Accuracy Assessment of Experimental Wet Bulb Globe Temperature Forecasts Across North Carolina and the Continental United States

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1. Introduction

Wet bulb globe temperature (WBGT) is a heat stress index that accounts for the effects of air temperature, humidity, wind speed, and solar radiation on body temperature. WBGT is the recommended method for assessing and managing workplace heat stress by the United States Occupational Safety and Health Administration (OSHA, 2017), and it is recommended outside the United States for occupational environments by the International Organization for Standardization (ISO, 2017). In addition, WBGT is increasingly used in high school athletics for modifying practice times and activities based on WBGT values, such as in the states of Georgia (Grundstein et al., 2015) and North Carolina (NCHSAA, 2016).

In the summer of 2019, the NOAA Southeast Regional Climate Center (SERCC) and the Carolinas Integrated Sciences and Assessments (CISA), one of eleven NOAA RISA program teams, developed a web-based WBGT forecast tool for the states of North Carolina and Virginia. Around the same time, the United States National Weather Service (NWS) added an experimental WBGT forecast to their gridded National Digital Forecast Database (NDFD). The SERCC/CISA forecast tool and the NWS experimental forecast, however, utilize different methods for estimating WBGT. In this paper, we describe these methods and assess their accuracy.

2. Data and Methods

Gridded NDFD forecast data (four runs per day: 0Z, 6Z, 12Z, 18Z) were archived from May 1–September 30, 2020. This data included the NWS experimental WBGT product (NWS WBGT) and the variables needed to estimate WBGT: 2-meter air and dew point temperature, 10-meter wind speed, and cloud cover.

WBGT is calculated according to the following formulation:

$$(1)\quad WBGT = 0.7 * NWB + 0.2 * Tg + 0.1 * Ta,$$

where NWB is the natural web bulb temperature, Tg is the black globe temperature, and Ta is the air temperature.

The SERCC/CISA WBGT, henceforth referred to as SC WBGT, utilized the Liljegren et al. (2008) methodology to estimate WBGT, as it has been shown to be the most accurate (Lemke & Kjellstrom, 2012; Patel et al., 2013). Since the NDFD wind speed forecast is at the 10-meter level, winds were logarithmically downscaled to 2 meters using Pasquil-Gifford Stability Categories (see details in Appendix A). Pasquil-Gifford Stability Categories provide an indicator of atmospheric turbulence, and thus the degree to which the faster wind speeds higher in the atmosphere are mixed down to the surface (US EPA, 2000).

The NWS experimental WBGT, hereafter referred to as NWS WBGT, utilizes the Dimiceli et al. (2001) methodology for estimating the black globe temperature. The NWS methodology assumes that the psychrometric wet bulb provides a reasonable estimate of the NWB; however, this is not the case under very warm and humid conditions with light wind speeds, which are common in the Southeast U.S. Under these conditions, NWB can greatly exceed the psychrometric web bulb providing a much higher WBGT. Also, the NWS WBGT does not downscale wind speeds to 2 meters, which is critical since WBGT is highly sensitive to changes in wind speed (Figure 1).

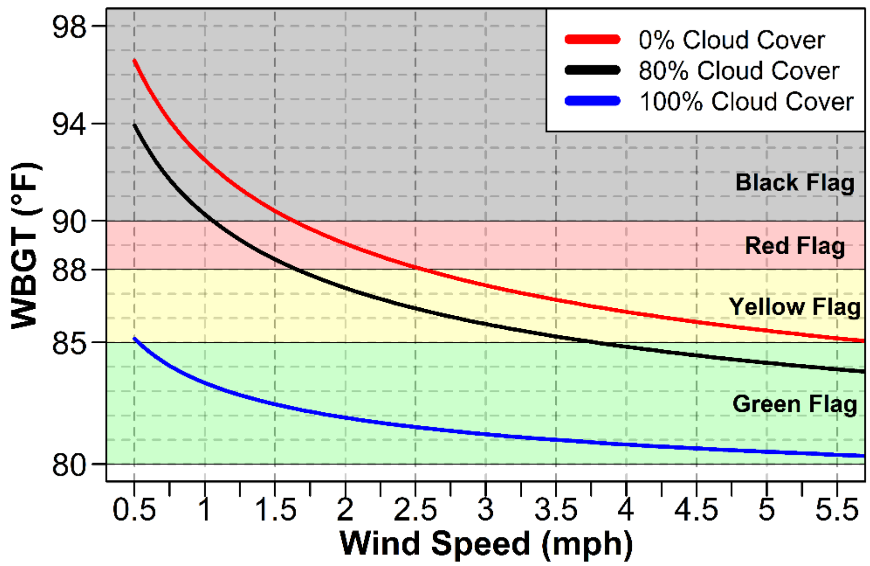

Figure 1: Relationship between WBGT (SC WBGT method) and wind speed for three categories of cloud cover, with an air temperature of 86°F and dew point of 70°F.

The last step for calculating the SC WBGT was to convert the NDFD forecast cloud cover to solar radiation. First, the clear-sky direct solar radiation for a given point and time was calculated, and then modified by the percentage cloud cover using the following formula: (2) $R0 * (1 - 0.75n^{3.4})$, where n is the cloud cover fraction (0.0–1.0) (Solar Radiation Cloud Cover Adjustment Calculator) (see details in Appendix B).

The one-day NWS and SC WBGT forecasts were compared against direct WBGT measurements made by a meter designed to meet the International Organization for Standardization (ISO) specifications for a WBGT monitor (details in Cooper et al., 2017). The direct WBGT measurements were made at two locations, Durham and Shelby, North Carolina, for a total of 45 days during the period 7/3/2020–9/14/2020, and data was recorded at 10–20 second intervals from sunrise until sunset.

The two WBGT forecasts were also compared at 837 ASOS/AWOS weather stations across the CONUS through the period 6/14/2020–8/31/2020. Because WBGT is not measured at these weather stations, the forecasts were compared against WBGT estimated by the Liljegren et al. (2008) methodology at these stations[1]. All meteorological variables required for estimating WBGT are routinely recorded at these stations, except for solar radiation. Thus, cloud cover observations were converted to estimates of solar radiation by modifying the clear-sky direct solar radiation for a given station at a given hour by the percentage cloud cover for each observation (see details in Appendix B).

Hourly averages of the ASOS/AWOS estimated WBGT values and the direct WBGT measurements were calculated and compared with the hourly NDFD forecast values. Due to the

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[1] Since the SC WBGT utilizes the Liljegren et al. (2008) methodology and the NWS WBGT does not, the SC WBGT forecast should be closer to the station estimated WBGT. Despite this, there is still utility in comparing both forecasts with station estimated WBGT since the Liljegren et al. (2008) method offers the most accurate estimation (Lemke & Kjellstrom, 2012; Patel et al., 2013), which is further confirmed in the results presented here.

high variability of WBGT over periods of 5–15 minutes, the hourly average was calculated using observations between five minutes before and five minutes after the hour. All forecast accuracy visualizations and statistics below were calculated by subtracting the observed WBGT from the forecast WBGT.

3. Results

3.1. WBGT Ground Truth

Substantial differences are revealed in the NWS WBGT and the SC WBGT forecasted values, as the NWS WBGT is 4–5°F cooler on average than the SC WBGT (Figure 2).

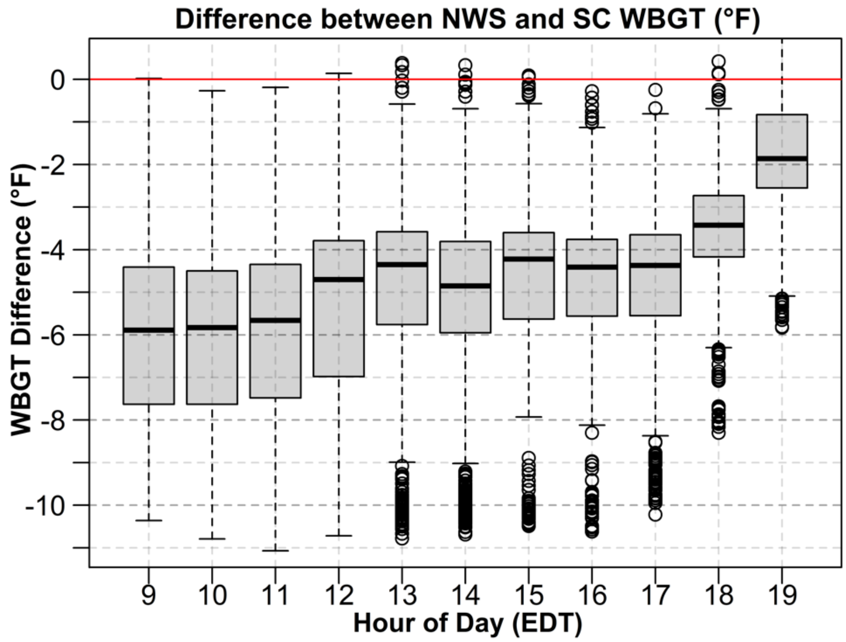

Figure 2: Difference between NWS WBGT and SC WBGT by hour of day for the 1-day forecast at the two locations in NC with WBGT measurements.

This cool bias is confirmed when comparing the forecast values with the observed WBGT values (Figures 3–4). Because obstacles shaded the instruments early and late in the day, boxes corresponding to hours in which the instruments were in direct sunlight are shaded in orange in Figures 3 and 4. Since the SC tool also provides a WBGT forecast for shaded areas, these values were compared to observed WBGT when the instruments were shaded. When comparing shaded observations to the non-shaded SC WBGT, there is a positive 4–5°F bias on average (Figure 3, a). This large positive bias is corrected when accounting for shade in the forecast (Figure 3, b).

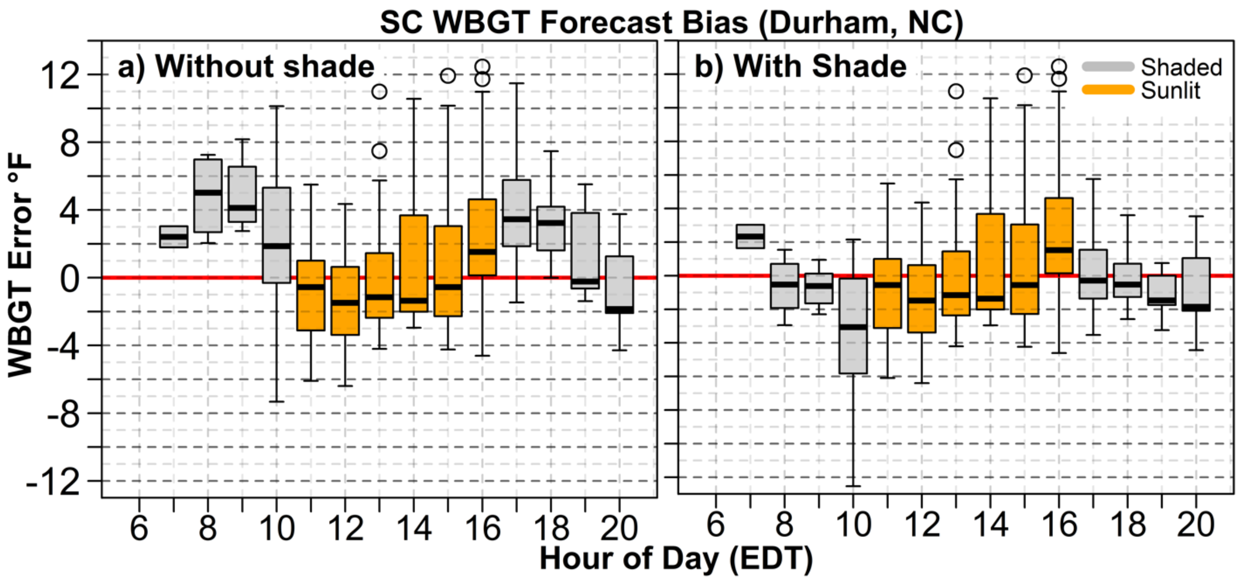

Figure 3: 1-Day WBGT forecast bias comparing shaded observations with non-shaded SC WBGT (a) and with SC shaded WBGT (b).

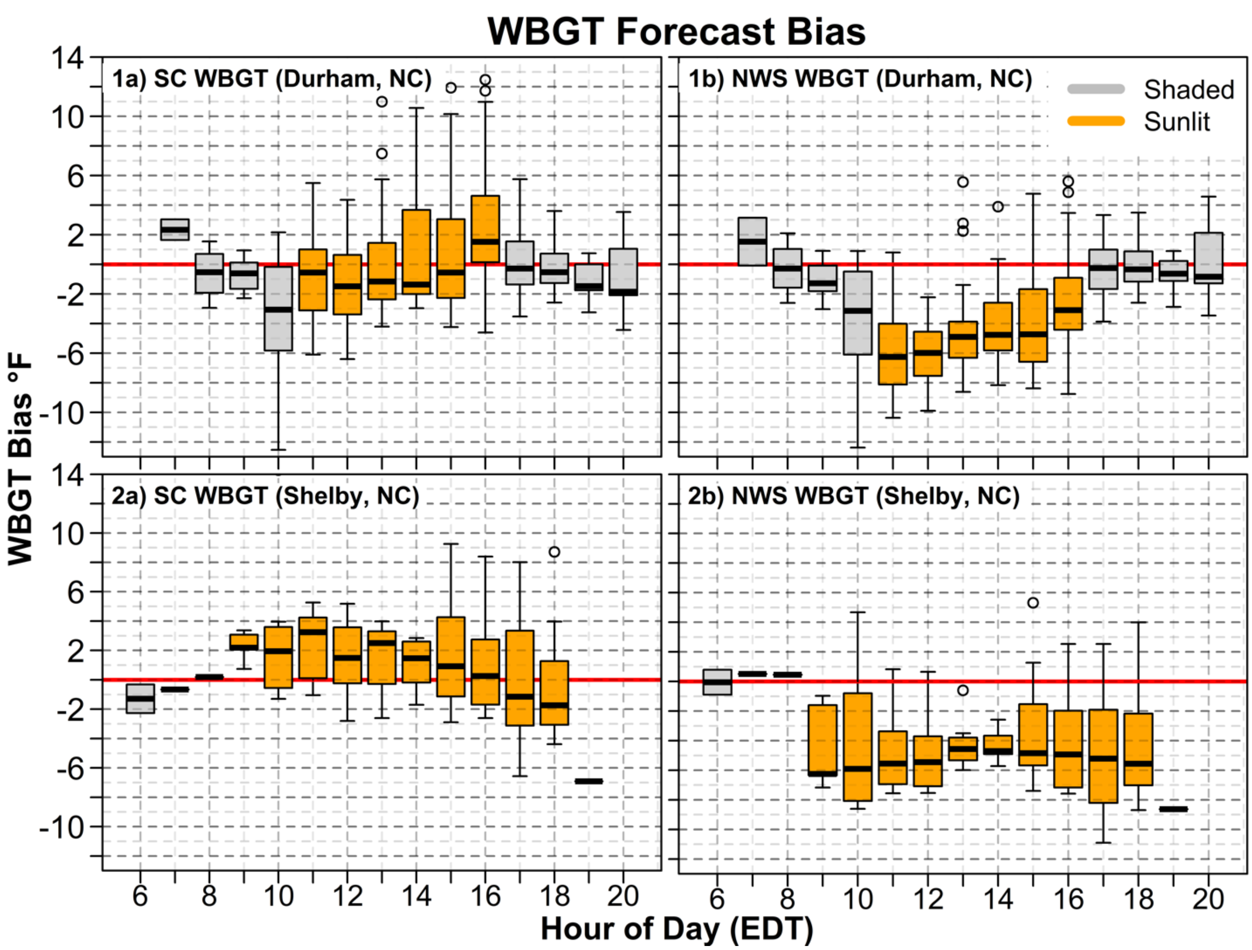

*Figure 4:*1-Day WBGT forecast bias by hour of day for Durham NC (1a–b) and Shelby, NC (2a–b), with shaded observations compared to shaded SC WBGT.

The average diurnal pattern of bias for both forecast methods are similar at the two locations (Figure 4). During the hours of 1100–1600, the SC WBGT forecast bias is 1–2°F, with a slight cool bias in Durham, NC (Figure 4, 1a) and a slight warm bias in Shelby, NC (Figure 4, 2a). Comparatively, the NWS Experimental WBGT bias is significantly greater, with a 4–6°F WBGT cool bias at both locations. The bias at 10 am at the Durham, NC site had higher variability due to inconsistent shading of the instruments at this hour (Figures 4, 1a).

The difference in the SC WBGT bias between the two locations can be attributed to differences in microclimate between the two sites: Durham is more sheltered than Shelby, NC. Since the NDFD wind speed forecast is tailored for open landscapes (e.g., airports), this results in forecasted wind speeds and WBGT being too high and too cool, respectively, in more sheltered landscapes (e.g., cities and wooded areas).

3.2. Estimated WBGT at ASOS/AWOS Stations

The two WBGT forecasts were also compared at 837 ASOS/AWOS weather stations across the CONUS. The pattern of the NWS WBGT being significantly cooler than the SC WBGT is also readily apparent in comparisons against ASOS/AWOS observations (Figure 5). The SC WBGT displays a slight positive bias, generally less than 1°F on average throughout the day, with the median bias maximized at 1300 hours (Figure 5, a). The NWS experimental WBGT forecast, on the other hand, shows a markedly greater 4°F cool bias during the daytime hours, with the median bias maximized in the morning hours between 08:00–10:00 when there is a cool bias of 5°F. This morning bias coincides with the diurnal period in which the largest difference is observed between the two forecast methods (Figure 5, b).

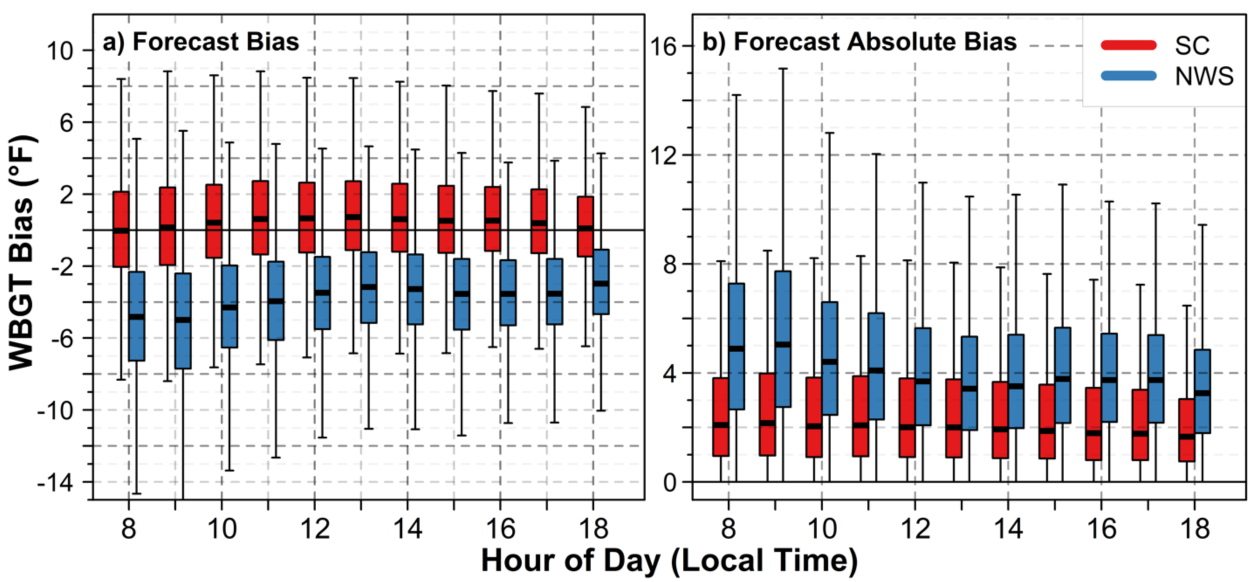

Figure 5: Difference (a) and absolute difference (b) between the two forecasts and the ASOS/AWOS estimated WBGT by hour of day (Forecast minus AWOS/ASOS WBGT).

In addition to the diurnal pattern of bias in the two WBGT forecasts, the spatiality of bias in forecasting daily maximum WBGT was plotted on maps across the CONUS (Figures 6–7). Regional differences are identified in the NWS WBGT forecast (Figure 7), with many stations in the Southeast, Mid-Atlantic, and Inter-Mountain West, showing a significant cool forecast bias. The SC WBGT forecast does not show significant regional biases (Figure 6). The cool bias in the NWS WBGT forecast is minimized across the northern Plains, extending south to Texas (Figure 7). Due to the sensitivity of WBGT to changes in wind speeds when winds are less than 2 mph, the climatologically faster wind speeds of this region relative to the Southeastern US may partially explain this pattern. Lastly, there are several stations with significantly higher magnitudes of bias relative to neighboring stations, suggesting that their microclimate is distinct (e.g., more or less sheltered, moist, etc.).

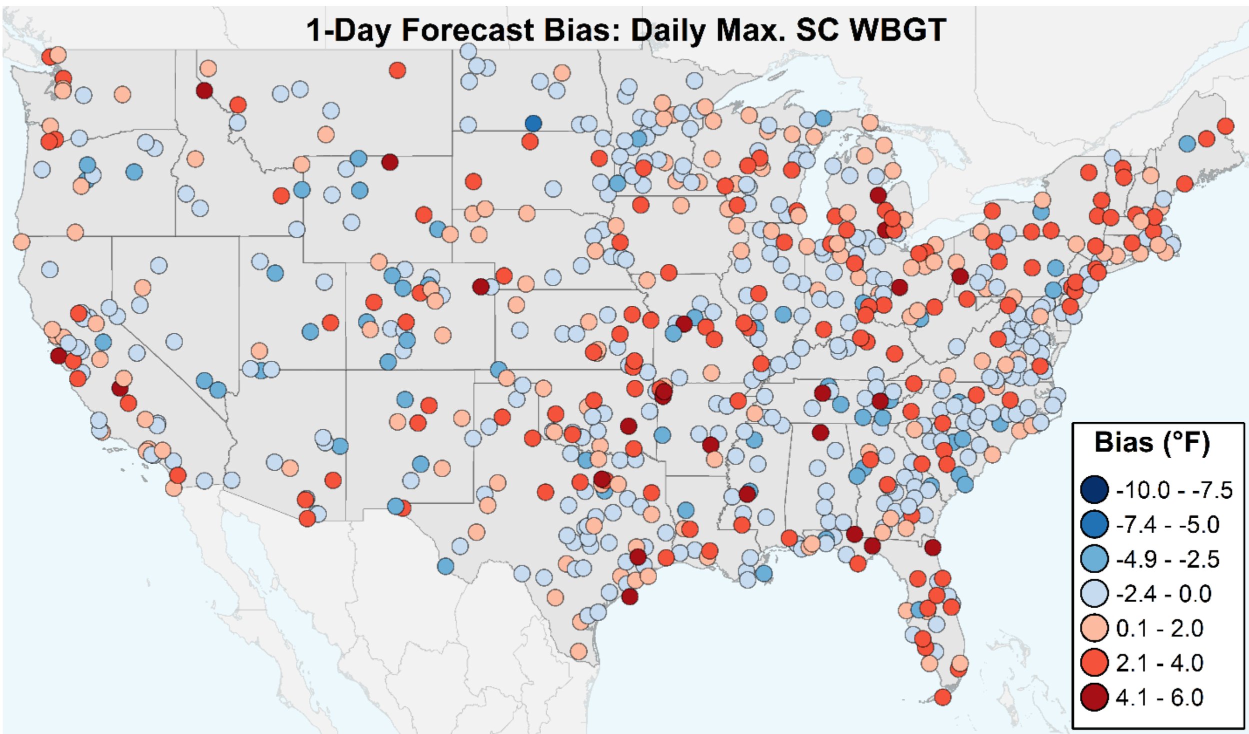

Figure 6: SC WBGT bias (°F) at ASOS/AWOS stations across CONUS (daily maximum forecasted WBGT minus daily maximum observed WBGT).

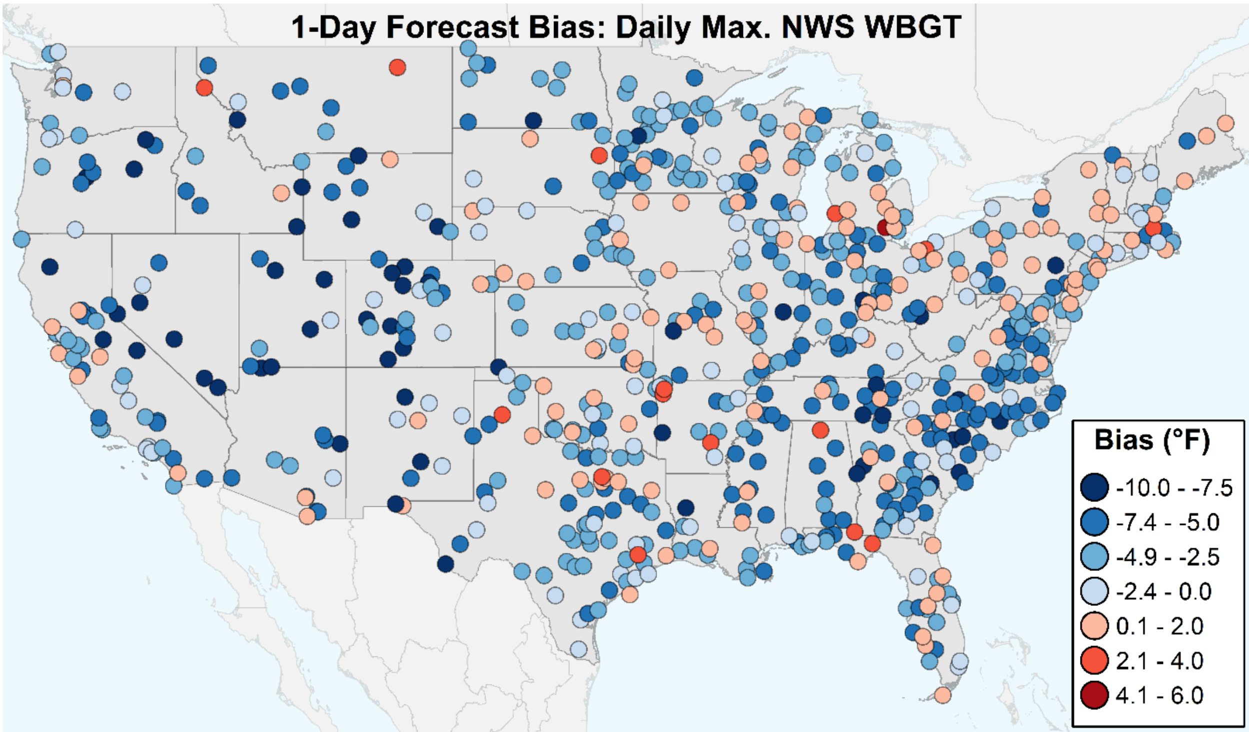

Figure 7: NWS WBGT bias (°F) at ASOS/AWOS stations across CONUS (daily maximum forecasted WBGT minus daily maximum observed WBGT).

4. Conclusion

In this paper, we compared two one-day WBGT forecast products, one from the NWS and the second from a web-based tool developed by SERCC and CISA. These forecasts were compared against 1) measurements from a WBGT meter at two locations in North Carolina and 2) estimated WBGT at ASOS/AWOS stations across the CONUS.

The following biases and patterns were identified for each forecast method:

1. SERCC/CISA WBGT
   - Compared to observed WBGT, the bias is 1–2°F on average under sunshine and varying degrees of clouds and 0.5–1°F in the shade.
   - At ASOS/AWOS stations, the bias is less than 1°F on average across all stations through the daytime hours, maximized at 1300 hours with a median bias of 0.73°F. Spatially, the bias in forecasting the daily maximum WBGT is within -3–2°F across the CONUS, with no significant regional variability.
     - With solar radiation highest at 1300 hours, errors in estimating solar radiation from ASOS/AWOS cloud observations and NDFD forecast cloud cover have a larger effect than at other times of day, leading to greater forecast bias.
     - The spatial discontinuity in bias, both in magnitude and direction (cool vs. warm) is hypothesized to be driven by microclimatic influences, especially surface roughness. While surface roughness is incorporated into the

downscaling of wind speeds from 10 meters to 2 meters, there is much local scale variability in roughness due to variations in the land cover character.

2. NWS WBGT
   - Compared to observed WBGT, there is a cool bias of 4–6°F on average throughout daytime hours. However, when the WBGT meter was shaded, this bias is minimized.
     - This bias can be explained by the NWS WBGT using wind speeds at 10 meters instead of 2 meters, since WBGT is extremely sensitive to small variations in wind speed (Figure 1). In addition, accurate estimation of the NWB is critical as it constitutes 70% of WBGT (Eq. 1). Since the psychrometric wet bulb is shielded from radiation while the NWB is not, substituting the NWB with the psychrometric leads to large underestimations of WBGT. This bias is seen here by the NWS WBGT having significantly higher accuracy while the instruments were shaded relative to when they were in the sun.
   - At ASOS/AWOS stations, there is an average cool bias of 4°F during daytime hours, with median bias maximized in the morning (08:00–10:00) at 5°F.
     - The morning bias is likely due to forecast challenges related to early morning clouds and fog. In addition, prior to sufficient surface heating for mixing, microclimatic effects on wind speed are especially important to account for by downscaling since surface roughness can greatly reduce the slower wind speeds of the morning.
   - WBGT is consistently under forecasted, with a cool bias maximized in the Southeastern states and Inter-Mountain West. The bias at the majority of stations is no less than 3.3°F too cool and varies to as much as 6–10°F cooler than estimated WBGT.
     - The larger bias across the Southeastern states can be attributed to the climatologically lower wind speeds of the region. Without downscaling wind speeds and using the psychrometric wet bulb temperature, WBGT in low wind environments will be grossly underestimated. This issue and subsequent bias is less apparent in windier regions, such as the Midwest and Plains, since the NWB and psychrometric wet bulb temperature converge when wind speeds are greater than 7 mph (Kopec, 1977).
     - The high variability of bias can be explained by the large impact of microclimate on WBGT, through both local sources of humidity and influences on wind speed.

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Appendix A

To downscale wind speeds in both the NDFD forecast grid and at ASOS/AWOS stations from 10 meters to 2 meters, the following logarithmic function was applied:

$$\text{(A1)} \qquad U_z = U_r\left(\frac{Z}{Z_r}\right)^p,$$

where Uz is the mean wind speed at height Z above ground, Ur is the mean wind speed at the reference height Zr, and p is the power-law exponent (US EPA, 2000). The power-law exponent was determined based on Pasquil-Gifford Stability classes, which were determined using the Solar Radiation Delta-T (SRDT) method. SRDT uses observed solar radiation during the day and low-level vertical temperature difference at night to classify atmospheric stability (US EPA, 2000).

Appendix B

Estimating WBGT requires solar radiation values. However, the NDFD forecast grid only contains forecast cloud cover percentage. To convert this percentage to a solar radiation value, first the clear-sky direct radiation value was calculated using the following function:

$$\text{(B1)} \qquad R_0 = 990 * \sin(\emptyset - 30),$$

where $\emptyset$ is solar elevation angle. Next, the clear-sky direct radiation was modified by the forecast percentage cloud cover using the following function:

$$\text{(B2)} \qquad R0 * (1 - 0.75n^{3.4}),$$

where n is the cloud cover fraction (0.0–1.0) (Solar Radiation Cloud Cover Adjustment Calculator).

Similarly to the NDFD, solar radiation values had to be estimated for ASOS/AWOS observations since these stations do not measure solar radiation directly, but instead measure cloud cover at multiple levels: clear (0–5%], few (5–10%], scattered (25–50%], broken (50–87%], and overcast (87–100%] (National Oceanic and Atmospheric Administration, Department of Defense, Federal Aviation Administration, & United States Navy, 1998).

For each level with measured cloud amounts, the reported amount was converted to percentage cloud cover using the maximum value from each range stated above: clear (5%), few (10%), scattered (50%), broken (87%), and overcast (100%). To derive a single percentage cloud cover value for each observation, the cloud level with the maximum amount of reported cloud cover was used, e.g. if an observation reported "few" at cloud level 1 and "scattered" at cloud level 2, scattered (50%) was the cloud amount used to calculate solar radiation for that observation. This cloud cover amount was then used in equation B2 to modify the clear-sky direct radiation value derived using equation B1.