(Tdp\text{-}Met+237.3)}$$

From the following psychrometric relationship using $T_{db\text{-}Met}$ and $T_{pwb\text{-}Met}$, $P_{v\text{-}p}$ was determined as (Bernard and Cross, Equation A3[4])

$$P_{v\text{-}p} = 0.6107\ e^{(17.27*Tpwb\text{-}Met)/(Tpwb\text{-}Met+237.3)} - 0.067*(T_{db\text{-}Met} - T_{pwb\text{-}Met})$$

Values of $T_{pwb\text{-}Met}$ were changed via the GoalSeek macro until there was no difference in $P_{v\text{-}Met}$ and $P_{v\text{-}p}$.

Qualitative data

In addition to quantitative data, the ambient conditions near the instrument clusters were characterized by three dichotomous decisions. These data were noted by the same person throughout the data collection.

- SKY: Clear (< 25% cloud cover) and Clouds (> 25% cloud cover)
- SUN: Direct (instruments in direct sunlight) and Shade (instruments were shaded by surrounding structures − not clouds)
- AIR: Still (Calm air or no perceptible movement) and Movement (perceptible air movement)

Data analysis

The data analysis was performed in two stages. The first stage framed the questions as paired comparisons of two

Table 1. Characteristics of data as mean, standard deviation (SD) and range

Description	Symbol	Mean	SD	Min	Max
Meteorological Data (n=284)					
Dry Bulb Temperature [°C]	$T_{db\text{-}Met}$	23.3	4.3	10.6	30.6
Dew Point Temperature [°C]	$T_{db\text{-}Met}$	13.1	6.1	–1.7	21.1
Water Vapor Pressure [kPa]	$P_{v\text{-}Met}$	1.6	0.6	0.5	2.5
Psychr. Wet Bulb Temperature [°C]	$T_{pwb\text{-}Met}$	17.1	4.4	7.2	22.5
Standard Instrument (n=272)					
Dry Bulb Temperature [°C]	$T_{db\text{-}Std}$	23.9	3.9	11.0	32.0
Natural Wet Bulb Temperature [°C]	$T_{nwb\text{-}Std}$	17.6	4.3	6.5	25.0
Globe Temperature [°C]	$T_{g\text{-}Std}$	27.9	6.8	10.5	46.0
WBGT [°C]	$WBGT_{Std}$	20.4	4.1	7.8	28.3
hs3700 – 50 cm Globe (n=271)					
Dry Bulb Temperature [°C]	$T_{db\text{-}hs3700}$	22.9	4.1	10.4	31.1
Natural Wet Bulb Temperature [°C]	$T_{nwb\text{-}hs3700}$	17.4	4.4	6.6	25.3
Globe Temperature [°C]	$T_{g\text{-}hs3700}$	26.2	5.5	11.1	39.6
WBGT [°C]	$WBGT_{hs3700}$	17.4	4.4	7.8	32.3
hs3700 – 50 cm Globe & RH (n=186)					
Dry Bulb Temperature [°C]	$T_{db\text{-}hs3900}$	21.7	3.6	10.5	27.8
Natural Wet Bulb Temperature [°C]	$T_{nwb\text{-}hs3900}$	16.9	3.7	9.0	22.3
Globe Temperature [°C]	$T_{g\text{-}hs3900}$	23.7	3.9	11.7	34.8
WBGT [°C]	$WBGT_{hs3900}$	18.7	3.6	9.7	23.3

measures and whether the differences were influenced by the qualitative data. The second stage used multiple linear regression for prediction purposes.

JMP v9 was used for the data analysis and significant differences were reported at $p<0.05$.

Results

There were observations during the daytime at six locations over 14 d in West-central Florida in the winter months. Table 1 provides the characteristics of the data as a mean, standard deviation and range. The number of complete observations for each data type is also provided, where the difference numbers may represent missing data on one metric, and it should be noted that the hs-3900 was used on the last nine days.

Paired comparisons

The two purposes point to a set of comparisons that were of interest. In effect, the paired comparisons assume a linear model with a unity slope and the intercept is the overall effect size between the mean values. A three-way ANOVA was used to explore the effects of the qualitative data, where the dependent variable was the temperature difference and the independent data were the three dichotomous qualitative variables. The first group were comparisons of the standard instrumentation to the meteorological data. The second was the comparison of dry bulb and globe temperatures in the standard instrument. The third group were comparisons of the standard to the electronic instruments. These are described in Table 2 along with the mean difference and the effect size of the statistically significant qualitative factors. When there were two or more significant factors, the two-way interactions were also tested. In all cases, there were no significant two-way interactions.

Table 2. Pair comparisons of environmental data with the overall mean differences and effect size (°C or°C-WBGT) of significant modifiers based on qualitative data

Comparison Pairs as ΔT	Mean	SKY	SUN	AIR
$T_{db\text{-}Std} - T_{db\text{-}Met}$	0.6	1.4	2.6	1.1
$T_{g\text{-}Std} - T_{db\text{-}Met}$	4.3	2.3	11.4	
$T_{pwb\text{-}Met} - T_{nwb\text{-}Std}$	0.5		1.6	0.8
$T_{g\text{-}Std} - T_{db\text{-}Std}$	3.8	1.0	8.0	
$T_{db\text{-}Std} - T_{db\text{-}3700}$	–1		0.5	
$T_{g\text{-}Std} - T_{g\text{-}3700}$	–1.4		4.4	
$T_{nwb\text{-}Std} - T_{nwb\text{-}3700}$	–0.1 (ns)			
$T_{nwb\text{-}Std} - T_{nwb\text{-}3900}$	0	0.4		
$WBGT_{Std} - WBGT_{3700}$	0.3		0.8	
$WBGT_{Std} - WBGT_{3900}$	–0.2			

ns=not significant.

Table 3. Regression models of selected measures

Model	r^2	SEE
Standard from Meteorological Data		
$T_{db\text{-}Std} = 5.4 + 0.82\ T_{db\text{-}Met} - 1.2$ SUN<Direct = 0; Shade = 1>	0.82	1.7
$T_{g\text{-}Std} = 7.5 + 1.00\ T_{db\text{-}Met} - 5.9$ SUN<Direct = 0; Shade = 1>	0.73	3.6
$T_{nwb\text{-}Std} = 1.4 + 0.97\ T_{pwb\text{-}Met} - 0.7$ SUN<Direct = 0; Shade = 1>	0.95	1.0
$WBGT_{Std}$ = 1.1 + 0.66 Tdb-Met + 2.9 Pv-Met – 1.8 SUN<Direct = 0; Shade = 1>	0.91	1.2
$T_{g\text{-}Std} = 1.6 + 1.19\ T_{db\text{-}Std} - 4.3$ SUN<Direct = 0; Shade = 1>	0.85	2.6
Standard from Instrument with Small Globe		
$T_{db\text{-}Std} = 2.3 + 0.94\ T_{db\text{-}hs3700}$	0.93	1.0
$T_{g\text{-}Std} = 1.6 + 1.03\ T_{g\text{-}hs3700} - 2.1$ SUN<Direct = 0; Shade = 1>	0.93	1.8
$T_{g\text{-}Std} = 2.6 + 0.93\ T_{g\text{-}hs3700adj} - 1.4$ SUN<Direct = 0; Shade = 1>	0.93	1.8
$T_{nwb\text{-}Std} = 0.4 + 0.97\ T_{nwb\text{-}hs3700}$	0.98	0.6
$WBGT_{Std} = 1.3 + 0.95\ WBGT_{hs3700}$	0.93	1.1
Standard from Instrument with Small Globe and RH		
$T_{db\text{-}Std} = 2.7 + 0.92\ T_{db\text{-}hs3900}$	0.90	1.1
$T_{g\text{-}Std} = -0.1 + 1.08\ T_{g\text{-}hs3900} - 1.2$ SUN<Direct = 0; Shade = 1>	0.84	1.8
$T_{nwb\text{-}Std} = -2.1 + 1.12\ T_{nwb\text{-}hs3900}$	0.98	0.6
$WBGT_{Std} = -1.6 + 1.10\ WBGT_{hs3900}$	0.97	0.7

SUN is a dichotomous variable that takes on a value of 0 when instrument is in the sun [Direct] and 1 when instrument is in the shade [Shade].

The largest mean differences were seen between dry bulb and globe temperatures, which was expected. Among the qualitative factors, the largest effect size was associated with the difference between dry bulb and globe temperatures due to SUN. Of note was the influence of two qualitative factors on the differences between the meteorological data and the standard instrumentation. SKY (i.e., cloud cover) and SUN (i.e., direct sun versus shade) influenced the relationship between standard measures of dry bulb and globe temperatures and the difference between the standard and the electronic devices. AIR (i.e., presence or absence of noticeable air movement) contributed to differences between the meteorological dry bulb and standard dry bulb and between meteorological psychrometric wet bulb and standard natural wet bulb. The effect sizes for SKY and AIR were smaller than for SUN.

Linear regression

Stepwise multiple linear regressions were used to develop relevant models to explore the use of meteorological data to predict standard measures of WBGT and comparisons between the standard method and two electronic instruments. To be added to the regression model, a factor had to reduce the standard error of estimate by 0.2°C or more and increase the r^2 by 0.02 or more. The stepwise regression results are provided in Table 3. Of the qualitative data, only the contrast between direct sunlight and shade (SUN) was a significant contributor.

Discussion

The dataset includes a reasonable range of conditions to test the principles of predicting WBGT from meteorological data and testing the validity of small globes and relative humidity sensors. Some hotter and more humid conditions in other regions of the world and during the summer season in Florida are outside the range of data reported in Table 1. This represents a limitation of the sample of data, and extrapolations should be done with caution.

As an overall note, the regression models of Table 3 have significant slopes and intercepts due to the large number of observations. This does not mean that an identity line (or a line with a slope of 1.0 and an offset) might not adequately describe the relationship.

Comparison of meteorological data and standard instrumentation

The paired comparisons between meteorological data and that measured by the standard instrumentation (see Table 2), showed some systematic differences. Further, the ANOVA showed that SUN, SKY and AIR all had statistically significant effects. Only SUN (direct sun versus shade) had an important contribution based on the multiple linear regression. This suggested that the differences in dry bulb might be explained by heating of the ground because the dry bulb was shield from the sun. Further, the difference is not large, and plays a small part in the calculation of WBGT.

The difference between meteorological dry bulb and globe temperature was not surprising. The ANOVA points to significant contributions by SKY and SUN, but only SUN emerged from the multiple linear regression. Being directly in the sun contributed over 5°C to the globe temperature compared to only indirect radiation from the outdoor surroundings when shaded. Another feature of the findings was the large standard error of estimate (3.6°C). While the variance was rather high, it was somewhat offset by the relatively low weighting of globe temperature in WBGT at 0.2, which means that the 95% confidence on the globe contribution would be about 1.2°C-WBGT.

Next we compared the psychrometric wet bulb based on the meteorological data to the natural wet bulb temperature on the ground. The ANOVA (Table 2) suggested that it would be sensitive to AIR and SUN, which was plausible. The multiple linear regression supported a relationship that included psychrometric wet bulb and SUN, but not AIR. The 95% confidence interval was about 1.6°C.

Following the method of Bernard and colleagues[4, 6], an average increase in globe temperature ($\Delta T_{g\text{-}d}$) in the direct sun above the meteorological dry bulb was 13.4°C and the increase in the shade was 1.6°C. Using these changes and adding 1°C to the $T_{pwb\text{-}Met}$ for natural wet bulb, a predicted WBGT was calculated. The actual versus predicted values are shown in Fig. 1 along with the identity line. The agreement was good. Thus one formulation for prediction of ambient WBGT is Equation 1.

$$WBGT = 0.7\,(T_{pwb} + 1) + 0.2\,(T_{db} + \Delta T_{g\text{-}d}) + 0.1\,T_{db} \qquad (1)$$

We then looked at predicting WBGT directly from meteorological data. The resulting equation (Table 3) found that water vapor pressure was a better than psychrometric wet bulb or dew point temperature. It also included dry bulb and SUN. For the Shade condition, the instrument would still receive indirect radiant heat from the surroundings because it was outdoors. The 95% confidence interval was about 2°C-WBGT. Repeating the equation as Equation 2:

$$WBGT = 1.1 + 0.66\,T_{db\text{-}Met} + 2.9\,P_{v\text{-}Met} - 1.8\,SUN\langle Direct = 0;\ Shade = 1\rangle \qquad (2)$$

Lemke and Kjellstrom have examined approaches to predicting WBGT from meteorological data and recommended the approach by Liljegren et al.[7] Liljegren et al. compared their predicted WBGT to measured values and reported a 95% confidence interval of 1°C-WBGT; Lemke and Kjellstrom found a similar result. The method required an assessment of the radiant heat flux from the sun and surroundings to achieve this level of precision. In the current study, the predicted WBGT had a mean error of estimate of 1.2°C-WBGT or an approximate 95% confidence interval of 2°C-WBGT. While estimates of radiant flux directly from the sun should be straightforward to estimate, the role of the surroundings in climate models will still be based on assumptions about the surroundings and thus increased uncertainty.

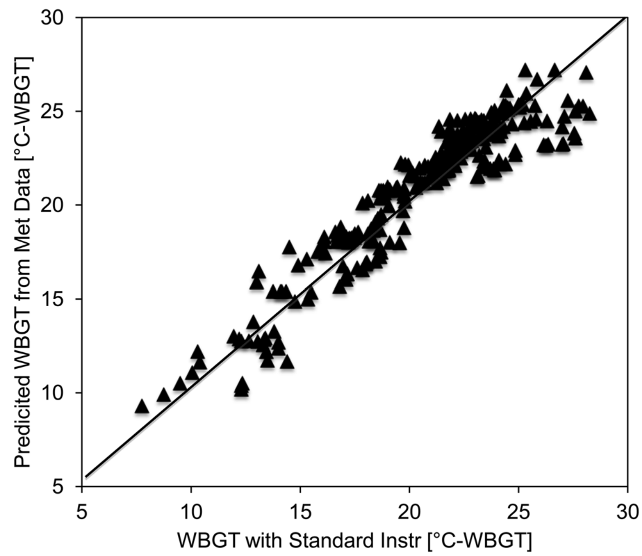

Fig. 1. Comparison of WBGTs from the standard instrument cluster to the predicted from meteorological data using Equation 1. The identity line is shown.

For real-time monitoring or near-term prediction, using a fixed increase in globe temperature based on past experience at the site should provide an adequate approximation. This is essentially the approach used by Bernard and colleagues for indoor environments with good ambient air circulation[4, 6]. For climate modeling, the recommendations of Lemke and Kjellstrom were sound[3]; or a method to approximate the elevation of globe based on latitude, time of day, and surroundings may provide an adequate approximation. That is, Equation 1 would be a good candidate model with locally determined values for $\Delta T_{g\text{-}d}$.

Validity of small globe with natural wet bulb temperature

There were two opportunities to compare a 50 mm globe to a standard globe via the hs-3700 and hs-3900. When pairwise comparisons were made to the standard globe there were significant differences and SUN was an effect for both. The effect of SUN was expected. Because there were more data for the hs-3700 and over a wider range, those outcomes were more reliable. From the re-

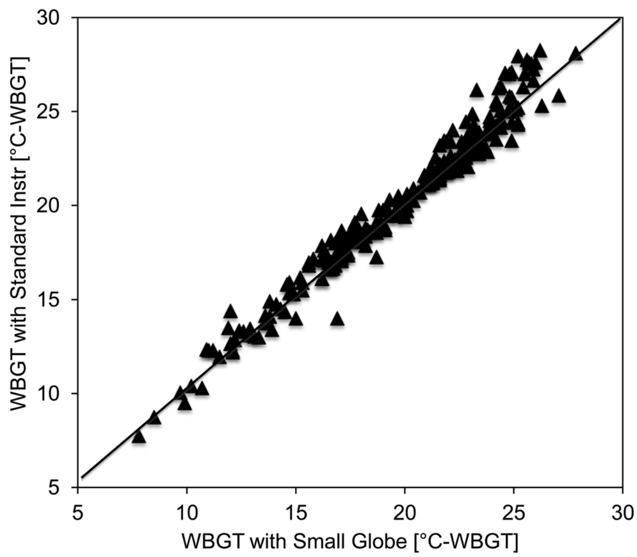

Fig. 2. Comparison of WBGTs from the standard instrument cluster to the electronic device with a small globe.
The identity line is shown.

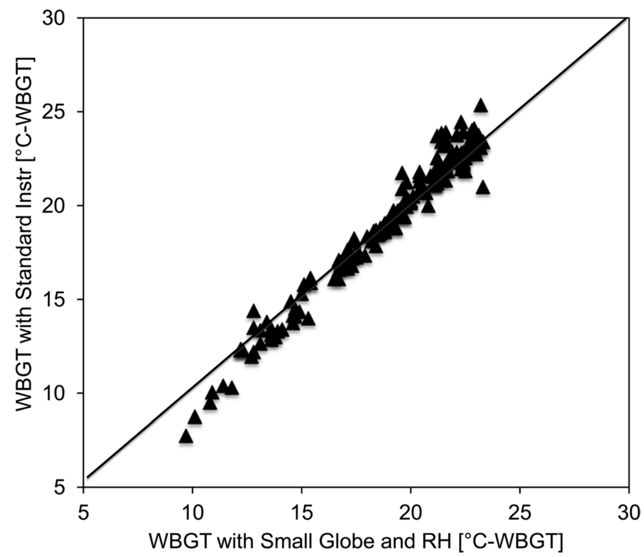

Fig. 3. Comparison of WBGTs from the standard instrument cluster to the electronic device with a small globe and relative humidity sensor.
The identity line is shown.

gression model comparing the standard globe to the small globe of the hs-3700, the correlation coefficient was very good at 0.93, but the standard error of estimate was somewhat high at 1.8°C (see Table 3).

To accommodate the globe size difference in moderate air movement, the following adjustment was made

$$T_{g\text{-}hs3700\text{-}adj} = T_{db\text{-}hs3700} + 1.4\,(T_{g\text{-}hs3700} - T_{db\text{-}hs3700})$$

Applying this adjustment did not improve either the r^2 or SEE, although the coefficients of the multiple regression did change (see Table 3). Thus, there is little practical advantage to making the adjustment.

Again, recognizing that the globe temperature plays a small role in the determination of outdoor WBGT, the contribution to uncertainty (95% confidence interval) will be in the order of 0.6°C-WBGT (and 0.9°C-WBGT for indoor determinations). While higher than prescribed sensor accuracy, it is within the normal variations in the environment. Therefore the smaller globe with or without a correction is acceptable for heat stress assessments.

When comparing the direct assessment of WBGT between the standard method and the hs-3700, the pair comparison showed little systematic differences (0.3°C-WBGT from Table 2). The multiple regression had a good correlation coefficient (0.93) with an SEE of 1.1. Figure 2 shows the WBGT data from the standard instrument cluster and the hs-3700, and the identity line was provided in the figure.

Validity of RH method for natural wet bulb temperature

A method first developed for the US Navy and now being used by others to assess WBGT is the waterless wet bulb, which uses relative humidity and dry bulb temperature to estimate natural wet bulb temperature. The process used by the hs-3900 was described above. No systematic difference was observed for the difference between the standard natural wet bulb temperature and the one estimated by the relative humidity method, but there was a small effect due to cloudiness. The multiple linear regression did not find cloudiness (SKY) to be an important contributor. The correlation coefficient was very good (0.98) with a 95% confidence of 1.0°C. The agreement was excellent with an uncertainty greater than instrument accuracy.

When the device was used to compute outdoor WBGT, the paired comparison with the standard showed little systematic difference. Again, the multiple regression showed good agreement with an r^2 of 0.97 and an SEE of 0.7°C-WBGT (95% confidence of 1.2°C-WBGT). Figure 3 shows the WBGT data from the standard instrument cluster and the hs-3900, with the identity line. Quest Technologies (now 3M) performed an independent evaluation of the method with improvements as it was adopted for the QT-44 and −46 (see Technical Note), and the comparison of instruments with a natural wet bulb and with the relative humidity method provided similar results for WBGT (SEE of about 0.4°C-WBGT)[8].

Conclusions

Meteorological data can be used to predict outdoor WBGT following several paths. The path with the greatest analytical foundation is the method of Liljegren et al.[7] as recommended by Lemke and Kjellstrom[3]. A path that estimates components of the WBGT index based on prior observation as suggested by Bernard[4, 6] is a second path (see Equation 1). Both of these have the advantage of knowing the components to parse out how the environment may contribute to heat stress, and they can be used in other models of thermal stress. Finally, a direct estimation of WBGT for meteorological data can be made based on prior observation (see Equation 2). Depending on method and ability to characterize the surface conditions, the variance of the estimate will be on the order of 1 to 2°C-WBGT.

The 50 mm globe size is a reasonable approximation of the standard size (150 mm), and the size adjustment may provide more precision. The relative humidity method of the waterless natural wet bulb provides a very good estimation of natural wet bulb temperature. The determination of WBGT from the electronic instruments (small globe with or without the relative humidity method) provide a good estimate of the WBGT from the standard instrument cluster.

The conclusions in this paper are limited by the range of data and thus some care is required in extrapolating the findings. The principles of analysis should hold for extended ranges. The prior experience with the approach described in Equation 1 for hotter environments[4, 6] supported that optimism.

Acknowledgement

Ms. Barrow's efforts were supported in part by US CDC/NIOSH Sunshine ERC training grant (T42OH008438). The views expressed in this paper are those of the authors.

Technical Note

The electronic instruments in this paper were furnished by Metrosonics. Metrosonics was purchased by Quest Technologies, who further developed the electronic instrumentation, especially the waterless wet bulb temperature. Quest Technology was purchased by and incorporated into 3M.

Unlike the hs-3700 and hs-3900, the QT-44 and −46 use adjustments for globe size based on a factor of about 1.4. The determination of natural wet bulb temperature from relative humidity follows a two-step iteration to determine psychrometric wet bulb and then adjusts the temperature for air speed and radiant heat following Bernard and Pourmoghani[6]. The estimation method was rigorously evaluated by Quest Technologies[8]. The performance should be an improvement over that reported here for the hs-3900.

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