The Scale-dependence of Groundwater Effects on Precipitation and Temperature in the Central United States

Michael Barlage, Fei Chen, Changhai Liu
NCAR/RAL

Gonzalo Miguez-Macho
U. Santiago de Compostela
• Recent effort to conduct CONUS region climate simulations at convection-permitting scale
• WRF Simulations
  • 4km spatial scale (1360x1016)
  • 51 vertical levels to 50 hPa
  • Thompson, YSU, RRTMG
  • Spectral nudging
  • Noah-MP LSM
  • 13 years (2001 – 2013)
  • Summarized in Liu, et al. 2017
• Follow-on study of Rasmussen et al. 2014
Temperature Bias over Central U.S.

- Temperature bias increases through the summer
• Recent effort to improve region climate simulations at convection-permitting scale

• WRF Simulations
  • 4km spatial scale (501x401)
  • 51 vertical levels to 50 hPa
  • Thompson, YSU, RRTMG
  • No SPECTRAL NUDGING
  • Noah-MP LSM
  • April – September 2012
Evolving Temperature Bias over Central U.S.

Temperature bias relative to PRISM

April
May
June
July
August

Temperature bias relative to PRISM

August
Central U.S. Focused Simulations

- Analyze precipitation and ET over Central Plains
- Stage IV radar/gauge precipitation analyses
  - 4km regridded to model domain
  - Convert hourly to monthly
- MODIS ET (MOD16A2)
  - 500m regridded to model domain
  - Convert 8-day to monthly
Precipitation Results

Monthly Precipitation

Precipitation compared to Stage IV

- **Stage IV**
- **Noah-MP**

<table>
<thead>
<tr>
<th>Month</th>
<th>Stage IV</th>
<th>Noah-MP</th>
</tr>
</thead>
<tbody>
<tr>
<td>APR</td>
<td>[Value]</td>
<td>[Value]</td>
</tr>
<tr>
<td>MAY</td>
<td>[Value]</td>
<td>[Value]</td>
</tr>
<tr>
<td>JUN</td>
<td>[Value]</td>
<td>[Value]</td>
</tr>
<tr>
<td>JUL</td>
<td>[Value]</td>
<td>[Value]</td>
</tr>
<tr>
<td>AUG</td>
<td>[Value]</td>
<td>[Value]</td>
</tr>
</tbody>
</table>
Evapotranspiration Results

Monthly Evapotranspiration

Evapotranspiration compared to MODIS ET

MODIS
Noah-MP
Default Noah-MP LSM in WRF uses 2-meter soil with free drainage LBC

Missing Processes?

Default Noah-MP

- Surface runoff
- Sub-surface runoff

P

ET
Region of warm bias consistent with locations where water table near surface
New Groundwater Representation in Noah-MP

Noah-MP options exist for
- free drainage soil lower boundary condition
- 1D aquifer interaction
- new option added for 1D interaction with horizontal aquifer transport

User note: not a river routing, overland flow scheme (see WRF-hydro)

Mass balance in groundwater storage:

\[ \frac{dS_g}{dt} = \Delta x \Delta y R + \sum_{i=1}^{8} Q_i - Q_r \]

Fan et al, JGR 2007
Miguez-Macho et al, JGR 2007
Missing Processes?

Add lower boundary that interacts with groundwater below

Default Noah-MP

Noah-MP with groundwater

Surface runoff

Sub-surface runoff

Interaction with aquifer

Additional soil layer
Activating groundwater provides a source of moisture in mid- to late-summer (negative slope of the blue line).
Precipitation Results

Monthly Precipitation

Precipitation compared to Stage IV

- Stage IV
- Noah-MP
- Noah-MP w/GW

[Graph showing monthly precipitation for April to August with different models and legend indicating Stage IV, Noah-MP, and Noah-MP w/GW.]
Evapotranspiration Results

Monthly Evapotranspiration

Evapotranspiration compared to MODIS ET

MODIS
Noah-MP
Noah-MP w/GW
Evolving Temperature Bias over Central U.S.

No Groundwater

April  May  June  July  August

Groundwater
Noah-MP vs. Noah-MP w/groundwater
Surface Verification

- Six-month 30km WRF simulations - 2010
- Spin-up soil for one year using offline HRLDAS
- IC/BC from NARR
- Verification against ~2600 surface stations

<table>
<thead>
<tr>
<th>Model</th>
<th>Season</th>
<th>Output field</th>
<th>Day bias</th>
<th>Day RMSE</th>
<th>Night bias</th>
<th>Night RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noah-MP</td>
<td>MAM</td>
<td>$T_{2m}$</td>
<td>0.5</td>
<td>1.0</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>w/GW</td>
<td>MAM</td>
<td>$T_{2m}$</td>
<td><strong>0.4</strong></td>
<td>1.0</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Noah-MP</td>
<td>JJA</td>
<td>$T_{2m}$</td>
<td>1.7</td>
<td>1.9</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>w/GW</td>
<td>JJA</td>
<td>$T_{2m}$</td>
<td><strong>1.1</strong></td>
<td><strong>1.6</strong></td>
<td><strong>0.1</strong></td>
<td><strong>0.9</strong></td>
</tr>
</tbody>
</table>

Regional bias improvements of 1.5°C

Green: Noah-MP w/GW improves  Red: Noah-MP w/GW degrades

Barlange, et al. 2015
• Significant sub-grid variability is missed when using coarse resolution
Scale Dependencies – Experiment

- Test multiple domains at 27km, 9km, and 3km for Apr – Aug 2012
- Use same physics in all simulations including scale-aware KF convection
Region of warm bias consistent with locations where water table near surface
Scale Dependencies – Experiment

- Cumulative distribution of depth to groundwater in the Central U.S.

27km  9km  3km
• For simulation without groundwater, 3km simulation shows the least precipitation
• 9km and 27km simulations have a similar total precipitation
For groundwater simulations, 27km simulations have the least precipitation.
3km and 9km simulations have a similar total precipitation.
All groundwater simulations have an increased precipitation relative to no GW
Groundwater effect is scale-dependent
Higher resolution groundwater simulations show the best performance.

Graph showing precipitation over time from April to September, with different resolutions and groundwater considerations.
August precipitation increased with groundwater in both resolutions.

Scale Dependencies – Experiment

9km

3km
METAR Station Comparison – 2-meter Temperature

- 27km simulations show little effect on August warm bias

August
- bias < -5
- -5 <= bias < -3

August
- -3 <= bias < -1
- -1 <= bias < 0
- 0 <= bias < 1
- 1 <= bias < 3
- 3 <= bias < 5
- bias >= 5
**METAR Station Comparison – 2-meter Temperature**

- 9km simulations show increasing effect of groundwater on bias reduction
- 9km simulations without groundwater warmer than 27km

August

- bias < -5
- -5 <= bias < -3

August

- -3 <= bias < -1
- -1 <= bias < 0
- 0 <= bias < 1
- 1 <= bias < 3
- 3 <= bias < 5
- bias >= 5
METAR Station Comparison – 2-meter Temperature

- 3km simulations show increasing effect of groundwater on bias reduction
- 3km simulations without groundwater warmer than 9km and 27km

August

- bias < -5
- -3 <= bias < -1
- -5 <= bias < -3
- -1 <= bias < 0

August

- 0 <= bias < 1
- 1 <= bias < 3
- 3 <= bias < 5
- bias >= 5
METAR Station Comparison – 2-meter Temperature

- 27km simulations with groundwater don’t have much improvement
- Blue is good, meaning bias is reduced

\[ \text{gw}_d1 \text{ (mean: -0.253)} \]

\[ \text{gw}_d1 \text{ (mean: -0.193)} \]

- July
  - bias < -2.5
  - -2.5 <= bias < -1

- August
  - -1 <= bias < -0.5
  - -0.5 <= bias < 0
  - 0 <= bias < 0.5
  - 0.5 <= bias < 1
  - 1 <= bias < 2.5
  - bias >= 2.5
METAR Station Comparison – 2-meter Temperature

- Much larger groundwater impact with 9km simulations

```plaintext
- gw_d2 (mean: -1.013)
- gw_d2 (mean: -0.781)
```

July
- bias < -2.5
- -2.5 <= bias < -1

August
- -1 <= bias < -0.5
- -0.5 <= bias < 0
- 0 <= bias < 0.5
- 0.5 <= bias < 1
- 1 <= bias < 2.5
- bias >= 2.5
**METAR Station Comparison – 2-meter Temperature**

- Groundwater impact even larger in 3km simulations

```
gw_d3 (mean: -1.601)
gw_d3 (mean: -1.241)
```

- **July**
  - bias < -2.5
  - -1 <= bias < -0.5
  - -2.5 <= bias < -1
  - -0.5 <= bias < 0

- **August**
  - 0 <= bias < 0.5
  - 1 <= bias < 2.5
  - 0.5 <= bias < 1
  - bias >= 2.5
Conclusions and Future Work

- Inclusion of groundwater in Noah-MP is beneficial in addressing late summer warm bias in central US
- Provides access to deep soil water in regional climate simulations and increases soil memory
- Additional years of simulation needed
  - Continuing with 2013 and 2014
  - What happens at 1km?
- Additional verification and analysis
  - Flux tower and soil moisture