Responses of heat stress to the climate warming from the perspective of temperature and humidity

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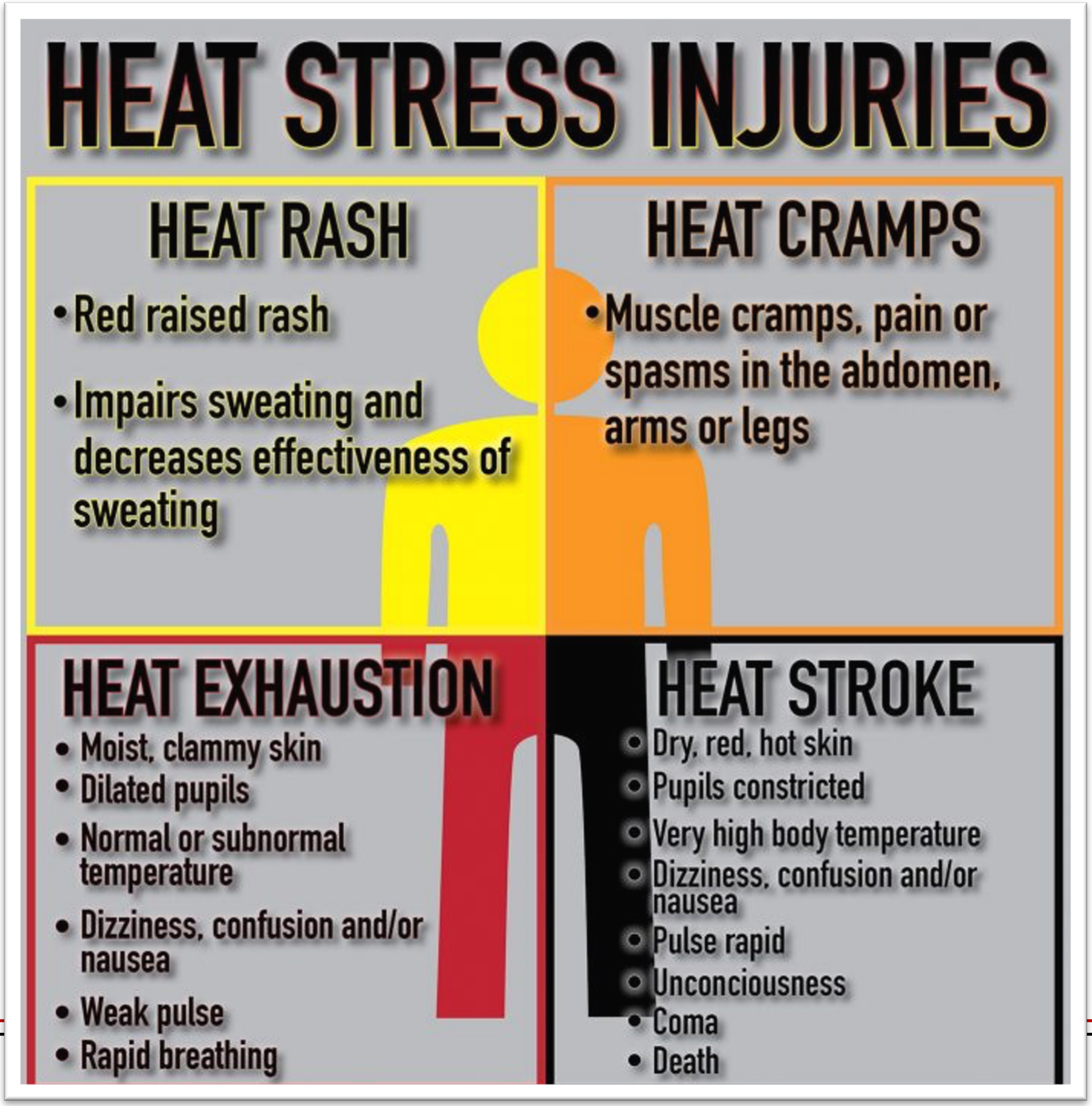
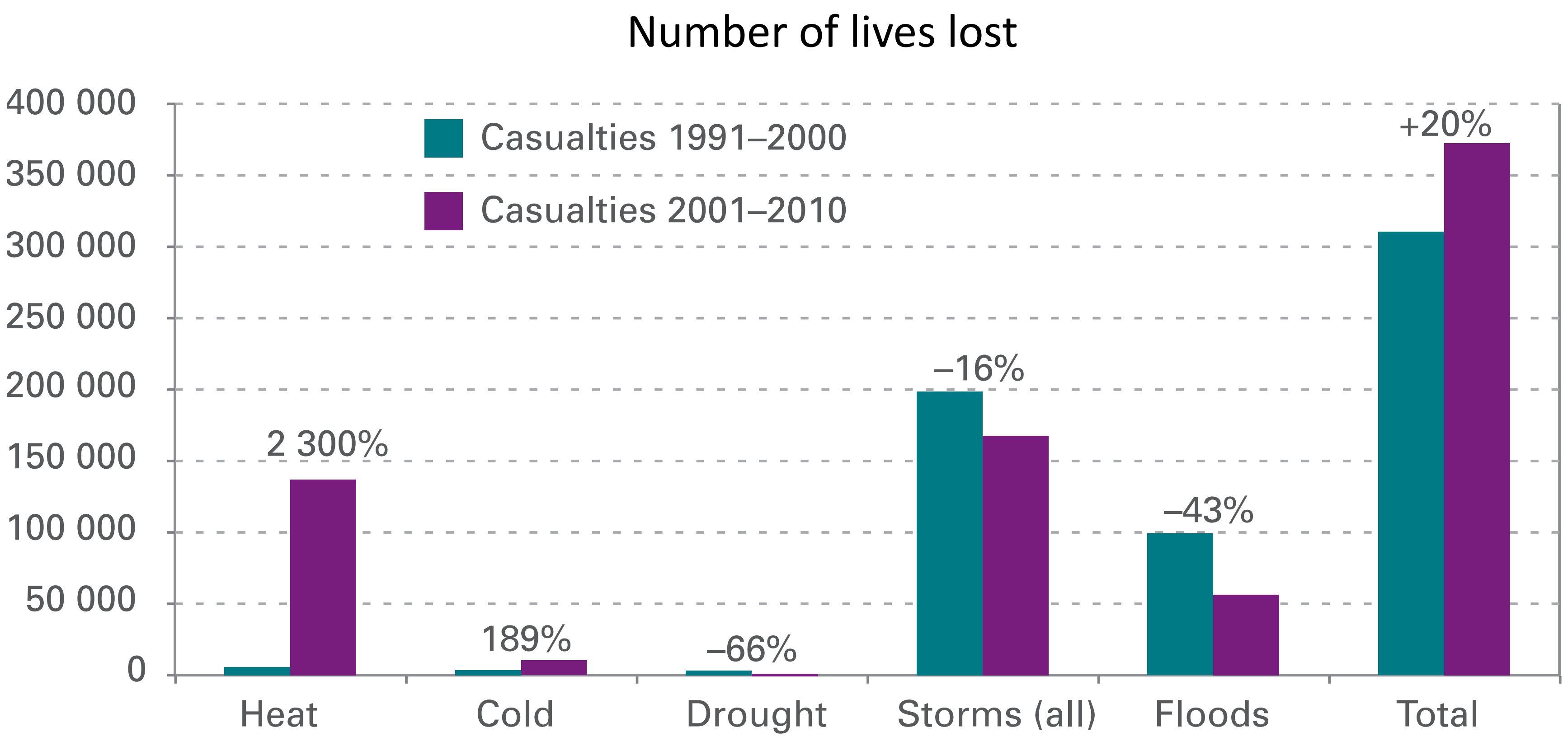
Motivation


HEAT STRESS INJURIES
HEAT RASH
• Red raised rash
• Impairs sweating and decreases effectiveness of sweating
HEAT CRAMPS
• Muscle cramps, pain or spasms in the abdomen, arms or legs
HEAT EXHAUSTION
• Moist, clammy skin
• Dilated pupils
• Normal or subnormal temperature
• Dizziness, confusion and/or nausea
• Weak pulse
• Rapid breathing
HEAT STROKE
• Dry, red, hot skin
• Pupils constricted
• Very high body temperature
• Dizziness, confusion and/or nausea
• Pulse rapid
• Unconciousness
• Coma
• Death

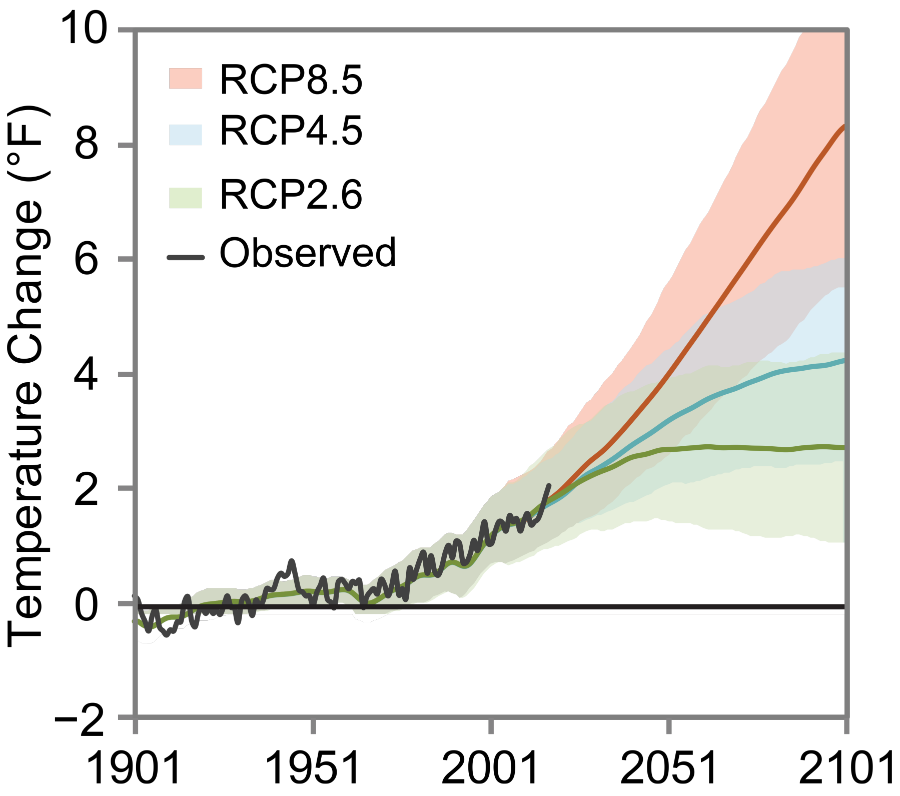
Motivation

Impact of extreme events during 2001-2010 compared with 1991-2000

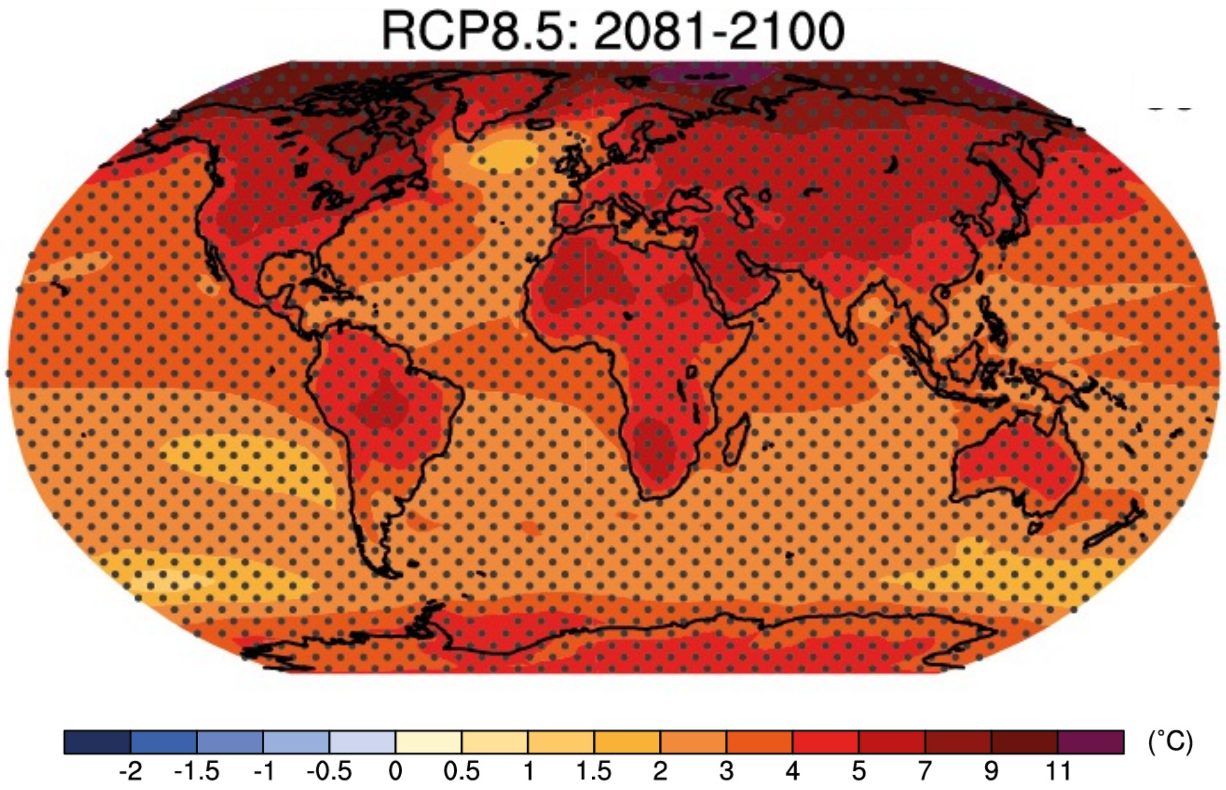


WMO (2013)

Increase in surface air temperature (T)

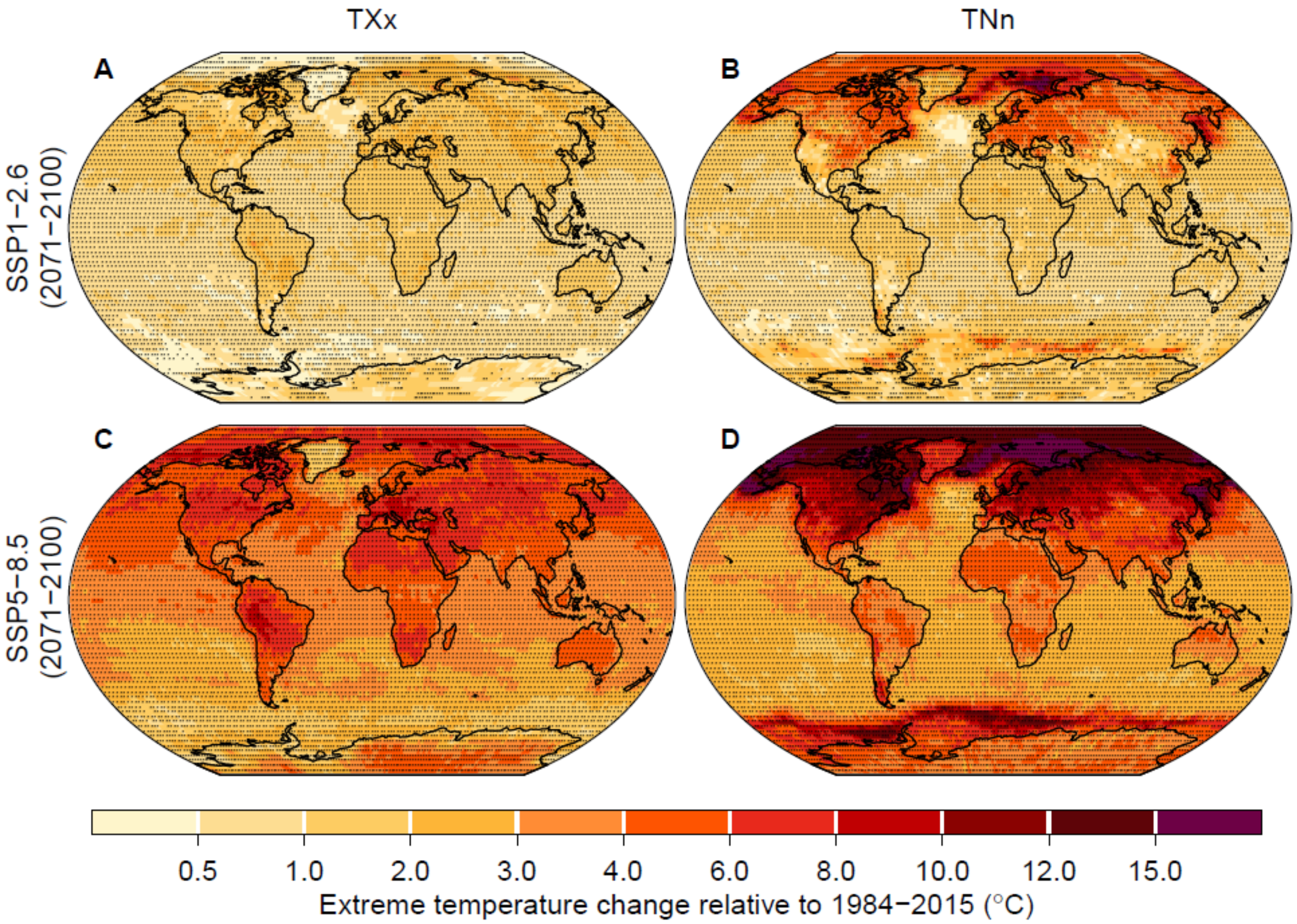


Multi-model ensemble of global-mean surface air temperature deviating from 1986-2005 (The Climate Science Special Report Fig.1.4)



39-model average of surface air temperature in 2081-2100 deviating from 1986-2005 (IPCC AR5 Fig. 12.11)

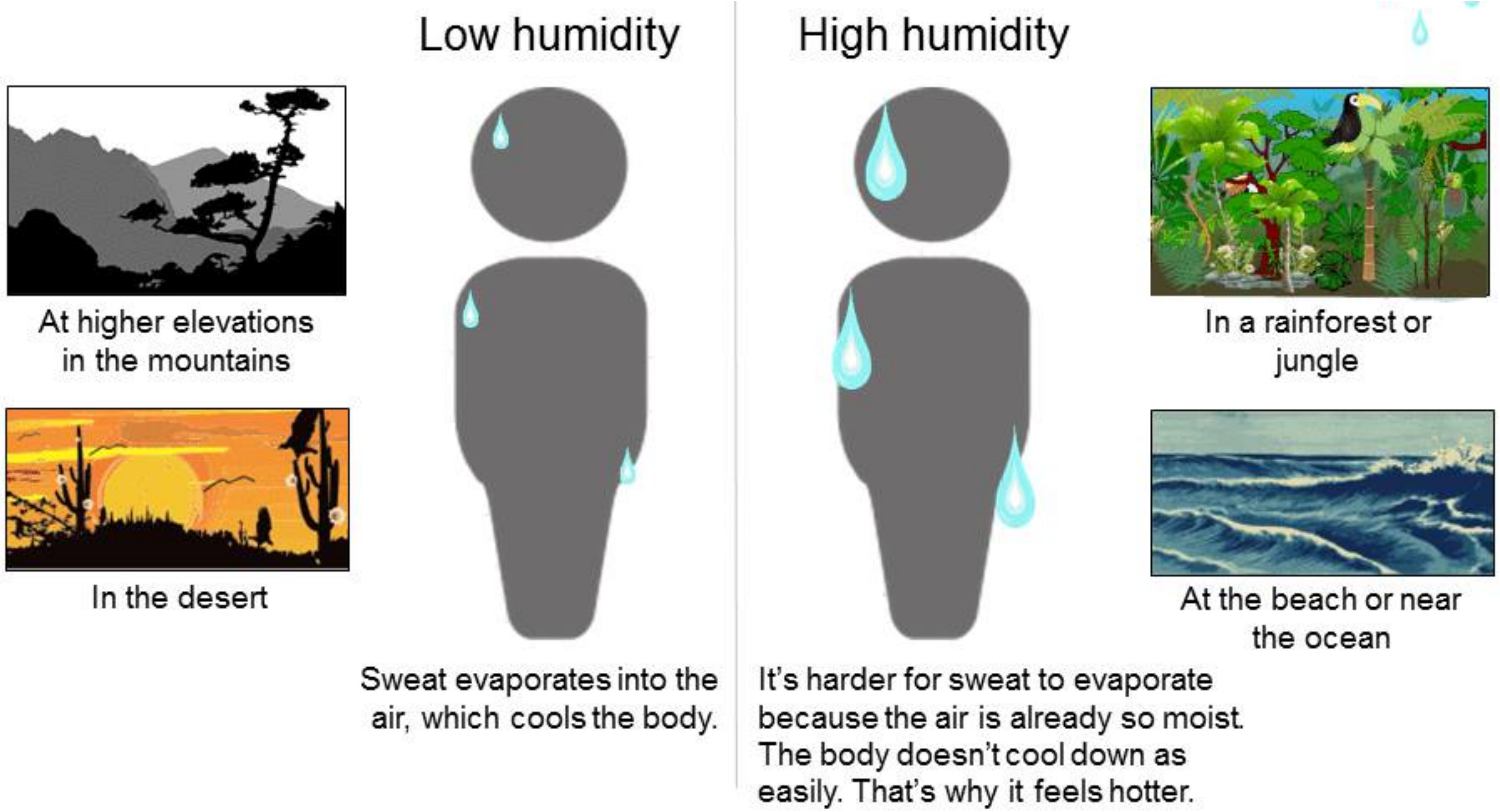
Increase in extreme temperature



Li et al. (2020)

Humidity is another important contributor to heat stress

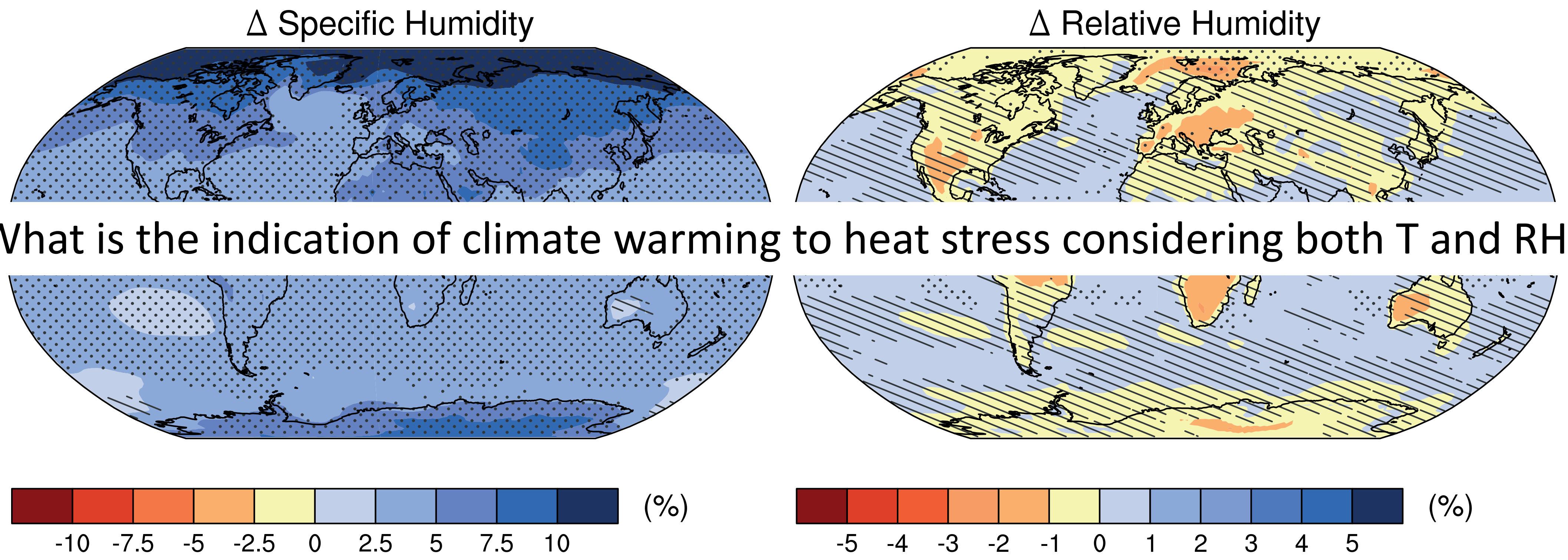
People feel hotter when relative humidity is higher even the temperature is the same



US National Weather Service

Over land, specific humidity increases while relative humidity (RH) decreases

2016-2035 relative to 1986-2005 under RCP4.5



What is the indication of climate warming to heat stress considering both T and RH?

IPCC AR5 (Fig. 11.14)

Outline

- Part I Emulate the evolving distribution of relative humidity conditional on daily maximum temperature in a warming climate

- Part II Responses of Wet-Bulb Globe Temperature to climate warming

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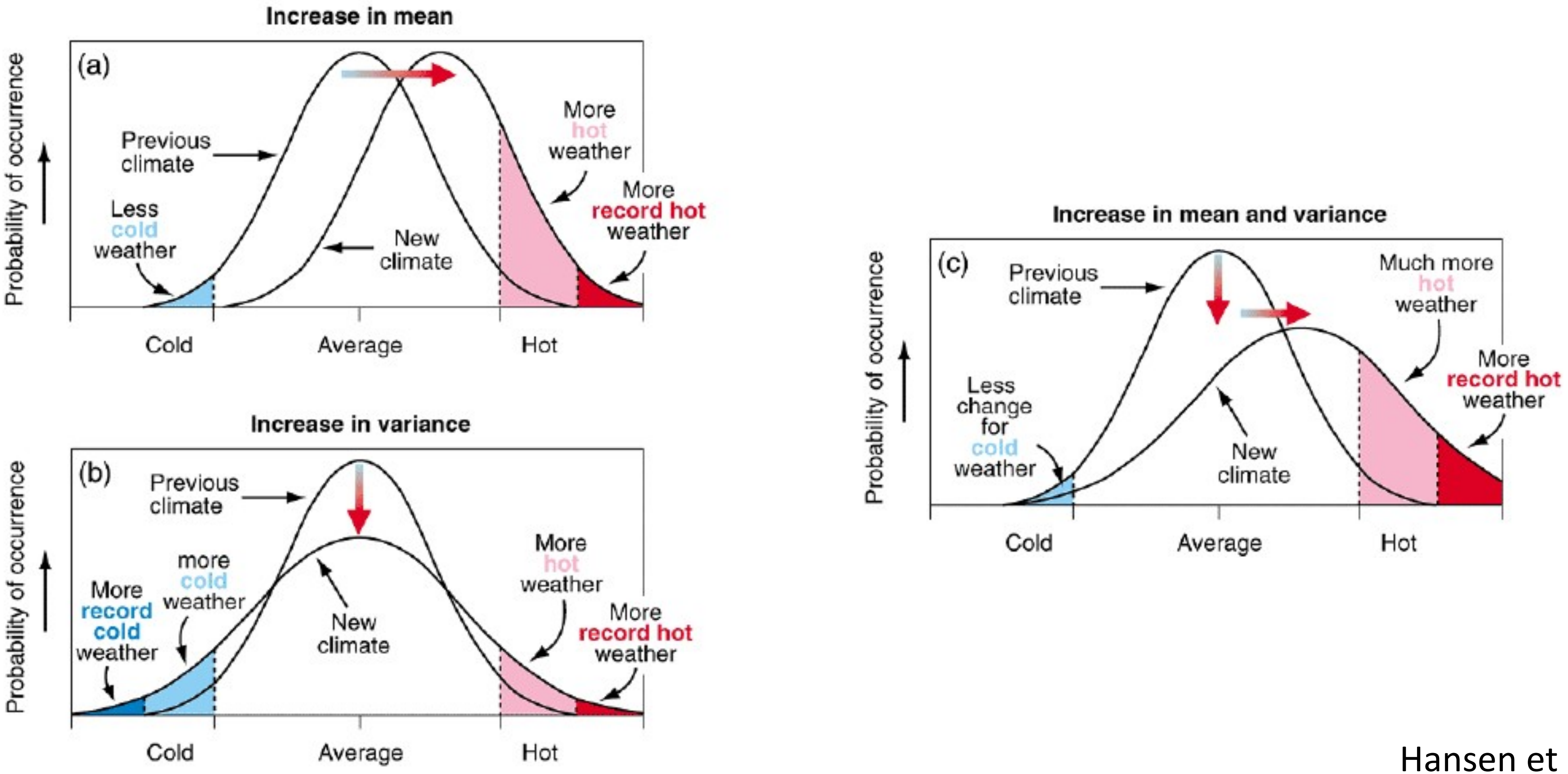
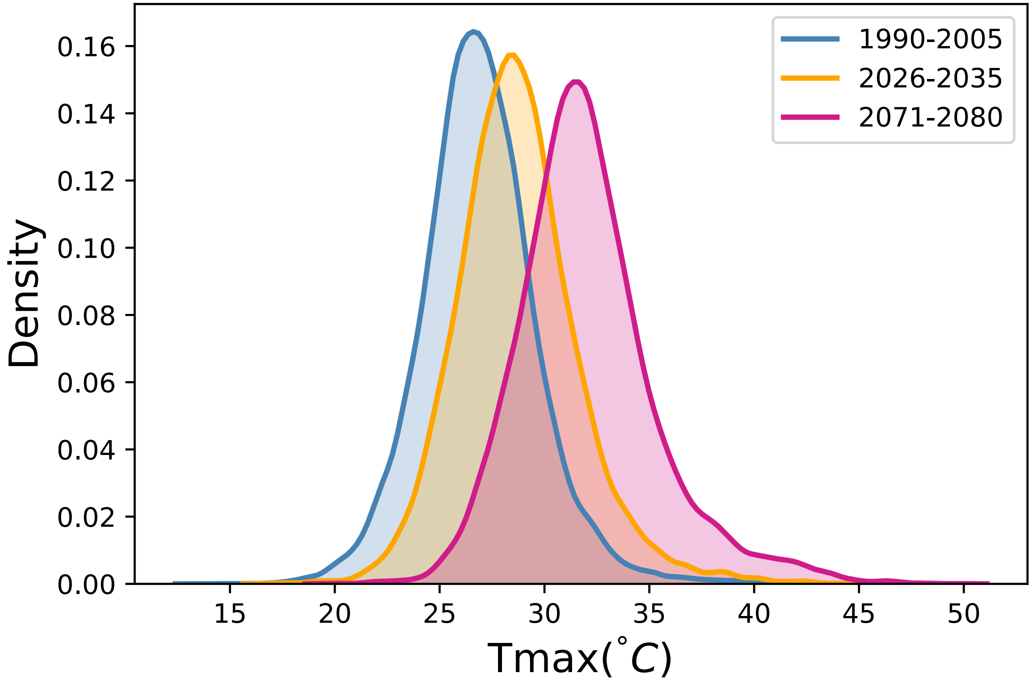
Common assumptions for evolving marginal distribution in a warming climate

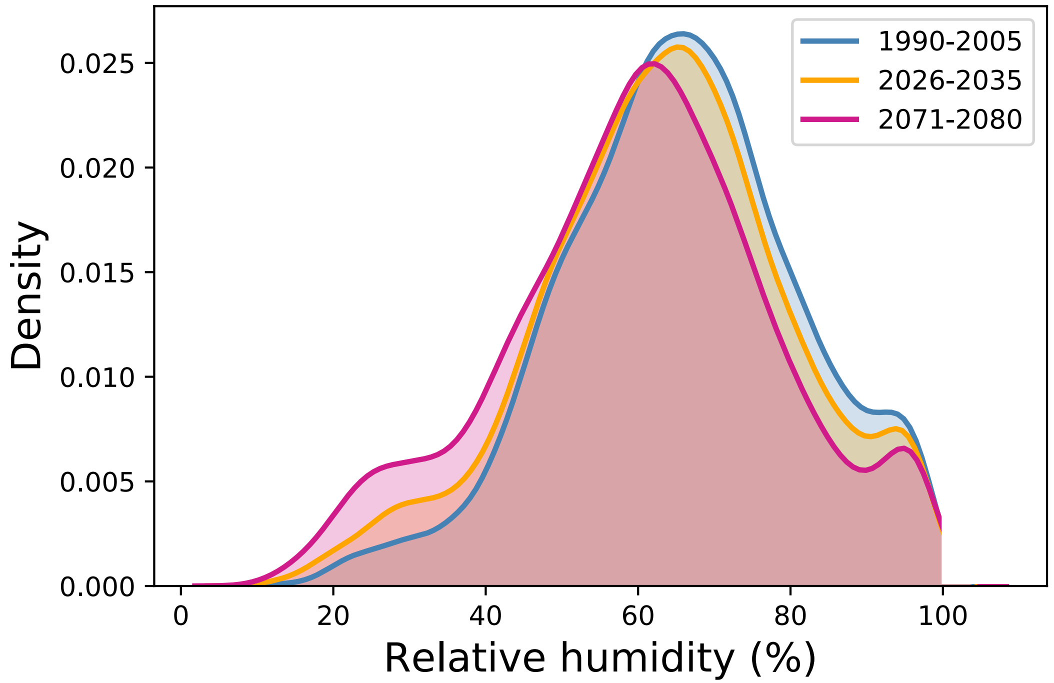


Hansen et al. (2012)

Evolving marginal distributions in a real case

July in Chicago (CESM LENS RCP8.5)





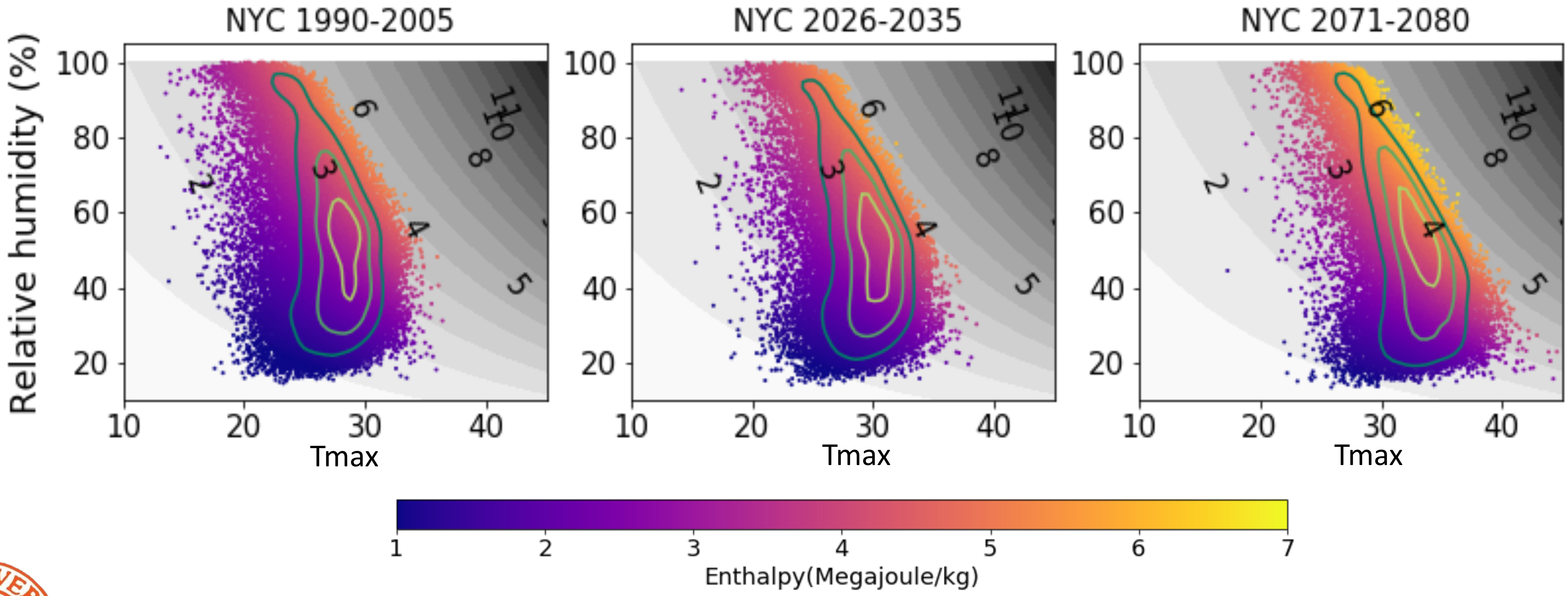
Mean:	26.90 ;	28.72;	32.04
STD:	2.72;	2.90;	3.29
Skewness:	0.42;	0.62;	0.81

Mean:	65.6 ;	63.49;	60.29
STD:	15.72;	16.68;	17.97
Skewness:	-0.16;	-0.20;	-0.15

Data: 35 members from CESM Large Ensemble 6-hourly data RCP8.5

Evolving Joint Distributions between Tmax and Relative Humidity (RH)

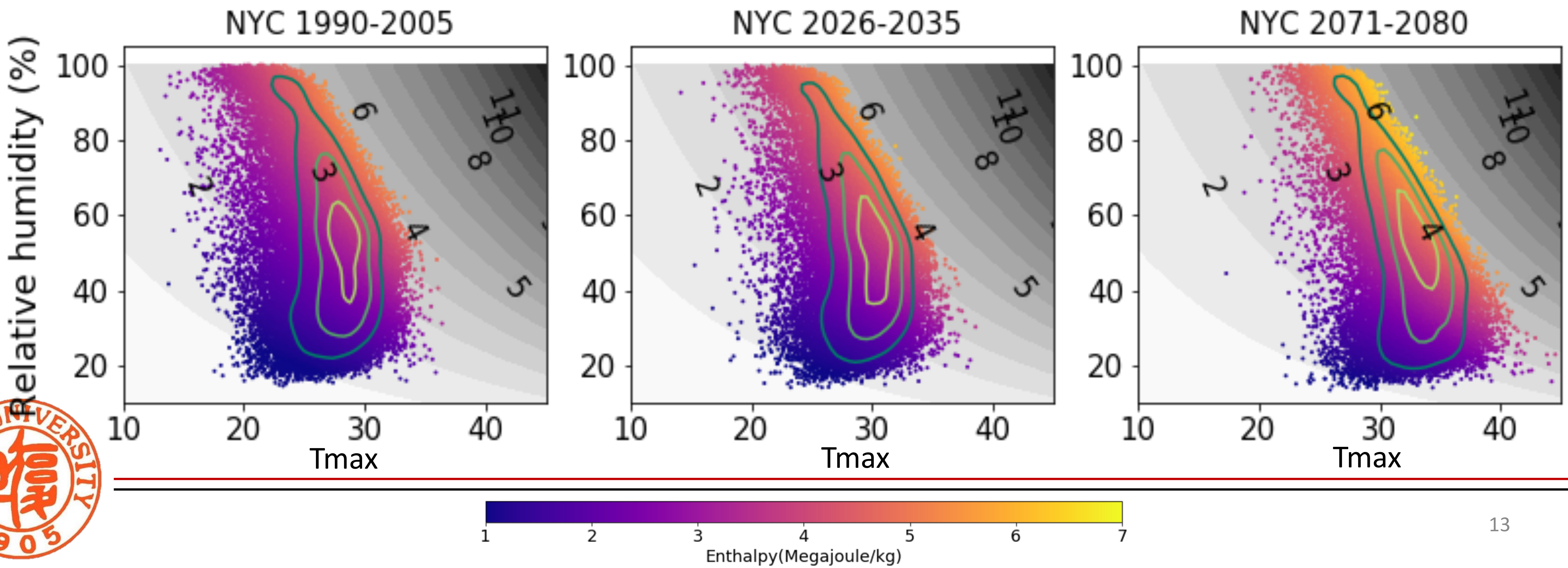
New York City July



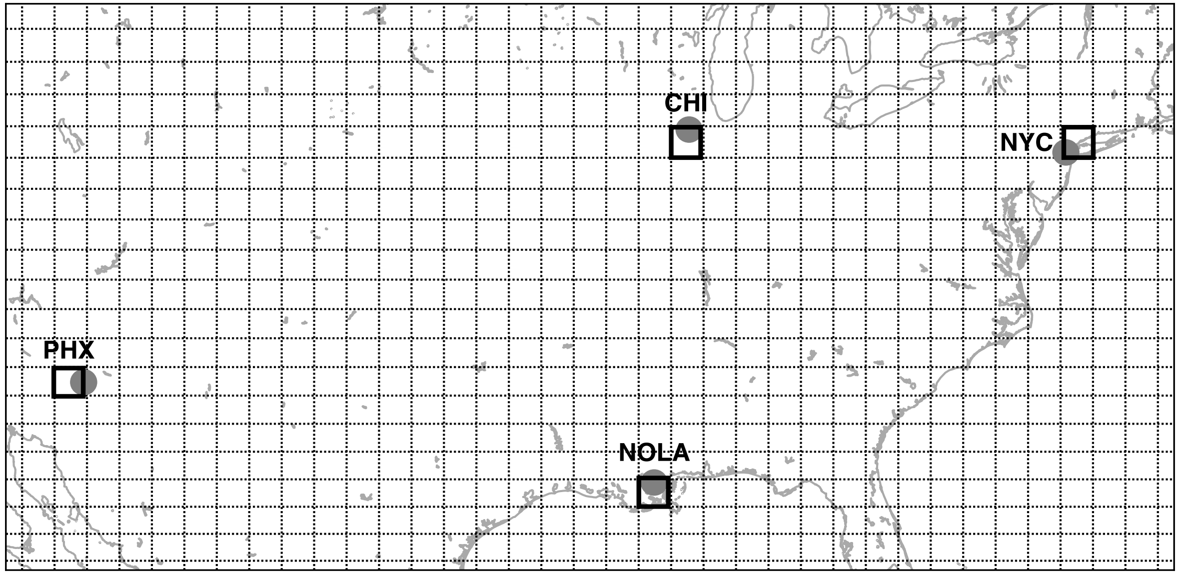
Evolving Joint Distributions between Tmax and Relative Humidity (RH)

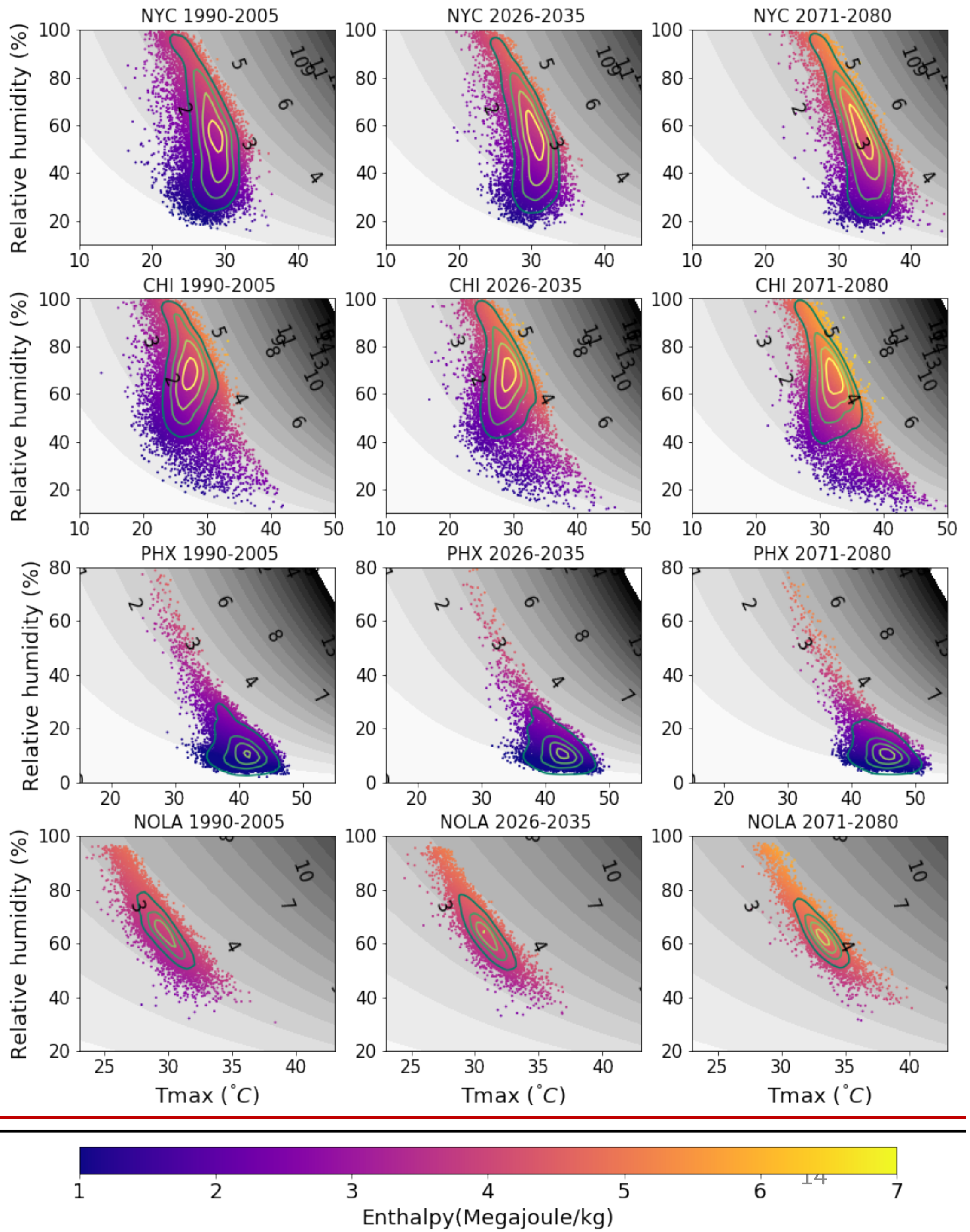
$$\text{Enthalpy} = \underbrace{Tmax \times C_p}_{\text{Sensible heat}} + \underbrace{RH \times \frac{e_{sat} \times 0.622}{P - e_{sat}} \times L}_{\text{Latent heat}}$$

New York City July



- NYC: New York City, humid temperate climate
- CHI: Chicago, hot-summer humid continental climate
- PHX: Phoenix, hot-desert climate
- NOLA: New Orleans, humid subtropical climate



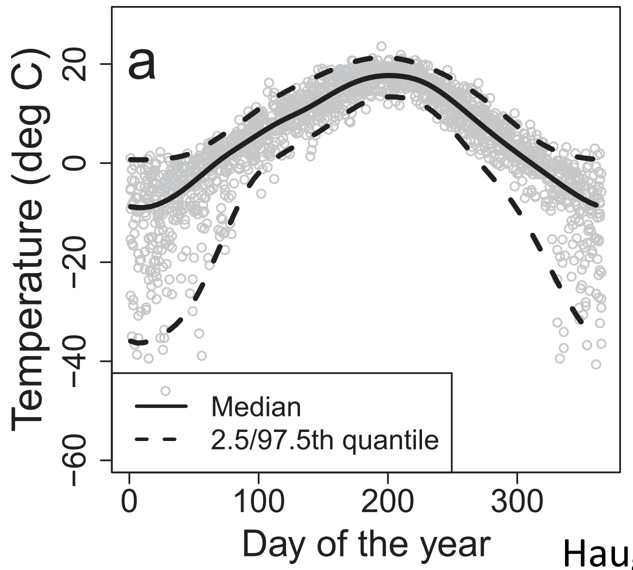


How to predict the evolving distribution of RH conditional on Tmax?

Quantile Regression

Multi-linear regression: $\hat{\boldsymbol{Y}} = \boldsymbol{X}\,\hat{\beta}$

Quantile regression: $\hat{\boldsymbol{Y}}_{\tau} = \boldsymbol{X}\hat{\beta}_{\tau}$



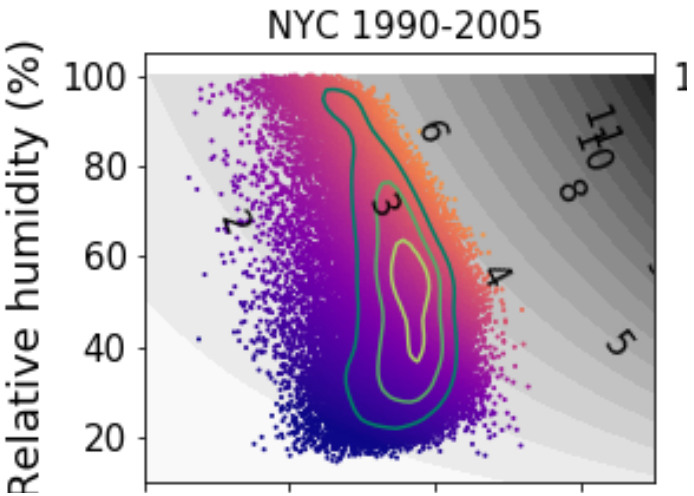
Haugen et al. (2018)

Advantages of quantile regression：

- Without assuming any particular statistical form for the distribution
- Allows any changes in shape of distribution

Emulating the distribution of RH on Tmax through Quantile Regression

$$\widehat{RH}_\tau(Tmax) = \theta + \gamma\,\underbrace{(Tmax - T_0)_+}_{\text{Kink function}} + \sum_{j=1}^{m} \eta_j\,\underbrace{K_j(Tmax)}_{\text{Cubic Spline function}} \tag{1}$$



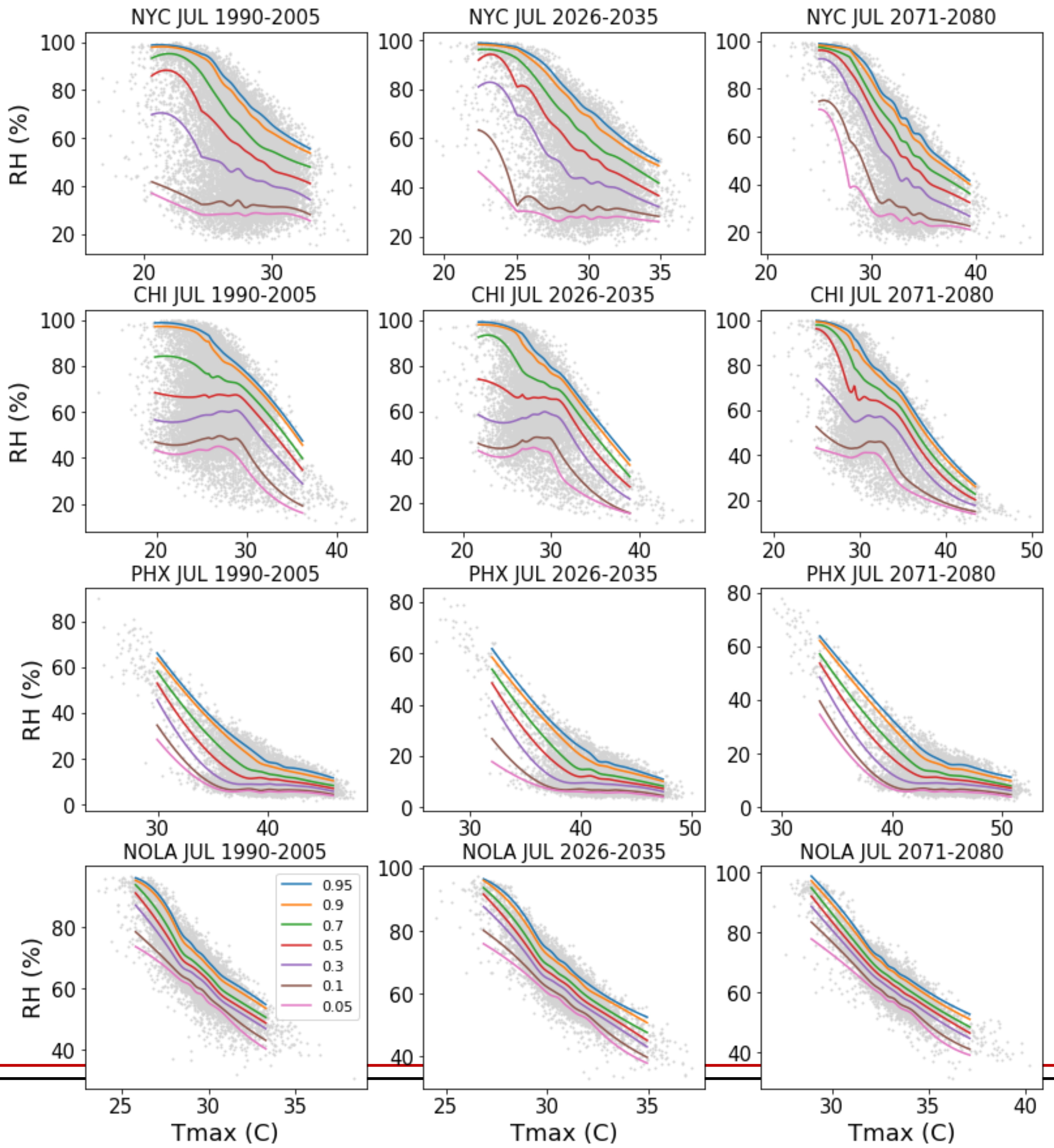
$$(Tmax - T_0)_+ = \begin{cases} Tmax - T_0, & Tmax \geq T_0 \\ 0, & Tmax < T_0 \end{cases}$$

Quantile regression solves the following minimization problem:

$$\tau \sum_{i=1}^{n} \left(RH_i - \widehat{RH}_\tau(Tmax_i)\right)_+ + (1-\tau) \sum_{i=1}^{n} \left(\widehat{RH}_\tau(Tmax_i) - RH_i\right)_+$$

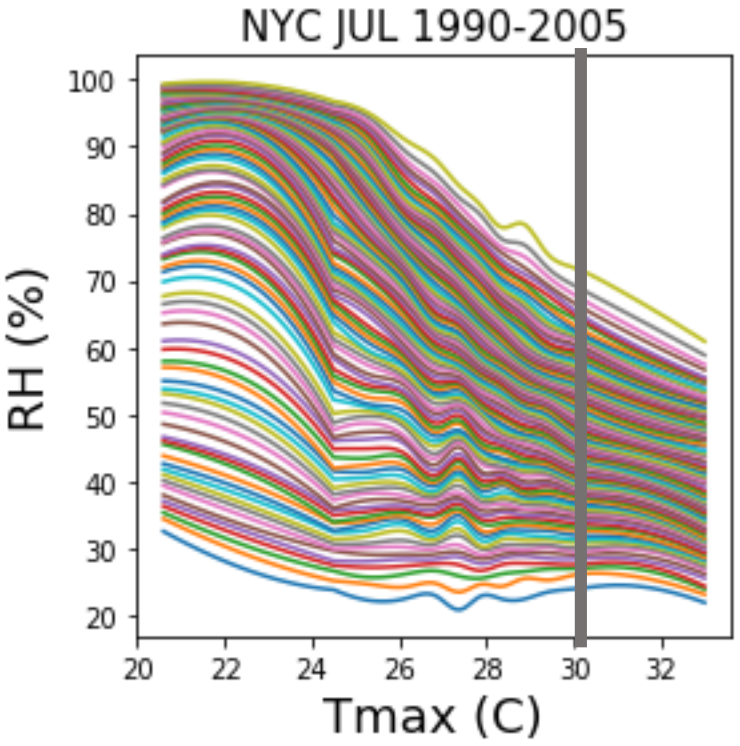
Lines: Estimated quantiles by the Quantile Regression Model (1)

Dots: raw data from CESM LENS

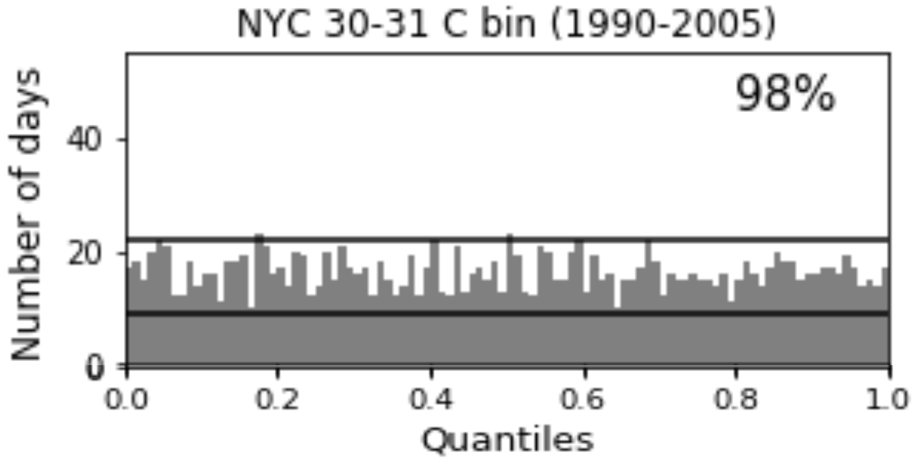


Model evaluation

Empirical inverse quantiles + cross validation of the RH data in a small Tmax interval (1 degree C)

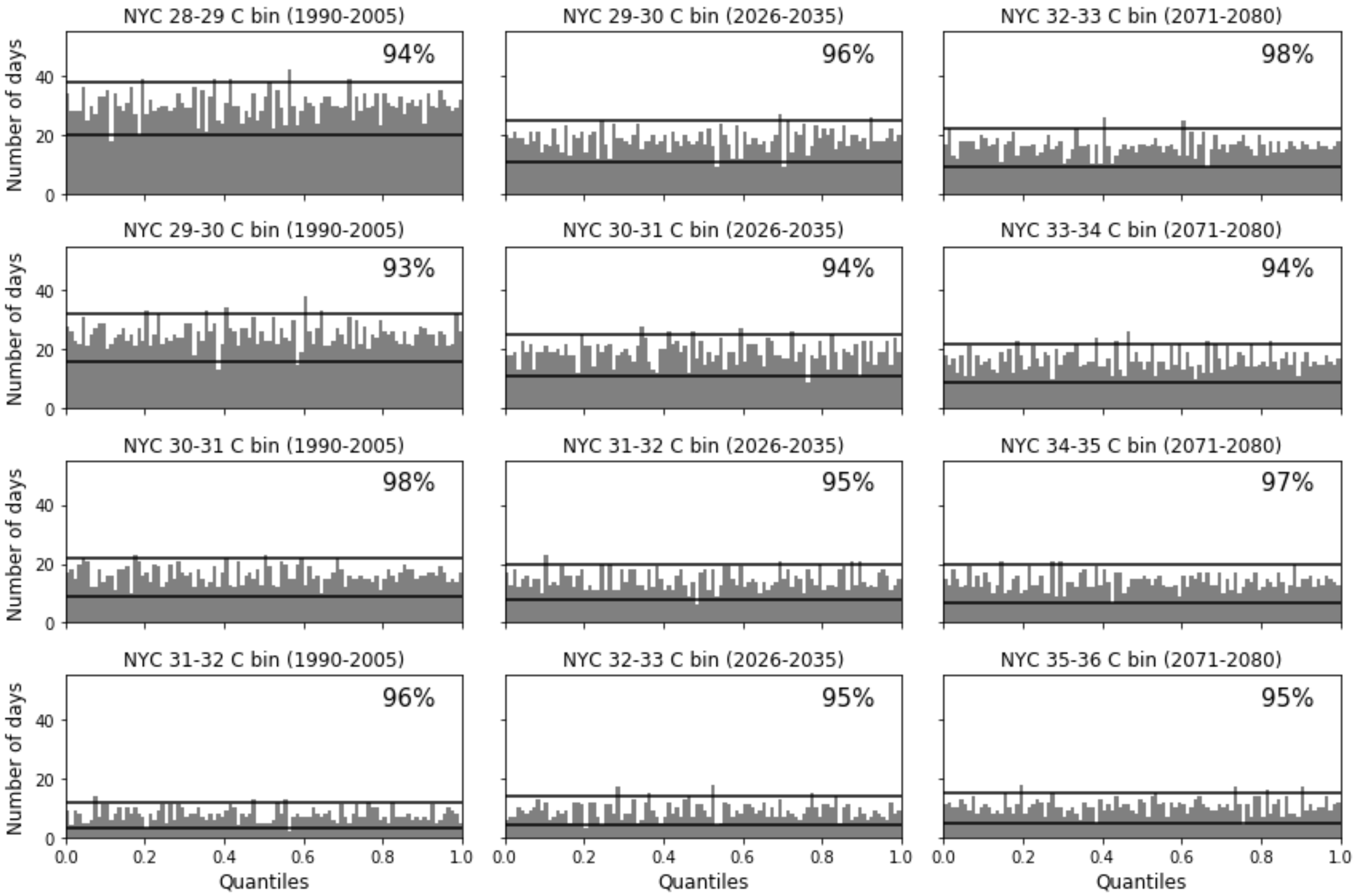


99 quantiles from 0.01 to 0.99



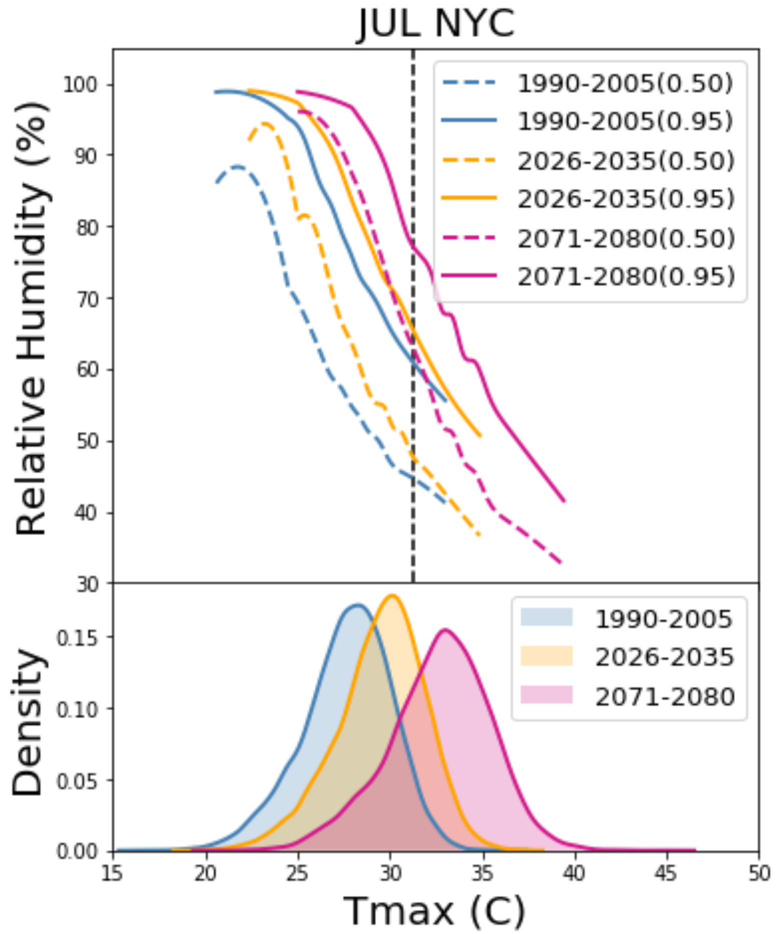
the solid lines mark the 0.025 (lower line) and 0.975 (upper line) of the binomial distribution the counts should follow if the model is accurate

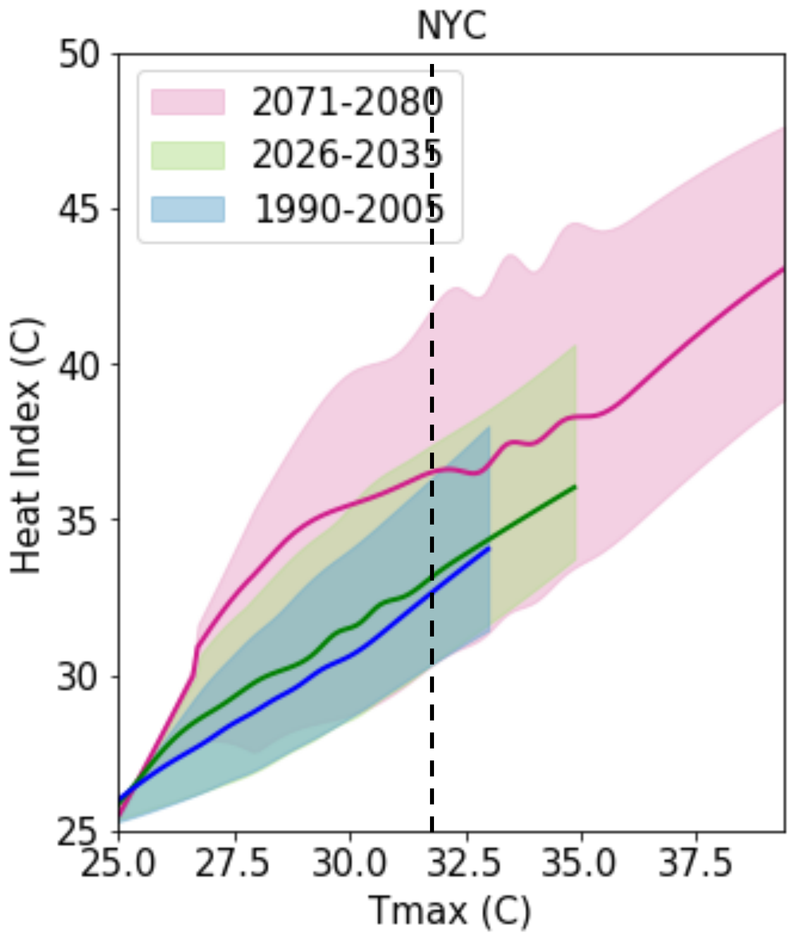
Model evaluation



At fixed temperature (e.g. 95th quantile in 1990-2005)

Increases in RH will amplify the heat stress in a future day when climate gets warmer.

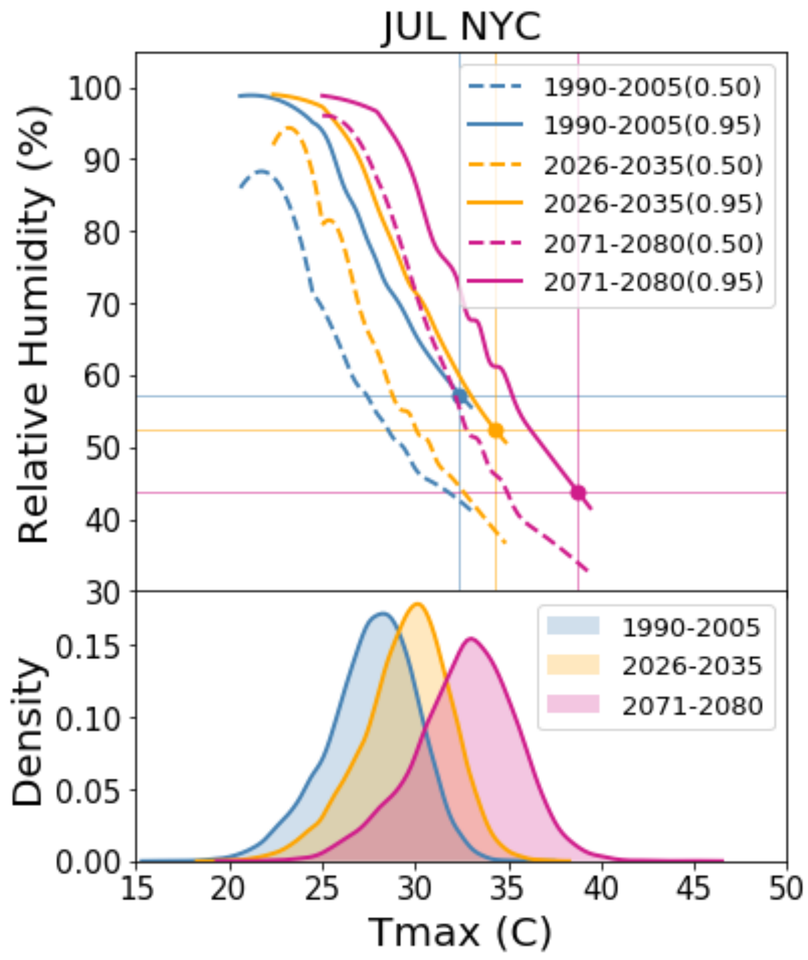


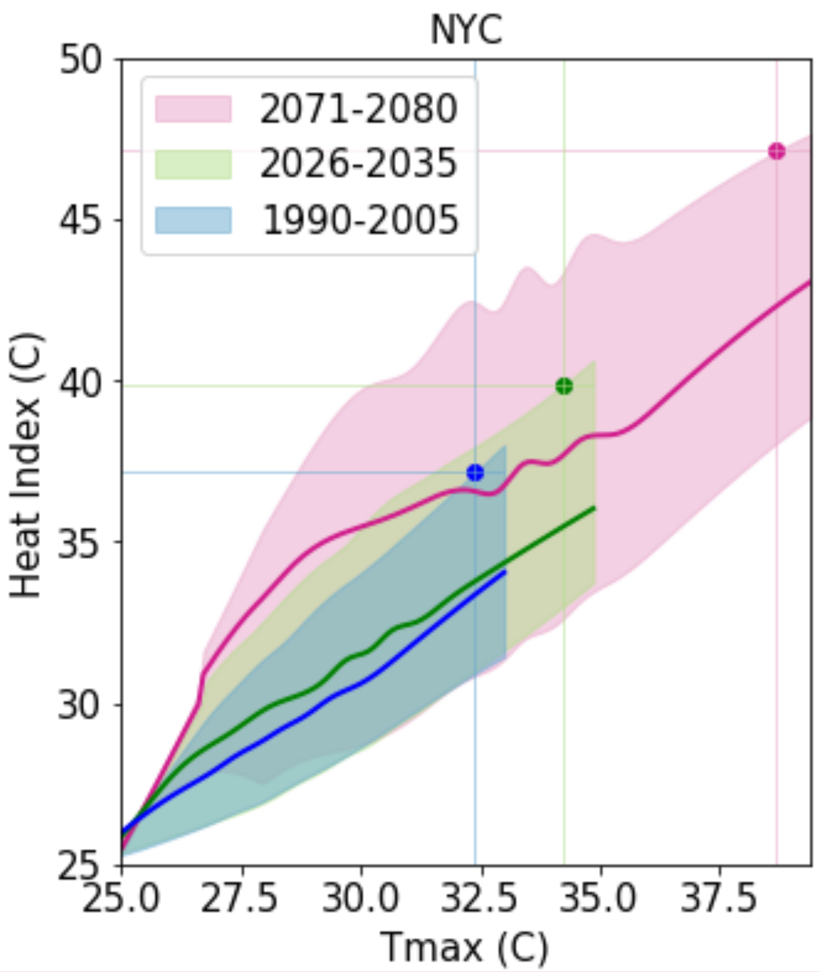


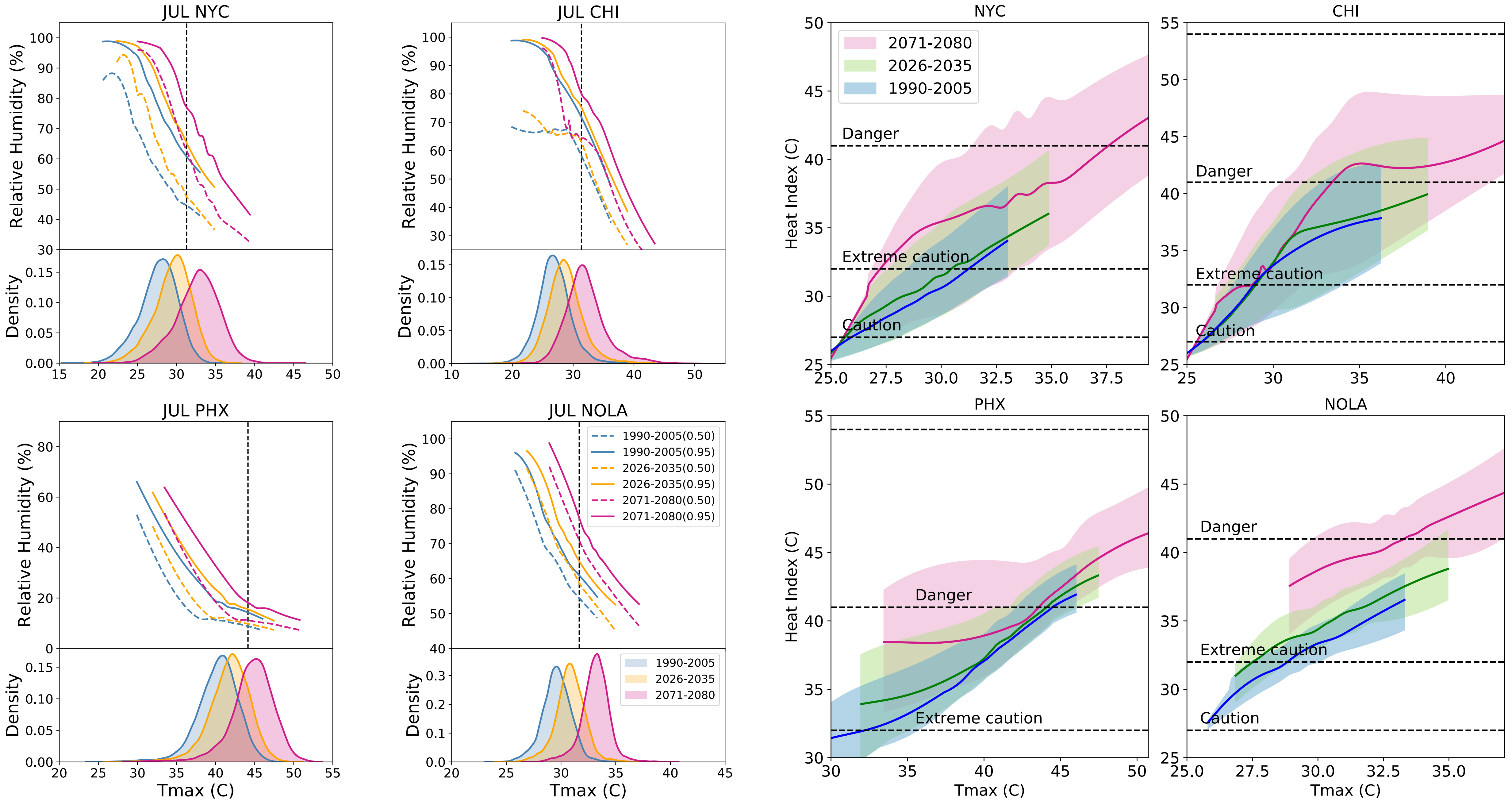
Heat Index: a metric measures intensity of heat stress considering both temperature and relative humidity (Rothfusz, 1990)

At fixed quantile of temperature (e.g. 95th quantile in each period)

In a warming climate, despite a modest decrease in RH, heat stress will tend to increase faster than temperature alone would indicate






JUL NYC
JUL CHI
JUL PHX
JUL NOLA
Relative Humidity (%)
Density
Tmax (C)
1990-2005(0.50)
1990-2005(0.95)
2026-2035(0.50)
2026-2035(0.95)
2071-2080(0.50)
2071-2080(0.95)
1990-2005
2026-2035
2071-2080
NYC
CHI
PHX
NOLA
Heat Index (C)
Danger
Extreme caution
Caution

Outline

- Part I Emulate the evolving distribution of relative humidity conditional on daily maximum temperature in a warming climate

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Wet bulb globe temperature

1. It is measurable

T_g
Globe temperature

T_{nw}
(nature)
wet-bulb temperature

T_a
(dry-bulb)
temperature

https://www.airmet.com.au/questemp-qt-34-heat-stress-monitor

2. Has been widely used in health guidelines

Table 1. ISO 7243: WBGT reference values

Metabolic rate (Wm^{-2})	WBGT reference value	
	Acclimatized (°C)	Not acclimatized (°C)
Resting $M < 65$	33	32
$65 < M < 130$	30	29
130 < M < 200 ~ walking	28	26
$200 < M < 260$	25 (26)*	22 (23)*
$M > 260$	23 (25)*	18 (20)*

The values given have been established allowing for a maximum rectal temperature of 38°C for the persons concerned.
*: Figures in brackets refer to sensible air movement.

Parsons (2006)

Wet bulb globe temperature

Wet-bulb globe temperature (WBGT):

$$WBGT = 0.7\times T_w + 0.2\ T_g + 0.1\times T_a$$

Simplified WBGT (appropriate for shaded conditions):

$$WBGT^* \approx 0.7\times T_w + 0.3\ \times T_a$$

Wet bulb temperature

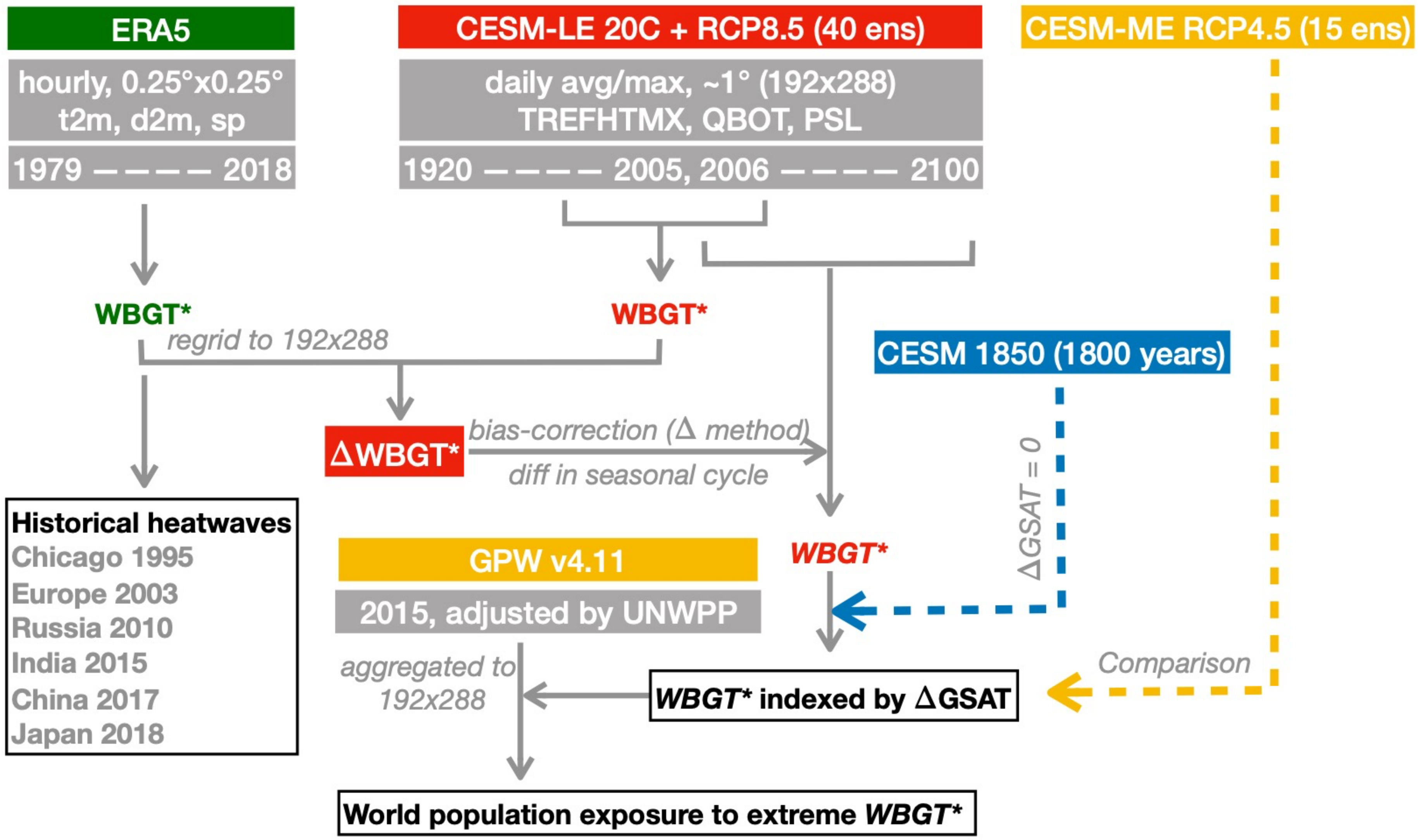
- Empirical relationship based on psychrometric chat (Stull 2011) ~ limited by ranges of observations
- Wet bulb potential temperature (DAVIES-JONES 2008) ~ designed for severe weather forecast
- Isobaric wet bulb temperature (Li et al. 2020) ~ the cooling of body through perspiration √

$$\underbrace{C_{pa}T_w + L_v q_s(T_w)}_{\text{Enthalpy of saturated moist air}} = \underbrace{C_{pa}T + L_v q}_{\text{Enthalpy of initial moist air}}$$

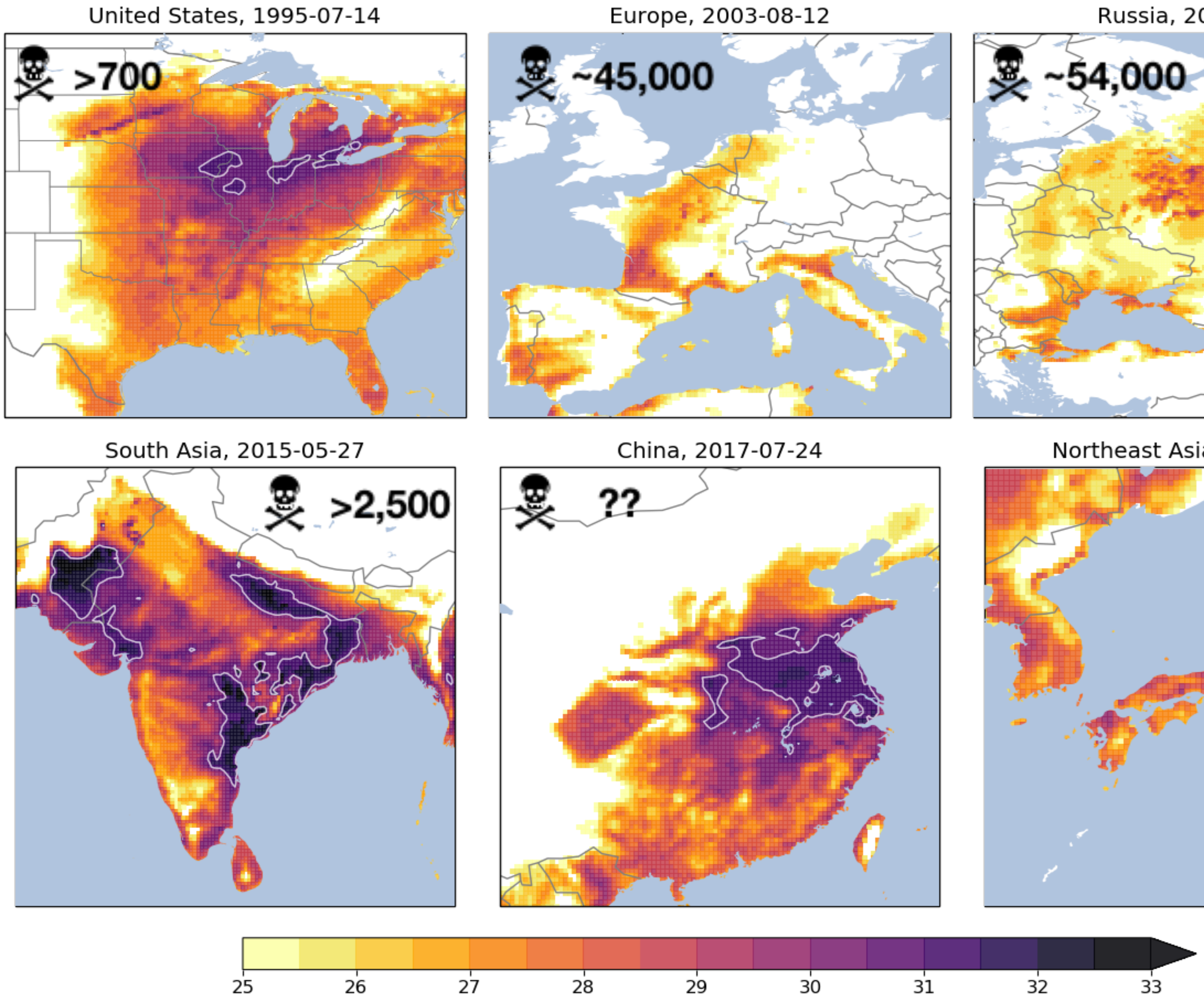
Enthalpy of saturated moist air

Enthalpy of initial moist air

Data and methods

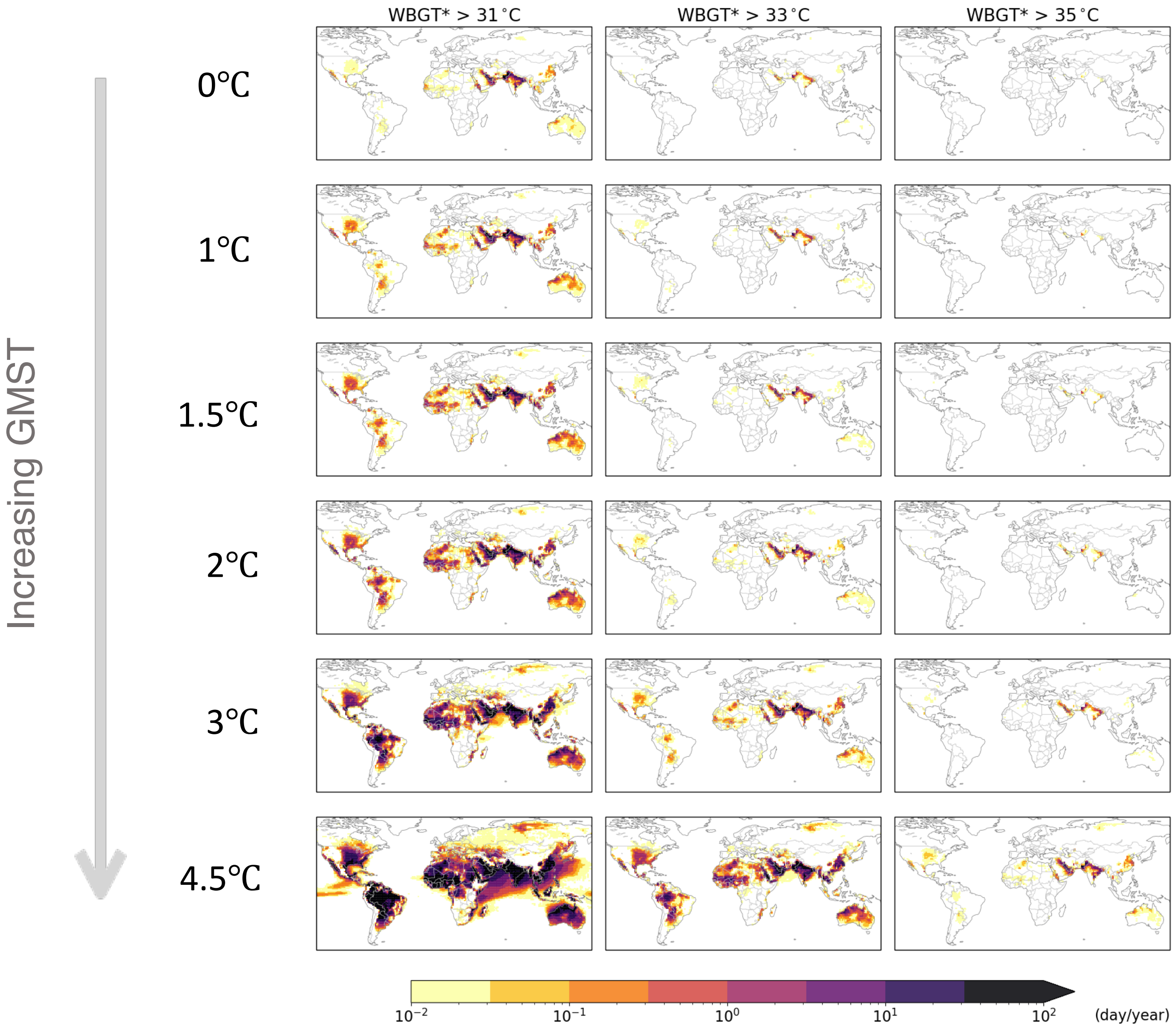


What is the historical heat stress like, measured by WBGT?


United States, 1995-07-14
>700
Europe, 2003-08-12
~45,000
Russia, 2010-08-06
~54,000
South Asia, 2015-05-27
>2,500
China, 2017-07-24
??
Northeast Asia, 2018-07-22
>180
25
26
27
28
29
30
31
32
33

What is the implication for heat stress, measured by WBGT, under the different level of global warming?

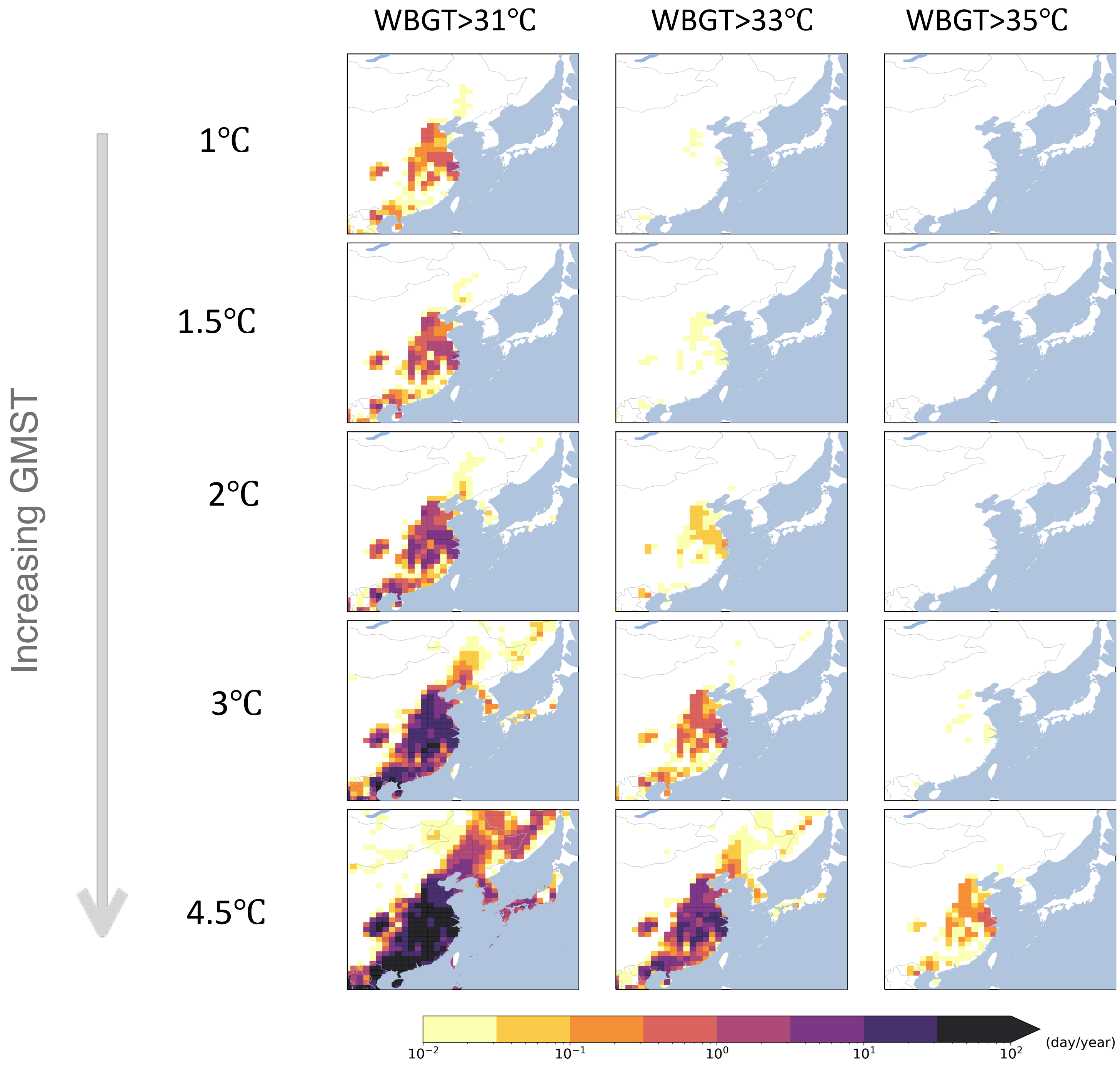
Changes in Frequency of Exceedance with $\Delta GMST$



31 ℃ ~ the peak of 1995 Chicago Heatwave

33 ℃ ~ humans maintain a normal core body temperature at resting

35 ℃ ~ maximum value calculated from historical observations

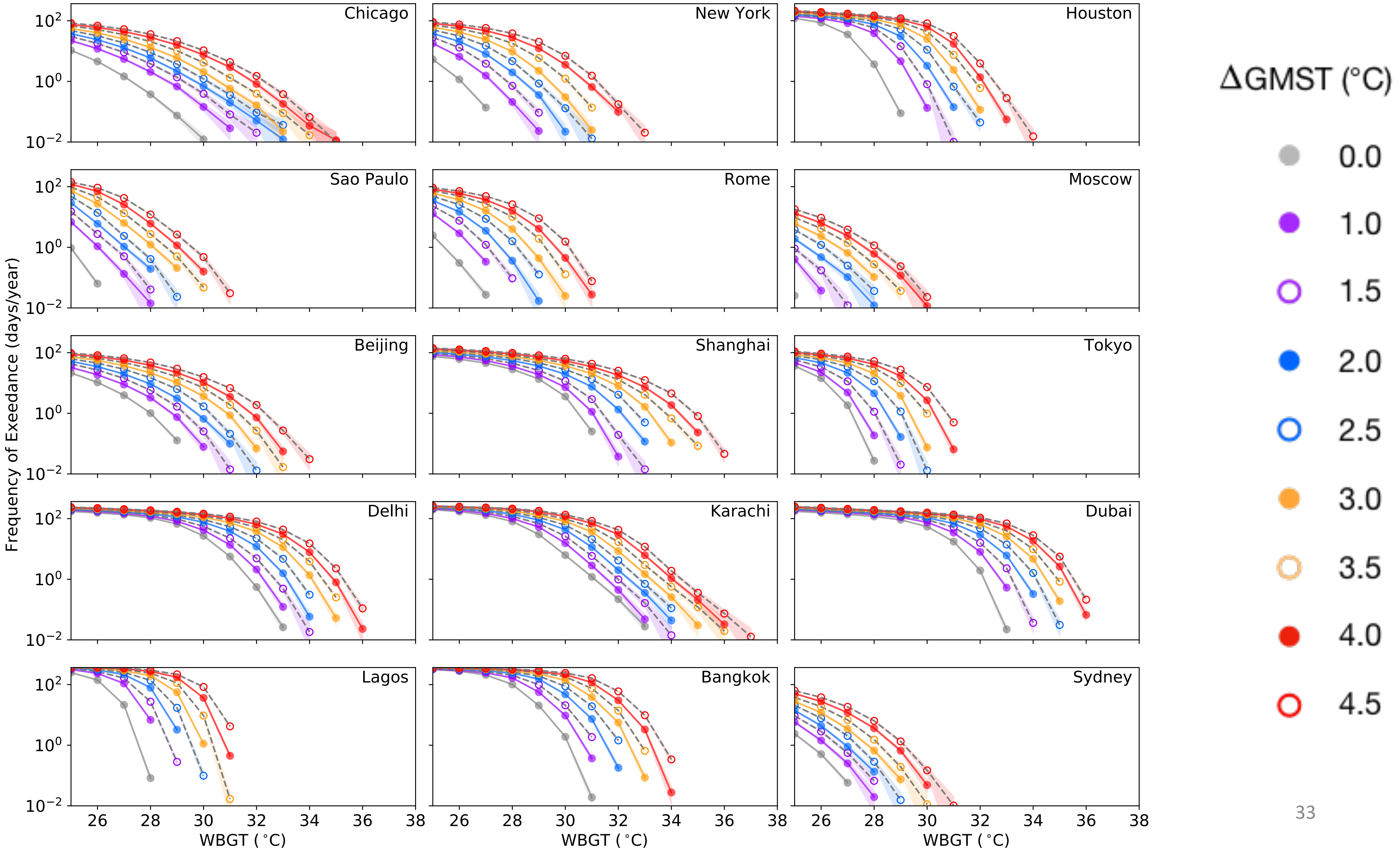


31 ℃ ~ the peak of 1995 Chicago Heatwave

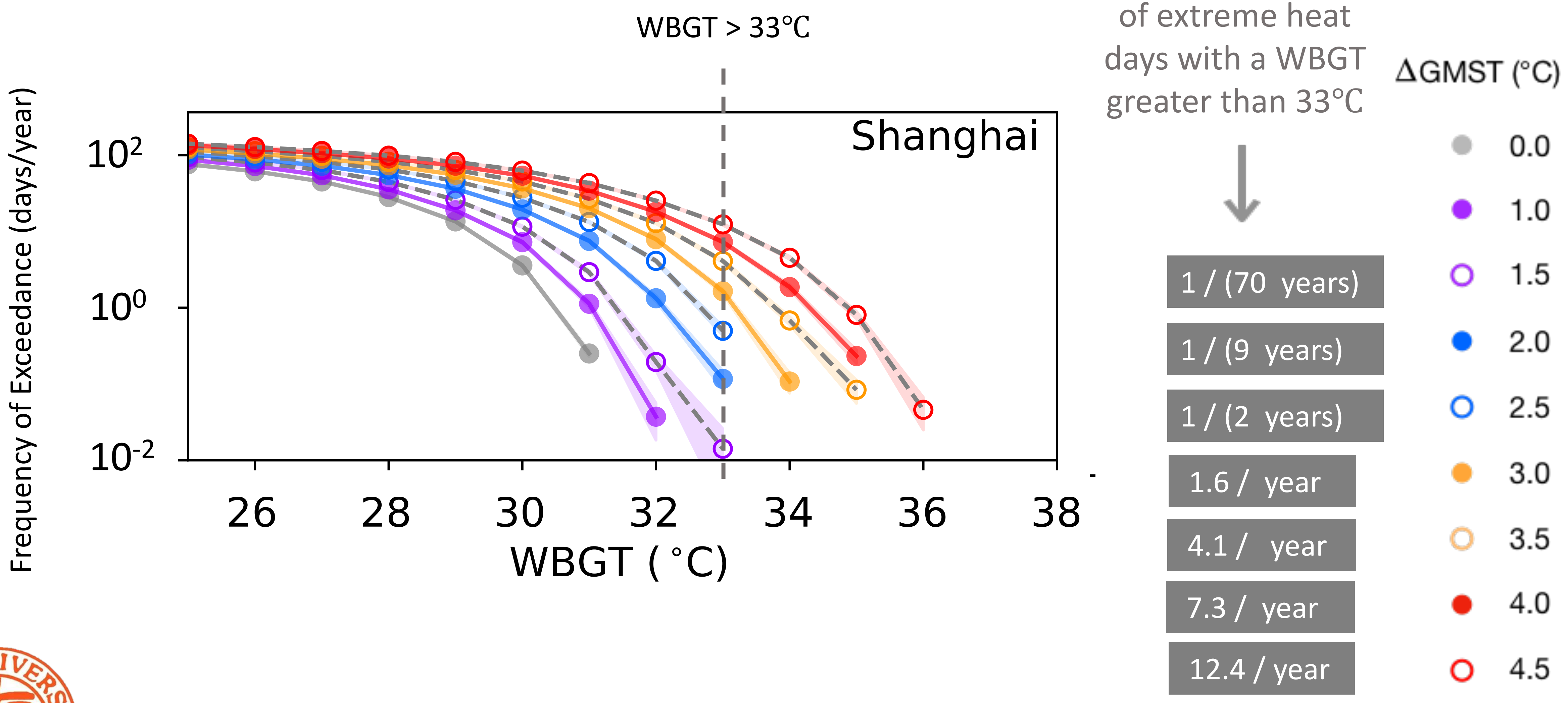
33 ℃ ~ humans maintain a normal core body temperature at resting

35 ℃ ~ maximum value calculated from historical observations

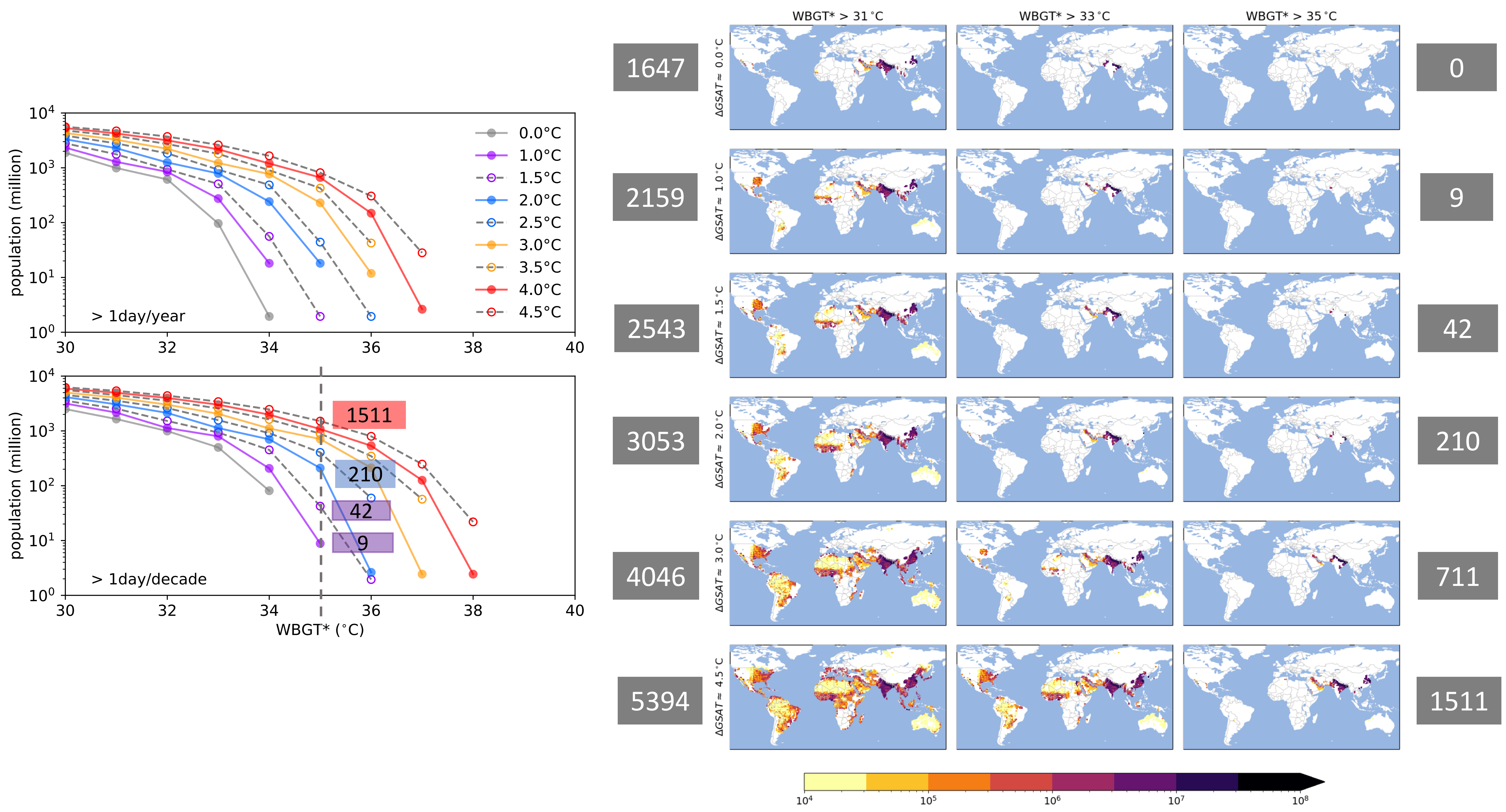
Changes in Frequency of Exceedance with $\Delta GMST$ (Selected Sites)



Changes in Frequency of Exceedance with $\Delta GMST$ (Shanghai)



World Population Exposure to Extreme WBGT



Key Takeaways

- Humidity is an important contributor to the impact of heat stress:
  - At fixed temperature, increases in RH will amplify the heat stress in a future day
  - In a warming climate, despite a modest decrease in RH, heat stress will tend to increase faster than temperature alone would indicate
- The frequency of heat-humidity extremes, measured using WBGT, will increase dramatically in response to global warming
- The benefit of limiting ΔGMST to 1.5°C rather than 2°C is evident in reducing world population exposure to life threatening heat stress.

FUDAN UNIVERSITY

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IRDR
Integrated Research on Disaster Risk

Risk Interconnectivity and Governance on WEather/Climate Extremes Impact and Public HEalth

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Recruitment

Position: Ph.D candidate, Postdoc

Research field： impact of weather/climate extremes on human health

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Thank You!

- J. Yuan*, M. I. Stein, and R. E. Kopp (2020). The evolving distribution of relative humidity conditional upon daily maximum temperature. Journal of Geophysical Research-Atmospheres. https://doi.org/10.1029/2019JD032100

- D. Li*, J. Yuan*, and R. E. Kopp (2020). Escalating Global Exposure to Compound Heat-Humidity Extremes with Warming. Environmental Research Letters. https://doi.org/10.1088/1748-9326/ab7d04

Convert sea level pressure to surface pressure

$$P = \rho RT \qquad (1)$$

$$dP = -\rho g dz \qquad (2)$$

$$dT = \Gamma dz \qquad (3)$$

(1) + (2) :

$$dP = -\frac{g}{RT} P\, dz \longrightarrow dlnP = -\frac{g}{RT} dz \qquad (4)$$

(3) + (4) :

$$dlnP = -\frac{g}{R\Gamma} \times \frac{dT}{T} = -\frac{g}{R\Gamma} dlnT$$

$$ln\left(\frac{Ps}{Psl}\right) = -\frac{g}{R\Gamma} ln\left(\frac{Ts}{Tsl}\right)$$

$$Ps = Psl \times \left(1 - \left(\frac{\Gamma z}{Ts}\right)\right)^{\frac{g}{R\Gamma}}$$