Analysis of wet-bulb globe temperature calculations using in-situ observations

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ABSTRACT

Using the Wet-Bulb Globe Temperature (WBGT) to measure heat injury risk is paramount; however, without affordable instruments, the public has to rely on formulas. These formulas either overestimate WBGT (bad for production) or worse, underestimate WBGT (bad for humans, heat injury risk increases significantly and unnecessarily). Data were collected from 16 June 2018 through 16 July 2018 from the QUESTemp°34 (Q34) and synchronous data from the Oklahoma Mesonet, and WBGT index values were compared from Q34's calculations, Mesonet calculation using approximations of natural wet bulb temperature and black globe temperature, and three equations utilized by Eglin Air Force Base. With roughly 2.5 weeks of valid, filtered data, it was determined that the Mesonet calculations underestimate the instruments', and all three of Eglins calculations overestimate the instruments'. Future work includes examining the algorithms created by the Tulsa Weather Forecast Office to calculate the Mesonet WBGT and comparing the WBGT to the Environmental Stress Index.

1. Introduction

The Wet-Bulb Globe Temperature (WBGT) is a derived quantity used to measure the potential for heat injury (e.g., heat cramps, heat exhaustion, and heat stress). An accurate estimate of the WBGT is necessary to avoid heat injury in athletes, military personnel, miners, industrial and other labor workers, and those taking the pilgrimage to Mekkah (Shapiro and Seidman 1990). Overestimation of the WBGT can result in productivity decreases because of too much rest time, but underestimations are far worse because underestimation of heat stress can cause increased heat injury cases due to lack of preparation. Wallace et. al. (2005) suggests that heat stress can cumulate from day-to-day training (and can be generalized to include anyone exerting themselves outside on a regular basis). Specialized instruments are available in measuring the WBGT, but are expensive and require non-standard calibrations (Biggar et. al. 2017). Therefore, special focus is required on formulas. In this paper, various formulas for the WBGT were tested to determine how accurate they are compared to an instrument, compared to one another, and if they are accurate enough to be used worldwide. With this, correction terms may need to be applied to the formulas to make them more accurate.

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2. Background

Wet Bulb Globe Temperature

The WBGT was formulated in 1957 by the United States Army and Marine Corps/Navy (Alfano et. al. 2014) as a way to measure the heat stress on the body (Biggar et. al. 2017) after many cases of heat illness and injury in the 1940s and 1950s at the Marine Corps Recruit Depot on Parris Island, SC (Wallace et. al. 2005). Early calculations involve the air temperature (T_a), natural wet-bulb temperature (T_{nwb}), and black globe temperature (T_{bg}) as a weighted average as follows:

$$WBGT = 0.7 * T_{nwb} + 0.2 * T_{bg} + 0.1 * T_a \tag{1}$$

Where T_{bg} is a function of air temperature, humidity, wind, and incoming solar radiation, which can be affected by solar elevation angle (*SEA*) and cloud cover, while T_{nwb} is a function of air temperature and dew-point temperature (T_d) (Moran 2017). A successful bout of WBGT implementations (Wallace et. al. 2005) led to the expansion of its applications to include occupational exertion

Heat Risk Category	**WBGT (°F)**	**Light Work (work/rest time per hour, acclimated in [])**	**Moderate Work**	**Heavy Work**
None	78-79.9	50/10 [60/0]	40/20 [60/0]	30/30 [50/10]
Low	80-84.9	40/20 [60/0]	30/30 [50/10]	20/40 [40/20]
Moderate	85-87.9	30/30 [60/0]	20/40 [40/20]	10/50 [30/30]
High	88-90	20/40 [60/0]	10/50 [30/30]	0/60 [20/40]
Extreme	>90	50/10 [60/0]	40/20 [60/0]	30/30 [50/10]

Table 1: Work/Rest ratios for different WBGT risk categories per hour.

Work Level	**Activity Examples**
Light	Sitting with light manual work
	Driving on unpaved surface
	Walking 2 mph on hard surface
Moderate	Painting with brush
	Lawn mowing with walk behind power mower on flat area
	Pushing light wheelbarrow
	Weeding or hoeing
	Walking 3.5 mph on hard surface
Heavy	Digging or shoveling
	Hand sawing wood
	Chopping wood
	Walking 4.5 mph on hard surface or 2.5 mph in sand

Table 2: Pertains to Table 1, examples of activities at each work load.

(e.g., miners and construction workers) and athletic exertion (e.g., running and team sports) (Lemke and Kjellstrom 2012; Alfano et. al. 2014). The formula has not changed since it was created, and in 1982 the formula was certified by the International Standards Organization (ISO 7243, ISO/DIS 7933) (Brocherie and Millet 2015; Moran et. al. 2001) and is used by organizations such as the American College of Sports Medicine (ACSM), International Olympic Committee (IOC), and the Occupational Safety and Health Administration (OSHA) (Brocherie and Millet 2015). Though many different articles have their own recommendations (and categories) for working when the WBGT is significant (>80°F), the Oklahoma Mesonet (2016) has specific information (Table 1) regarding heat risk and work/rest ratios. The table also includes work/rest ratios for those acclimated to the heat (in square brackets). Acclimatization will vary from person to person but the Oklahoma Mesonet (2016) suggests five days of heat exposure, starting at 20% of full exposure and increasing exposure by 20% each day. Table 2 (Oklahoma Mesonet 2016) shows examples what qualifies as light, moderate, and heavy work to assist in the interpretation of the WBGT values.

Heat Index vs. WBGT

One of the more commonly used terms in discussing apparent temperature is the Heat Index. It requires two parameters: air temperature and relative humidity, and it is calculated with a fairly simple to understand algorithm created by the National Weather Service. However, its drawbacks are that it neglects solar radiation (because it is measured in the shade) and does not take into account other factors that may affect the way one feels temperature (e.g., amount of clothing, acclimatization, etc.) (Moran 2017). As a result, it cannot be used to accurately represent heat stress in active people and is better left as an index for inactive individuals in the shade. Figure 1 shows that it can be inferred that the two indexes are not comparable because it is not a 1:1 ratio (from Heat Index to WBGT). The WBGT, as described in Section 2a, is much better at estimating heat stress in individuals. However, in

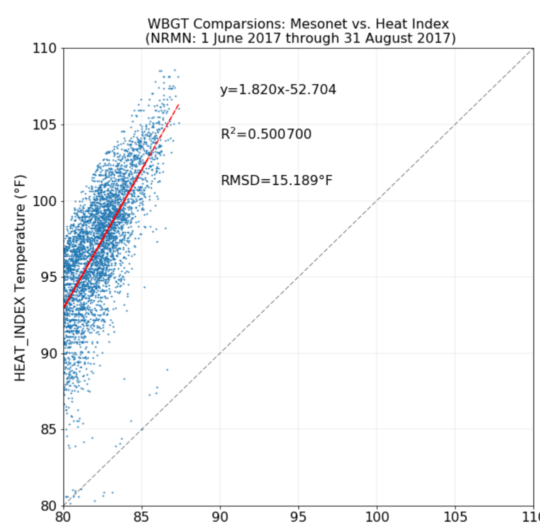

Figure 1: Comparison of Mesonet's WBGT estimation to Heat Index, calculated by an NWS algorithm.

locations where specialized instruments are inaccessible, calculating the WBGT cannot be done directly.

Environmental Stress Index vs. WBGT

Moran et. al. (2001) developed an index called the Environmental Stress Index (ESI) as an alternative to the WBGT. The idea was to use parameters that were easier than wet-bulb temperature (T_w) and T_{bg} to measure. Their argument was that relative humidity (RH) is a better replacement to T_w because T_w requires instrument rotation for ninety seconds, and requiring a six inch black globe is not practical because of the twenty to thirty minute wait for the instrument to reach equilibrium. Using RH, T_a, and solar radiation (SR), Moran et. al. (2001) fit the following formula to their collected data:

$$\begin{aligned} ESI = 0.63 * T_a - 0.03 * RH \\ +0.02 * SR + 0.0054(T_a * RH) \\ -0.073(0.1 + SR)^{-1} \end{aligned} \tag{2}$$

While their data fit well (R^2 ranged from 0.981 to 0.985 on their three stations), ESI is a dimensionless unit, while units of WBGT are those of temperature (°F or °C). Also, newer instruments that measure heat stress diminish the T_w and T_{bg} shortcomings in three ways. First, these instruments do not require rotation of the wet wick; they use T_{nwb} instead. Second, using a two inch black globe can be corrected for a six inch black globe using extrapolation. Thirdly, after initial adjustment, these instruments do not require time to adjust to the environment because they can be left outside with little human interaction. Even though Moran et. al. (2001) gives plenty of data, the paper fails to explain the significance of the numbers precisely in terms of heat injury risk. As such, the ESI has limited ability to quantify heat stress.

3. Data

Two data sources are utilized in this study: The Oklahoma Mesonet and the QUESTemp°34 instrument (Q34) by 3M. The Oklahoma Mesonet (hereafter Mesonet) is a network of 120 automated stations (with at least one in each of Oklahomas 77 counties) created by scientists at the University of Oklahoma and Oklahoma State University. Data collection began on 1 January 1994 and is collected every five minutes where it undergoes automated quality assurance checks (Shafer et. al. 2000) before it is uploaded to the Internet for the public to collect, analyze, and interpret. The Mesonet station utilized is the Norman, OK station (Station ID = NRMN) located at Max Westheimer Airport. Table 3 (adapted from the Oklahoma Mesonet) shows the variables collected every five minutes at the NRMN site, with those variables used in this study indicated with an asterisk.

Variable ID	Description
RELH*	Relative Humidity at 1.5 m (%)
TAIR*	Air Temperature at 1.5 m (°C)
WSPD	Wind Speed at 10 m (m s^{-1})
WVEC	Vector Wind Speed at 10 m (m s^{-1})
WDIR	Average Vector Wind Direction at 10 m (°)
WDSD	Wind Direction Standard Deviation at 10 m (°)
WSSD	Wind Speed Standard Deviation at 10 m (m s^{-1})
WMAX	Maximum Wind Speed at 10 m (m s^{-1})
RAIN	Rain since 00 UTC at 0.6 m (mm)
PRES*	Barometric Pressure at 0.75 m (mb)
SRAD*	Solar Radiation (W m^{-2})
TA9M	Air Temperature at 9 m (°C)
WS2M*	Wind Speed at 2 m (m s^{-1})

Table 3: Variable IDs used on the Oklahoma Mesonet website and what they measure.

The Q34 is an instrument created by 3M that directly measures all three parameters of the WBGT, with data being observed every five minutes. The T_{nwb} sensor utilizes a wick and has a reservoir for distilled or deionized water. A daily refill of the water reservoir was required to ensure there is enough water in the reservoir, and a weekly change of the wick is necessary to maintain the purity of the wick. Maintenance was performed before noon when possible to minimize errors due to human interactions with the instrument and any data that the instrument collects during this time were flagged from the database to ensure data quality. In addition, because the instrument is not waterproof, the instrument was covered with a garbage bag when precipitation was expected and the data were flagged during these times in the database. The T_a sensor is shielded by white plastic covers attached at an angle to shield it from incoming solar radiation and wind. Conversely, the T_{bg} sensor is a black globe two inches in diameter with a copper plate just inside the black coating. It is corrected for a six inch diameter black globe for a more accurate reading (3M 2017). It is intentionally unshaded to allow for direct interactions with solar radiation and wind.

Mesonet and Q34 are both stationed at Max Westheimer Airport (∼35.26°N, 97.47°W) (Google Maps) 33.88 m apart from each other (Google Maps). Table 3 has the heights at which each relevant observation is situated at the station. The Q34s base is 1.5875 m above the ground (measured with a Lufkin 25' x 1" Tape Measure, hereafter LTM) It sits on a 1"x1" metal beam (LTM) and is connected to a Duracell Ultra 12V 100AH Deep Cycle AGM SLA battery, continuously charged by solar panels.

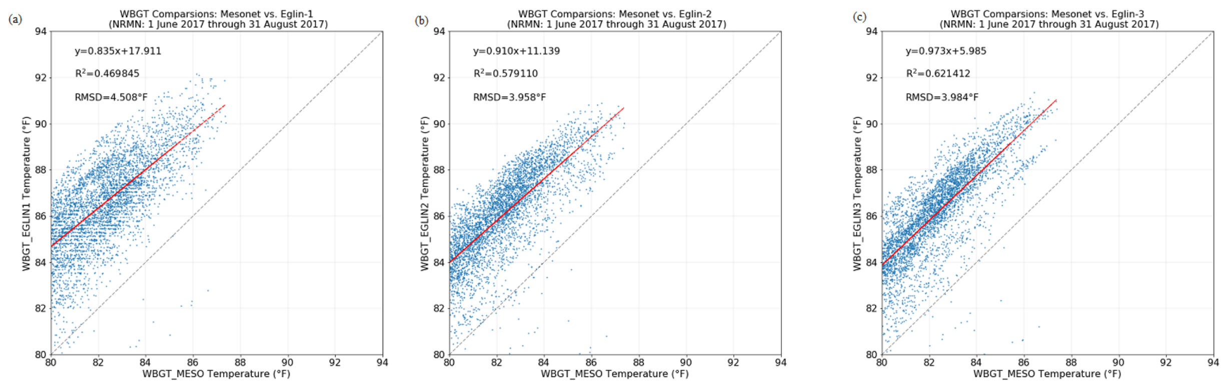

Figure 2: Comparison of Mesonet's WBGT to each of Eglin's WBGT.

4. Methodology

Collection of Data

Data were collected in two phases: the preliminary phase and the current phase. The preliminary phase involved collecting data from the meteorological summer of 2017 (1 June 2017 0000 UTC through 31 August 2017 2355 UTC) using only Mesonet data. The current phase of data introduces the Q34, where data were collected from 16 June 2018 0000 UTC through 16 July 2018 2355 UTC. Mesonet data were collected from the same time period as the Q34.

Equations and Calculations

Five formulas for WBGT were used in this study. The Instrument WBGT (WBGT_INS) is given by the ISO equation (Eq. 1), measuring all three parameters directly. The Mesonet WBGT (WBGT_MESO) is also given by Eq. 1, measuring T_a directly but using estimating algorithms made by Tulsa WFO for T_{nwb} and T_{bg} (WBGT_MESO). Equations Eglin-1, Eglin-2, and Eglin-3 are given by Equations 3, 4, and 5, respectively. T_a and v are calculated directly, T_d is calculated by Tulsa WFOs algorithm and SEA is calculated by formulas from Fundamentals of Atmospheric Modeling (Jacobson 2005) and the Global Monitoring Division (2018).

$$WBGT = 4.18 + 0.59(T_a) + 0.32(T_d) \tag{3}$$

$$WBGT = 5.16 + 0.49(T_a) + 0.34(T_d) + 2.46(sin(SEA)) \tag{4}$$

$$WBGT = 4.50 + 0.52(T_a) + 0.35(T_d) + 2.68(sin(SEA)) - 0.10(v) \tag{5}$$

Comparisons

In the preliminary phase, WBGT_MESO was compared to each of WBGT_EGLIN1, WBGT_EGLIN2, and WBGT_EGLIN3 using the preliminary data only. The goal was to understand the differences between the index results; no right or wrong can be inferred between the formulas. The current phase had two sets of comparisons: the Q34 parameters compared to the Mesonet parameters (T_a, T_{nwb}, and T_{bg} from each), and WBGT_INS compared to each of WBGT_MESO, WBGT_EGLIN1, WBGT_EGLIN2, and WBGT_EGLIN3. In all comparisons except for those involving single parameters, any results below 80°F was removed from the data because according to Table 1, because any readings below that threshold are not likely to cause heat injury in most individuals.

5. Results

Formulas Comparison

Figure 2 shows WBGT_MESO compared to WBGT_EGLIN1 (Fig. 2a), WBGT_EGLIN2 (Fig. 2b), and WBGT_EGLIN3 (Fig. 2c). In all three cases, Eglin's equations estimated a higher WBGT than WBGT_MESO. As more variables were added, the bias became more linear, as the slope of the best-fit line goes from 0.835 in Figure 2a to 0.973 in Figure 2c. An increase (from 0.469 to 0.621) in R^2 values with more variables indicated the correlation between WBGT_MESO and the Eglin estimations become stronger. The RMSD decreased from Figure 2a to Figure 2b (4.508°F to 3.958°F) but increased to 3.984°F in Figure 2c. This is a 0.655% difference, so the difference was not considered to be significant enough to state that the RMSD increased from Figure 2b to Figure 2c, considering the percent difference in Figure 2a to Figure 2b is 12.993%.

Parameter Comparison

Figure 3 shows parameter comparisons of T_a (Fig. 3a), T_{bg} (Fig. 3b), and T_{nwb} (Fig. 3c) between Q34 (labeled as 'Instrument' on this and subsequent figures) and Mesonet.

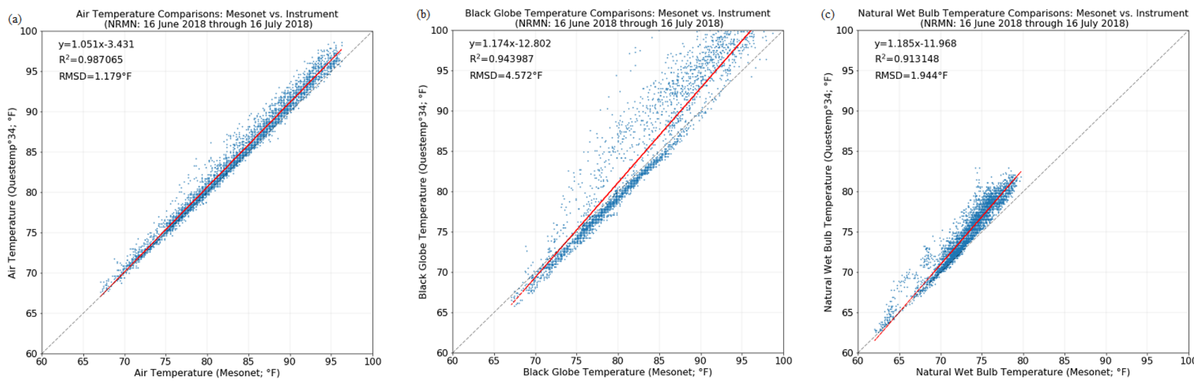

Figure 3: Comparison of Mesonet's WBGT parameters to Instrument parameters.

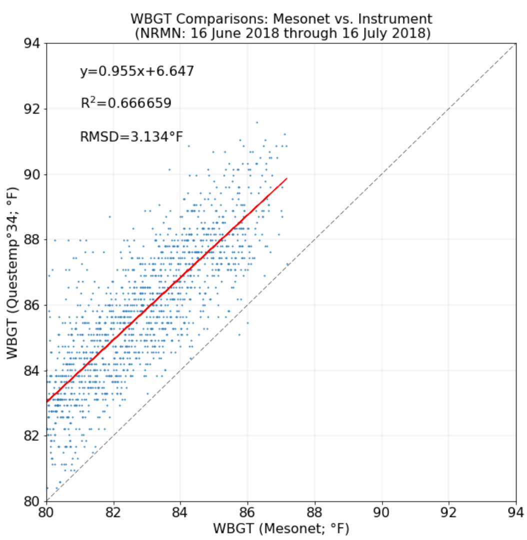

Figure 4: Comparison of Mesonet WBGT to Instrument WBGT.

In Figure 3a, although T_a was directly measured by both Q34 and Mesonet, there were minor differences between the two. However, with an R^2 value of 0.987, a slope of the best-fit line of 1.051, and a RMSD being 1.179°F, this difference was almost negligible. Figure 3b shows an interesting pattern: nearly half of the points on the graph fall on (or close to) the $y = x$ line (gray-dashed). The other half of the points show that Q34 measures significantly higher T_{bg} values than Mesonet estimates. With an R^2 value of 0.944 and RMSD of 4.572°F, the deviations were significantly greater than those in Figure 3a, although the correlation was still fairly strong. In Figure 3c, the Q34 measured T_{nwb} read consistently higher than the Mesonet estimate. While the correlation was not as strong as that in Figure 3b (R^2 = 0.913), the deviation was less (RMSD = 1.944°F).

Index Comparisons

Figure 4 shows the WBGT comparisons between Q34 and Mesonet, where there is a near linear bias (slope of best fit line is 0.955). However, the R^2 value is 0.667 and the RMSD is 3.134°F. Figure 5 shows WBGT_INS compared to WBGT_EGLIN1 (Fig. 5a), WBGT_EGLIN2 (Fig. 5b), and WBGT_EGLIN3 (Fig. 5c). The best fit line for all three Eglin equations have very similar slopes (0.810 in Fig. 5a, 0.818 in Fig. 5b, and 0.814 in Fig. 5c) and all three Eglin equations estimate higher WBGT values than Q34 measures. As more variables were added Eglin's equation (that is, looking from Fig. 5a to 5c), the correlation became stronger (R^2 values go from 0.567 in Fig. 9a to 0.658 in Fig. 5c) and deviation decreased (RMSD goes from 2.139°F in Fig. 5a to 1.782°F in Fig. 5c).

6. Conclusion

Discussion of Limitations

There were some issues that arose during data collection. First, the power supply was hooked up to an external battery in a way that the cables could easily lose contact with the power port on the instrument if it was disturbed too much. This was done to start data collection as quickly as possible. In most cases of Q34 resetting, this happened when the instrument was covered when a rainstorm was about to move in to the area. A solution to this problem is to hook up an approved cable to the output port for future data collection. Another issue arose during the time period of 2 July 2018 1250 UTC to 9 July 2018 2020 UTC when there was a foreign substance covering the pyranometer on the NRMN station, invalidating the data. Although this did not impact the Q34 data directly, it did mean

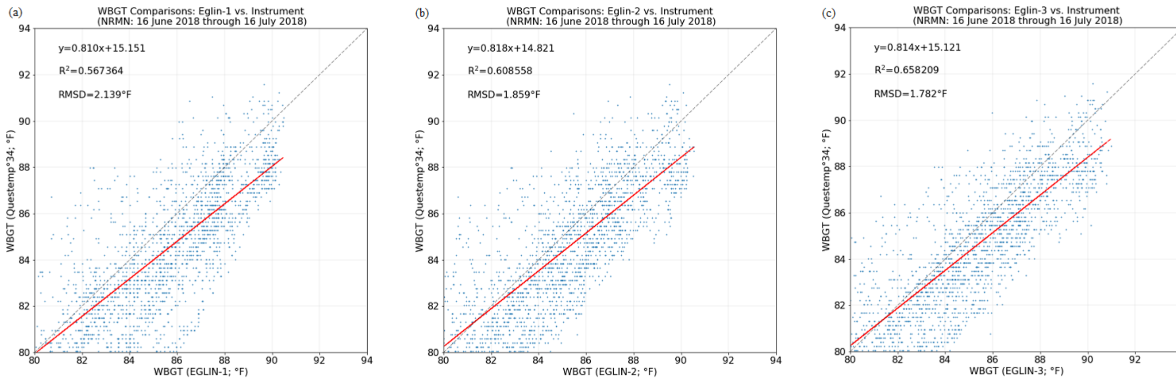

Figure 5: Comparison of each of Eglins' WBGT indexes to Instrument WBGT.

that T_{bg} was not calculated using Tulsa WFO's algorithm, and no comparisons were made between WBGT_INS and WBGT_MESO. Frequent checks of on-line Mesonet data need to be made to avoid future significant data losses due to mishaps pertaining to the pyranometer.

Discussion of Results

Out of the one month of data, only about two and a half weeks of data were considered valid for purposes of comparison. Looking at the preliminary data results, it is necessary that the Solar Elevation Angle (found in Eglin-2 and Eglin-3) is included in the equations. Including wind speed (found in Eglin-3) helped, although as shown by Alfano et. al. (2014), wind is not a linear factor in the WBGT as it is represented in the Eglin-3 equation. The parameter comparisons between Q34 and Mesonet, showed that the Q34, according to the best fit line, measured higher across all three parameters. This may be caused by the Q34 being situated lower to the ground (approximately 0.4 m lower) than the sensors on the NRMN station, as the surface of the Earth heats up before the air above it. It can be inferred in Figure 4 from an almost-parallel best fit line (in red) and $y = x$ line (dashed gray) that there is almost a linear bias between Q34 and Mesonet. While more data is needed to confirm this hypothesis, the initial data shows a constant correction term can be applied to the WBGT_MESO after it is calculated. With the data collected, this appears to be +3.3°F. Figure 5 showed that Eglin-3 is the better of the three equations to use due to the highest correlation and lowest deviations. However, the slope of the best fit line is not parallel to the $y = x$ line, meaning additional data needs to be collected to determine a possible correction factor.

Future Work

Given additional observations/modification, the next step of verification would be to focus on the algorithms made by Tulsa WFO to estimate T_{bg} and T_{nwb} for any possible additions or modifications to them. Following up on the work done in Moran et. al. (2001), data could be collected to see how well the Q34 and ESI compare.

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