Ubiquitous Increase of Extreme Heat Stress under Global Warming

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Record-Breaking Heatwave around the World

Global heat wave flashpoints since May 2018

- **Canada**: Up to 70 deaths in Quebec, Canada, from the heat
- **Sweden**: Record fires reach Arctic Circle
- **Pakistan**: Heat wave kills around 69 people in May in Karachi
- **Japan**: Record heat, 118 dead, thousands hospitalised
- **United States**: California/Western US fires, at least eight dead
- **UK and Europe**: Heat wave and drought
- **Greece**: Fires, 83 dead
- **South Korea**: Heat wave, 23 dead

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**The Guardian**

Heatwave seems to make manmade climate change real for Americans

The record-breaking high temperatures across much of North America appear to be shaping people’s thinking, a survey finds.

**Temperatures hit new highs in European heatwave**

Records are usually broken by tenths of a degree, but last week’s heatwave was startling.

**BBC NEWS**

Japan heatwave declared natural disaster as death toll mounts

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113 degrees in France: why Europe is so vulnerable to extreme heat

All-time temperature records have been broken in the heat wave sweeping the continent.

**France 40C heatwave could break June records**

Extreme heat is a vivid climate change signal

The length, intensity, and frequency of heat waves are on the rise, and Europe’s soaring weather this week comports with what scientists expect as the climate changes, though it will take some time to tease out the specific extent of humanity’s role in the current wave.
RegCM4 Simulations under CORDEX-CORE Framework

- Model: Regional Climate Model ver. 4 (RegCM4)
- ICBC: HadGCM2-ES & MPI ESM & NorESM driven by RCP8.5 scenario
Selection of 0.48°C & 2°C & 3°C Warming Periods

- Individual GCMs have their own warming phase in response to emission forcing

<table>
<thead>
<tr>
<th>GCMs</th>
<th>0.48°C Warming</th>
<th>2.0°C Warming</th>
<th>3°C Warming</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPI-ESM-MR</td>
<td>1978</td>
<td>2038</td>
<td>2060</td>
</tr>
<tr>
<td>NorESM1-M</td>
<td>1991</td>
<td>2048</td>
<td>2073</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>1997</td>
<td>2036</td>
<td>2055</td>
</tr>
</tbody>
</table>
Bias Correction: Quantile Mapping

- Quantile mapping is applied to daily maximum temperature in order to remove systematic bias of raw output

Schematic representation of the concept of QM

- Quality of observational data

<table>
<thead>
<tr>
<th>Domain</th>
<th>Source</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>E-OBS</td>
<td>0.1° x 0.1°</td>
</tr>
<tr>
<td>South Asia</td>
<td>India Meteorological Department</td>
<td>1° x 1°</td>
</tr>
<tr>
<td>East Asia</td>
<td>CN05.1 (China) + KMA Station (Korea)</td>
<td>0.25° + Stations</td>
</tr>
<tr>
<td>Southeast Asia</td>
<td>ERA-Interim</td>
<td>0.25°</td>
</tr>
<tr>
<td>Australia</td>
<td>Bureau of Meteorology, Australia</td>
<td>Stations</td>
</tr>
</tbody>
</table>
Frequency Distribution of Daily Tmax during the 3 Hottest Months

**Paris**

- **Historical**
- **RCM [RF]**
- **RCM [+2°C]**
- **RCM [+3°C]**

**London**

- **Historical**
- **RCM [RF]**
- **RCM [+2°C]**
- **RCM [+3°C]**

**Budapest**

- **Historical**
- **RCM [RF]**
- **RCM [+2°C]**
- **RCM [+3°C]**
Interannual Variability of Tmax Anomaly

Observation - Anomaly of daily Tmax

Londen

Paris

Budapest
Frequency Distribution of Daily Tmax during the 3 Hottest Months

**Graphs:**
- **Paris**
  - X-axis: Daily Tmax
  - Y-axis: Events each year
- **London**
  - X-axis: Daily Tmax
  - Y-axis: Events each year
- **Budapest**
  - X-axis: Daily Tmax
  - Y-axis: Events each year

Legend:
- Grey: Historical
- Orange: Hot year
- Black: RCM [RF]
- Blue: RCM [+2°C]
- Red: RCM [+3°C]
ECDF of Daily Tmax during the 3 hottest months
Consecutive Hot Days > 95th of Reference Tmax

![Graphs showing the distribution of consecutive hot days in Paris, London, and Budapest with different scenarios: Historical, Hot year, RCM [RF], RCM [+2°C], RCM [+3°C].](image)
East Asia: Characteristics of Temperature Change

Chongqing

Shanghai

Daegu

Graphs showing the distribution of daily maximum temperatures and percentile distributions for different durations in Chongqing, Shanghai, and Daegu. The graphs compare historical and hot year data with simulations under different climate change scenarios.
South East Asia: Characteristics of Temperature Change

Hanoi

Bangkok

Jakarta
Intensification of Heat Stress

Risk Level: Extreme
Risk Level: High
Risk Level: Moderate

- OBS [CLIM]
- OBS [Hotyrs]
- RCM [Ref]
- RCM [+2°C]
- RCM [+3°C]
Take Home Message

- With the acceleration in global warming, extreme hot temperatures have emerged as one of the most prominent risks.

- The distinct behaviors of maximum temperature that appeared in historical extremes largely represent the statistical analog of the distribution pattern expected under 3°C global warming based on fine-scale climate projections.

- The statistically extremely rare events will become increasingly normal if global average temperature is allowed to increase by 3°C.
Thank you for your attention!

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Wet-bulb temperature is particularly useful in human health applications associated with heat stress, because evaporation is the primary means by which bodies cool in hot environments; thus, when $T_w$ is high, evaporative cooling is restricted and the body core temperature may rise (Davis et al. 2016).

$35^\circ C$ is the threshold value of $T_W$ beyond which any exposure for more than 6-hour would likely be intolerable even for the fittest of humans resulting in hyperthermia. In current climate, $T_W$ rarely exceeds $31^\circ C$. 
Various Metrics of Moist Temperature

- **Wet-bulb temperature ($T_w$)**
  - $T_w$ is the temperature at which air becomes saturated by evaporation at constant pressure.
  - $T_w$ is empirical value to which a wetted thermometer will drop under vaporization.
  - $T_w$ is particularly useful in human health applications associated with heat stress, because evaporation is the primary means by which bodies cool in hot environments.

  \[
  T_w = T \tan[0.151977(RH\% + 8.313659)^{1/2}] + \tan(T + RH\%) - \tan(RH\% - 1.676331) + 0.00391838(RH\%)^{3/2} \tan(0.023101RH\%) - 4.686035. \quad \text{[From Stull 2011]}
  \]

- **Wet-bulb globe temperature (WBGT)**
  - WBGT is the empirical combinations of $T_w$, $T_a$, and $T_g$ to measure heat stress.

  \[
  \text{WBGT} = 0.7T_w + 0.2T_g + 0.1T_a
  \]
  (where, $T_g$ black globe temperature)
  (where, $T_w$ wet-bulb temperature)

  \[
  \text{WBGT} = 0.567T_a + 0.393e + 3.94
  \]
  (where, $e$ vapor pressure)

- **Apparent temperature ($T_{app}$)**
  - $T_{app}$ combines temperature and humidity into a single index for the assessment of human comfort in the warm season.

  \[
  T_{app} = 2.719 + 0.994T_a + 0.016(T_d)^2
  \]
  (where, $T_a$ dry-bulb temperature)
  (where, $T_d$ dew-point temperature)