**Trends and Disparities of Dangerous Humid Heat Exposure Among Incarcerated People in the United States**

**Supplementary Information**

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**Incarceration Data**

We use carceral facility (referring to prisons, jails, and other carceral facilities) locational boundaries (polygon latitudinal and latitudinal coordinates) and population data from the Homeland Infrastructure Foundation-Level Data (HIFLD), produced by the United States Department of Homeland Security.1 We included 4,078 operational and populated prisons, jails, and carceral facilities including ICE detention centers, juvenile or geriatric facilities, and halfway houses in the continental United States in our analysis. Of these, there were 232 federal, 1,606 state, 2,142 county, and 73 local facilities. Twenty-five (0.6% of total) carceral facilities did not fall into these categories and were classed as ‘other’. Texas had the single most prisons and jails (411 or 10.1% of total). In total, in 2018, there were 2,032,647 incarcerated people in included prisons and jails, of which 187,847 were in federal, 1,202,930 in state, 604,699 in county, 25,267 in local, and 11,904 in other. Texas was also the state with the single most incarcerated people (233,601 or 11.5% of total). The single largest prison by population was Cook County Jails, IL, with 8,216 incarcerated people.

**Climate data**

The Parameter-elevation Relationships on Independent Slopes Model (PRISM) dataset from Oregon State University provides high-resolution (4 km grids) daily Tmax and maximum vapor pressure deficit (VPDmax) from 1981 - to near present.2 As described in,3-5 mean fields are produced by interpolating data from a dense network of weather stations with a spatial-weight regression model that uses landscape features like elevation and aspect to predict daily meteorological conditions across the continental United States (CONUS). PRISM data has been well-validated [ref] and shown to be well-suited for heat-related epidemiological research in the United States.5 The 4-km dataset is freely available.

**Daily WBGTmax Estimates**

Daily Tmax and VPDmax mean fields from PRISM were converted to approximated indoor or shaded WBGTmax following the procedure used in previous work.6,7 Following 5, first, VPDmax are converted to daily minimum relative humidity fields (eq. 1)

(eq. 1)

with Tmax in °C, VPDmax in Pa, and RHmin in %. Next, we combine Tmax, converted to °F, and RHmin to create daily maximum heat index (HImax) mean fields following the U.S. National Weather Service’s (NWS) procedure.8 To calculate HImax for each day, we use Tmax and RHmin to best align relatively humidity at the time the daily maximum temperature occurs during a given diurnal cycle.5 NWS first estimates HImax using Steadman's simplified equation:

(eq. 2)

If the resulting HImax is greater than 80°F, then the complete Rothfusz equation is estimated as

(eq. 3)

with the following adjustments: if Tmax between 80°F – 113°F and RHmin less than 13%, adjustment a is subtract (eq. 4) and if Tmax between 80°F – 87°F and RHmin greater than 85%, adjustment 2 (eq. X) is added.

(eq. 4)

(eq. 5)

We then use the quadratic relationship identified in previous work9 between HImax and WBGTin to convert HImax values to an approximated indoor WBGTmax (eq. 6).

(eq. 6)

Outdoor wet bulb globe temperature (WBGTout) is a linear combination of wet bulb temperature (Tw), black globe temperature (Tg) and dry bulb temperature (Td) (eq. 7), whereas indoor wet bulb globe temperature (WBGTin) combines only Tw and Tg (eq. 8). Both require in-situ field instruments to correctly measure, though several methods exist to approximate WBGTout from meteorological data.10

(eq. 7)

(eq. 8)

We recognize that the WBGTmax approximation used in this analysis assumes fixed wind speeds (0.5 m s-1) and neglects radiated heat of WBGTout. But given that incarcerated Americans spend the preponderance of their time indoors and that most carceral facilities lack AC, WBGTin is appropriate to measure how humid heat exposure and changed across carceral facilities in the continental United States. Further, WBGT thresholds are used by multiple organizations, including ISO and the US National Institute for Occupational Safety & Health (NIOSH), to identify occupational risks related to heat stress and it is widely used in environmental epidemiological research across a range of context to assess relationship between heat and human health. For example, evidence from epidemiological research in Qatar found strong correlation between cardiovascular mortality among Nepali migrant workers and elevated monthly average WBGTmax (Pradhan *et al*. 2019) and recent research has demonstrated both outdoor and indoor wet bulb globe temperature are robust when assessing associations between short-term temperature exposure and various kidney diseases in New York State (Chu  *et al*. 2023).

**Validation of WBGTmax**

The PRISM dataset is extensively validated and deriving HImax from PRISM has been shown to be appropriate to use for environmental epidemiological research, including identifying warm days across the United States. Nonetheless, numerous gridded observational climate datasets exist, including reanalysis products like the European Centre for Medium-Range Weather Forecasts (ECWMF) ERA5. Recent findings suggests that, when correlated against station observations, the accuracy of both PRISM and ERA5 derived WBGT may vary by climate zone in the United States.

To illuminate the degree to which PRISM-derived WBGT used in this analysis compares to WBGT derived from ERA5 (available at 31km) and from ground stations, we estimated the correlation between average summer month (May – September) daily Tmax, RHmin, and WBGTmax for PRISM, ERA5, and HadISD (a quality-controlled subset of ISD), available from the Met Office Hadley Centre for Climate Science and Services. We selected stations within the contiguous United States, and then applied further quality-control steps as enumerated in Raymond et al. 2020 (doi:10.1126/sciadv.aaw1838), plus an additional requirement that less than 10% of days be missing during 2015 to 2020.



**Figure S1** Monthly correlation of daily Tmax, RHmin, and WBGTmax during 2015 – 2020 for HadISD stations, PRISM climate grids, and ERA5 reanalysis data for the United States.

Figure S1 shows the month Person’s R2 correlation for Tmax, RHmin, and WBGTmax and suggests that ERA5 and PRISM are well-correlated at the national level for all three metrics. ERA5 tends to be better correlated with ISD observations of WBGTmax most months, but PRISM performs better in 2016 and 2020.



**Figure S2** Monthly correlation of daily Tmax, RHmin, and WBGTmax during 2015 – 2020 for HadISD stations, PRISM climate grids, and ERA5 reanalysis data for the United States for days HADISD stations reported Tmax greater than 26°C.

Because we are concerned with hot days, we reperform the analysis of Figure 1, but for only to include days ISD stations measured Tmax greater than 26°C (Figure 2). The correlation is weaker for PRISM for hotter days compared to ERA5, though not for all months. Both ERA5 and PRISM are widely used in environmental epidemiological research and both datasets have been expensively validated (ref). The weaker correlation of PRISM we present here merits further investigation. As noted above, emerging research (ref), suggests that the strength of the correlation depends on the climate region of the stations. But a full intercomparison it is outside the scope of this research brief.

**Calculating humid heat exposure and trajectories of change metrics**

For each carceral facility, we calculated the number of days in each year during 1982-2020 that were greater than 28°C WBGTmax (n\_daysyear). We first assigned the average number of days per year WBGTmax exceeded 28°C from 2016 - 2020. Then, we measured exposure during 2016 - 2020 by multiplying the number of incarcerated people housed at each carceral facility in 2018 by the average number of days WBGTmax exceeded 28°C from 2016 - 2020.

To calculate the disparities between carceral facilities with the rest of the state, we calculated state-level estimates for n\_daysyear by aggregating across counties in each state in each year using county-level population weights derived from the NCHS Vintage 2020 bridged-race dataset during 1990 - 201911 and from the US Census Bureau prior to 1990.12 We then made a population-weighted estimate of the state-level carceral facility value for n\_daysyear and subtracted the estimate calculated for the entire state to obtain the annual estimated disparity in exposure to humid heat days in each year of study in each state.

To estimate trajectories of change in dangerous humid heat, we performed a linear regression of n\_daysyear ~ year to estimate the change in n\_daysyear per year from 1982 - 2020. Using this fitted linear regression for each carceral facility, we then used the estimated parameter (β) multiplied by the number of years between 1982 - 2020 (37 years) to estimate the fitted change in number of humid heat days.

**References**

1. U.S. Department of Homeland Security, HIFLD Open Data, https://hifld-geoplatform.opendata.arcgis.com, Accessed July 10, 2023.
2. PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu, data created 4 Feb 4, 2014, accessed Jul 10, 2023.
3. C. Daly, J. I. Smith, K. V. Olson, Mapping Atmospheric Moisture Climatologies across the Conterminous United States. *PLOS ONE* 10, e0141140 (2015).
4. Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., ... & Pasteris, P. P. (2008). Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology: a Journal of the Royal Meteorological Society, 28(15), 2031-2064.
5. Spangler, K. R., Weinberger, K. R., & Wellenius, G. A. (2019). Suitability of gridded climate datasets for use in environmental epidemiology. Journal of exposure science & environmental epidemiology, 29(6), 777-789.
6. Tuholske, C., Caylor, K., Funk, C., Verdin, A., Sweeney, S., Grace, K., ... & Evans, T. (2021). Global urban population exposure to extreme heat. Proceedings of the National Academy of Sciences, 118(41), e2024792118.
7. Bernard, T. E., & Iheanacho, I. (2015). Heat index and adjusted temperature as surrogates for wet bulb globe temperature to screen for occupational heat stress. Journal of Occupational and Environmental Hygiene, 12(5), 323-333.
8. National Weather Service, Heat Index Equation, https://www.wpc.ncep.noaa.gov/html/heatindex\_equation.shtml Accesssed July 10, 2023).
9. Bernard, T. E., & Iheanacho, I. (2015). Heat index and adjusted temperature as surrogates for wet bulb globe temperature to screen for occupational heat stress. Journal of Occupational and Environmental Hygiene, 12(5), 323-333.
10. Q. Kong, M. Huber, Explicit Calculations of Wet-Bulb Globe Temperature Compared With Approximations and Why It Matters for Labor Productivity. *Earths Future* 10, e2021EF002334 (2022).
11. U.S. Census Bureau, U.S. Census Populations With Bridged Race Categories (2022), Accessed, https://www.cdc.gov/nchs/nvss/bridged\_race.htm Accessed July 17, 2023.
12. U.S. Census Bureau, U.S. Bureau, County Intercensal Tables 1980-1990. https://www.census.gov/data/tables/time-series/demo/popest/1980s-county.htmlAccessed July 17, 2023).