It's not just the heat, it's the humidity.

Downscaled Wet-Bulb Temperature Projections and Implication for Future Summer Experiences from the *American Climate Prospectus*

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Economic Risks of Climate Change: An American Prospectus

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www.climateprospectus.org

Humid heat extremes

- The combination of high temperatures with high humidity is more uncomfortable, and potentially more dangerous, than high temperatures under drier conditions.

NOAA's National Weather Service

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										

Increasing danger

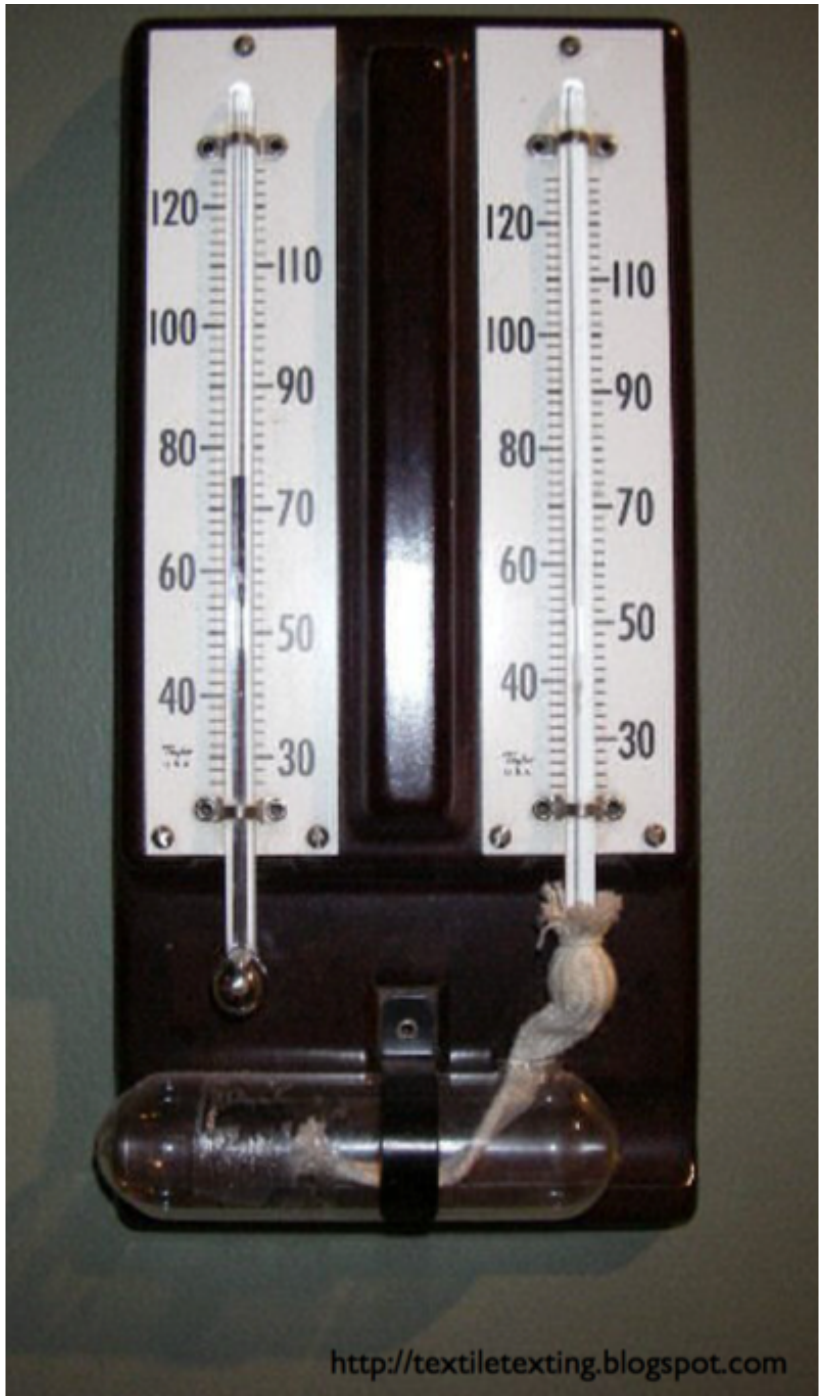
Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

Caution | Extreme Caution | Danger | Extreme Danger

- Humidity and high temperatures are leading cause of death from extreme weather events (e.g. 1995 Chicago heatwave)

Assessing humid heat stress with wet-bulb temperature

- Wet-bulb temperature is the temperature measured by a fully ventilated thermometer with its bulb wrapped in a soaked cloth
- It reflects the ability of mammals to cool themselves by sweating



Wet-bulb temperature records

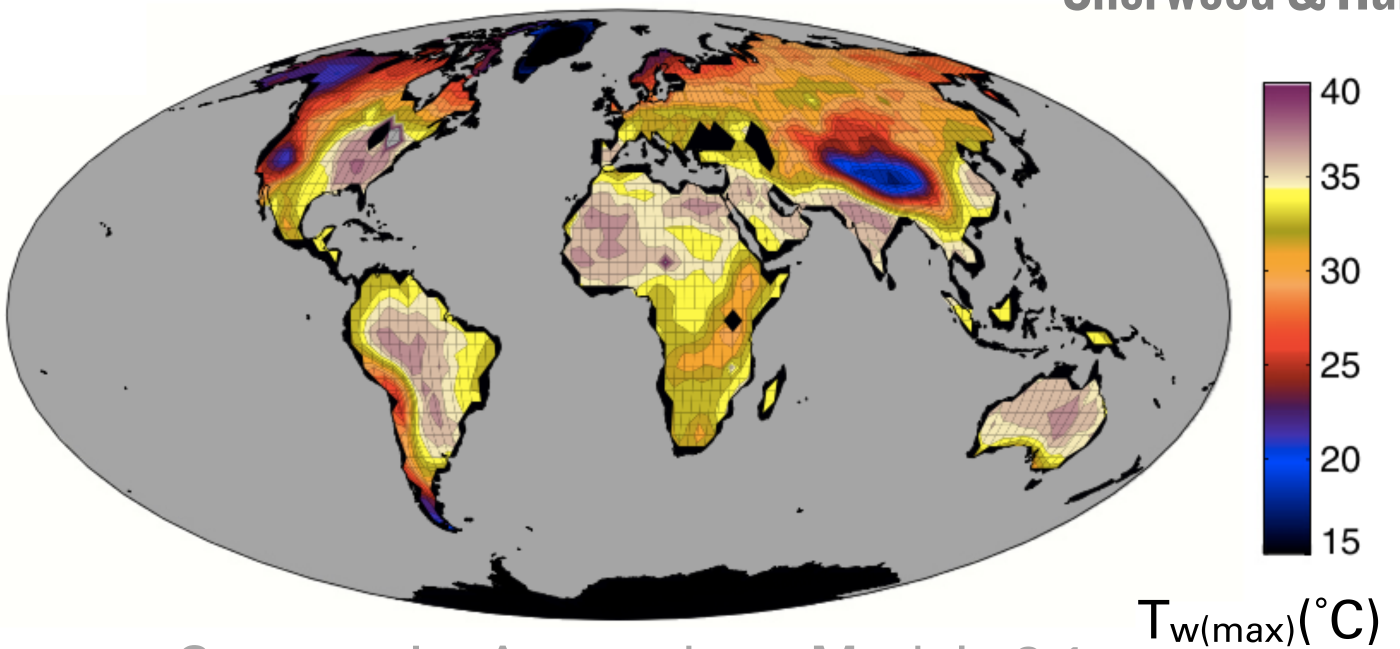
US: 33°C in Appleton, WI, on July 13, 1995 at 5pm (temperature of 38°C, dew point of 32°C)

1995 Chicago heat wave experienced peak wet-bulb temperatures close to 32°C for consecutive days

An hour of vigorous, shaded activity at a wet-bulb temperature of 33°C raises core body temperature to the heat stroke limit of 40°C.

Previous wet-bulb temperature studies using one GCM

Sherwood & Huber (2010)



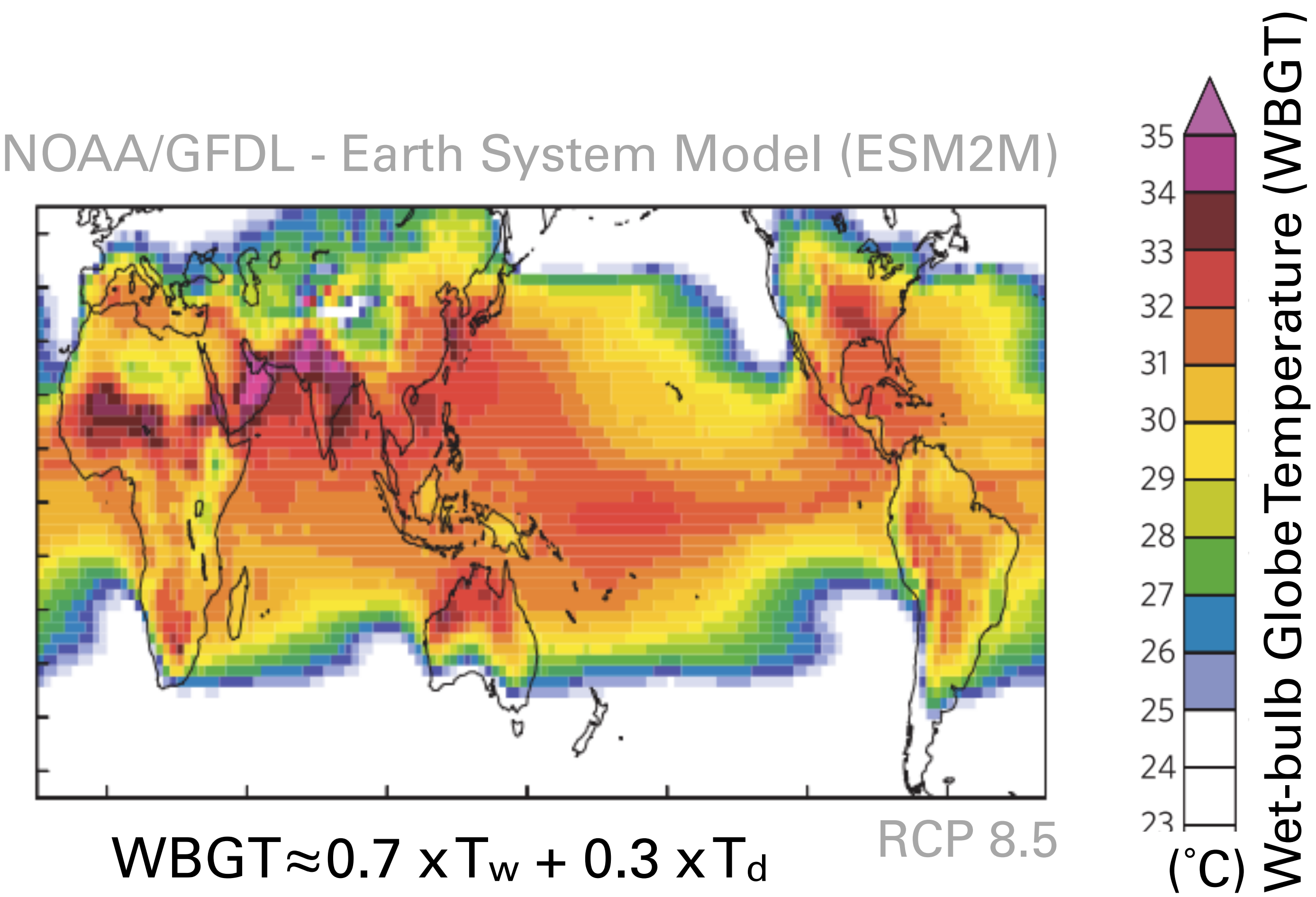
Community Atmosphere Model v3.1

- With 11-12 ˚C of global mean warming much of southeastern U.S., areas of India and China uninhabitable during portions of the year
- Areas of uninhabitability could dwarf that affected by rising sea level

Dunne et al. (2013)

- Global capacity to perform heavy labor reduces to less than 40% by 2200 in hottest months
- Eastern U.S. exposed to humid heat stress only present in hottest regions of the present day

NOAA/GFDL - Earth System Model (ESM2M)



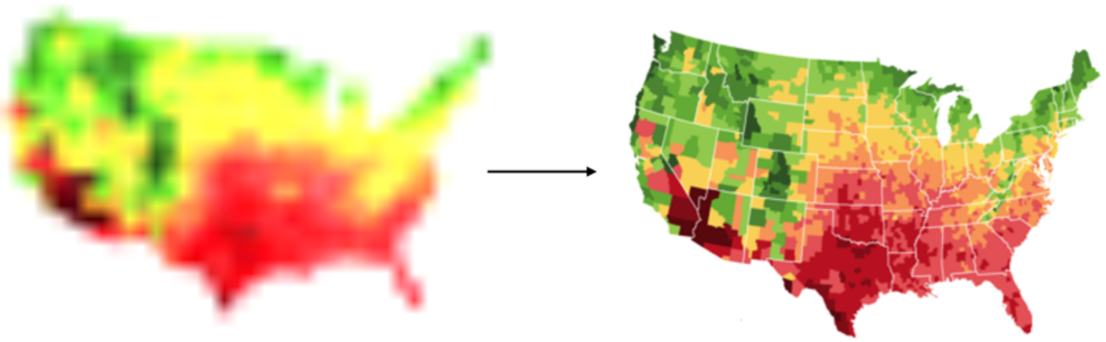
$WBGT \approx 0.7 \times T_w + 0.3 \times T_d$

RCP 8.5

Compiling high-resolution projections of wet-bulb temperature

Challenges:

- Multiple models used (probabilisitic approach; *see Technical Appendix I of ACP*)
- County-level spatial scales



- No available humidity downscaling methods (obs. reliability?)

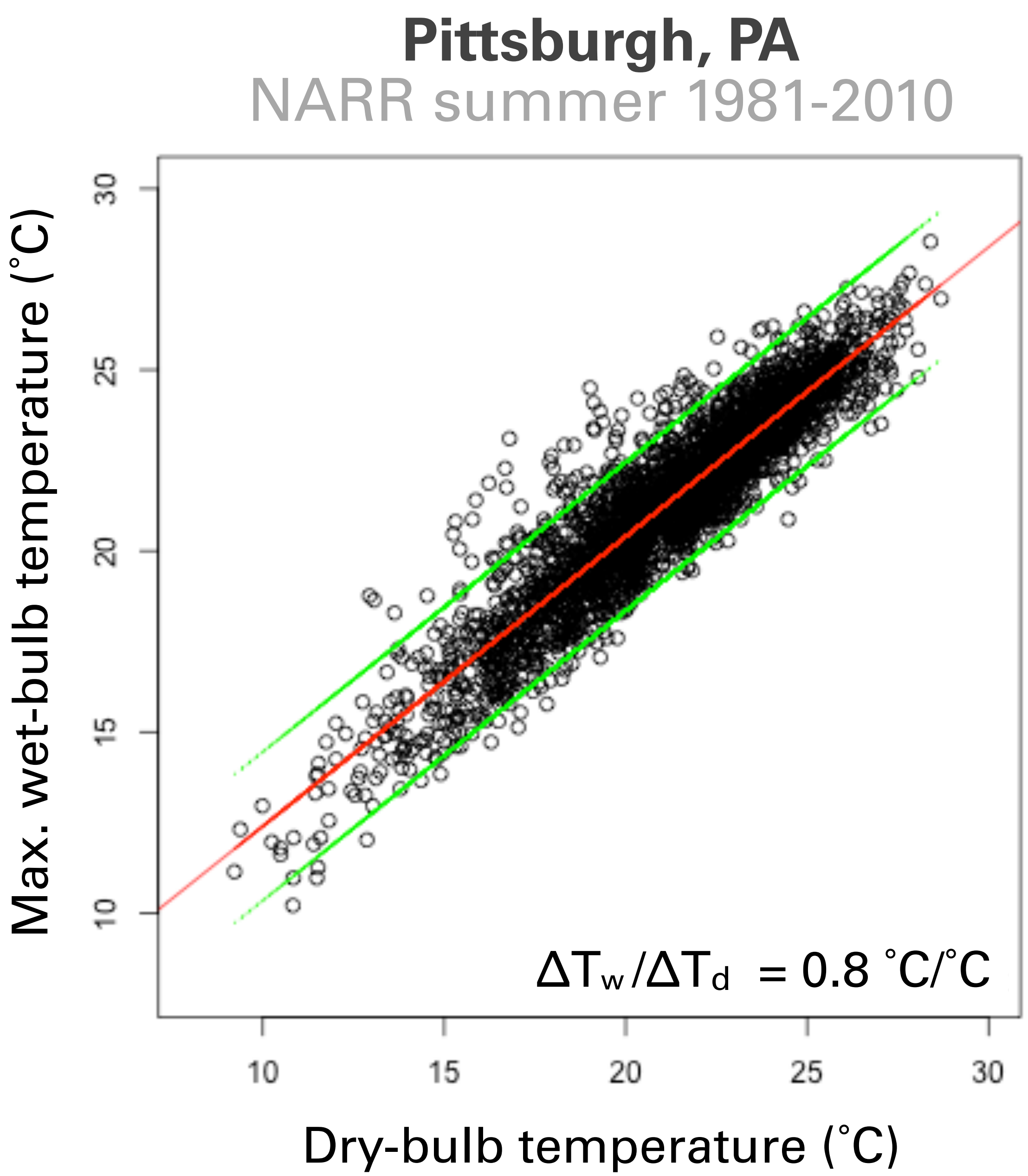
Wet-bulb projection approach:

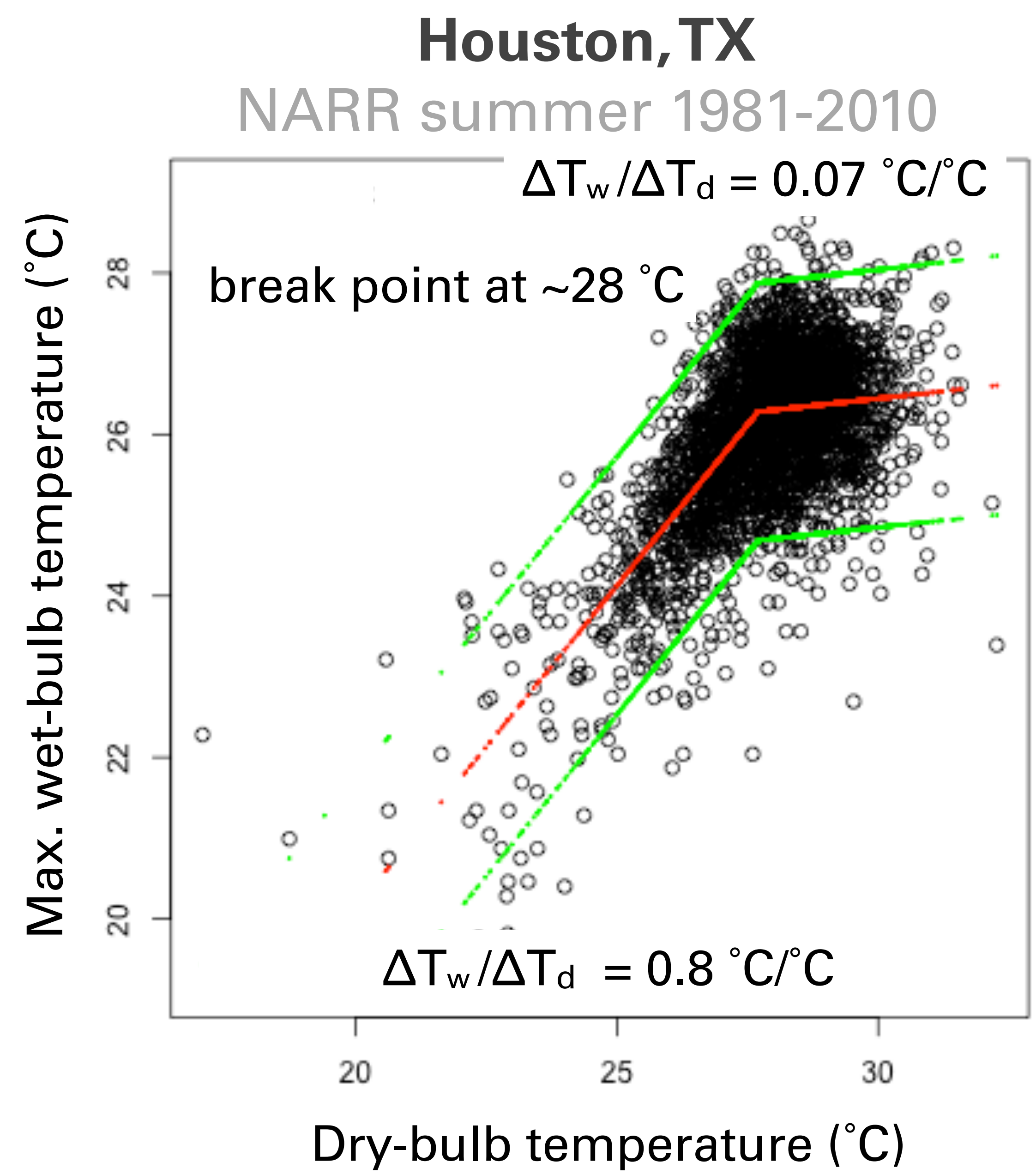
Combine historical wet-bulb and dry-bulb temperature relationships from the North American Regional Reanalysis (NARR) with the probability distribution of local temperature change.

Step 1: Estimate the conditional wet- and dry-bulb distribution

Step 2: Use a linear model to shift the conditional distribution

Step 1: Estimate conditional distribution





Depending on the Bayesian Information Criterion (BIC), fit a linear model or piece-wise linear model:

$$T_w(T) \quad = \quad b_0 + \beta_0 T_d + \epsilon.$$

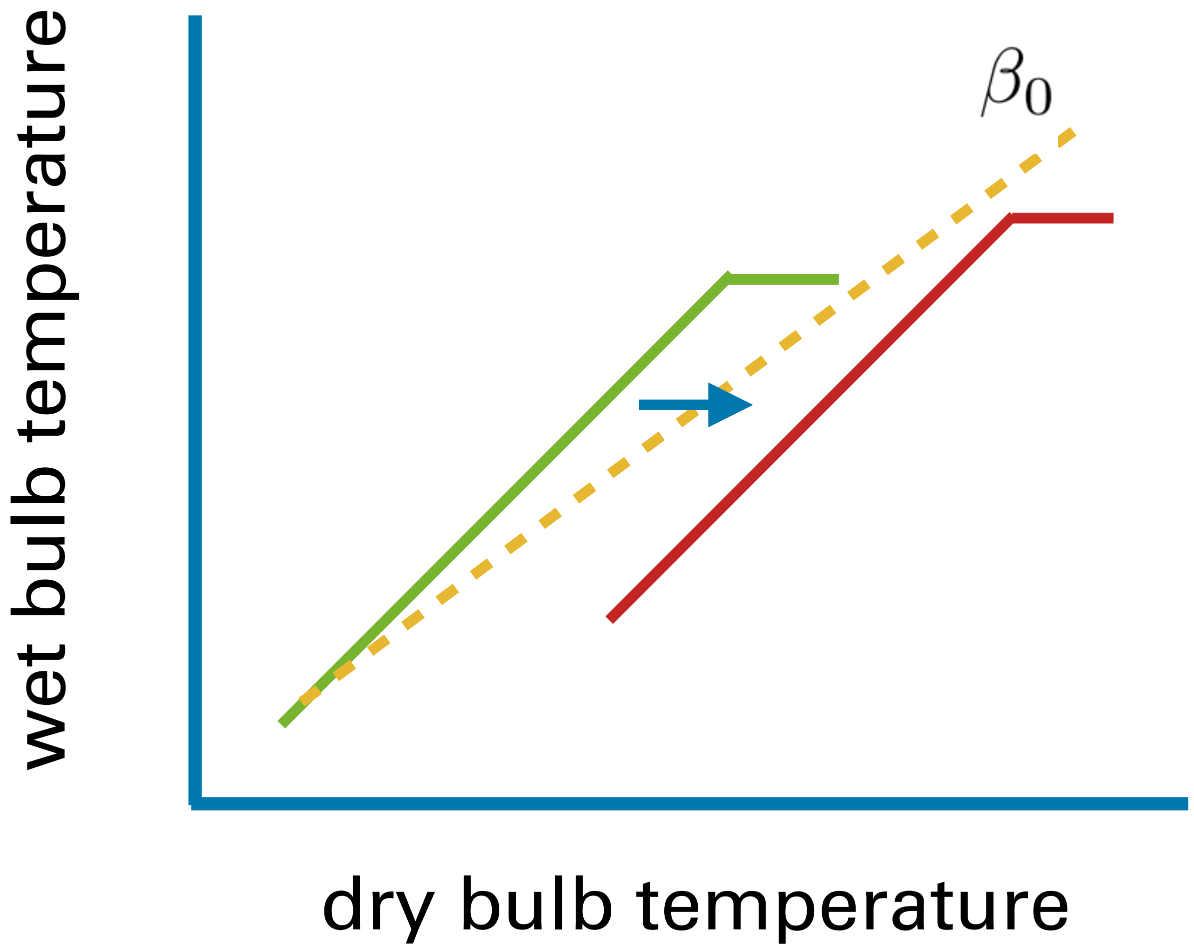
$$T_w(T) \quad = \quad b_1 + \beta_1 \min(T_d, T_0) + \beta_2 \max(0, T_d - T_0) + \epsilon.$$

T_w = wet-bulb temp. b_o, b_1 = y-intercepts
T_d = dry-bulb temp. T_o = break point
β_o, β_1, β_2 = linear slopes

Step 2. Use linear model to shift conditional distribution

- To account for the effects of climate change, we shift the conditional distribution upwards by a linear function of local forced temperature change:

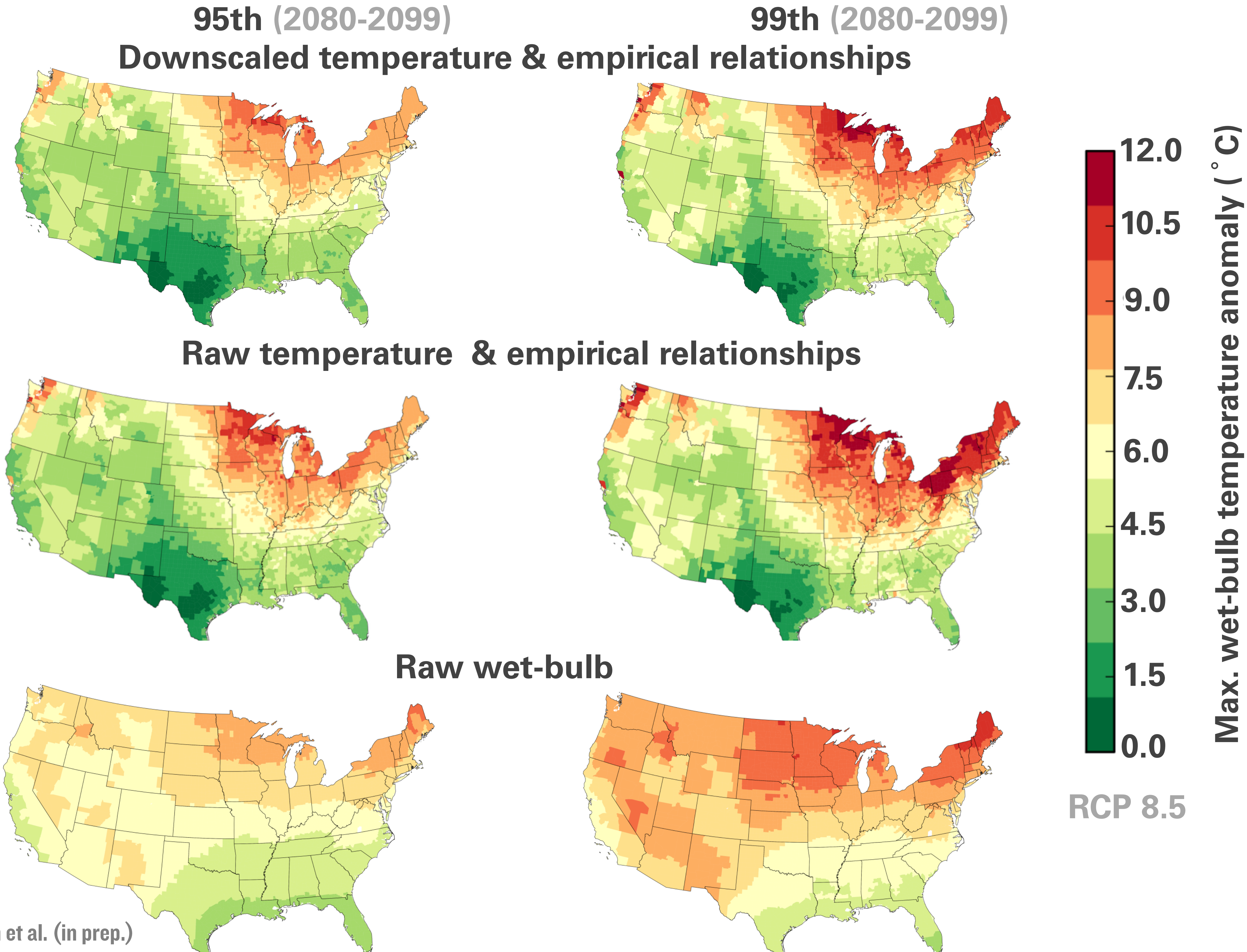
$$T_w(T_d, \Delta T_f) \quad = \quad T_w(T_d - \Delta T_f) + \beta_0 \Delta T_f$$



β_0 = slope of standard linear regression

ΔT_f = local forced temperature change

Comparing empirical projections with a CMIP5 model (CNRM-CM5)



Rasmussen et al. (in prep.)

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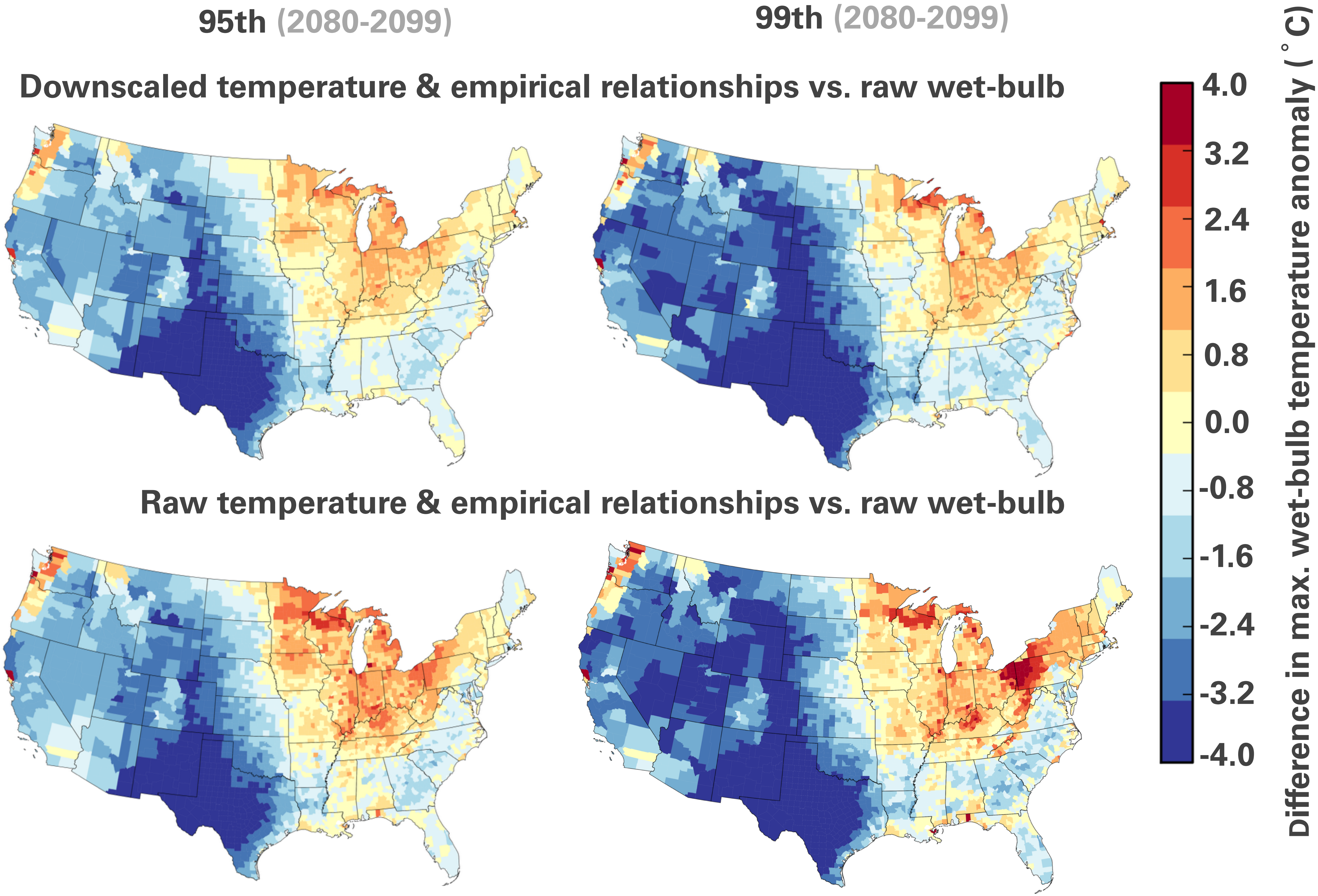

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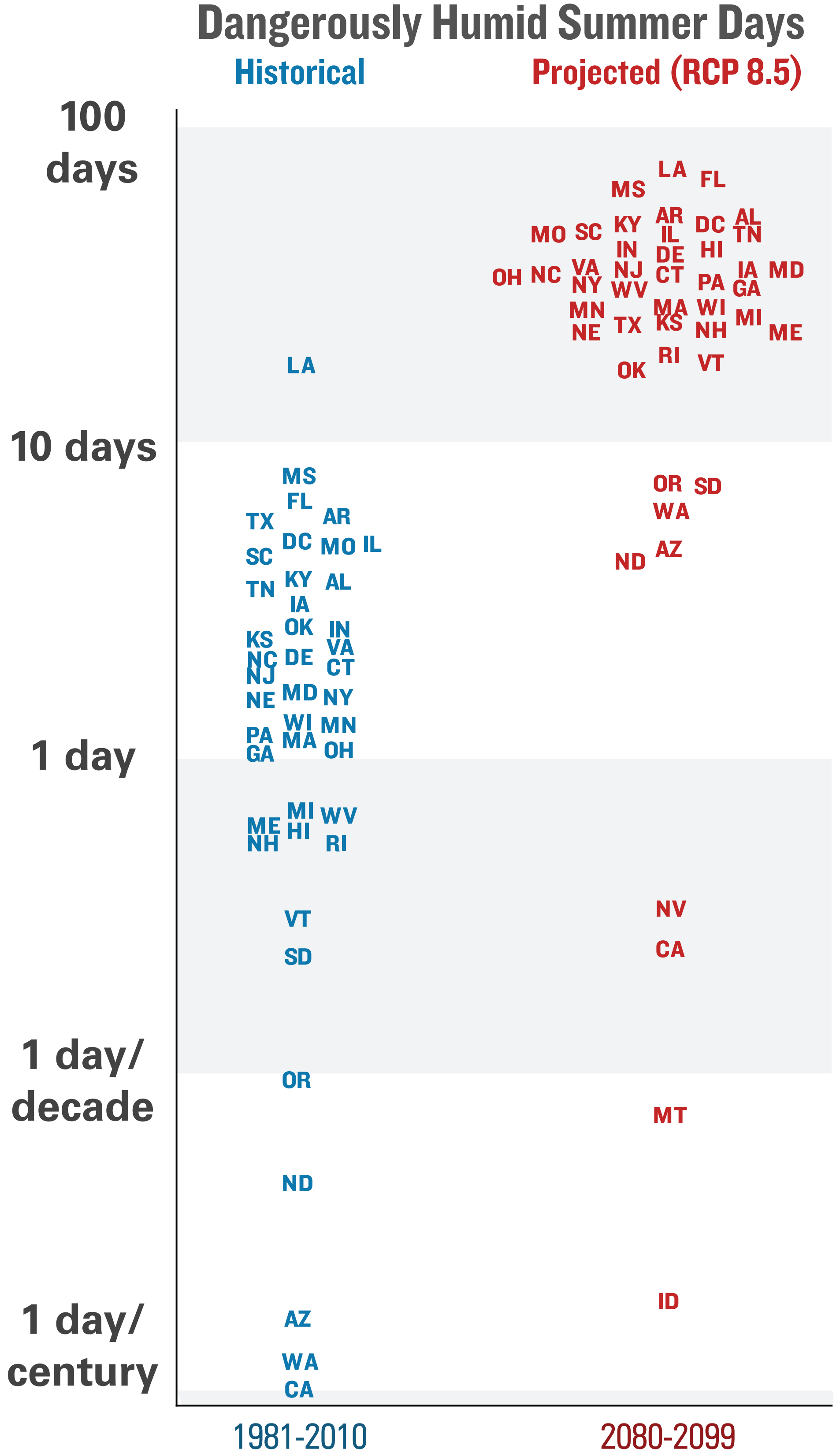
American Climate Prospectus Humid Heat Stroke Index

"It's not just the heat, it's the humidity."

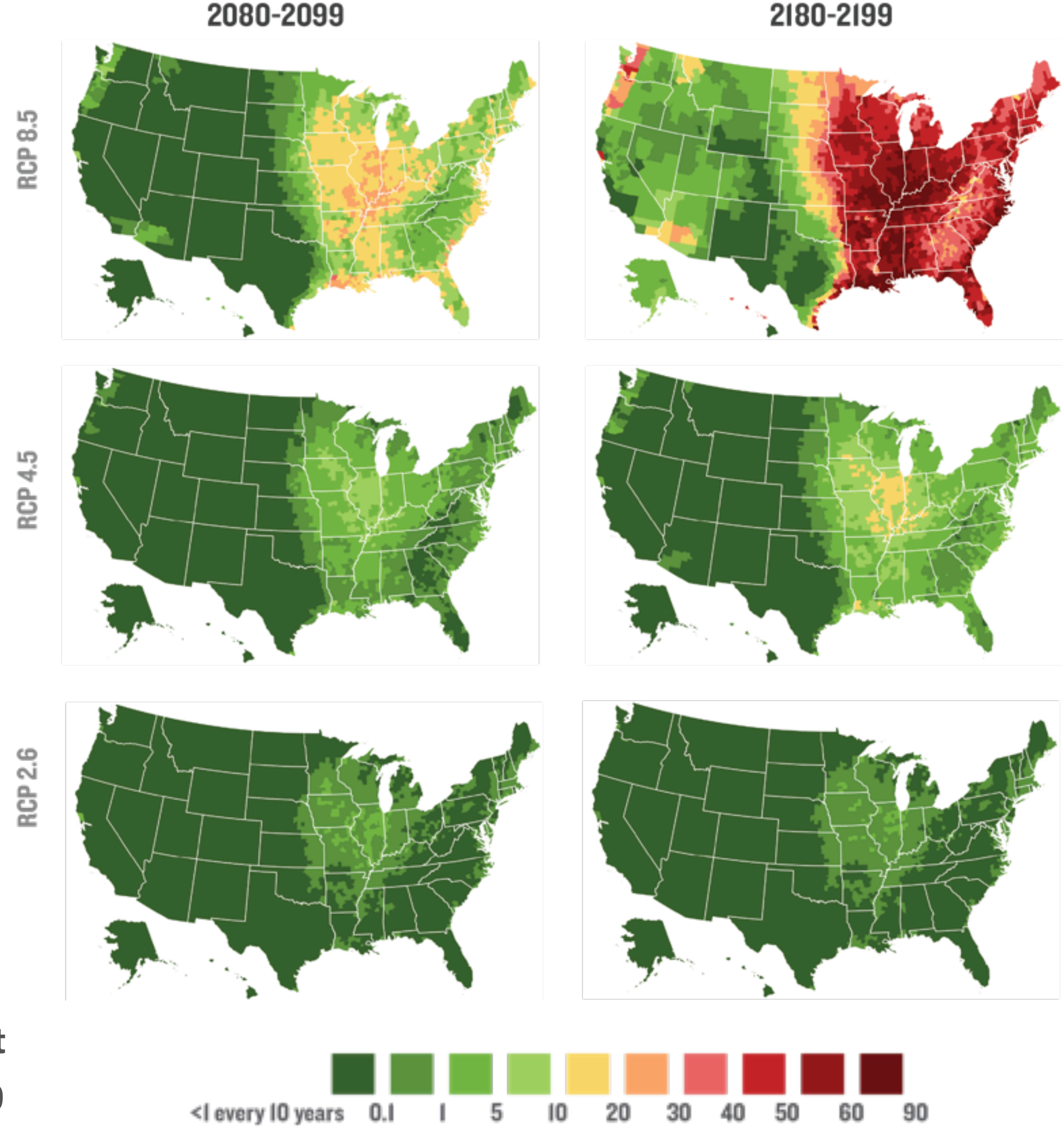
ACP HHSI	Peak Wet Bulb Temperature	Description (hottest part of day)
I	74°F-80°F (23.3°C-26.7°C)	Uncomfortable. Typical of much of summer in the Southeast.
II	80°F-86°F (26.7°C-30.0°C)	Dangerous. Typical of most humid parts of Texas and Louisiana in hottest summer month, and most humid summer days in Washington and Chicago.
III	86°F-92°F (30.0°C-33.3°C)	Extremely dangerous. Comparable to Midwest during peak days of 1995 heat wave.
IV	>92°F (>33.3°C)	Extraordinarily dangerous. Exceeds all U.S. historical records. Heat stroke likely for fit individuals after less than one hour of moderate activity in the shade.

Projections from the American Climate Prospectus



Expected Category II+ ACP Humid Heat Stroke Index days per summer, 2080-2099

Expected number of Category III+ ACP Humid Heat Stroke Index days in a typical summer



American Climate Prospectus: Economic Risks in the United States

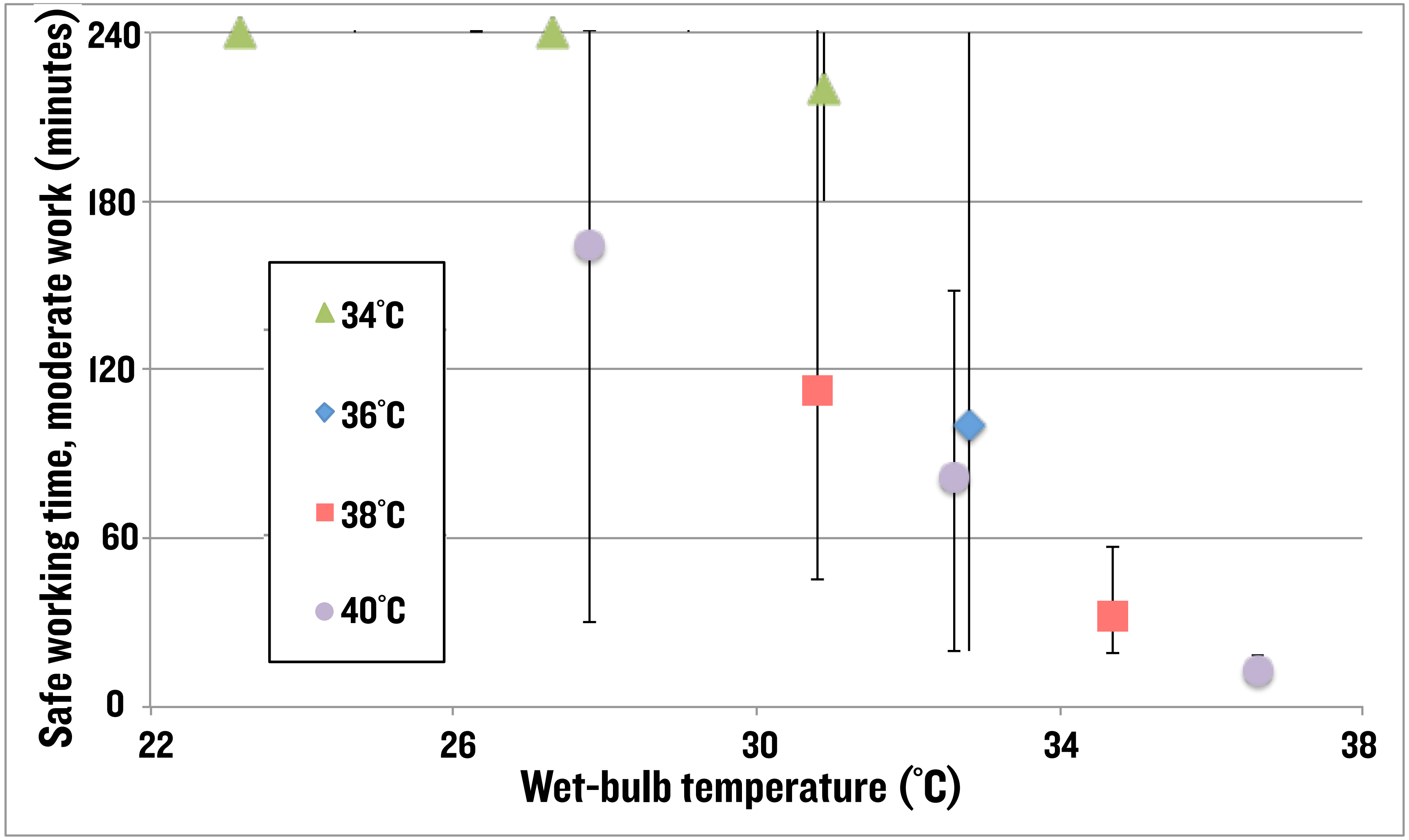
Key takeaways

- Under RCP 8.5:
    - By late 21st century, dangerously humid Cat. II+ days are expected to characterize most of summertime in the eastern U.S., with > 50% of U.S. population expected to experience > 1 week of extremely dangerous Cat. III+ days year $^{-1}$
    - By late 22nd century, extremely dangerous Cat. III+ days are expected to characterize most of summertime in the eastern U.S., with > 30 extraordinarily dangerous Cat. IV days year $^{-1}$

- Mitigation can greatly reduce risk. By late 21st century:
    - Under RCP 4.5, only 1/3 U.S. population expected to experience 1 Cat. III day year $^{-1}$
    - Under RCP 2.6, only ~4% of U.S. population expected to experience 1 Cat. III day year $^{-1}$

Extra Slides

Laboratory studies: reductions in labor productivity

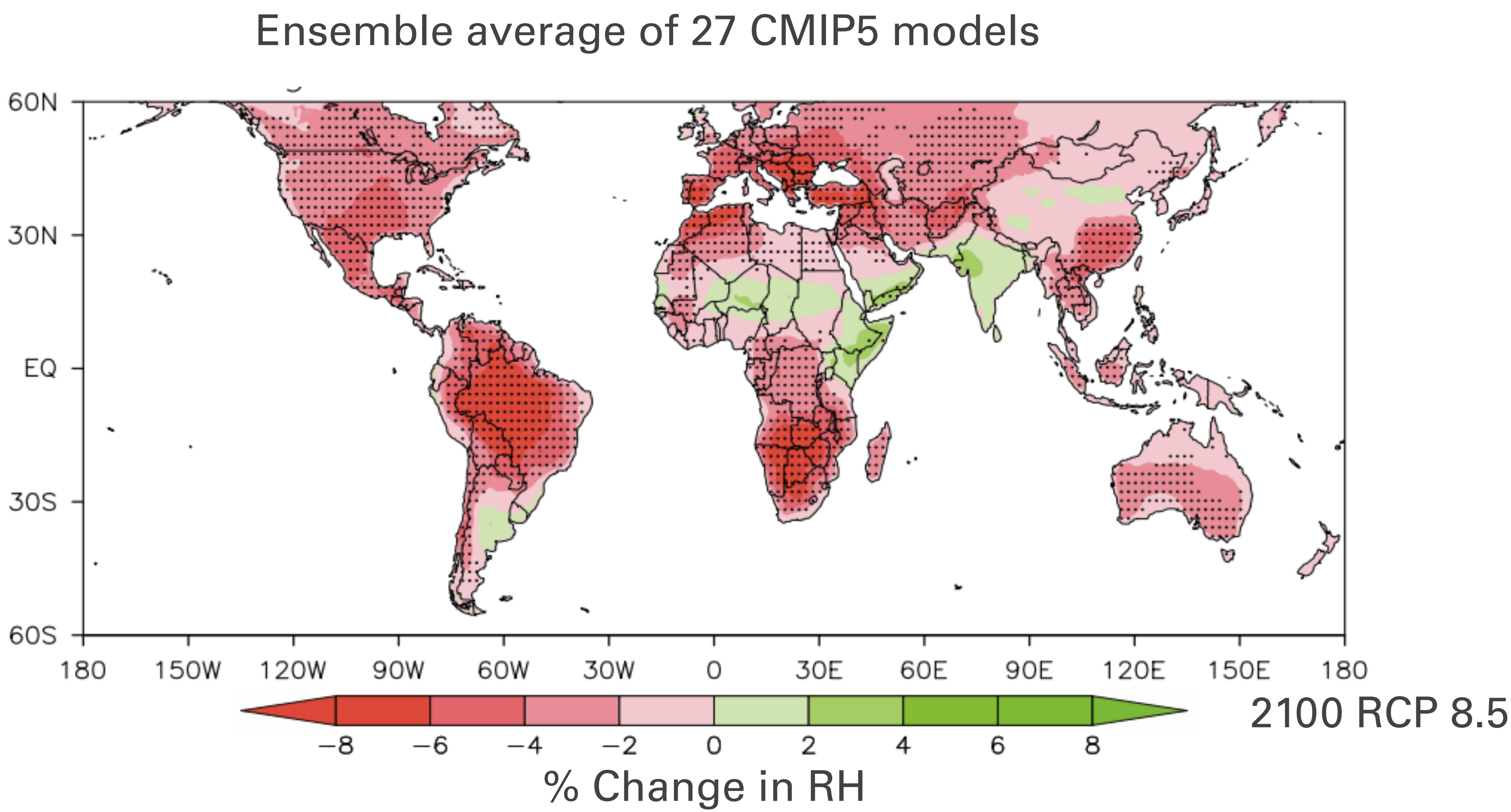


- Participants assembled hardware under varying humidities
- Vitals signs (pulse, blood pressure, ect.) were taken through out the experiment

- Safe working times decline as wet-bulb temperature increases at constant dry-bulb temperature

Liang et al. (2011)

Relative humidity is not expected to be stationary with global warming



- Reflected in slopes above the breakpoint, smaller ΔT_wet for ΔT_dry

Sherwood and Fu (2014)