US Corn Belt Enhances Regional Precipitation Recycling

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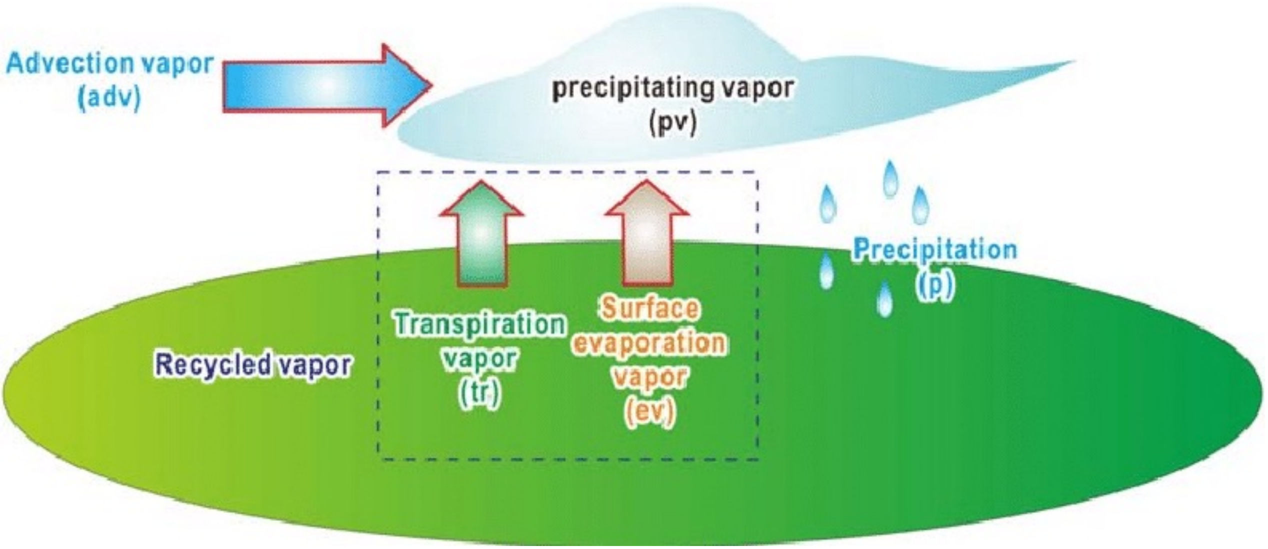
Precipitation Recycling is an important component in the water cycle



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

$$\rho = \frac{Prec_{local}}{Prec_{total}}$$

- 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

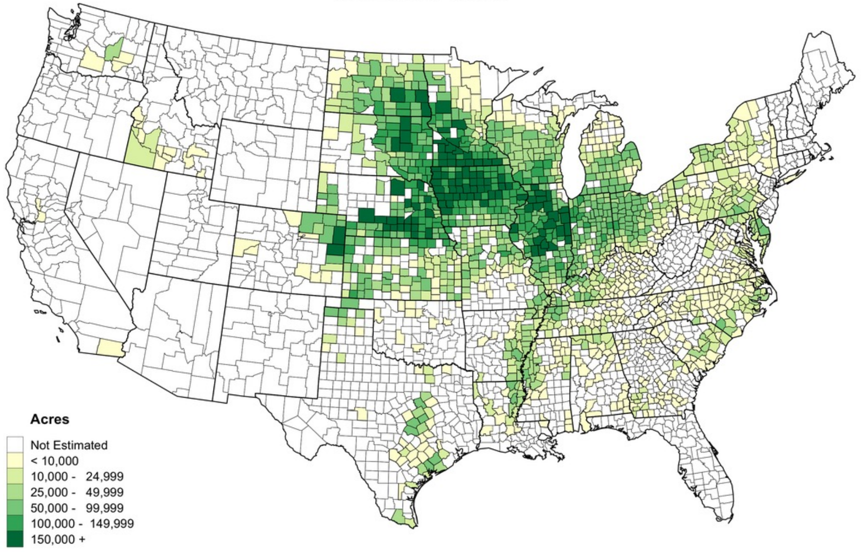
Deforestation

Wetland drainage

Croplands and Irrigation

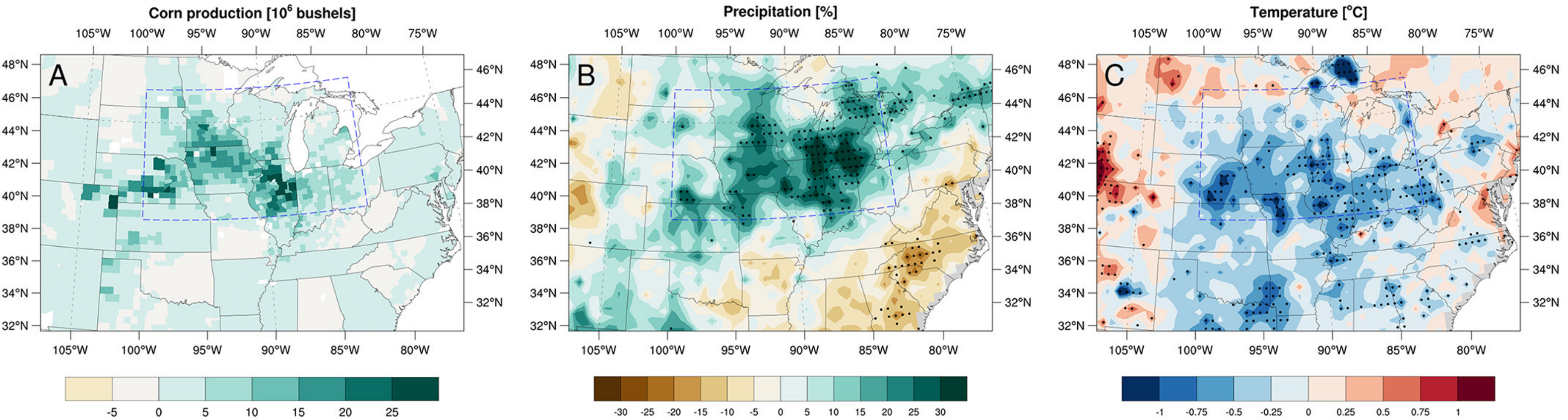
Extensive croplands and agricultural management in US Corn Belt have substantially modified regional climate

Corn for Grain 2022
Harvested Acres by County
for Selected States



US is the largest corn producing nation in the world, accounting for 31% of global production

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)



The United States's Corn Belt is making its own weather

Plentiful crops are changing rainfall and temperature trends

16 FEB 2018 · BY KIMBERLY HICKOK

Productive corn fields are responsible for unique weather changes in the central United States. ISTOCK/COMSEASTOCK

Research Question:
What are the contributions of crop growth and irrigation managements to regional climate? precipitation recycling?

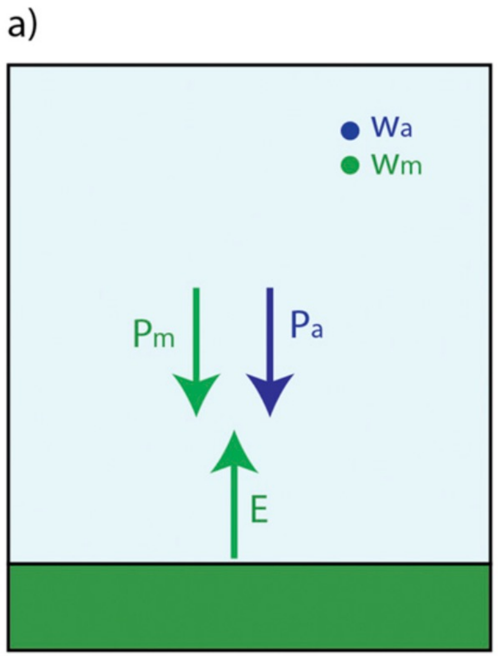
Various methods to estimate precipitation recycling ratio in Central US

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.

Recycling ratio	Time scale	Area	Method	Reference
		Monthly RR		
22%, 34%, 33%	Mean J, J, A	20° by 10° (2.4 × 10^6 km^2)	Budyko-type analytic model	Brubaker et al. (1993)
41% and 33%	April–July 1988 and 1993, respectively	4 × 10^6 km^2	Back-trajectory algorithm	Dirmeyer and Brubaker (1999)
30%, 39%, 35%	Mean J, J, A	20° by 10° (2.4 × 10^6 km^2)	Eltahir and Bras model	Bosilovich and Schubert (2001)
32%	Mean J, J, A	4 × 10^6 km^2	Back-trajectory algorithm	Brubaker et al. (2001)
14%	Average JJA	15° by 10° (1.8 × 10^6 km^2)	Water vapor tracers	Bosilovich and Schubert (2002)
25% (northern plains); 26% (southern plains)	Average JJA	10° by 8° (1 × 10^6 km^2) and 10° by 12° (1.5 × 10^6 km^2)	Water vapor tracers	Bosilovich (2003)
From 19% to 24%	May, J, J, A	1.23 × 10^6 km^2	Simple recycling equation	Zangvil et al. (2004)
18%	Average JJA	1 × 10^6 km^2	DRM	Dominguez et al. (2006)
32%, 35%, and 40%	J, J, and A	22° by 12° (3 × 10^6 km^2)	General bulk model	Burde et al. (2006)
2.2%, 6.2%, and 18.0%	Effective	10^4, 10^5, 10^6	Back-trajectory algorithm	Dirmeyer and Brubaker (2007)
		Daily RR		
From 15% to 30%	May, J, J, A	1.23 × 10^6 km^2	Simple recycling equation	Zangvil et al. (2004)
22%, 25%, 23%, 20%	May, J, J, A	4 × 10^6 km^2	Water vapor tracers	Bosilovich and Chern (2006)

Dominguez and Kumar, 2008

Note: PR ratio depends on the area of analysis



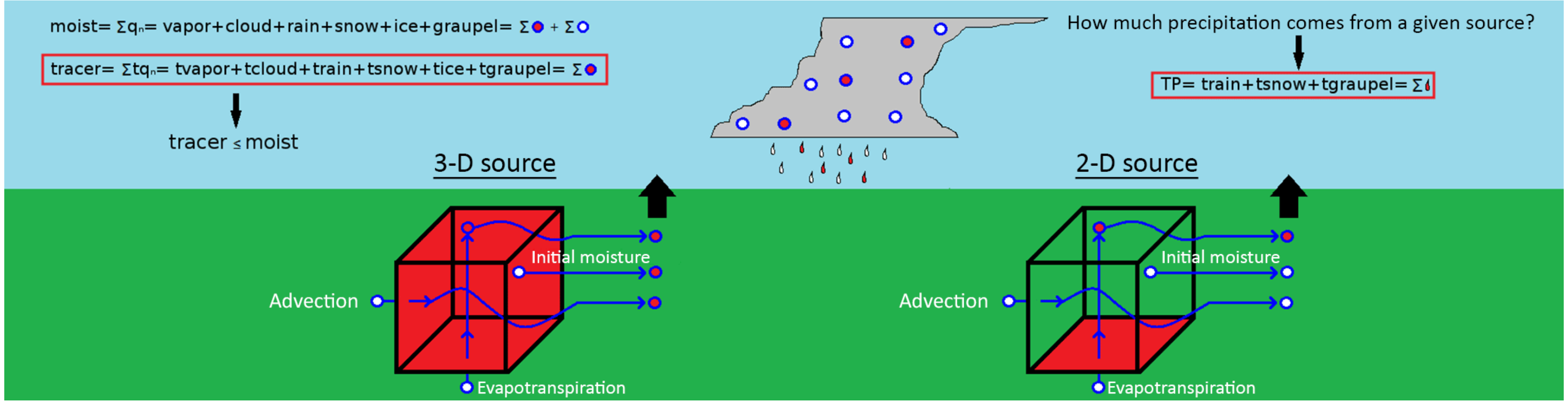
(Dominguez et al. 2020)

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

b) Offline tracking model (Eulerian or Lagrangian)

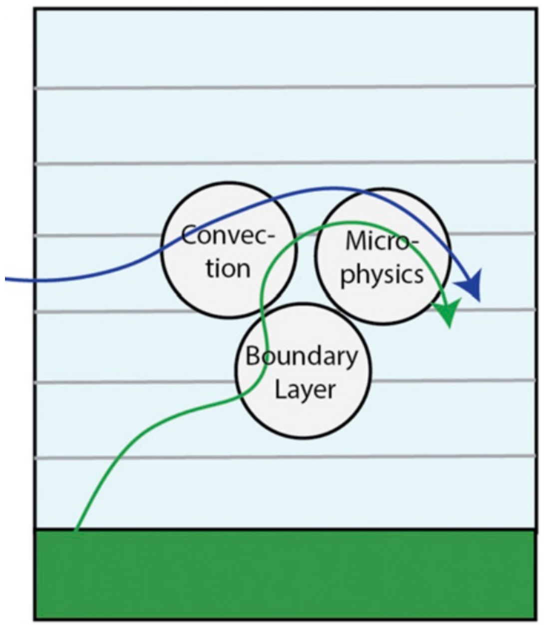
c) Online Water Vapor Tracer model (Insua-Costa & Miguez-Macho, 2018) most complex

WRF-Water Vapor Tracer



Insua-Costa and Miguez-Macho 2018

c) Dominguez et al. 2020



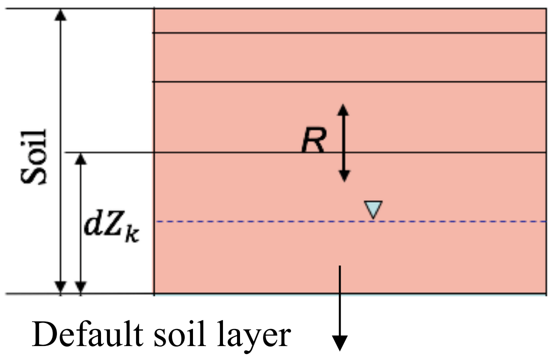
$$\frac{\partial q_n}{\partial t} = -\boldsymbol{v} \cdot \nabla q_n + \nu_q \cdot \nabla^2 q_n + \left(\frac{\partial q_n}{\partial t}\right)_{\mathrm{PBL}} + \left(\frac{\partial q_n}{\partial t}\right)_{\mathrm{microphysics}} + \left(\frac{\partial q_n}{\partial t}\right)_{\mathrm{convection}},$$

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

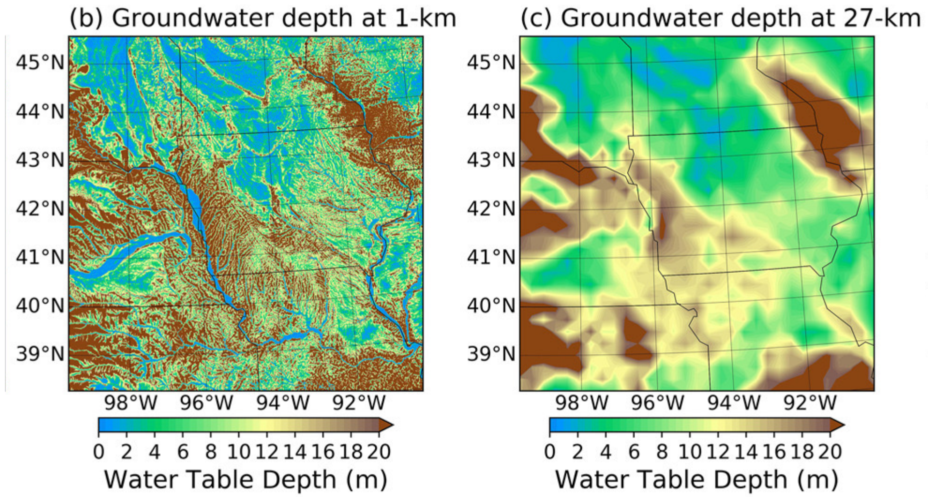
The power of complex models is evident when analyzing individual cases/seasons where the local-scale processes are important.

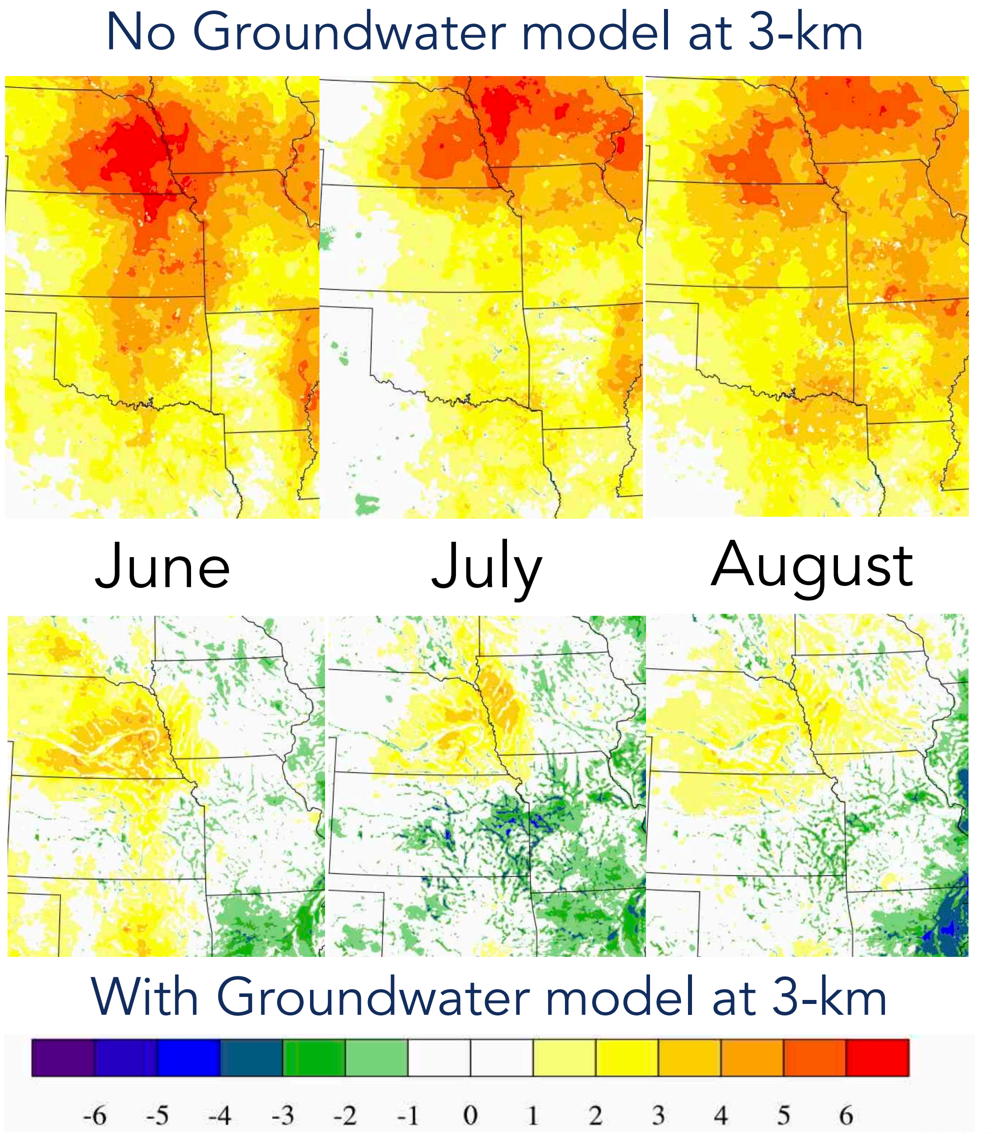
Previous studies neglected complex **land surface processes** contributing to local ET

1. Shallow Groundwater-Soil Moisture Interactions depend on model resolution



Groundwater-soil moisture interactions depend on model resolution



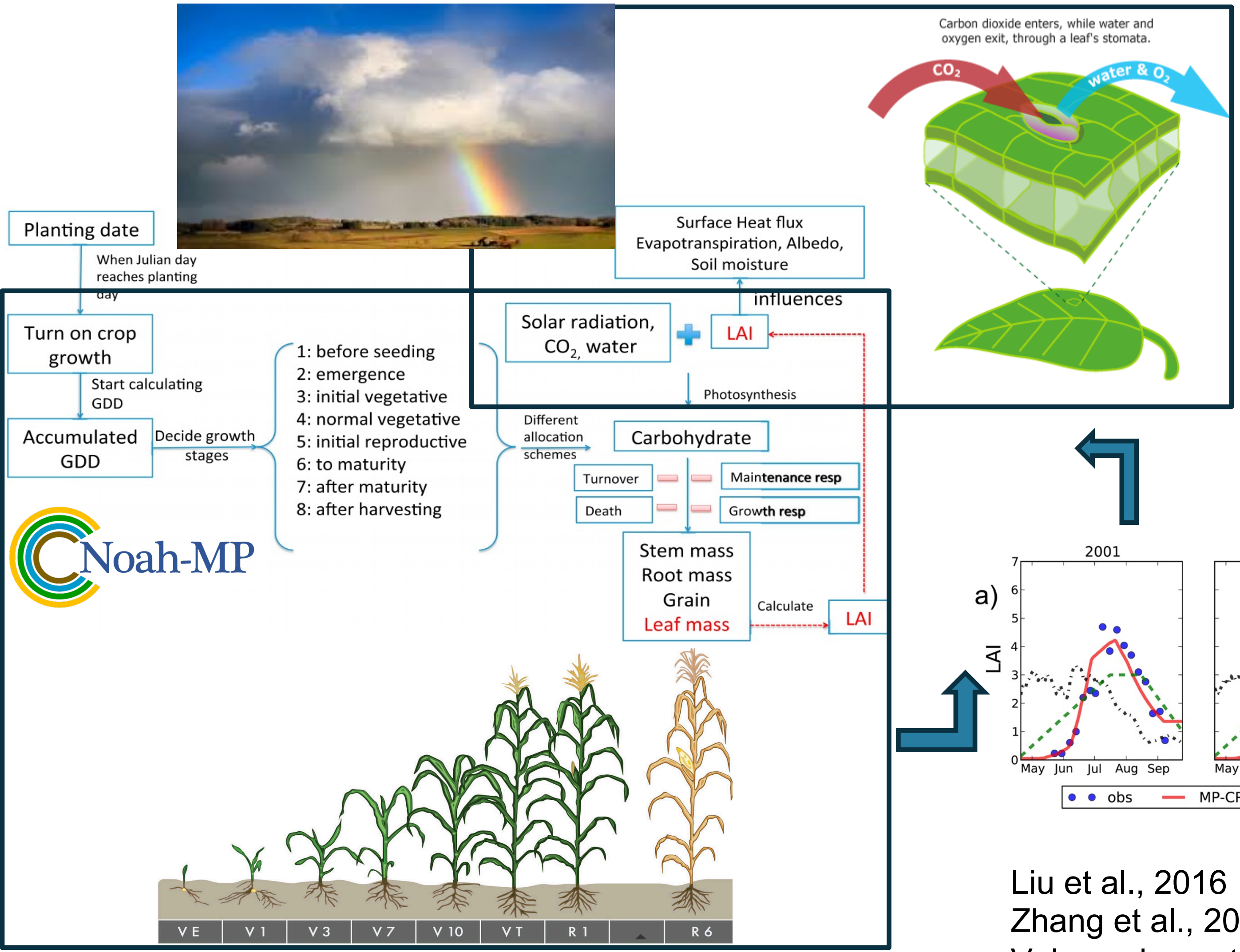


Barlage et al., 2021

Coupling groundwater to LSM and RCM reduces summer warm biases

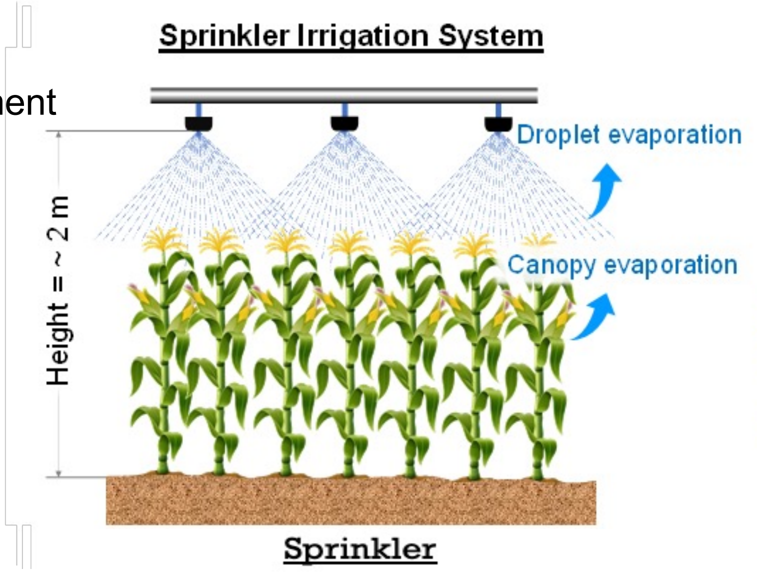
2. Crop growth and Irrigation management

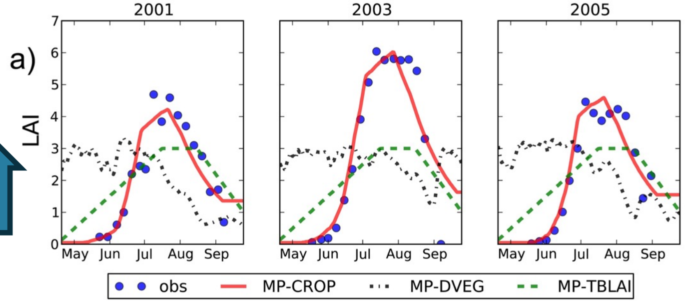
Photosynthesis & Stomatal control

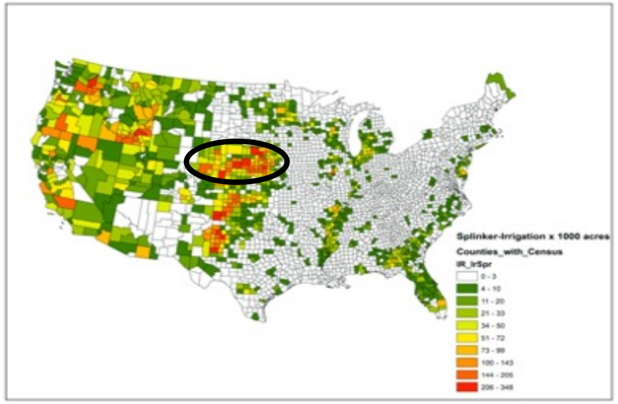


Dynamic Crop Growth & Carbon Allocation

Irrigation management

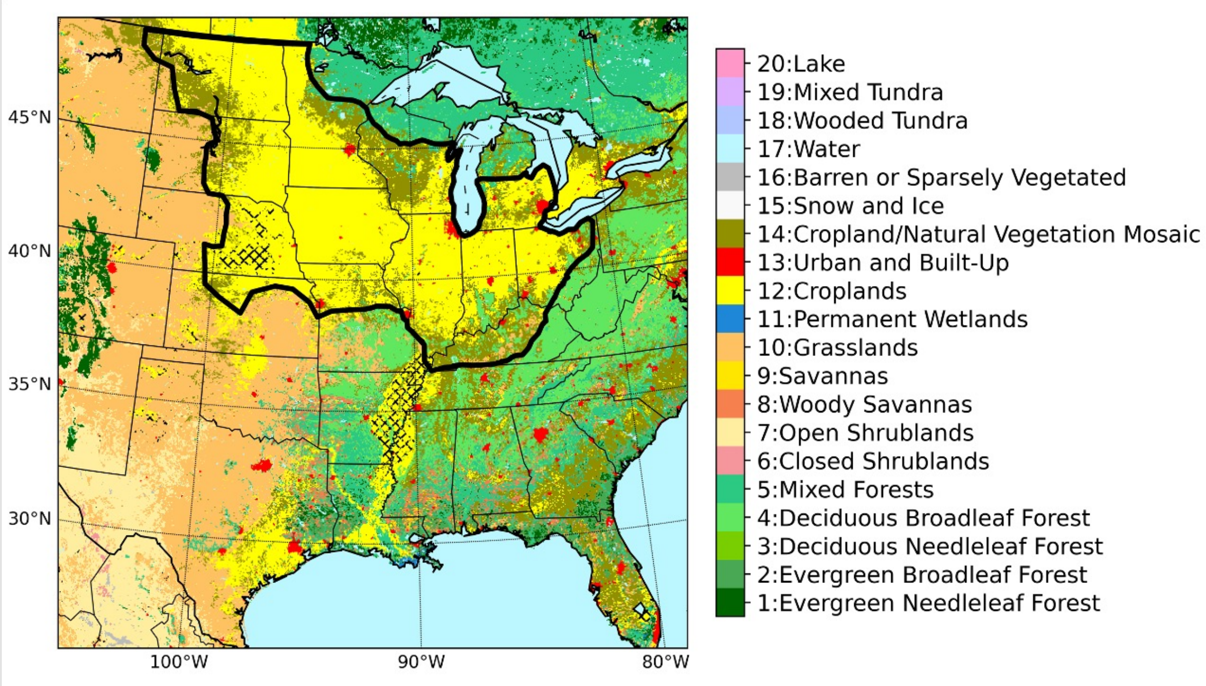






Liu et al., 2016
Zhang et al., 2020
Valayamkunnath et al., 2022

- **WRF Domain setup:**



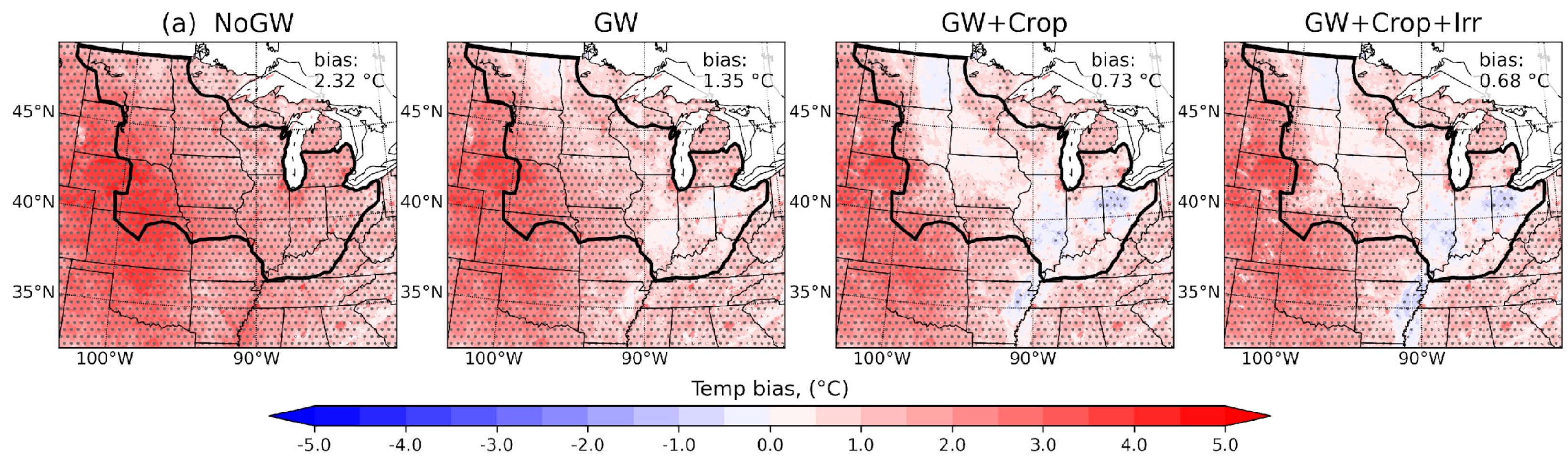
Black outline: Corn Belt region
Hatched region: Irrigation
Zhang et al. 2024 (in revision)

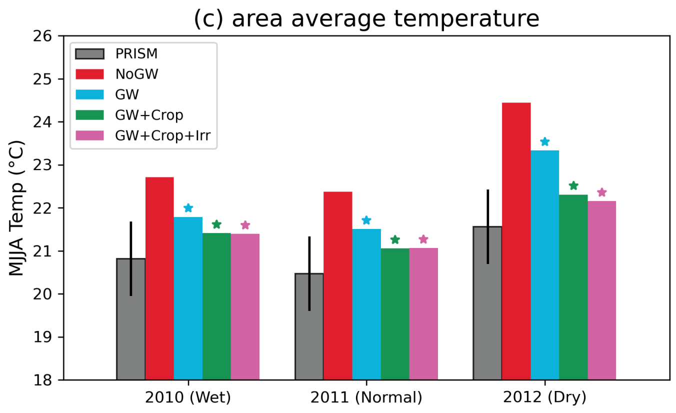
- **Simulation Design:**
- **2010 (wet), 2011 (normal), 2012 (dry)**
- Growing season: From **04-01 to 09-01** (first month spin-up, analyze MJJA)
- 4-km grid spacing (convection-permitting)
- No spectral nudging
- Four simulations with different land surface processes:

Simulation	Groundwater interaction	Vegetation Dynamics	Irrigation Management
1. Baseline (NoGW)	Free Drainage	Prescribed MODIS monthly LAI	No
2. GW	MMF groundwater model	Prescribed MODIS monthly LAI	No
3. DynCrop (GW+Crop)	MMF groundwater model	Dynamic Crop Model	No
4. Irrigation (GW+Crop+Irr)	MMF groundwater model	Dynamic Crop Model	Yes

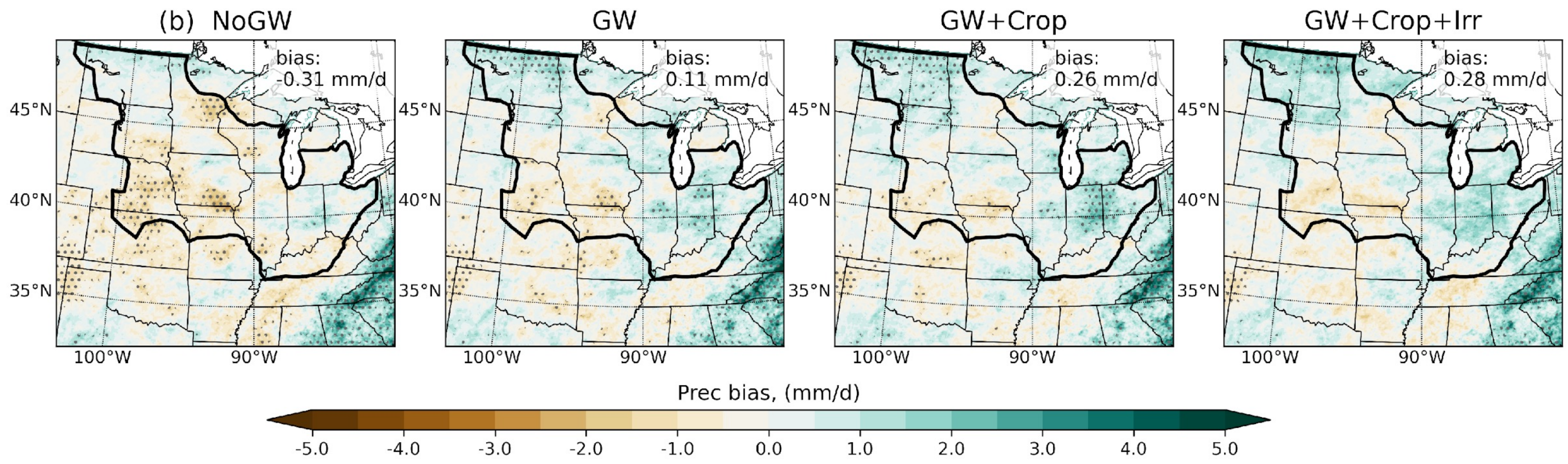
Coupled GW+Crop+Irrigation system - cooling temperatures and enhancing precipitation

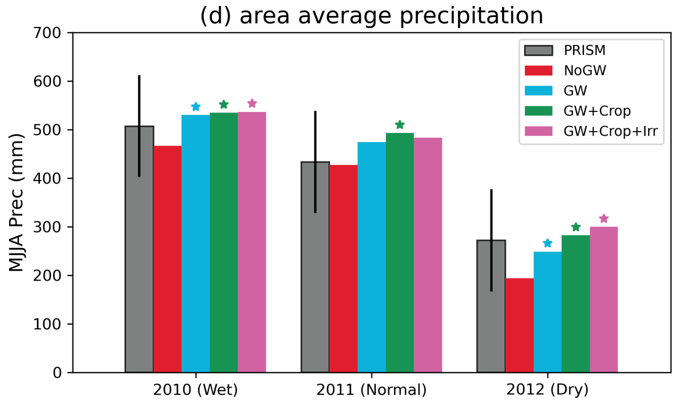
MJJA temperature





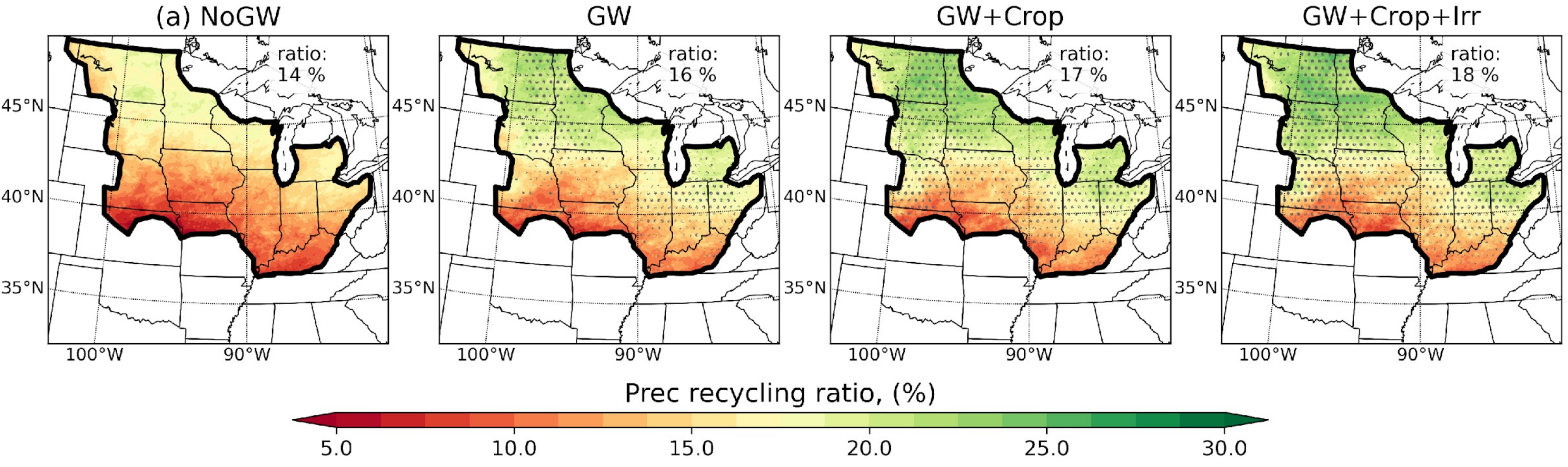
MJJA precipitation



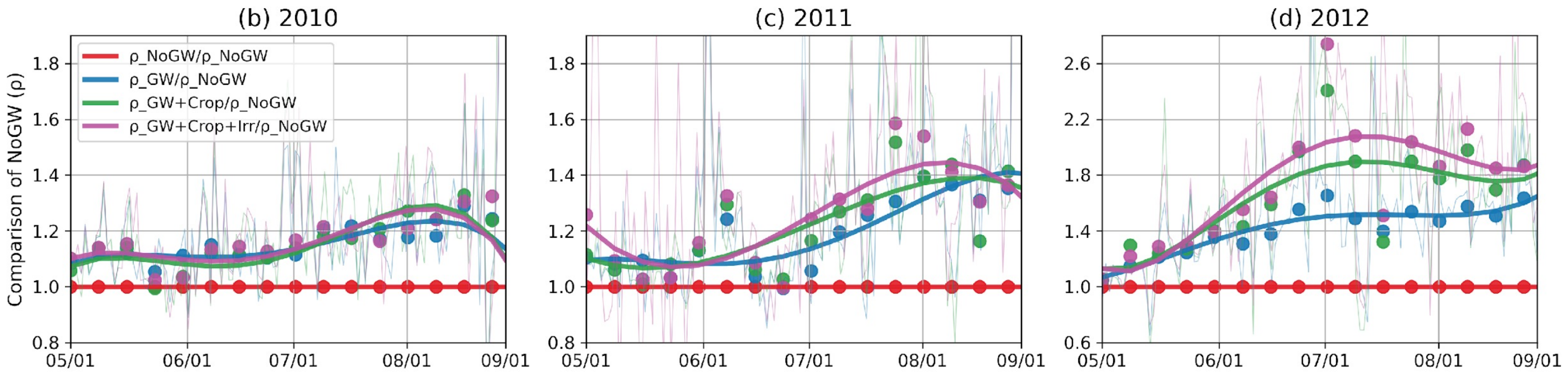


With Coupled GW-Crop-Irrigation, warm summer warm and dry bias significantly improved (dotted and stars)

Precipitation Recycling Ratio - Spatial Gradient & Temporal evolution



$$\rho = \frac{Prec_{tracer}}{Prec_{total}}$$

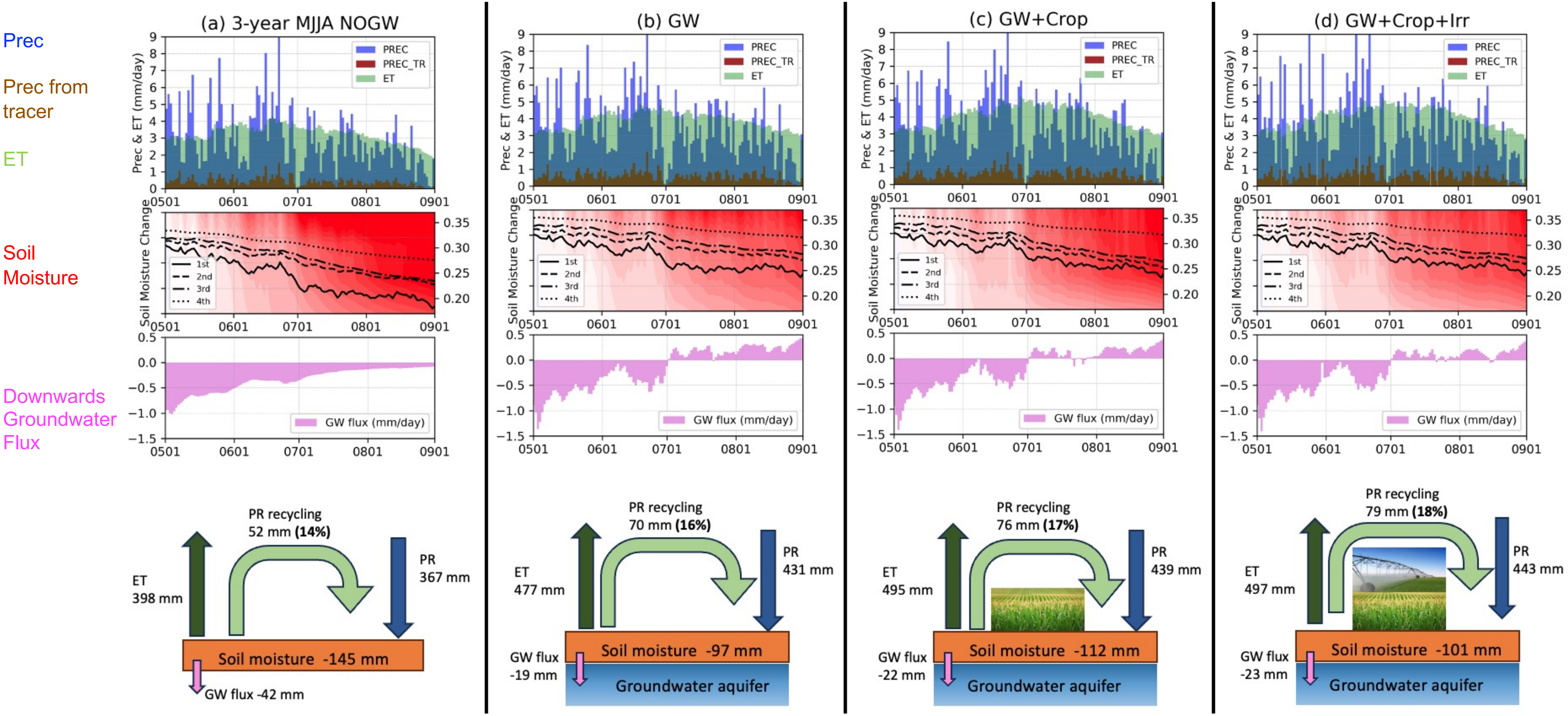


Enhancement recycling ratio shows stronger seasonal cycle in with crop and irrigation

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

JJA – Local-scale environment
- Peak of the growing season

Enhanced Precipitation Recycling explained by water balance

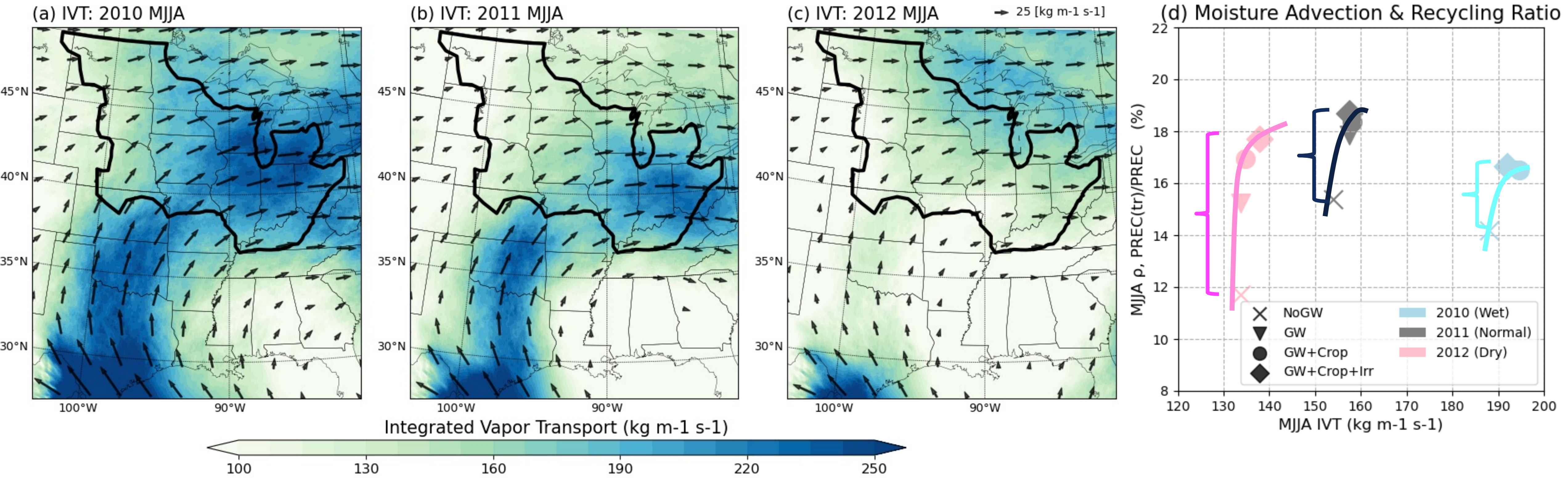


GW supplies soil moisture from below

Crop effectively transports moisture from soil to the atmosphere

Irrigation adds additional water from top

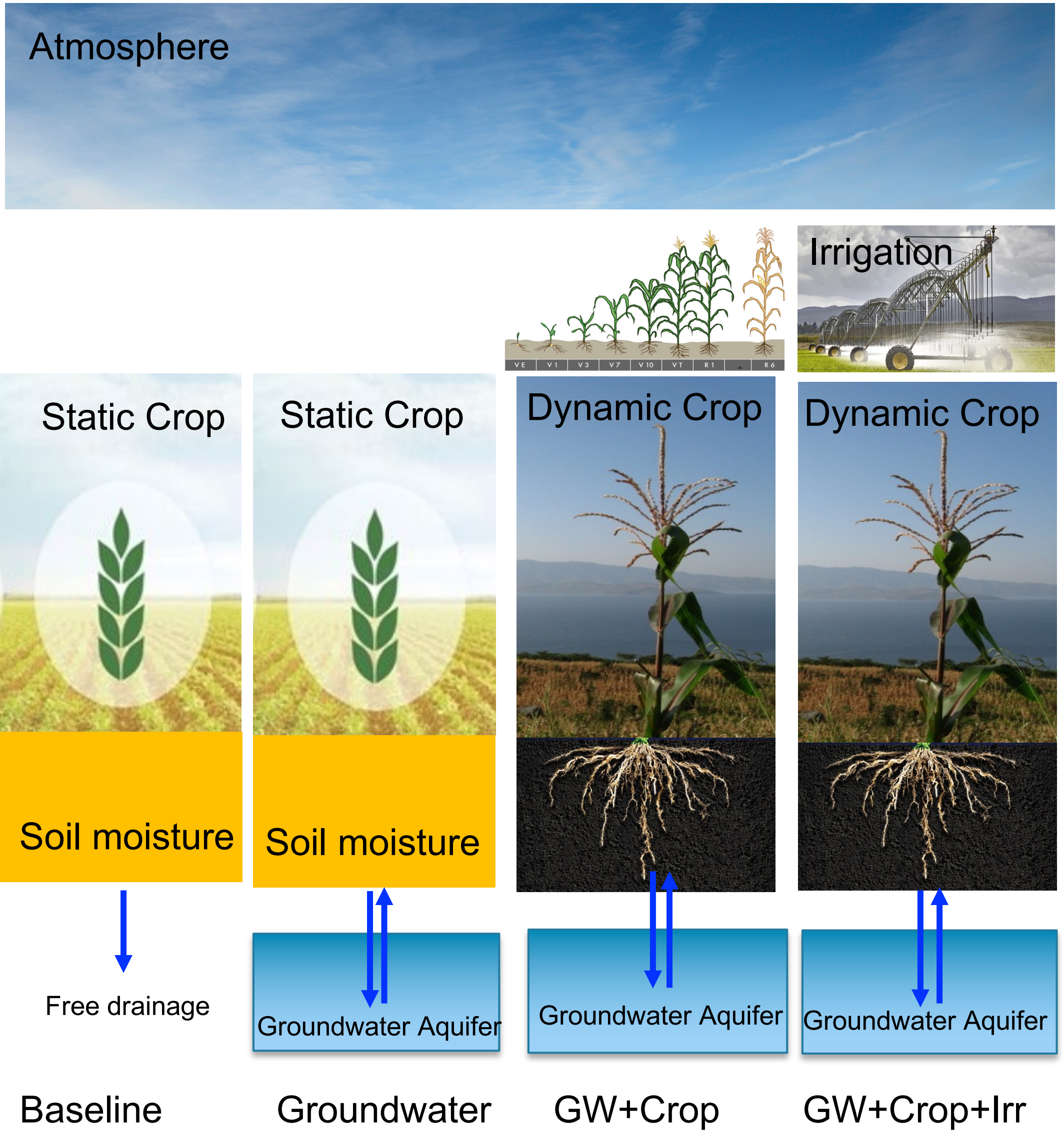
Interannual variability of precipitation recycling: moisture advection vs local ET



$$IVT = \frac{1}{g}[\left(\int_{surface}^{top} qudp\right)^2 + \left(\int_{surface}^{top} qvdp\right)^2]^{1/2}$$

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

Earth System Modeling - Groundwater-Soil-Vegetation-Atmosphere Continuum

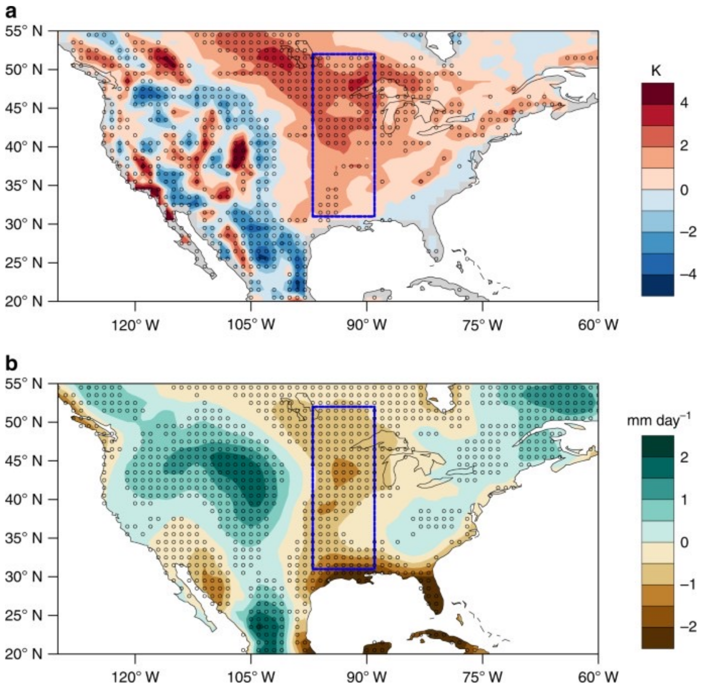


Article | Open Access | Published: 12 October 2017

Causes of model dry and warm bias over central U.S. and impact on climate projections

Yanluan Lin, Wenhao Dong, Minghua Zhang, Yuanyu Xie, Wei Xue, Jianbin Huang & Yong Luo

Nature Communications **8**, Article number: 881 (2017) | Cite this article



LETTER • OPEN ACCESS

The central role of forests in the 2021 European floods

Damián Insua-Costa[3,1], Martín Senande-Rivera[1], María Carmen Llasat[2] and Gonzalo Miguez-Macho[1]

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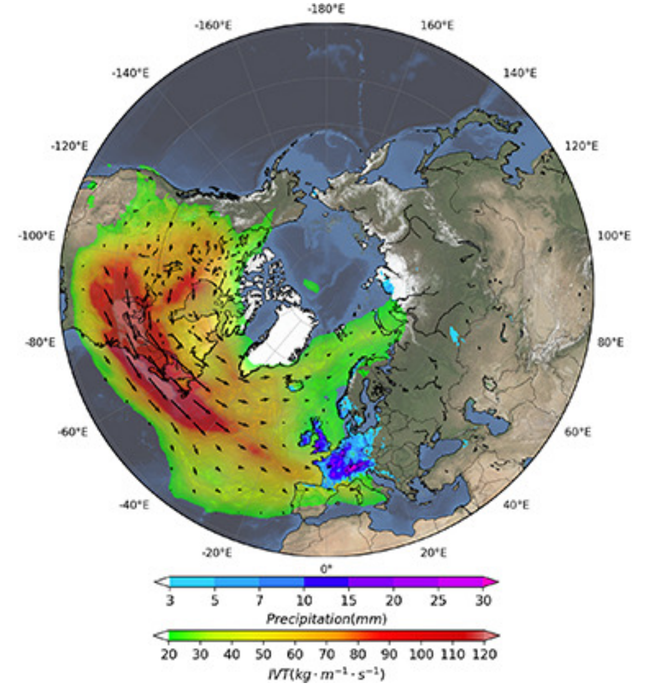
Environmental Research Letters, Volume 17, Number 6
Citation Damián Insua-Costa *et al* 2022 *Environ. Res. Lett.* **17** 064053



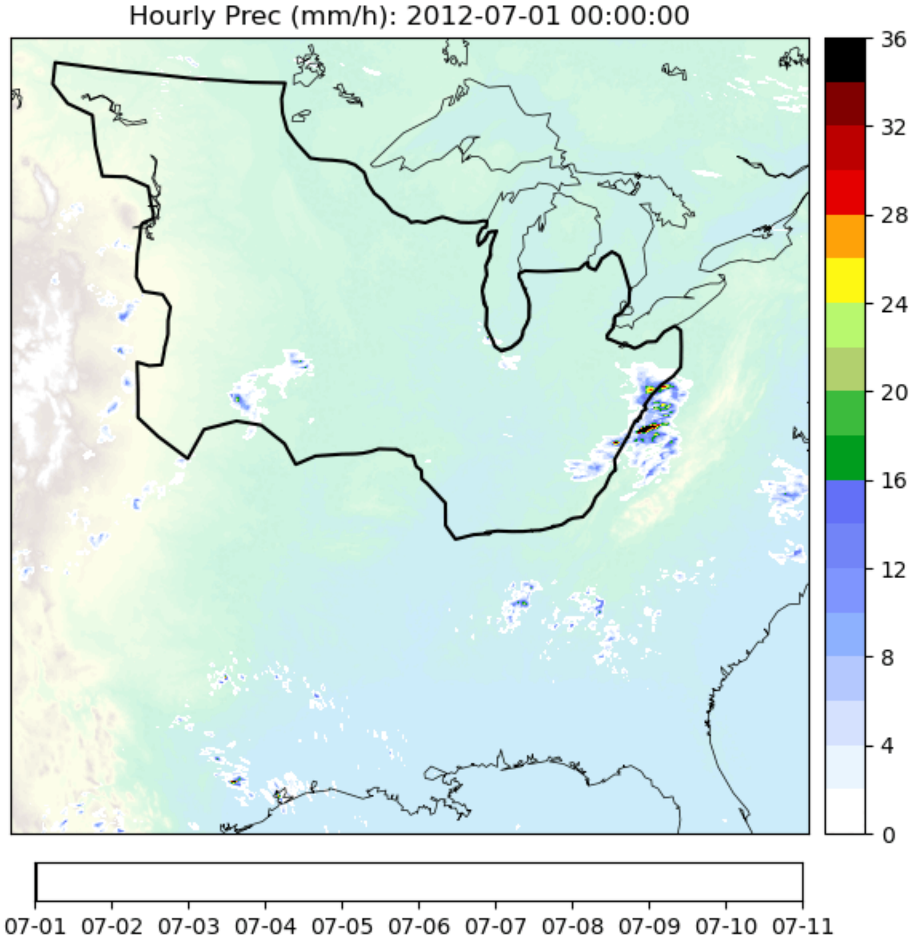
"…dry bias with the precipitation deficit leading the warm bias over this region is associated with the widespread failure of models in capturing strong rainfall events in summer over the central U.S. …" (missing precipitation recycling?)

More realistic land surface processes + convection-permitting resolution + large-scale model domain is the key.

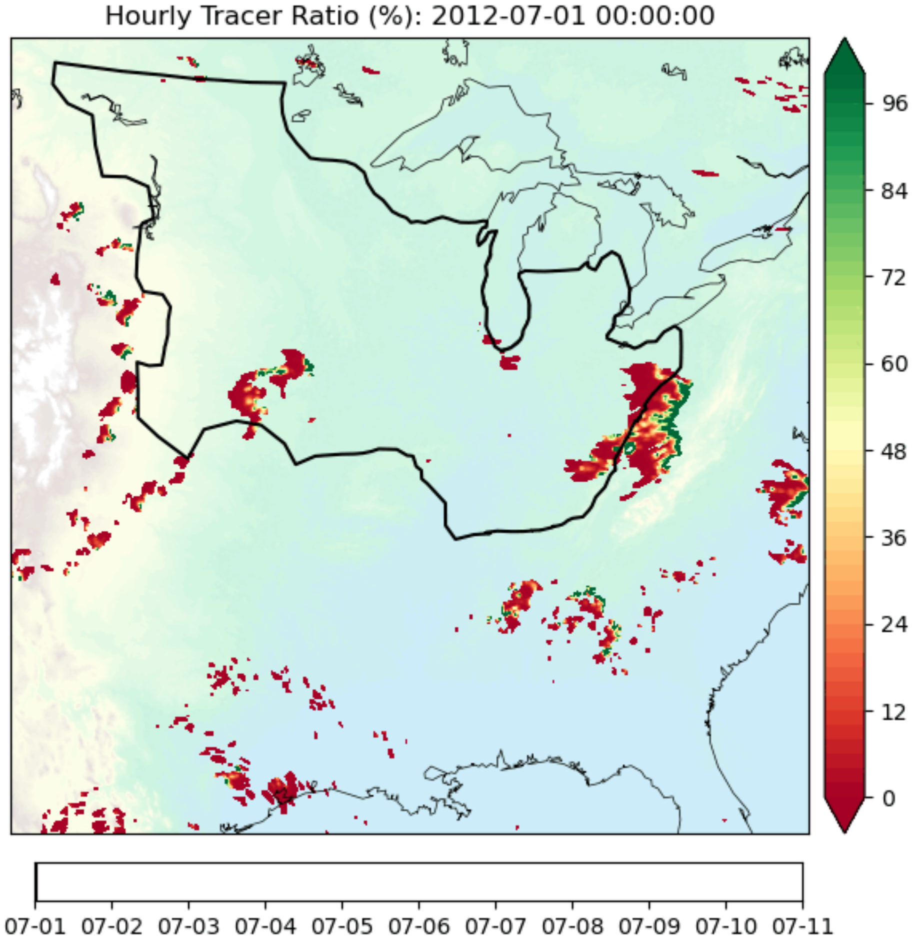
Future work

Cropland ET contributions to individual storm events

Hourly Precipitation

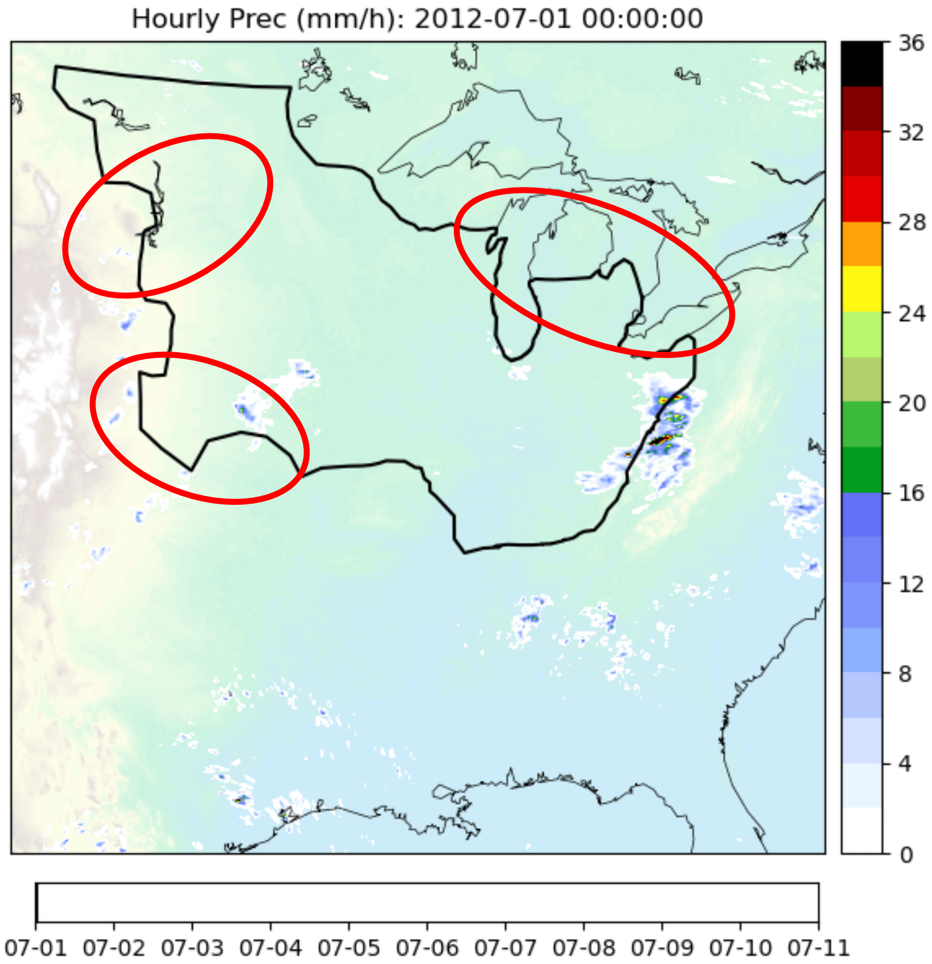


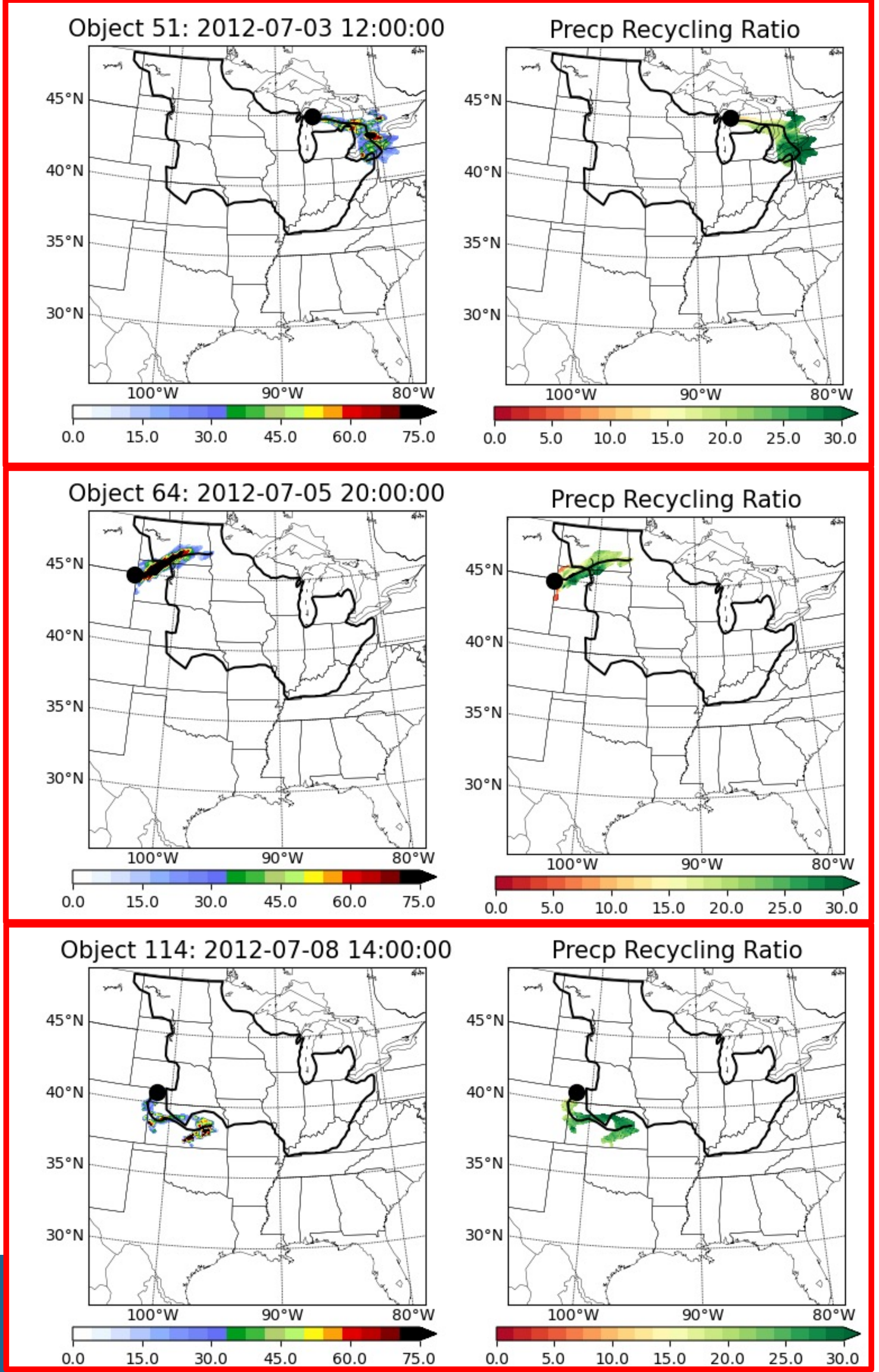
Cropland ET Contribution ratio (%)



On-going work:

What are the moisture contribution to mesoscale convection storms?

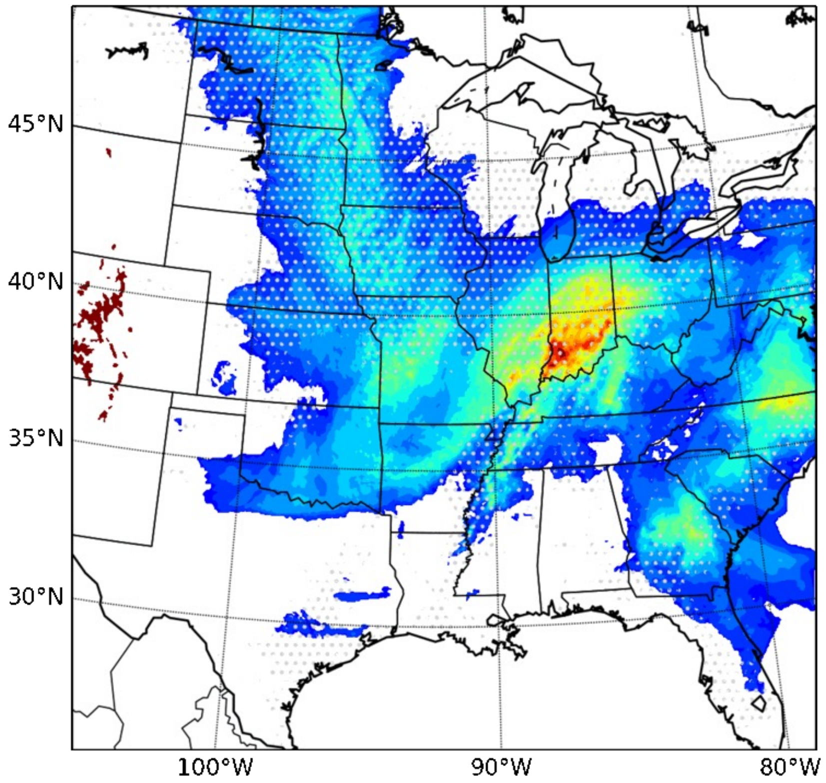




Discussion & Conclusion

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

Hourly Integrated Water Vapor from Tracer



- (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