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

Jiacan Yuan\textsuperscript{1,3}
Michael I. Stein\textsuperscript{2}, Robert E. Kopp\textsuperscript{3}, Dawei Li\textsuperscript{3,4}

1. Department of Atmospheric and Oceanic Sciences, Fudan University, CN
2. Department of Statistics, University of Chicago, US
3. Department of Earth and Planetary Sciences, Rutgers University, US
4. Department of Geosciences, University of Massachusetts Amherst, US
Motivation
Motivation

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

Figure 17 (a) shows that, during the decade 2001–2010, more than 370,000 lives were lost owing to extreme climate conditions, including heat, cold, drought, storms and floods, marking an overall increase of +20 per cent with respect to the previous decade, 1991–2000. This increase is due mainly to the dramatic increase in the total reported deaths arising from heatwaves in 2003 and 2010. In fact, in 1991–2000, total

Figure 16. Number of natural disasters, 1980–2010 (source: MunichRe NatCatSERVICE)

Figure 17. Impact of extreme events during 2001–2010 compared with 1991–2000: (a) total number of lives lost; and (b) economic losses in millions of US$. The percentages above the bars indicate the change in losses during 2001–2010 compared to 1991–2000 (data source: EM-DAT/CRED).

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

Figure 4. Projected changes in 50-year return values of TXx and TNn. (A-D) The CMIP6 multi-model median changes in the 50-year return values of TXx and TNn in 2071-2100 under the lower SSP1-2.6 and higher SSP5-8.5 scenarios relative to 1985-2014. (E-F) The corresponding changes at 2.0°C and 4.0°C global warming above preindustrial relative to the 1.0°C global warming. 

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

**Low humidity**
- At higher elevations in the mountains
- In the desert
- Sweat evaporates into the air, which cools the body.

**High humidity**
- In a rainforest or jungle
- At the beach or near the ocean
- It's harder for sweat to evaporate because the air is already so moist. The body doesn't cool down as easily. That's why it feels hotter.

US National Weather Service
Over land, specific humidity increases while relative humidity (RH) decreases.
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
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
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

NYC 1990-2005

NYC 2026-2035

NYC 2071-2080

Relative humidity (%)

Tmax

Relative humidity (%)

Tmax

Relative humidity (%)

Tmax

Enthalpy (Megajoule/kg)
Evolving Joint Distributions between Tmax and Relative Humidity (RH)

Enthalpy = $T_{max} \times C_p + RH \times \frac{e_{sat} \times 0.622}{P - e_{sat}} \times L$

- Sensible heat
- 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: \( \hat{Y} = X \hat{\beta} \)

Quantile regression: \( \hat{Y}_\tau = X \hat{\beta}_\tau \)

Advantages of quantile regression:

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

Figure 3: Illustration of results of our quantile estimation procedure using the 50-member CESM ensemble. The figure shows ensemble average daily temperatures for the year 1850 for the three representative locations a–c plotted in October 2018. The solid line represents the median daily temperature, and dashed lines show the 2.5% and 97.5% quantiles estimated by our procedure. The locations of the points outside of the 0.025 and 0.975 quantile curves are fairly evenly spread across day of year (notwithstanding the sizes of the exceedances), suggesting that these estimated quantile curves capture the seasonal cycle in CESM daily temperatures for three latitude locations. These examples show the benefit of explicitly modeling the seasonal cycle in variability that are well represented by our smooth estimates. Relevant features that are captured include an asymmetry that are well represented by our smooth estimates.

Figure 4 (not shown): Shows initial and final distributions in our example locations for aggregated 15-day periods in winter and summer. Regarding the spatial characteristics of temperature spread (variability) from early to late winter, such as the decrease in winter temperatures, but the distributions also change in terms of standard deviations and skewness. Means uniformly shift to warmer temperatures, but the distributions also change in terms of standard deviations and skewness.

Figure 5 (not shown): Shows how the predictor matrix \( X \) refers to a unique value of a variable, each column corresponds to a basis function, and each row \( t \) has 32 columns, each corresponding to one basis function, and 365 rows. To get a confidence interval for each entry of the predictor matrix, we use 32 basis functions in total, including an intercept term. We then fit each quantile of temperature using this matrix, we construct our temperature model. As an example of a typical model fit, we show in Appendix B details about uncertainty quantification. As an example of a typical model fit, we show in Appendix B details about uncertainty quantification.

Figure 6 (not shown): Shows the seasonal fit rather than that of the long-term trend. The seasonal cycle in CESM daily temperatures for three representative locations a–c are plotted in October 2018. To facilitate comparison with previous studies, we first compare the initial and final time windows 1850–64 and 2086–2100. Means uniformly shift to warmer temperatures, but the distributions also change in terms of standard deviations and skewness.

Regarding the spatial characteristics of temperature variability, such as the decrease in winter temperatures, but the distributions also change in terms of standard deviations and skewness. Means uniformly shift to warmer temperatures, but the distributions also change in terms of standard deviations and skewness.

Figure 7 (not shown): Shows the seasonal fit rather than that of the long-term trend. The seasonal cycle in CESM daily temperatures for three representative locations a–c are plotted in October 2018. To facilitate comparison with previous studies, we first compare the initial and final time windows 1850–64 and 2086–2100. Means uniformly shift to warmer temperatures, but the distributions also change in terms of standard deviations and skewness.

Fig. 3. Haugen et al. (2018)
Emulating the distribution of RH on Tmax through Quantile Regression

\[
\hat{RH}_\tau(T_{max}) = \theta + \gamma (T_{max} - T_0)_+ + \sum_{j=1}^{m} \eta_j K_j(T_{max})
\]

Kink function \hspace{2cm} Cubic Spline function

\[
(T_{max} - T_0)_+ = \begin{cases} T_{max} - T_0, & T_{max} \geq T_0 \\ 0, & T_{max} < T_0 \end{cases}
\]

Quantile regression solves the following minimization problem:

\[
\tau \sum_{i=1}^{n} \left( RH_i - \hat{RH}_\tau(T_{max_i}) \right)_+ + (1 - \tau) \sum_{i=1}^{n} \left( \hat{RH}_\tau(T_{max_i}) - RH_i \right)_+
\]
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

GOOD!
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. 95\textsuperscript{th} 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.
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
Wet bulb globe temperature

1. It is measurable

\[ T_g \]  
Globe temperature

\[ T_{nw} \]  
(wet-bulb temperature)

\[ T_a \]  
(dry-bulb) temperature

2. Has been widely used in health guidelines

Table 1. ISO 7243: WBGT reference values

<table>
<thead>
<tr>
<th>Metabolic rate (Wm(^{-2}))</th>
<th>WBGT reference value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acclimatized (°C)</td>
</tr>
<tr>
<td>Resting ( M &lt; 65 )</td>
<td>33</td>
</tr>
<tr>
<td>( 65 &lt; M &lt; 130 )</td>
<td>30</td>
</tr>
<tr>
<td>( 130 &lt; M &lt; 200 ) ~ walking</td>
<td>28</td>
</tr>
<tr>
<td>( 200 &lt; M &lt; 260 )</td>
<td>25 (26)*</td>
</tr>
<tr>
<td>( M &gt; 260 )</td>
<td>23 (25)*</td>
</tr>
</tbody>
</table>

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):

\[ WBGT = 0.7 \times T_w + 0.2 \times T_g + 0.1 \times T_a \]

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

\[
\frac{C_{pa} T_w + L_v q_s(T_w)}{C_{pa} T + L_v q} = \frac{C_{pa} T_w}{C_{pa} T}
\]

Enthalpy of saturated moist air  Enthalpy of initial moist air
Data and methods

ERA5
- hourly, 0.25°x0.25°
- t2m, d2m, sp
- 1979 ———— 2018

CESM-LE 20C + RCP8.5 (40 ens)
- daily avg/max, ~1° (192x288)
- TREFHTMX, QBOT, PSL
- 1920 ———— 2005, 2006 ———— 2100

CESM-ME RCP4.5 (15 ens)

WBGT* regrid to 192x288

CESM 1850 (1800 years)

Historical heatwaves
- Chicago 1995
- Europe 2003
- Russia 2010
- India 2015
- China 2017
- Japan 2018

GPW v4.11
- 2015, adjusted by UNWPP
- aggregated to 192x288

△WBGT* bias-correction (△ method)
- diff in seasonal cycle

△GSAT = 0

Comparison

WBGT* indexed by △GSAT

World population exposure to extreme WBGT*
What is the historical heat stress like, measured by WBGT?
What is the implication for heat stress, measured by WBGT, under the different level of global warming?
Changes in Frequency of Exceedance with $\Delta GMST$

$0^\circ C$

$1^\circ C$

$1.5^\circ C$

$2^\circ C$

$3^\circ C$

$4.5^\circ C$

$31^\circ C$ ~ the peak of 1995 Chicago Heatwave

$33^\circ C$ ~ humans maintain a normal core body temperature at resting

$35^\circ C$ ~ maximum value calculated from historical observations
1 °C
1.5 °C
2 °C
3 °C
4.5 °C

31 °C ~ the peak of 1995 Chicago Heatwave

33 °C ~ humans maintain a normal core body temperature at resting

35 °C ~ maximum value calculated from historical observations

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

$\Delta GMST$ ($^\circ$C)

- 0.0
- 1.0
- 1.5
- 2.0
- 2.5
- 3.0
- 3.5
- 4.0
- 4.5

Frequency of Exceedance (days/year)

WBGT ($^\circ$C)
Changes in Frequency of Exceedance with $\Delta GMST$ (Shanghai)

Frequency of extreme heat days with a WBGT greater than 33°C

- 1 / (70 years)
- 1 / (9 years)
- 1 / (2 years)
- 1.6 / year
- 4.1 / year
- 7.3 / year
- 12.4 / year

Frequency of Exceedance (days/year)

WBGT > 33°C

WBGT (°C)

Frequency of Exceedance (days/year)
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.
Risk Interconnectivity and Governance on WEather/Climate Extremes Impact and Public HElth

极端天气/气候事件与人体健康风险互联与治理国际卓越中心
Recruitment

Position: Ph.D candidate, Postdoc

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

Contact: Jiacan Yuan (袁嘉灿) jcyuan@fudan.edu.cn
Thank You!


Convert sea level pressure to surface pressure

\[ P = \rho RT \]  \hspace{1cm} (1)

\[ dP = -\rho g \, dz \]  \hspace{1cm} (2)

\[ dT = \Gamma \, dz \]  \hspace{1cm} (3)

(1) + (2) : \hspace{1cm} \frac{dP}{RT} = -\frac{g}{RT} \, P \, dz \hspace{1cm} \Rightarrow \hspace{1cm} d\ln P = -\frac{g}{RT} \, dz \hspace{1cm} (4)

(3) + (4) : \hspace{1cm} d\ln P = -\frac{g}{RT} \Gamma \times \frac{dT}{T} = -\frac{g}{RT} \, d\ln T

\[ \ln \left( \frac{P_s}{P_{sl}} \right) = -\frac{g}{RT} \ln \left( \frac{T_s}{T_{sl}} \right) \]

\[ P_s = P_{sl} \times \left( 1 - \left( \frac{\Gamma z}{T_s} \right) \right)^{\frac{g}{RT}} \]