Heat Stress Metrics and Data

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CLEAR Statistical Capacity Building Workshop

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Outline

- How Heat Impacts Health
- Heat Stress Metrics
  - Air temperature
  - Heat index
  - Humidex
  - Wet bulb temperature
  - Wet bulb globe temperature
  - UTCI
- Importance of Scale
  - Spatial
  - Temporal
  - Diurnal Cycle
- Correlation of Heat Stress Metrics
- Observational Data
  - Stations
  - Gridded Data
- Climate Projections
- File Types
- Download ERA5
- Python Example (if time)

Brainstorm: how does heat impact human health?

<u>Things to Consider</u>

- Where does exposure occur?
- When does exposure occur?
- What are the mechanisms that cause harm to health and well-being?
- What socioeconomic, cultural, economic, demographic, and political factors mediate or amplify impacts?

Brainstorm: how does extreme heat impact human health?

…

How does heat impact human health?

How does heat impact human health?

Brainstorm: What meteorological factors that influence heat stress?

…

Meteorological factors that influence heat stress.

(Dry)
Air Temperature

Meteorological factors that influence heat stress.

**(Dry)
Air Temperature**

**Atmospheric
Moisture**

Radiation

Wind

Meteorological factors that influence heat stress.

(Dry)
Air Temperature

Atmospheric
Moisture

Radiation

Wind

Clothing

Heat stress metrics

- There are over 300 different metrics in use to define heat stress.
- There is no “official” definition of a heat wave.
- Important to be clear why a heat stress metric is being selected and how it is constructed.
- Recommend using several metrics in environmental epidemiological analysis when possible.
- Today we will cover six metrics: air temperature, heat index, humidex, wet-bulb temperature, wet-bulb globe temperature, and universal thermal comfort index

Air Temperature

- **Actual air temperature** measured by a standard thermometer freely exposed to the air **<u>but shielded from moisture and radiation.</u>**
- Same as “dry-blub temperature”, “surface air temperature” or “2-meter air temperature (T2m)”
- Most widely meteorological observation available
- Psychrometric – a property of thermal dynamics

Baldwin *et al.* 2023

Air Temperature

The relationship between moisture and temperature is really important for climate projections due to **<u>exponential scaling of humid-heat.</u>**

Baldwin *et al.* 2023

Heat Index

- Non-linear combination of 2-meter air temperature and relative humidity.
- Estimates what it “feels like” on a hot day.
- Used by the U.S. National Weather Service to issue early warnings about hazardous heat.
- Relatively simple to calculate.
- Assumes shaded, low-wind conditions
- Effective range: 26.7°C (80°F) to 50°C (122°F).
- Often is higher than air temperatures, but not always.

NWS Heat Index — Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

Caution — Extreme Caution — Danger — Extreme Danger

HI = -42.379 + 2.04901523*T + 10.14333127*RH - .22475541*T*RH - .00683783*T*T - .05481717*RH*RH + .00122874*T*T*RH + .00085282*T*RH*RH - .00000199*T*T*RH*RH

ADJUSTMENT = [(13-RH)/4]*SQRT{[17-ABS(T-95.)]/17}

ADJUSTMENT = [(RH-85)/10] * [(87-T)/5]

HI = 0.5 * {T + 61.0 + [(T-68.0)*1.2] + (RH*0.094)}

Humidex

- Very similar to Heat Index
- Non-linear combination of 2-meter air temperature and but based on **dew point or vapor pressure**, not relative humidity.
- Estimates what it “feels like” on a hot day.
- Used by the Canadian Government.
- Relatively simple to calculate.
- Assumes shaded, low-wind conditions
- Often is higher than air temperatures, but not always.

Humidex for range 15–43 °C

Dew point (°C)	Temperature (°C)																													
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
10	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
11	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
12	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
13	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
14	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
15	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
16		21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
17			22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
18				24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
19					26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
20						28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
21							29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
22								31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
23									33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
24										35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
25											37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55
26												39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
27													42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58
28														44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59

Wet-bulb Temperature (WBT or Tw)

- Psychrometric – a property of thermal dynamics
- The lowest temperature reached only by evaporation.
- Measured with a wet cloth over a thermometer.
- **WBT = T2m, air is fully saturated (e.g. 100% relative humidity).**
- Proposed theoretical limit of human survivability to heat extremes (exposure to Tw > 35°C theorized to kill humans after six hours of exposure).
- Several methods exist to approximate Tw, but generally requires T2m, dew point, temperature (Td) and surface pressure (p)
- Often lower than air temperature.

Fig. 1 Observed global extreme humid heat.
Color symbols represent the 99.9th percentile of observed daily maximum TW for 1979–2017 for HadISD stations with at least 50% data availability over this period. Marker size is inversely proportional to station density.

Raymond *et al.* 2020

Wet-bulb Globe Temperature (WBGT)

- WBGT ≠ WBT (often confused!)
- Combination of air temperature, moisture, radiation and wind speed.
- Developed by the US Military in the 1950s
- **Dry Air (Td) + WBT (Tw) + globe (Tg)**
- WBGT=0.7Tw+0.2·Tg+0.1Td (outdoor)
- WBGT=0.7Tw+0.3Tg (indoor)
- Designed to be measured in-situ, but several methods exist to measure with gridded meteorological data
- Lower than air temperature
- Most often used in occupational health

Cheung *et al.* 2016

Universal Thermal Comfort Index (UTCI)

- International Society of Biometeorology (ISB) create a standardized metric in 1998
- Accurately measure impacts of heat across climates and validated with a thermo-physiological model
- Capture effects of extremes
- Combination of air temperature, moisture, radiation and wind speed
- Not a simple metric to calculate from meteorological data
- Often lower than air temperature

Figure by Stephaney Gyaase

Importance of Scale

<u>Do we have the human location data to measure ...</u>

- How long was a person exposed?
- Where was a person exposed?

Space-Time Prism

Importance of Scale

<u>Do we have the human location data to measure ...</u>

- How long was a person exposed?
- Where was a person exposed?

<u>Do we have the climate location data to measure ...</u>

- How long was a person exposed?
- Where was a person exposed?

Space-Time Prism

Importance of Spatial Scale

100 x 100 km

Importance of Spatial Scale

100 x 100 km

Station

Importance of Spatial Scale

100 x 100 km

Station

ERA-5 Temperature Record 25 x 25 km

Importance of Spatial Scale

100 x 100 km

Station

ERA-5 Temperature Record 25 x 25 km

CHIRTS-Daily 5 x 5 km

Verdin *et al.* 2020

Importance of Spatial Scale

CMIP-6
Climate Projection
100 x 100 km

Station

ERA-5
Temperature
Record
25 x 25 km

New
CHC-CMIP6
Projections
5 x 5 km

Williams *et al.* 2024

Importance of Temporal Scale

Raymond *et al.* 2024

The Diurnal Cycle

- Must align meteorological inputs in the diurnal cycle to construct heat stress metrics like WBT or UTCI.
- If you have hourly data … estimate metric at each hour, then average all 24 hours or extract the max/min for a given day.
- Or using daily minimum moisture and maximum temperature
- **Always be clear how daily minimum, maximum and/or average are calculated**

Raymond *et al.* 2024

Correlation between metrics … Dodowa

Correlation between metrics … Kintampo

Correlation between metrics … Navrongo

Why don’t they correlate and what are the implications?

Figure by Stephaney Gyaase

Why don’t they correlate and what are the implications?

- Fundamentally measuring different things.
- Many are unitless (UTCI, WBGT, etc.)
- Choosing metrics based on data availability is okay.
- But, when possible, analysis should be run with several metrics (at least dry air and one humid-heat)
- Metrics will scale differently.

Figure by Stephaney Gyaase

Observational Climate Data

NCAR | CLIMATE DATA GUIDE CDG

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Climate Data

The ***Climate Data Guide*** is a high-traffic expert knowledge portal providing concise and reliable information on the climate data that are essential for measuring and predicting physical climate risk.

Currently, the ***Climate Data Guide*** curates expert insights on over 200 observational datasets and climate indices, searchable or browseable in the list below.

To find a specific dataset or climate variable, jump to the the search box. For only the datasets paired with guidance written by experts, select the "Datasets with guidance" button when using the search box.

Data creators, data publishers, and scientists who use climate data are invited to join our Network of Experts by contributing commentaries on data strengths and limitations to the ***Climate Data Guide***. What type of data are included? See this discussion.

With the exception of about 25 climate indices, **the Climate Data Guide does not host datasets. Data cannot be downloaded from this site**. However, links are provided to download locations under the "Data Access" section of each dataset page.

https://climatedataguide.ucar.edu/climate-data

Weather Station Data

- GMET (ask Edmund)
- Berkeley Earth
  - https://berkeleyearth.org/data/
  - About 50,000 Individual station data used to produce monthly record.
- HadISD Stations:
  - https://www.metoffice.gov.uk/hadobs/hadisd/index.html
  - Quality controlled sub-daily data from NOAA NCEI's Integrated Surface Database.
  - About 10,000 stations.
  - 1931 – present
  - Few stations for Africa
- CRUTEM5 Temperature station data:
  - https://www.metoffice.gov.uk/hadobs/crutem5/data/CRUTEM.5.0.2.0/download.html
  - monthly-mean temperature records from 10639

Weather Station Data

- Weather station data is not usually available in a use-friendly format.

- Quality control is important.
  - Station go offline
  - Stations don’t all have the same reporting time-period
  - Stations get moved.

Weather Station Data

Gridded Observation Datasets

- NOAA Climate Prediction Center Global Unified Temperature
  - https://psl.noaa.gov/data/gridded/data.cpc.globaltemp.html
  - 0.5° spatial resolution (very course-grained)
  - 1979 – present
  - Daily min & max 2m air temperature

- CHIRTS-daily
  - https://www.chc.ucsb.edu/data/chirtsdaily
  - Blends satellite data and station data to down-scale ERA5 (more later)
  - 0.05° (about 5km) spatial resolution
  - Daily min & max 2m air temperature
  - 1983 – 2016 (experimental version to present available)

Climate Reanalysis Data

- Weather models use “initial conditions” (e.g. observations) to forecast the near-term weather.
- Reanalysis products use “initial conditions” to hindcast the weather.
- Produce sub-daily (hourly) ocean, land, and atmospheric conditions.

Climate Reanalysis Data

Four main global reanalysis products:

- ERA5 & ERA5-Land produced by the European Union
  - https://www.ecmwf.int/en/research/climate-reanalysis
  - Since 1950, Hourly at 25 and 9 km respectively
- MERRA2 produced by NASA:
  - https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/
  - Since 1980 6 hours, 0.5° latitude × 0.625°
- NCEP/NCAR Reanalysis:
  - https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html
  - Since 1948, 6 hours, 1.875 × 1.904129 gaussian grid
- JRA-55:
  - https://data.ucar.edu/dataset/jra-55-japanese-55-year-reanalysis-daily-3-hourly-and-6-hourly-data
  - 1958 onward, 3-hour, 1.55°

Climate Reanalysis Data

Four main global reanalysis products:

- ERA5 & ERA5-Land produced by the European Union
  - https://www.ecmwf.int/en/research/climate-reanalysis
  - Since 1950, Hourly at 25 and 9 km respectively
- MERRA2 produced by NASA:
  - https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/
  - Since 1980 6 hours, 0.5° latitude × 0.625°
- NCEP/NCAR Reanalysis:
  - https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html
  - Since 1948, 6 hours, 1.875 × 1.904129 gaussian grid
- JRA-55:
  - https://data.ucar.edu/dataset/jra-55-japanese-55-year-reanalysis-daily-3-hourly-and-6-hourly-data
  - 1958 onward, 3-hour, 1.55°

Climate Reanalysis Data

- Climate reanalysis products don't agree in the tropics, where the majority of humans live.
- Summer = Winter
- Only 2 "heat waves" documented in Africa since 1900 (Harrington & Otto 2020)

Fig. 5

From: Challenging the universality of heatwave definitions: gridded temperature discrepancies across climate regions

Difference in monthly climatologies of Tmax (1983–2015). Each map depicts the number of months difference between the hottest month in the two datasets being compared

Coughlan de Perez *et al.* 2023

Land surface temperature (LST)

- Land Surface Temperature (LST) derived from remote-sensing
- LST is the temperature emitted from the Earth's surface
- Grass vs. carpark on a sunny, hot day …
- Does not correlate that well with air temperature, much less heat stress metrics like WBGT
- Highly variable over space and time
- Recommend: do not use LST an independent exposure in environment epidemiology

Scott *et al.* 2017

A few points on historical climate data

- All historical observational and reanalysis data will have error, reporting gaps, and uncertainty.
- It's important to be aware of this uncertainty.
- Some teams are preforming their analysis using multiple dataset to triangulate the results.
- When in doubt, contact a data producer or reach out to someone who is an expert in that specific dataset.

Coughlan de Perez *et al.* 2023

A few points on historical climate data

Stations

- Advantages: spatial precision, temporal record “ground-truth”, unmodeled
- Disadvantages: low spatial coverage, data gaps, stations move, recording errors

Gridded Products

- Advantages: consistent model; global coverage,
- Disadvantages: biased, course-resolution, assimilation errors

Climate Projections: CMIP6

- **CMIP6 (Coupled Model Intercomparison Project Phase 6):** global climate modeling initiative that provides standardized simulations from dozens of **General Circulation Models (GCMs)** under a range of greenhouse gas scenarios.
- **Historical simulations:** the mid-19th century to 2014 and are calibrated against observational data, allowing researchers to evaluate model performance.
- **Future projections**, called **ScenarioMIP**, run from 2015 to 2100 (and beyond in some cases), using socioeconomic pathways (SSPs) to represent different emissions trajectories.
- CMIP6 GCMs offer **global coverage** with a typical spatial resolution of ~1–2° latitude/longitude (**roughly 100–200 km**) and **daily to monthly temporal resolution.**
- Resolution too coarse for local-scale impacts without downscaling.
- CMIP6 outputs such as temperature, humidity, wind speed, and surface radiation can be used to calculate metrics like **Heat Index**, **Humidex**, **Wet-Bulb Temperature**, **WBGT**, and **UTCI**.

Climate Projections: CMIP6

- **Radiative forcing** refers to the change in Earth's energy balance due to greenhouse gases and other drivers, measured in **watts per square meter (W/m^2)**.
- The **RCPs (Representative Concentration Pathways)**—used in CMIP5—were defined by their level of radiative forcing in 2100 (e.g., RCP4.5 = +4.5 W/m^2).
- While no single GCM is "correct," using a **multi-model ensemble** provides a robust way to characterize uncertainty and identify consistent patterns in heat stress trends.
- **SSPs (Shared Socioeconomic Pathways)** replace the older **RCPs (Representative Concentration Pathways)** used in CMIP5.
- While RCPs focused solely on **radiative forcing trajectories** (e.g., RCP8.5 = +8.5 W/m^2 by 2100), SSPs combine socioeconomic narratives (e.g., inequality, sustainability, fossil development) with emissions pathways.
- **RCP-SSP Scenarios**, such as SSP1-2.6 (low emissions) and SSP5-8.5 (high emissions), to bracket the range of possible futures.

Down-Scaled Projections: CHC-CMIP6

- ‘Delta-method’: uses historical record to down-scale and correct CMIP6 Projections

- Daily **5-km** min/max air temperature, max heat index, max indoor WBGT, precipitation, average vapor pressure deficit, etc. projections.
- Data for SSP245 (middle) and SSP585 (worst) for 2030 and 2050

Down-Scaled Projections: CHC-CMIP6

Down-Scaled Projections: NEX-GDDP-CMIP6

- Statistical down-scaled to 25km
- Multiple GCMs available
- 0.25°C (~25 km) resolution
- Daily data for 2020 – 2100
- Can construct most heat stress metrics: heat index, WBT, WBGT, etc.

Figure by Daniel Bose

File Types

<u>GeoTIFF (.tif)</u>

- Usually 2 dimensional with (lat x long)
- Each file is 1 time slice and one meteorological variable (e.g. air temperature)
- Commonly used with GIS software like QGIS
- Coordinate reference system and projection important

<u>NetCDF (.nc)</u>

- 3-dimentional data cube (time x lat x long)
- Each file can have more than one meteorological variable (e.g. air temperature and precipitation)
- Coordinate reference system and projection important

Data Extraction Workflow

- Xarray Python package to creates stacked, 3d data arrays that uses labels for all data and coordinates.
- Very easy to subset and extract climate by time and by location.
- All we need are the latitude and longitude of the clusters
- Extract data with just a few lines of code.

Data Extraction Workflow

- ERA5 Hourly Climate Reanalysis

- Download hourly
  - 2 meter air temperate (t2m)
  - 2 meter dew point temperature
  - surface pressure (not using today)

- Set extent to Ghana
  - Lat: -3.75 – 1.5
  - Long: 4 – 11.5

- Format NetCDF

- API for bulk download available

https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=download

Data Extraction Workflow

Step 1: Download Data (t2m, d2m, pressure) from ERA5 Website as a NetCDF

Data Extraction Workflow

Step 1: Download Data (t2m, d2m, pressure) from ERA5 Website as a NetCDF

Step 2: Open as Xarray Dataset

Data Extraction Workflow

Step 1: Download Data (t2m, d2m, pressure) from ERA5 Website as a NetCDF

Step 2: Open as Xarray Dataset

Step 3a: With t2m and d2m, create hourly relative humidity (RH).

Step 3b: With t2m and RH, create hourly heat index (HI) and wet-bulb temperature (WBT)

Data Extraction Workflow

Step 1: Download Data (t2m, d2m, pressure) from ERA5 Website as a NetCDF

Step 2: Open as Xarray Dataset

Step 3a: With t2m and d2m, create hourly relative humidity (RH).

Step 3b: With t2m and RH, create hourly heat index (HI) and wet-bulb temperature (WBT)

Step 4a: Find daily maximum HI, WBGT, t2m, and minimum t2m.

Step 4b: save out daily min/max as NetCDF

Data Extraction Workflow

Step 1: Download Data (t2m, d2m, pressure) from ERA5 Website as a NetCDF

Step 2: Open as Xarray Dataset

Step 3a: With t2m and d2m, create hourly relative humidity (RH).

Step 3b: With t2m and RH, create hourly heat index (HI) and wet-bulb temperature (WBT)

Step 4a: Find daily maximum HI, WBGT, t2m, and minimum 2.

Step 4b: save out daily min/max as net CDF

Step 5a: Load cluster locations from .csv file

Step 5b: Extract daily values at cluster locations + save.

Data Extraction Workflow

Step 1: Download Data (t2m, d2m, pressure) from ERA5 Website as a NetCDF

Step 2: Open as Xarray Dataset

Step 3a: With t2m and d2m, create hourly relative humidity (RH).

Step 3b: With t2m and RH, create hourly heat index (HI) and and wet-bulb temperature (WBT)

Step 4a: Find daily maximum HI, WBGT, t2m, and minimum 2.

Step 4b: save out daily min/max as net CDF

Step 5a: Load cluster locations from .csv file

Step 5b: Extract daily values at cluster locations + save.

Step 6: Start statistical analysis …

Thank you!

GitHub Tutorial: https://github.com/cascadet/ERA5Extract

Data Links & References

Data

- ERA5: https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=download
- CHIRTS: https://chc.ucsb.edu/data/chirtsdaily
- CHC-CMIP6: https://chc.ucsb.edu/data/chc-cmip6
- NASA NEX GDDP: https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6

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