Methodology for the Union of Concerned Scientists' Analysis of Extreme Temperature Impacts on Children and the Electricity Grid

Data Approach

Localized Constructed Analogs (LOCA) statistically downscaled daily maximum temperature, minimum temperature and minimum relative humidity were downloaded from Cal-Adapt (Pierce et al. 2018) for each model that contained all three variables (ACCCESS1-0, CanESM2, CCSM4, CNRM-CM5, GFDL-CM3, HadGEM2-CC, HadGEM2-ES, MIROC5) for three scenarios. Data was acquired for the entire historic and future predicted periods (midcentury (2035-2064) and late century (2070-2099)). Data was subsetted spatially by keeping only data points in and adjacent to the San Joaquin Valley. Further the data was temporally decimated by dropping all data in the year 2100 to ensure a complete and uniform set of data for the period 2006 to 2099. The emission scenarios are RCP 4.5, RCP 8.5, and RCP 4.5 for 2045-2065 (Paris 2°C).

Statistics Used for Wet Bulb Globe Temperature (WBGT)

This study presents statistics showing the variability and spread between individual models. For each scenario and period both raw counts above health-related thresholds and anomalies relative to the historical period were calculated. In each period the average[1] number of exceedances in a period was calculated for each model (Figure 1). The mean, median, IQR (difference between 75th and 25th percentiles), 25th and 75th percentiles were calculated across all the models for cells of interest based on the point location of cities or substations.

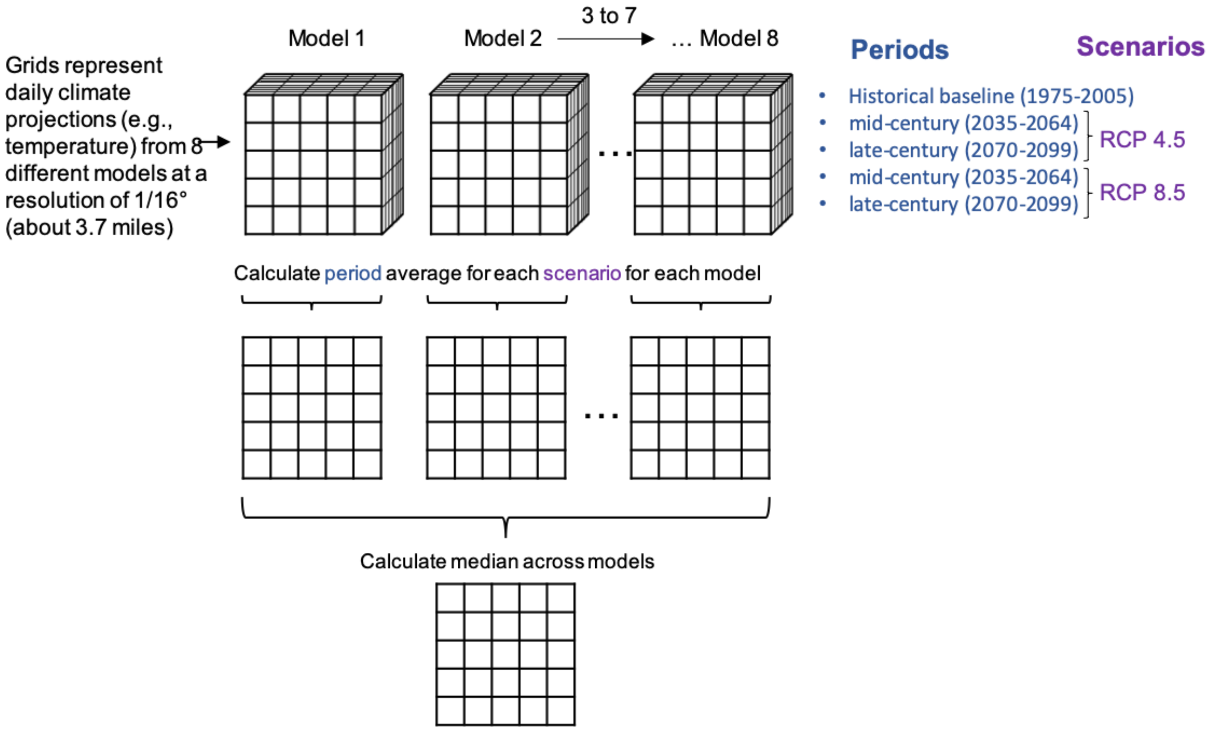

Figure 1. General methodology diagram. The process was repeated individually for each period and scenario.

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Wet Bulb Globe Temperature Index Calculation Methodology

The WGBT index is a mathematical estimation of the combined heating effects of temperature, moisture, wind and solar radiation upon the human body. The WGBT is calculated as a weighted average of dry bulb (ambient temperature), black globe (solar radiation), and wet bulb (humidity) (Yaglou and Minard, 1957) (Equation 1).

$$WBGT = 0.7 * \mathrm{Tw} + 0.2 * \mathrm{Tg} + 0.1 * \mathrm{Ta} \tag{1}$$

where Tw is the wet bulb temperature, Tg is the globe thermometer temperature, and Ta is the air temperature. Tw represents a potential cooling of human skin via evaporation – a function of atmospheric moisture content; Tg represents the radiative heating of the sun and surrounding landscape upon the body – a function of solar radiation, air temperature, and wind speed, and Ta represents the potential for direct heat exchange via conduction with the surrounding air – a function of air temperature alone.

Wet bulb temperature was calculated based on air temperature and relative humidity according to Equation 2 developed by Stull et al. (2011), where RH% is the percentage of relative humidity.

$$\begin{aligned} Tw = Ta \operatorname{atan}\left[0.151997\,(RH\% + 8.313659)^{\frac{1}{2}}\right] + \operatorname{atan}(Ta + RH\%) - \operatorname{atan}(RH\% - 1.676331) \\ + 0.00391838(RH\%)^{\frac{3}{2}} \operatorname{atan}(0.023101\mathrm{RH\%}) - 4.686035 \end{aligned} \tag{2}$$

Historically, efforts were made to simplify the calculation of WGBT, with a particular focus on being able to re-create WBGT values using parameters readily available from typical weather stations (i.e. temperature, dewpoint, wind speed, and cloud cover). These efforts made necessary assumptions and estimations to replicate a complex system from more simple predictors. Often, results were predicated on typical conditions for a given regional climate. For example, simplification efforts in the southeastern United States were commonly made with assumptions about high values of relative humidity which are inappropriate for the dry, semi-arid conditions experienced in the San Joaquin Valley during the hottest months. For these reasons a rigorous and robust calculation of the components of the WGBT is necessary.

WBGT calculations required four inputs: temperature, relative humidity, wind speed and radiation. Our calculation approach is based on Original FORTRAN code by James C. Liljegren, which was translated to R in the *heatstress* package available on CRAN by Ana Casanueva. It represents an improvement upon open-source code repositories, by simulating the radiative effects at peak heating times (between 3 and 4pm in the afternoon, depending on time of year) rather than assuming peak heating at noon, and by providing a varying wind speed based on time of year (rather than a set wind speed). Liljegren's method has been shown to be highly accurate within 1C of measured WBGT values in diverse climates. Kjellstrom et al compared WBGT models, and found Liljegren's to be the best. However, this approach introduces some assumptions that may be considered conservative (i.e. under-estimating WBGT), as we explain below.

Temperatures used were daily historical or projected maximum temperature values from LOCA. Relative humidity values were taken to be the minimum daily relative humidity values from LOCA dataset. We note that the minimum relative humidity value is *likely* to be at or near the period of maximum temperature, but on some days (particularly those early in the year when evapotranspiration is high) this may represent an underestimation of relative humidity, leading to lower values of WBGT. Using the projected daily maximum temperature may result in more conservative estimates, since another paper on the temporal pattern of WBGTs found the highest values occurred around noon due to high solar radiation.

Radiation was explicitly calculated for each day of the year based on historical (climatological) normal values. Using hourly observations of cloud cover (from ISD database for Fresno Yosemite Airport) average cloud cover at the hour of max temperature was derived for each day of the year. This cloud fraction (typically 20% to 25% in peak summer months) is in turn multiplied by the historical fraction of the clouds that are opaque (31.9%) to come up an estimated cloud effect rate for reducing solar radiation. This cloud cover reduction value was then multiplied by the maximum potential solar radiation (as a function of day of year, and hour of maximum temperature for that day of the year) to produce a climatological solar insolation to pass to the WGBT. Values were calculated for Fresno and applied to all grid-cells in the SJV. This approach is conservative on two fronts: (1) it is possible that on any given hot day cloud cover could be less than climatology and (2) radiation is highest near noon, which typically, is not the hottest part of the day. Some days the WBGT could be higher when radiation is higher but before the peak temperature is reached (3pm to 5pm, depending on time of year).

The climatological wind speed for each day of the year at Fresno Yosemite Airport for the hour of the hottest temperature was calculated and is supplied to the WGBT calculations. Power law was applied to winds observed at 10m to a height representative of human bodies (2m). The exponent used in the transform (0.2) was chosen to be reflective of representative conditions for the SJV and during the warm season. Wind data provided may represent a conservative approach: (1) by looking at 2m, rather than 1.5m for impacts on the human body and (2) would not be reflective of periods of calm or lighter winds during any given hour, which would cause the WBGT to increase. Because we held speed and solar radiation constant for future WBGT value calculations, given the high level of uncertainty in projecting how they change due to global warming, we are not fully capturing all of the potential changes in the WBGT.

We note that in the historical period, cloud cover fraction and wind speed increased during periods of extreme heat, relative to the climatology. This may offset some of the underestimating factors introduced in the methods.

A number of constants are required for the WBGT algorithm to function, we used the following reference values following after Liljegren (2008): proportion of direct to diffuse radiation (0.8) and an air pressure 1010 hPa. A fixed air pressure is likely reasonable for the major cities of the San Joaquin Valley, as the cities are very near to sea level, ranging in elevation from approximately 10 feet in Stockton to just over 400 feet in Bakersfield. For allowed relaxation sensitivities for globe temperature calculations in the algorithm we used an optimization tolerance of 0.1, and for wet bulb temperature calculations we use an optimization tolerance of 0.01.

Liljegren JC, Carhart R, Lawday P, Tschopp S, Sharp R (2008) Modeling wet bulb globe temperature using standard meteorological measurements. J Occup Environ Hyg 5, 645–55

Minimum Nighttime Temperatures Calculation Methodology using Cal-Adapt

The minimum temperature LOCA dataset from Cal-Adapt was considered as the Nighttime temperature. Code to extract the minimum value per year in each period (1975-2005 for historical, and 2035-2064 or 2070-2099 for mid- or late-century) was developed using Python programming language. We then calculated the average minimum temperature in each period. This process was repeated for each model, and the presented values represent the median across models for each period and scenario. Specific values for cities were extracted considering the grid cell corresponding to the center point of cities limits.

Median Number of Days above Thresholds Calculation Methodology

Code to count the number of days per year that temperatures go above a certain threshold (e.g., 109°F or 86°F) was developed using Python programming language. We then calculate the average numbers of days per year exceeding the threshold in each period. This process was repeated for each model and the presented maps represent the median number of days across models for each period and scenario (Figure 1).

The LOCA dataset includes maximum and minimum daily temperatures. For average temperature we used a simple average among these two ($\frac{Tmax + Tmin}{2}$).

The transmission line GIS dataset was downloaded from the California Energy Commission website. City information was a TIGER2016 Places layer.

Using Python, we calculated the total number of days in each grid cell that would exceed a threshold, for each scenario and each period. For the Rapid Action, Late-Century, we used RCP 4.5 and the timeframe of 2045-2065, since that roughly approximates a 2°C increase in temperature. The transmission lines were assessed using ArcGIS to determine the highest median number of days along a line. Initially, it was done manually examining the max number of days per grid along the line for the no action, mid-century analysis. For future analyses, it will be automated. The maximum number of days per city was also assessed manually by choosing the center-most grid for each city of interest.

The substation GIS dataset was downloaded from the California Energy Commission website. City information was a TIGER2016 Places layer. We created a heat map of the total number of days in each grid cell that would exceed the 24-hour average temperature of 86°F, for each scenario and each timeframe. Using ArcGIS, we determined how many substations and cities would experience a median of more than a month’s worth of days above this temperature.

Caveats and Limitations of Our Analysis

Our analysis has several caveats and limitations.

General

- Our analysis does not consider technology changes, adaptation or future changes in acclimatization. Adaptive measures, such as air-conditioning, and acclimatization can help reduce heat exposure and vulnerability to heat-related illnesses and death. There are, however, limits to the human ability to adapt to heat. Similarly, we do not attempt to project how the electric grid operation, planning, and technologies, and school facilities adapt between now and mid-century.

WBGT

- There are limits to the used of WBGT as a metric of heat stress. We chose to employ the WBGT index since it is the most commonly used index for athletic and occupational purposes, and it accounts for solar radiation and wind. It was designed for rigorous outdoor exertion in sunlight in hot, humid conditions; it may be less informative in hot, dry and hot, very humid climates or when winds are low. This metric also requires assumptions about the level of activity and is susceptible to measurement and calibration errors. Equipment to measure WBGT in the field can be expensive, so some organizations support using heat index if WBGT information is not available. However, heat index and WBGT cannot be directly compared since they use different calculations and factors to determine heat stress. The heat stress index has limitations as well for measuring exertional heat stress, as previously mentioned. Both indices were developed specifically for adults, not children, and for use in hot, humid areas, not hot, dry conditions.* More research is needed to identify the most appropriate heat stress metric for youth under hot, dry conditions like those normally found in the Valley. There is no perfect heat stress metric, but existing ones can help inform heat modification decisions.
- The WBGT index values may be an underestimate. We held wind and solar radiation constant, based on the average values occurring on each calendar day during the historical period. Changes in these factors could increase or decrease the WBGT. There is a high level of uncertainty in projecting these changes due to global warming at a local level. In addition, the Fourth California Climate Assessment projected very small reductions in wind speed and no change in solar radiation for the Valley by the end of the century. We also used solar radiation levels that corresponded to the time of daily maximum value, which may have resulted in lower WBGT values. The maximum temperature was the only temperature data available for our analysis.
- Our analysis does not consider population growth or changes in land use patterns. We also do not account for the influence of the urban heat island effect or the temperature increase of common heat-retaining surface materials where children play (e.g., asphalt, dark rubber,

concrete and artificial turf) to dangerous levels to the touch. Hotter surfaces can raise air temperatures near the surface, which is closer to children than adults. Our results may therefore be underestimates. We did not account for the urban heat island effect that could intensify the heat levels youth experience. Nor did we consider their closer proximity to hot surfaces on playgrounds, school lots, and athletic fields than adults. More research is needed to understand if and to what degree these latter surfaces heat the air directly above them.

Electricity grid

- We did not examine the cooling influence of wind on transmission and distribution lines since we focused on ambient temperature. If winds are sufficient, they can reduce the operating temperature of a line and the number of days that they have the potential to exceed maximum operating temperatures. The lines are also rated conservatively using the worst-case conditions (high ambient temperature and low wind). If ratings are updated to reflect actual ambient conditions, operators may find additional capacity.
- We did not evaluate the impact of vegetation clearance practices under transmission lines, which could influence the allowable level of line sag.

*J. Vanos, personal communication, 2019