NDFD Wet Bulb Globe Temperature Algorithm and Software Design

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Origins

In April 2019, the National Weather Service (NWS) Meteorological Development Laboratory (MDL) was asked by the NWS Analyze, Forecast and Support Office to generate Wet Bulb Globe Temperature (WBGT) forecasts experimentally for the National Digital Forecast Database (NDFD). The initial request was to generate forecasts for the CONUS domain only, but a subsequent request expanded this to include experimental forecasts for Hawaii, Guam and Puerto Rico. Some NWS Weather Forecast Offices (e.g., WFO Tulsa, TSA) had already been generating WBGT forecasts locally and posting images on their websites, or supporting web-based interactive tools that compute WBGT. The requirement given MDL was to generate experimental forecasts of WBGT on a national scale using operational NDFD forecasts as input.

Methodology

The scientific basis for generating forecasts of WBGT from weather element forecasts routinely produced by WFOs for NDFD is described by Dimiceli and Piltz (2013). The authors employed an algorithm from the Occupational Safety and Health Administration to compute WBGT:

$$WBGT = 0.7NWB + 0.2BGT + 0.1DB$$

Where NWB = Natural Wet Bulb Temperature

BGT = Black Globe Temperature

DB = Dry Bulb Temperature

The forecast for the natural wet bulb temperature is computed from NDFD forecast data and equations that estimate incoming solar radiation flux. Dry bulb temperature comes from NDFD 2-meter surface temperature forecasts. Additionally, the authors derived an equation by which the black globe temperature forecast can be estimated from standard NDFD forecast data and estimated incoming solar radiation.

Tulsa Smart Tool

The starting point for the NDFD WBGT software application was a Python Smart Tool written for the Graphical Forecast Editor (GFE) which is used to prepare grids for NDFD. The tool computes daily maximum WBGT values for the TSA county warning area from grids of parameters available within the GFE. Solar radiation flux values are calculated by a Python module that contains solar physics algorithms. Due to the relatively small geographical area covered by TSA, some parameters in the calculations were considered to be constant across the domain (e.g., sunrise/sunset times, zenith angle for a single central latitude/longitude). The maximum forecast WBGT value for each day is computed using the Dimiceli and Piltz equation described above. In addition to the solar radiation flux, forecaster-edited grids of temperature, dew point temperature, wind speed and sky coverage as well as model guidance grids of surface pressure are inputs to the tool.

Significant changes were made to adapt the TSA tool for national use with NDFD. One of these was to modify the TSA algorithm to compute hourly forecasts of WBGT, as opposed to one daily maximum value for each grid point. All of the input parameters (T, Td, Wind, etc) are available and issued at hourly resolution in NDFD. However, this required the calculation of solar radiation flux values at each hour as opposed to computing just one daily maximum value, as in the TSA tool. Other changes were necessitated by the much larger geographical domain of the NDFD CONUS grids. Input to the solar radiation flux calculations which could be considered as constants across a relatively small WFO domain cannot be treated as such over the entire CONUS. Thus, values such as time of sunrise/sunset, time zone, zenith angle, and time of solar noon are computed uniquely for every NDFD grid point. Finally, the TSA tool had to be ported from Python to C++, the predominant programming language used by NDFD software, and in which all the NDFD data I/O APIs are written. Additionally, since Python is an interpreted programming language, it does not have the level of computational performance that a compiled language such as C++ has when executing many mathematical calculations over very large datasets. NDFD issues new forecasts twice per hour, so software execution speed needs to be optimized to a very high degree.

The NDFD WBGT Application

The first experimental version of the NDFD WBGT application went online in the summer of 2019. The biggest challenge in the porting process was to adjust for the larger geographic domains and increased temporal resolution of the output. The geographic domain (CONUS, Hawaii, Guam and Puerto Rico) and the forecast period (early, extended) are passed in as arguments and the code initially computes a list of valid times for which WBGT forecasts will be calculated. For each 24-hour day of the specified forecast period, the following data are computed at every grid point of the specified domain:

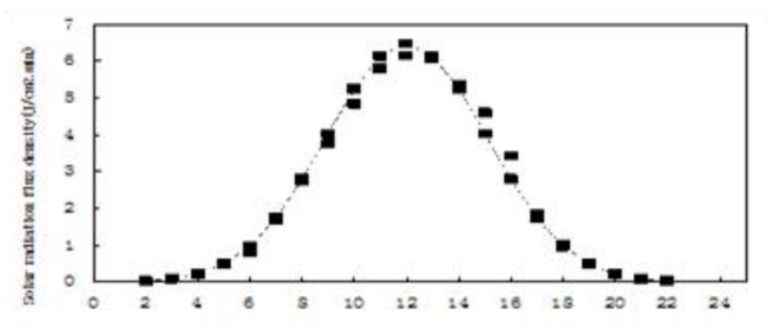
- The local time of both sunrise and sunset
- The length of time of daylight
- The local time of solar noon
- The maximum solar radiation flux value

Maximum potential solar radiation flux for each grid point is computed as a function of latitude and day of the year. The other data are needed in the calculation of gridded solar radiation flux values for each hour, which are then used to compute the hourly WBGT forecasts.

Estimating Hourly Solar Radiation Flux in NDFD

Although some NWS forecast models provide gridded guidance for downward solar flux, the NDFD application estimates hourly solar flux from the daily maximum value (assumed to occur at solar noon) and a curve which defines the daily variation of solar radiation incident on the ground surface. The decision was made to compute the hourly solar flux values, as opposed to using NWS model guidance, in order to avoid introducing new dependencies on data external to the NDFD Central Server System. There exists a significant amount of data management overhead whenever acquiring new datasets (usually from the NOAA Operational Model Archive and Data Distribution System, NOMADS) within NDFD. There is also the issue that model guidance generally does not provide hourly values, so additional temporal interpolation of these data would be required, regardless.

The methodology by which hourly solar flux values are computed from the maximum daily values assumes that the potential maximum for the day occurs at solar noon. The daily variation of incoming solar radiation on a horizontal surface can be described by a Gaussian curve with the peak intensity at solar noon (Guo, 2017).



Diurnal change model of solar radiation flux density incident on the forest canopy

Based on the time of day of each forecast, the NDFD algorithm estimates the location on the curve and using interpolative methods, calculates a potential solar flux value for that hour.

NDFD Forecast Mosaics in WBGT Computation

Mosaics of the following standard NDFD forecast elements are required as input to compute the components of the WBGT algorithm given by Dimiceli and Piltz

- Surface air temperature (T)

- Surface Dew Point Temperature (Td)
- Percentage of Total Sky Cover (Sky)
- Surface (2 meter) Wind Speed (WSpd)

NDFD forecasts of these elements are available at hourly resolution from 1-36 hours, 3-hour resolution to 00Z Day 4, and at 6-hour resolution from Day 4 through Day 7.

With a single exception, NDFD forecasts are used as input without any adjustments, other than unit conversion. The one exception is Wind Speed. NDFD Wind Speed forecasts are valid at 10m height. WBGT is computed at 2 meters, the same height as standard air temperature. To downscale the 10m winds to 2m, the NDFD application applies the Log Law to the 10 m wind speeds. The Log Law is specified as:

$$v \approx v_{\text{ref}} \cdot \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{\text{ref}}}{z_0}\right)}$$

Where:

- V = velocity to be calculated at height z
- Z = height above ground level for velocity v
- V_{ref} = known velocity at height z_{ref}
- Z_{ref} = reference height where v_{ref} is known
- Z_0 = roughness length in the current wind direction

High resolution surface roughness length grids for the CONUS as well as for the other NDFD domains were derived from USGS MODIS 15 arcsecond Global Land Cover data set. The land cover data was translated to roughness length values using the table given in Appendix A.

Other Supporting Data

The algorithm to compute WBGT requires some additional data, including surface air pressure. Mean sea level pressure guidance is obtained from the National Blend of Models (NBM) and reduced to station pressure using fine-resolution NDFD terrain data. NBM forecast guidance is already available on the NDFD Central Server to fill in holes for missing WFO forecasts. One of the components in the calculation of black globe temperature is surface albedo. In the TSA Smart Tool, surface albedo was specified as a constant (0.2, grassy surfaces). Since albedo values vary widely across the CONUS, surface albedo, obtained from NOAA17 AVHRR3 satellite data is used in NDFD as input to obtain approximate albedo values at each grid point.

Another input to the algorithm is cosine of the zenith angle (Z). The TSA tool fixed cosine(Z) as a constant. The NDFD application computes a dynamic cosine(Z) which is dependent upon grid point latitude and the date/time of the forecast hour. To compute the cosine of the zenith angle, a Solar Position and Intensity module (SOLPOS) was linked to the NDFD application. SOLPOS was written by the Department of Energy's National Renewable Energy Laboratory (https://www.nrel.gov/grid/solar-resource/solpos.html).

Recent Updates and Improvements

Not long after the first NDFD WBGT forecasts began production, the application source code was shared with members of the public and scientific community interested in how NDFD WBGT forecasts were being generated. Blaine Thomas, a meteorologist working at the U.S. Army White Sands Missile Range in New Mexico provided valuable feedback on the code. He identified some errors in the original TSA algorithms that passed through into the NDFD application and suggested algorithm changes based on observational records of WBGT across various locations. Below is a list of updates and departures from the initial NDFD software (and in some cases from the Dimiceli and Piltz algorithms) based on that feedback:

- Direct beam versus diffuse solar radiation – Initially the proportion of direct versus diffuse was computed such that the diffuse portion was equal to the total sky coverage (between 0.0 and 1.0) and the direct beam was calculated as 1.0 – diffuse. At times with very low cloud cover, this would translate to very high direct beam values, and, suggested by observational data, lower black globe temperatures than expected. Based on this, the code was modified to cap the direct beam proportion at 0.75.
- Convective heat transfer coefficient – An important component in the calculation of black globe temperature is the convective heat transfer coefficient (H). The TSA tool set H to a constant value of 0.315. It was found that this value results in black globe temperatures that are too low. Based on observations at White Sands and other sites, it was determined that H should be treated as a variable. In the NDFD application, during daylight hours, the value is set to 0.228, while at night, the value is set to zero.
- Adjustment of solar flux using cloud cover – The initial version of NDFD application only used Sky cover in computing the direct versus diffuse beam portions of solar radiation. Observations suggest that lack of Sky cover influence on the computed solar flux values likely will lead to overestimates in the black globe temperature and natural wet bulb temperatures. To adjust the solar flux value based on Sky cover, a formula by Kasten and Czeplak (1980) is applied:

  $$R = R_0 \, (1 - 0.75n^{3.4})$$

  Where
  R = solar flux adjusted for Sky cover
  R_0 = maximum possible solar flux (clear sky)
  n = Sky cover (0.0-1.0)

R (the adjusted solar flux) replaced R_0 in the calculation of black globe temperature and natural wet bulb temperature.

- Calculation of the natural wet bulb temperature – The TSA tool, and the original version of the NDFD application used the following regression equation to estimate the natural wet bulb temperature component of WBGT:

$$T_{nwb} = T_w + 0.0021S - 0.43u + 1.93$$

Where
T_{nwb} = the natural wet bulb temperature
T_w = the thermodynamic wet bulb temperature
S = Solar radiation flux
u = wind speed (m/s)

Natural wet bulb temperatures estimated by this method were found to be significantly lower than measured observations. To address these errors, and since NWB is the largest component of the WBGT calculation, a new regression equation was implemented that adds the wet bulb depression (T_{wd}):

$$T_{nwb} = T_w + 0.001651S - 0.09555u + 0.13235T_{wd} + 0.20249$$

Observations have shown that this new method reduces NWB average error and bias significantly over a range of different observation locations.

Future Work and Conclusions

There have been many recent updates to the application. Still more analysis is needed to determine the level of accuracy and what sorts of biases may exist in the current version. However, there are very few observations of WBGT across the country at this time. There is a long term record of WBGT observations at five US Army test ranges and additional records of black globe temperature available from the North Carolina ECONet and the Hennepin County (MN) Mesonet (Thomas, 2020). One push to get more observational data is being made by the Range Commanders Council Meteorology Group (RCC-MG) of the US Army. In 2021, the group began a data collection campaign of WBGT observations at numerous sites across the country, in a variety of different climate regimes. This activity occurred during the warm season and ended in October 2021. Clark and Konrad (2020) performed an accuracy assessment between the NDFD WBGT forecasts and those produced by a web-based tool they developed for stations in the North Carolina and Virginia region. Unfortunately this analysis was done on data produced by an early version of the NDFD software and as such included forecast data with a cold bias.

Potential updates to the NDFD WBGT application may include bias correction based on climate regimes. It has been shown by Thomas that significant differences in the calculation of the natural wet bulb temperatures occur between dry and humid climates. Adjustments similar to that described above to the natural wet bulb regression could be targeted for these different climate types in a future version.

Appendix A: Land Use to Roughness Length Translation Table

Name	MODIS Category	Roughness Length (m)
Water	0	0.002
Evergreen Needle	1	1.5
Evergreen Broad	2	1.5
Deciduous Needle	3	1.5
Deciduous Broad	4	1.5
Mixed Forest	5	1.5
Closed Shrub	6	0.1
Open Shrub	7	0.1
Woody Savanna	8	1.5
Savanna	9	0.5
Grassland	10	0.0002
Permanent Wetland	11	0.2
Cropland	12	0.1
Urban	13	1.0
Natural Vegetation	14	0.3
Snow/Ice	15	0.0002
Barren	16	0.0002