Predicting Extreme Climate with Earth System Models
A Top-Down Look at the Southern Great Plains

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1. Introduction on extremes

2. Multi-scale interactions as sources of uncertainties

3. The Southern Great Plains

4. Uncertainties in future projections

5. Summary
Definition of Extremes:

1. Absolute indices, e.g., hottest or coldest temperature of a year, maximum 1 day or 5-day precipitation rates
2. Threshold indices, e.g. number of days when a fixed temperature or precipitation threshold is exceeded
3. Duration indices, e.g., length of wet and dry spells, or warm and cold spells
4. Percentile-based threshold indices, e.g., exceedance rates above or below a the 10th or 90th percentile in a reference base period
<table>
<thead>
<tr>
<th>Indicator name</th>
<th>Abbrev.</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frost days</td>
<td>FD</td>
<td>Number of days with $T_{\min} &lt; 0 , ^\circ C$</td>
</tr>
<tr>
<td>Icing days</td>
<td>ID</td>
<td>Number of days with $T_{\max} &lt; 0 , ^\circ C$</td>
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<tr>
<td>Summer days</td>
<td>SU</td>
<td>Number of days with $T_{\max} &gt; 25 , ^\circ C$</td>
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<tr>
<td>Tropical nights</td>
<td>TR</td>
<td>Number of days with $T_{\min} &gt; 20 , ^\circ C$</td>
</tr>
<tr>
<td>Cool nights</td>
<td>TN10p</td>
<td>% of days with $T_{\min} &lt;$ the historical 10th percentile value</td>
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<tr>
<td>Warm nights</td>
<td>TN90p</td>
<td>% of days with $T_{\min} &gt;$ the historical 90th percentile value</td>
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</tr>
<tr>
<td>Maximum $T_{\min}$</td>
<td>TNx</td>
<td>Monthly maximum value of $T_{\min}$</td>
</tr>
<tr>
<td>Minimum $T_{\min}$</td>
<td>TNn</td>
<td>Monthly minimum value of $T_{\min}$</td>
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<td>Monthly minimum value of $T_{\max}$</td>
</tr>
<tr>
<td>Diurnal range</td>
<td>DTR</td>
<td>Monthly mean difference between daily $T_{\max}$ and $T_{\min}$</td>
</tr>
<tr>
<td>Growing season length</td>
<td>GSL</td>
<td>Number of days between the first 6-day span with daily mean temperature above 5 °C and the first span after July 1 (in NH) with daily mean temperature below 5 °C</td>
</tr>
<tr>
<td>Warm spell duration index</td>
<td>WSDI</td>
<td>Annual count of at least six consecutive days with $T_{\max} &gt;$ the historical 90th percentile value</td>
</tr>
<tr>
<td>Cold spell duration index</td>
<td>CSDI</td>
<td>Annual count of at least six consecutive days with $T_{\min} &lt;$ the historical 10th percentile value</td>
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<tr>
<td>Maximum 1-day precipitation</td>
<td>RX1day</td>
<td>Monthly maximum 1-day precipitation (mm)</td>
</tr>
<tr>
<td>Maximum 5-day precipitation</td>
<td>RX5day</td>
<td>Monthly maximum consecutive 5-day precipitation amount (mm)</td>
</tr>
<tr>
<td>Simple daily intensity index</td>
<td>SDII</td>
<td>Mean precipitation amount on wet days (mm)</td>
</tr>
<tr>
<td>Number of heavy precipitation events</td>
<td>R10</td>
<td>Annual count of days with precipitation $&gt; 10 , mm$</td>
</tr>
<tr>
<td>Number of very heavy precipitation days</td>
<td>R20</td>
<td>Annual count of days with precipitation $&gt; 20 , mm$</td>
</tr>
<tr>
<td>Consecutive dry days</td>
<td>CDD</td>
<td>Maximum number of consecutive days with precipitation $&lt; 1 , mm$</td>
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<tr>
<td>Consecutive wet days</td>
<td>CWD</td>
<td>Maximum number of consecutive days with precipitation $&gt; 1 , mm$</td>
</tr>
<tr>
<td>Very wet days</td>
<td>R95p</td>
<td>Annual total precipitation derived from days $&gt; 95\text{th} , %$</td>
</tr>
<tr>
<td>Extremely wet days</td>
<td>R99p</td>
<td>Annual total precipitation derived from days $&gt; 99\text{th} , %$</td>
</tr>
<tr>
<td>Annual total precipitation</td>
<td>PRCPTOT</td>
<td>Annual total precipitation on all days.</td>
</tr>
</tbody>
</table>

(Schoof et al. 2016)
- Extremes are often driven by interactions of systems with different temporal and spatial scales

- Extremes are application-specific

All these require ESM
Hurricane Harvey

Maximum rainfall for a 4-day period > 1000 mm
Wettest tropical hurricane brought heavy Rain and caused catastrophic flooding

(Xia 2017)
DEEP TROUGH IN THE EAST

STRONG UPPER HIGH GETS STRONGER
Hurricane Irma

GFS 500mb Geopotential Height & Normalized Anomaly (based on CFSR 1981-2010 Climatology)
Init: 12z Aug 31 2017  Forecast Hour: [168]  valid at 12z Thu, Sep 07 2017

Position of this high one critical piece of puzzle

Where will trough be?
Hurricane Sandy
Hurricane Sandy Surface Wind Speed
Extremes are application specific

Sewage treatment plant as an example

(Kenward et al. 2013)
Multi-scale Interactions as Sources of Uncertainties
Multi-scale interactions
An example of multi-scale interactions
The Madden-Julian Oscillation MJO

Courtesy of Adames
Precipitation (40 days)  MJO  850 hPa wind velocity potential

Phase 2
Phase 3
Phase 4
Phase 5
Phase 6
Phase 7
Phase 8
Phase 1

NOAA
Boundary-layer turbulence, shallow convection, and cumulus congestus pre-condition deep convections

(Benedict and Randall 2007)
Cloud radiative feedbacks from low clouds

(Zhang et al., 2013 JAMES)
The “NESTS-SCOPE” Mechanism

(Zhang et al., 2013 JAMES)
Special About the Southern Great Plains

Fronts

Low-level jet

Thunderstorms

Land-atmosphere coupling
Percentage of precipitation associated with fronts

(Catto and Pfahl, JGR 2013)

Strength of land-atmosphere interaction

(Seneviratne et al. Nature, 2006)
A strong precipitation event during the ARM MC3E Field Campaign

(Wang et al. 2017)
(Xie et al. 2014)
Mesoscale convective systems
Not resolved in current climate models

(Houze 2014)
Resolution alone is necessary, but not sufficient
Sensitivity of MCS reflectivity on cloud microphysics (An ARM MC3E Event)

(Fan et al. 2017)
One element of microphysical process: collision-coalescences

- Grazing air trajectory
- Collector drop
- Collected drop
- Geometric cross section
- Effective cross section

Local flow shear

Droplet clustering
Complexity of cloud microphysics

- evaporation
- activation, nucleation scavenging
- precipitation formation
- collision scavenging
- aqueous chemistry
- wet deposition
- below-cloud scavenging

- in-crystal aerosol
- interstitial aerosol
- in-droplet aerosol
- aerosol in cloud-free air
Future Projections and Uncertainties over the SGP
RCP8.5

Changes of Tropical Night Days (Tmin > 20°C)

RCP8.5

Changes of Very Wet Days (P > 95th percentile) %
Changes of LLJ and Precipitation

(Feng, Leung et al. Nature Communications 2016)
Uncertainties from GCM can be large and systematic

CMIP5 Model biases
(Lin et al. 2017 Nature Communications)
Artistic Schematics of the ARM SGP Facility
Land-atmosphere coupling

(Wulfmeyer et al., 2016)
Heavy rain

In subsequent no-rain days

Less solar radiation & lower temperature

Light rain

In subsequent no-rain days

More solar radiation & Higher temperature
Summary

- Extreme events often arise from a combination of systems on multiple scales. Simulations of their correct spatial-temporal relations are needed to capture their combined impact for specific applications.

- Upscale feedbacks cause large uncertainties in extremes from unresolved processes of scales ranging from cloud-aerosol microphysics, shallow convection, and cloud systems.

- Over the SGP, most current ESMs miss strong convective events, leading to underestimation of the subsequent shallow convective clouds and overestimation of downward shortwave radiation, thus warm and dry biases.