Evaluating Climate Projection for Drought and Extreme Surface Temperatures over South-Central US

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Based on Fu et al. 2012, submitted to J. Climate
2009 Report on global climate change impacts in the United States (Karl et al)

IPCC AR4 models projected 15-30% decrease of rainfall and nearly double the number of days when $T>90F$.

Projected Spring rainfall change by 2080s-2090S compared to that of 1971-2000

Number of days when $T_s>90F$ during 1961-1971

Projected number of days when $T_s>90F$ by 2080-2099

Recent Past (1961-1971 Average)

Projected End-of-Century under Lower Emissions Scenario (2080-2099 Average)

Projected End-of-Century under Higher Emissions Scenario (2080-2099 Average)

Number of Days per Year

-40 -30 -20 -10 0 10 20 30 40 >40

Precipitation Change in Percent

0 15 30 45 60 75 90 105 120 135 150 165 180 195 210 >210

Number of Days per Year

0 15 30 45 60 75 90 105 120 135 150 165 180 195 210 >210
However,

- **Large inter-model discrepancy in projected future rainfall changes**
- **Which projections should we believe?**

Projected rainfall change during April to June in 2079-99 relative to 1979-1999. (source: Figs 10 and 11 of Cook et al. 2008)
How can we determine creditability of the CMIP5 climate projection?

- Does the multi-models ensemble projection necessarily outperform individual model projection over Texas and SC US?

  - Gleckler et al. (2008), Pierce et al. (2009): An ensemble mean, especially a multi-model ensemble mean projection, can outperform the best quality model because the former allows cancellation of offsetting errors in the individual global models.

- What should we do if majority of the models have similar biases?
Criteria for our process-based model evaluation Metrics:

- Relevant to climate projection
  - Response to increase of the global sea surface temperature
  - Surface water budget and drought indices
  - Surface meteorological conditions
- Capture processes that control droughts over Texas
  - Large-scale circulation
- Can be compared to long-term observations
  - Connection with ENSO
**IPCC AR5 Models and Datasets Used for Evaluation:**

### Datasets:
- **CPC US-Mexico daily rainfall** (Higgins et al. 1996), 1°
- **GHCN daily Tmax, Tmin** (Vose et al. 1992), 2.5°
- **NLADAS** (Rodell et al. 2004), ET, 1/8°, 1980-2007
- **ERSSTv3b SST** (Smith et al. 2008), 2.0°, 1854-2005
- **NCEP reanalysis** (Kalnay et al 1996; Kistler et al. 2001), 2.5°, 1948-present

All the datasets and models are re-mapped to 2.5° spatial resolution.

### Periods:
- **1950-2005; meteorological data**
- **1980-2005: surface energy/water balance.**

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### Table 1. Description of CMIP5 models used in this study

<table>
<thead>
<tr>
<th>Model (Fig marker)</th>
<th>Institute (Country)</th>
<th>Available Ensembles</th>
<th>Components (Resolutions)</th>
<th>Calendar</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC11M4 (A)</td>
<td>National Center for Atmospheric Research (USA)</td>
<td>6</td>
<td>F99_g16 (0.9 x 1.25_gx1v6)</td>
<td>No leap</td>
<td>Gent et al., 2011</td>
</tr>
<tr>
<td>GFDL-ESM2M (B)</td>
<td>NOAA/Geophysical Fluid Dynamics Laboratory (USA)</td>
<td>1</td>
<td>Atm: AM2 (AM2p14, M45L24) Ocn: MOM4.1 (1.0° lat x 1.0° lon, enhanced tropical resolution: 1/3 on the equator)</td>
<td>No leap</td>
<td>John Dunne et al., 2012</td>
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<tr>
<td>GFDL-ESM2G (C)</td>
<td>NOAA/Geophysical Fluid Dynamics Laboratory (USA)</td>
<td>1</td>
<td>Atm: AM2 (AM2p14, M45L24) Ocn: MOM4.1 (1.0° lat x 1.0° lon, enhanced tropical resolution: 1/3 on the equator)</td>
<td>No leap</td>
<td>John Dunne et al., 2012</td>
</tr>
<tr>
<td>GISS-E2-R (D)</td>
<td>NASA/Goddard Institute for Space Studies (USA)</td>
<td>5</td>
<td>Atm: GISS-E2 (2.0° lat x 2.5° lon) Ocn: R</td>
<td>No leap</td>
<td>Schmidt et al., 2006</td>
</tr>
<tr>
<td>HadGEM2-CC (E)</td>
<td>Met Office Hadley Centre (UK)</td>
<td>3</td>
<td>Atm: HadGEM2 (N96L60) Ocn: HadGEM2 (Lat: 1.0-0.3 Lon: 1.0-4.0)</td>
<td>360 d/y</td>
<td>Collins et al., 2011; Martin et al., 2011</td>
</tr>
<tr>
<td>MPI-ESM-LR (F)</td>
<td>Max Planck Institute for Meteorology (Germany)</td>
<td>3</td>
<td>Atm: ECHAM6 (T63L47) Ocn: MPIOM (GR15L40)</td>
<td></td>
<td>Raddatz et al., 2007; Marksland et al., 2003</td>
</tr>
<tr>
<td>IPSL-CM5A-LR (G)</td>
<td>Institut Pierre Simon Laplace (France)</td>
<td>5</td>
<td>Atm: LMDZ4 (96 x 95 x 39, 1.875° lat x 3.75° lon) Ocn: ORCA2 (2 x 2L31, 2.0° lat x 2.0° lon)</td>
<td>No leap</td>
<td>Marti et al., 2010</td>
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<tr>
<td>MIROC5 (H)</td>
<td>AORI, NIES &amp; JAMSTEC (Japan)</td>
<td>4</td>
<td>Atm: AGCM6 (T85L40) Ocn: COCO (COCO4.5)</td>
<td>No leap</td>
<td>Watanabe et al., 2010</td>
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<tr>
<td>MRI-CGCM3 (I)</td>
<td>Meteorological Research Institute</td>
<td>3</td>
<td>Atm: GSMUV (TL159L48)</td>
<td></td>
<td>Yukiwakita et al., 2011</td>
</tr>
</tbody>
</table>

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### Diagram:

![South-Central (SC) US Domain](image.png)

- **South-Central (SC) US Domain**
Evaluate seasonal cycles of climatic surface conditions:

- **Cold bias in daily maximum surface temperature (Tmax)**
- **Wet biases in Precipitation (P), Evapotranspiration (ET), esp. during spring & summer**
- **Large discrepancies in seasonal rainfall**

Black line: observations, **Bold Red line**: multi-model ensemble mean
Probability distributions of $T_{max}$, $T_{min}$, $P$ and drought indices (SPI6 and SPI9)

- $T_{max}$: underestimate warmer $T_{max}$ and overestimate cooler $T_{max}$
- $T_{min}$: underestimate cooler $T_{min}$, overestimate warmer $T_{min}$ (consistent with wet bias)
- $P$: underestimate non-rain and heavy rainrate, overestimate light rainrate
- SPI: reasonably realistic, but underestimate intensity of extreme drought.
Number of days/yr when $T_{\text{max}}>90\text{F} \ & \ 100\text{F}$:

- Reverse the E-W gradient of extreme $T_{\text{max}}$ over Texas,
- Most of models overestimate occurrence of extreme $T_{\text{max}}$ over the southeastern Great Plains,
- Large inter-model discrepancies

highlight better models
Evaluation of Large-scale atmospheric circulation:

- Most of the models underestimate the 500hPa ridge over central US in summer and strength of jet in spring (except for CCSM4).
- Probably responsible for wet and cold biases in spring and summer.

Figure 6: Comparison of the modeled Z500hPa pattern by each CMIP5 models with that of NCEP-CDAS1.

*Circles highlight better models*
- 1/2 models underestimate lower tropospheric westerly winds (U850) in spring and summer.
- Underestimate lower tropospheric southerly winds (V850) in spring.
About a half of the models

- underestimate correlation with ENSO in winter
- overestimate ENSO connection in spring, summer and fall
- Because of errors in ENSO teleconnection pattern (not shown)

Figure 9: Correlations between Niño4, Niño3 and SC US rainfall. “Star” indicates significant correlation coefficient at 95% confidence level using student t-test.
Observation shows the global increase of sea surface temperature (SST) as the leading mode for SST variance (Schubert et al. 2008).

Few models realistically capture this global increase of SST mode (CCSM4 and MPI).

😊: Few models fail to capture the warming mode.
Modeled response of summer rainfall over SC US to the increasing global SST mode:

- Most of the models underestimate the change of summer rainfall over SC US associated with global increase of SST over the period of 1900-2005.

- Only CCSM4 captures the observed relationship between the increase of global SST mode and increase of summer rainfall over SC US.
CCSM4 overall ranks the best, especially in SC US rainfall response to increase of global SST.

Response to increase of the global sea surface temperature

Surface conditions

Surface water budget and drought indices

Large-scale circulation

Connection with ENSO

### Table 2: Ranking of model performance for SC US regional climate change

<table>
<thead>
<tr>
<th>Variables</th>
<th>Models</th>
<th>CCSM4</th>
<th>GFDL-ESM2G</th>
<th>GFDL-ESM2M</th>
<th>GISS-E2-R</th>
<th>HadGE</th>
<th>MPI</th>
<th>IPSL</th>
<th>MIROC5</th>
<th>MR1</th>
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<tr>
<td>Tier-1: Forced variability or change</td>
<td>Correlation with global SST warming:</td>
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<td>GW_SST</td>
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<td>2.5</td>
<td>2.5</td>
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<td>2.5</td>
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<tr>
<td>Tier-2: natural variability</td>
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<td>3</td>
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<td>2.3</td>
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</table>

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CCSM4 overall ranks the best, especially in SC US rainfall response to increase of global SST.
Projected change of Tmax during 2073-2099 relative to 1979-2005:

- Models consistently project a disproportional increase of occurrence of high Tmax (>90°F - 108°F) by
  - 25-50% under low emission (but unlikely RCP4.5) scenario (CO₂ reaches 650 ppm by 2100)
  - 50-100% under high emission (business as usual, RCP8.5) scenario (CO₂ reaches 1350 ppm by 2100)

- Recall that these models tend to underestimate Tmax.

Best performing model projection

Multi-model ensemble projection
Projected change of Tmin in 2073-2099 relative to 1979-2005.

Models consistently project a strong increase of occurrence of Tmin ≥ 80°F several folds under the high emission (RCP8.5) scenario.
Projected change of rainrate in 2073-2099 relative to 1979-2005.

- Increase of non-rainy days and low rainrate and decrease of medium rainrate.
Projected change of surface net water flux in 2073-2099 relative to 1979-2005:

Under the high emission (business as usual, RCP8.5) scenario:

- Both multi-models and best performing model project net drying, by ~20% of P-ET in spring and summer, despite differences in details.

- Increase of rainfall (P) and ET during winter and spring, decrease of rainfall and ET in summer.

- Net drying in spring is dominated by increase of ET, whereas drying in summer is dominated by decrease of P.

- Outliners in projections tends to be the worst performing models.
Conclusions:

The 9 climate models that participated in the IPCC AR5 we evaluated

- share common wet and cold biases, due to underestimate mid-tropospheric ridge in summer, the upper-level jet strength and westerly low-level winds in spring. Most of the models cannot adequately capture the changes of SC US rainfall with ENSO and the increase of global SST.

- consistently project ~20% decrease of net P-ET (dry) in spring-summer by 2073-2099 relative to 1979-2005, under the “business as usual” emission scenario (RCP8.5), despite differences in details.