US Corn Belt Enhances Regional Precipitation Recycling

Zhe Zhang, Cenlin He, Fei Chen, Gonzalo Miguez Macho, Changhai Liu, Roy Rasmussen

2024/06/04
Precipitation Recycling is an important component in the water cycle

Precipitation recycling (PR) ratio – the contribution of local evapotranspiration to precipitation within a region

\[ \rho = \frac{\text{Prec}_{\text{local}}}{\text{Prec}_{\text{total}}} \]

- characterize land surface impacts to the atmosphere (land-atmosphere interactions)
- Important implications for designing land use management and estimating water availability
- Particularly important for regions with large land-use change and human activities

Deforestation  Wetland drainage  Croplands and Irrigation
Extensive croplands and agricultural management in the US Corn Belt have substantially modified regional climate. Increasing precipitation and cooling temperature in the US Corn Belt along with substantial crop yield and production growth in the 20th century (Alter et al., 2017).

Research Question:
What are the contributions of crop growth and irrigation managements to regional climate? precipitation recycling?
Various methods to estimate precipitation recycling ratio in Central US

Dominguez and Kumar, 2008

Note: PR ratio depends on the area of analysis

**Table 1. Estimates of the ratio of recycled to total precipitation (RR) for the central United States estimated by different studies. Since RR depends on the area of analysis, we include the area of each study for comparison.**

<table>
<thead>
<tr>
<th>Recycling ratio</th>
<th>Time scale</th>
<th>Area</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly RR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22%, 34%, 33%</td>
<td>Mean J, J, A</td>
<td>20° by 10° (2.4 × 10° km²)</td>
<td>Budyko-type analytic model</td>
<td>Brubaker et al. (1993)</td>
</tr>
<tr>
<td>41% and 33%</td>
<td>April–July 1988 and 1999, respectively</td>
<td>4 × 10² km²</td>
<td>Back-trajectory algorithm</td>
<td>Dirmeyer and Brubaker (1999)</td>
</tr>
<tr>
<td>30%, 39%, 35%</td>
<td>Mean J, J, A</td>
<td>20° by 10° (2.4 × 10° km²)</td>
<td>Eltahir and Bras model</td>
<td>Bosilovich and Schubert (2001)</td>
</tr>
<tr>
<td>32%</td>
<td>Mean J, J, A</td>
<td>4 × 10² km²</td>
<td>Back-trajectory algorithm</td>
<td>Brubaker et al. (2001)</td>
</tr>
<tr>
<td>14%</td>
<td>Average JJA</td>
<td>15° by 10° (1.8 × 10° km²)</td>
<td>Water vapor tracers</td>
<td>Bosilovich and Schubert (2002)</td>
</tr>
<tr>
<td>25% (northern plains); 26% (southern plains)</td>
<td>Average JJA</td>
<td>10° by 8° (1 × 10° km²) and 10° by 12° (1.5 × 10° km²)</td>
<td>Water vapor tracers</td>
<td>Bosilovich (2003)</td>
</tr>
<tr>
<td>From 19% to 24%</td>
<td>Mean, J, J, A</td>
<td>1.23 × 10² km²</td>
<td>Simple recycling equation</td>
<td>Zangvil et al. (2004)</td>
</tr>
<tr>
<td>18%</td>
<td>Average JJA</td>
<td>1 × 10² km²</td>
<td>DRM</td>
<td>Dominguez et al. (2006)</td>
</tr>
<tr>
<td>32%, 35%, and 40%</td>
<td>J, J, and A</td>
<td>22° by 12° (3 × 10° km²)</td>
<td>General bulk model</td>
<td>Burde et al. (2006)</td>
</tr>
<tr>
<td>2.2%, 6.2%, and 18%</td>
<td>Effective</td>
<td>10°, 10°, 10°</td>
<td>Back-trajectory algorithm</td>
<td>Dirmeyer and Brubaker (2007)</td>
</tr>
<tr>
<td>Daily RR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From 15% to 30%</td>
<td>Mean, J, J, A</td>
<td>1.23 × 10² km²</td>
<td>Simple recycling equation</td>
<td>Zangvil et al. (2004)</td>
</tr>
<tr>
<td>22%, 25%, 23%, 20%</td>
<td>May, J, J, A</td>
<td>4 × 10² km²</td>
<td>Water vapor tracers</td>
<td>Bosilovich and Chern (2006)</td>
</tr>
</tbody>
</table>

a) Analytical atmosphere water budget model simplified well-mixed atmosphere assumption

b) Offline tracking model (Eulerian or Lagrangian)

c) Online Water Vapor Tracer model (Insua-Costa & Miguez-Macho, 2018) most complex
WRF-Water Vapor Tracer

WRF-WVT has the most complex representation of atmospheric processes, thus is treated as the truth.

The power of complex models is evident when analyzing individual cases/seasons where the local-scale processes are important.

Previous studies neglected complex land surface processes contributing to local ET.
1. Shallow Groundwater-Soil Moisture Interactions depend on model resolution

Default soil layer
Free drainage

Groundwater-soil moisture interactions depend on model resolution

(b) Groundwater depth at 1-km
(c) Groundwater depth at 27-km

No Groundwater model at 3-km

With Groundwater model at 3-km

Coupling groundwater to LSM and RCM reduces summer warm biases

Barlage et al., 2021
2. Crop growth and Irrigation management

Photosynthesis & Stomatal control

Irrigation management

Sprinkler Irrigation System

- Droplet evaporation
- Canopy evaporation

Sprinkler

Liu et al., 2016
Zhang et al., 2020
Valayamkunnath et al., 2022
Simulation Design:
- 2010 (wet), 2011 (normal), 2012 (dry)
- Growing season: From 04-01 to 09-01 (first month spin-up, analyze MJJA)
- 4-km grid spacing (convection-permitting)
- No spectral nudging
- Four simulations with different land surface processes:

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Groundwater interaction</th>
<th>Vegetation Dynamics</th>
<th>Irrigation Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Baseline (NoGW)</td>
<td>Free Drainage</td>
<td>Prescribed MODIS monthly LAI</td>
<td>No</td>
</tr>
<tr>
<td>2. GW</td>
<td>MMF groundwater model</td>
<td>Prescribed MODIS monthly LAI</td>
<td>No</td>
</tr>
<tr>
<td>3. DynCrop (GW+Crop)</td>
<td>MMF groundwater model</td>
<td>Dynamic Crop Model</td>
<td>No</td>
</tr>
<tr>
<td>4. Irrigation (GW+Crop+Irr)</td>
<td>MMF groundwater model</td>
<td>Dynamic Crop Model</td>
<td>Yes</td>
</tr>
</tbody>
</table>

WRF Domain setup:
- 40°N to 30°N
- 100°W to 80°W
- 20: Lake
- 19: Mixed Tundra
- 18: Wooded Tundra
- 17: Water
- 16: Barren or Sparsely Vegetated
- 15: Snow and Ice
- 14: Cropland/Natural Vegetation Mosaic
- 13: Urban and Built-Up
- 12: Croplands
- 11: Permanent Wetlands
- 10: Grasslands
- 9: Savannas
- 8: Woody Savannas
- 7: Open Shrublands
- 6: Closed Shrublands
- 5: Mixed Forests
- 4: Deciduous Broadleaf Forest
- 3: Deciduous Needleleaf Forest
- 2: Evergreen Broadleaf Forest
- 1: Evergreen Needleleaf Forest

Black outline: Corn Belt region
Hatched region: Irrigation
Zhang et al. 2024 (in revision)
Coupled GW+Crop+Irrigation system - cooling temperatures and enhancing precipitation

**MJJA temperature**

(a) NoGW

GW

GW+Crop

GW+Crop+Irr

**MJJA precipitation**

(b) NoGW

GW

GW+Crop

GW+Crop+Irr

With Coupled GW-Crop-Irrigation, warm summer warm and dry bias significantly improved (dotted and stars)
Precipitation Recycling Ratio - Spatial Gradient & Temporal evolution

Enhancement recycling ratio shows stronger seasonal cycle in with crop and irrigation

May – Large-scale environment driven
- Beginning of the growing season
JJA – Local-scale environment
- Peak of the growing season

\[ \rho = \frac{\text{prec}_{\text{tracer}}}{\text{prec}_{\text{total}}} \]

(a) NoGW
(b) 2010
(c) 2011
(d) 2012

Prec recycling ratio, (%)

5.0 10.0 15.0 20.0 25.0 30.0
Enhanced Precipitation Recycling explained by water balance

(a) 3-year MJJA NOGW
(b) GW
(c) GW+Crop
(d) GW+Crop+Irr

Prec from tracer
ET
Soil Moisture
Downwards Groundwater Flux

GW supplies soil moisture from below
Crop effectively transports moisture from soil to the atmosphere
Irrigation adds additional water from top
Interannual variability of precipitation recycling: moisture advection vs local ET

(1) strongest in 2010 (wet year) and weakest in 2012 (dry year)
(2) Largest local contribution in 2012 (dry) and least in 2010 (wet)

\[ IVT = \frac{1}{g} \left[ \left( \int_{\text{surface}}^{\text{top}} q\,dp \right)^2 + \left( \int_{\text{surface}}^{\text{top}} qv\,dp \right)^2 \right]^{1/2} \]
"...dry bias with the precipitation deficit leading the warm bias over this region is associated with the widespread failure of models in capturing strong rainfall events in summer over the central U.S. ..." (missing precipitation recycling?)

More realistic land surface processes + convection-permitting resolution + large-scale model domain is the key.
Future work
Cropland ET contributions to individual storm events

Hourly Precipitation
Hourly Prec (mm/h): 2012-07-01 00:00:00

Cropland ET Contribution ratio (%)
Hourly Tracer Ratio (%): 2012-07-01 00:00:00
On-going work:
What are the moisture contribution to mesoscale convection storms?
Discussion & Conclusion

- First time coupling the GW-Crop-Irrigation system in the convection-permitting model
- WVT reveals insight of precipitation recycling in details

- (1) GW-Crop-Irrigation induce strong cooling effects on temperature and increase precipitation
- (2) Enhanced precipitation were originated from croplands in US Corn Belt through precipitation recycling (14~18%)
- (3) Three processes contribute differently:
  - GW supplies soil moisture from below
  - Crop effectively transport soil moisture to the atmosphere
  - Irrigation adds additional water from top
- (4) Strong interannual variability – strongest in 2012 dry year (from 11~18%) when large-scale moisture advection (LLJ from Gulf of Mexico) is weak