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Modeling Regional Water Stress Using a Coupled Modeling Framework with GCAM and Regional Water System Models

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JGCRI Integrated Assessment Technical Workshop, College Park, MD
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Overarching science questions

- What are the dominant pathways for human-earth system interactions that influence the water cycle?
- How will the water cycle change as a result of climate change vs changes in socio-economic and engineering systems to mitigate and adapt to climate change?
- What are the vulnerabilities of energy, water, and food to changes in climate mean, variability, and extreme?

A coupled modeling framework

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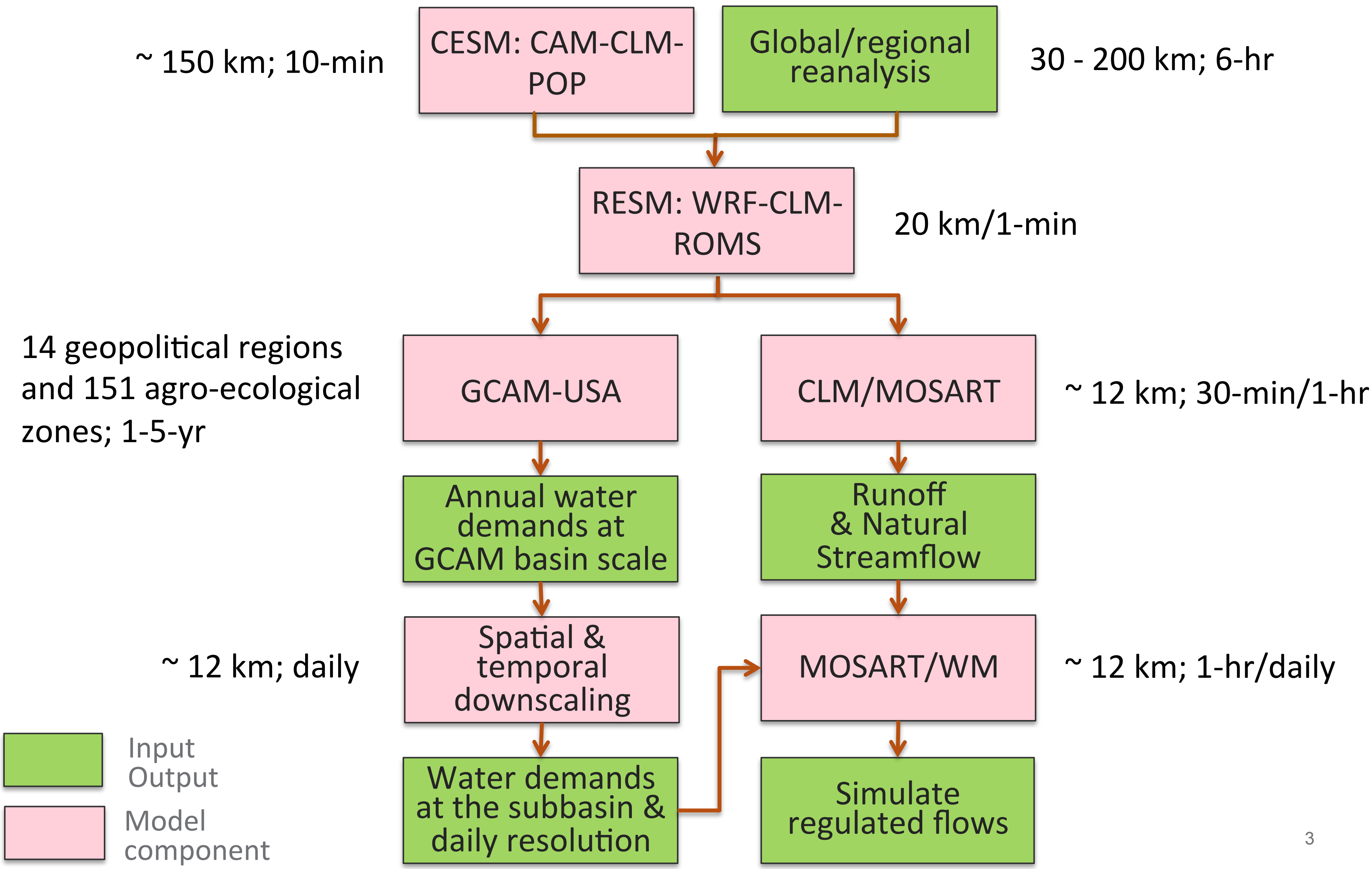

Community Land Model (CLM): soil hydrology

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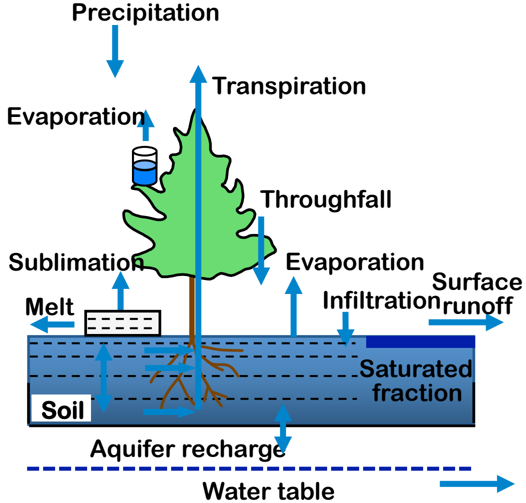
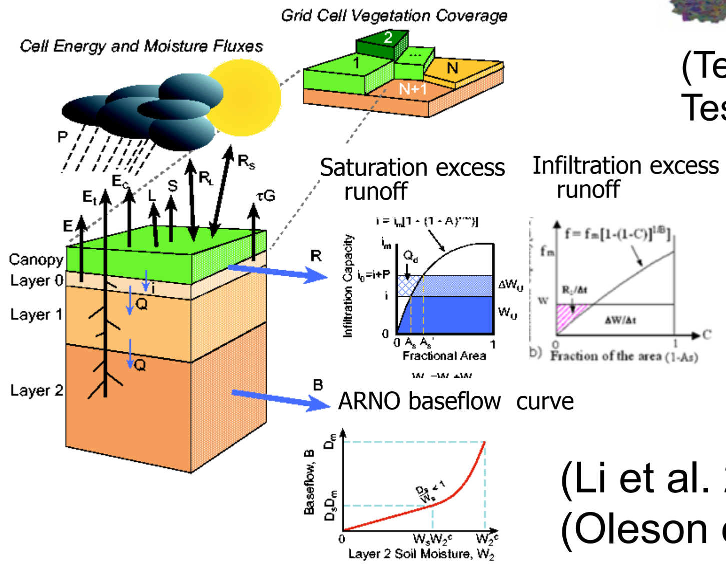
CLM hydrology

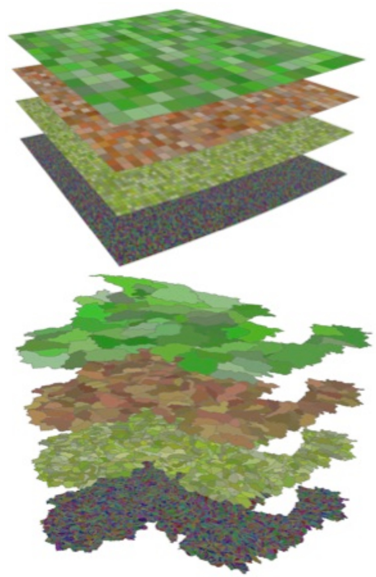


VIC formulation



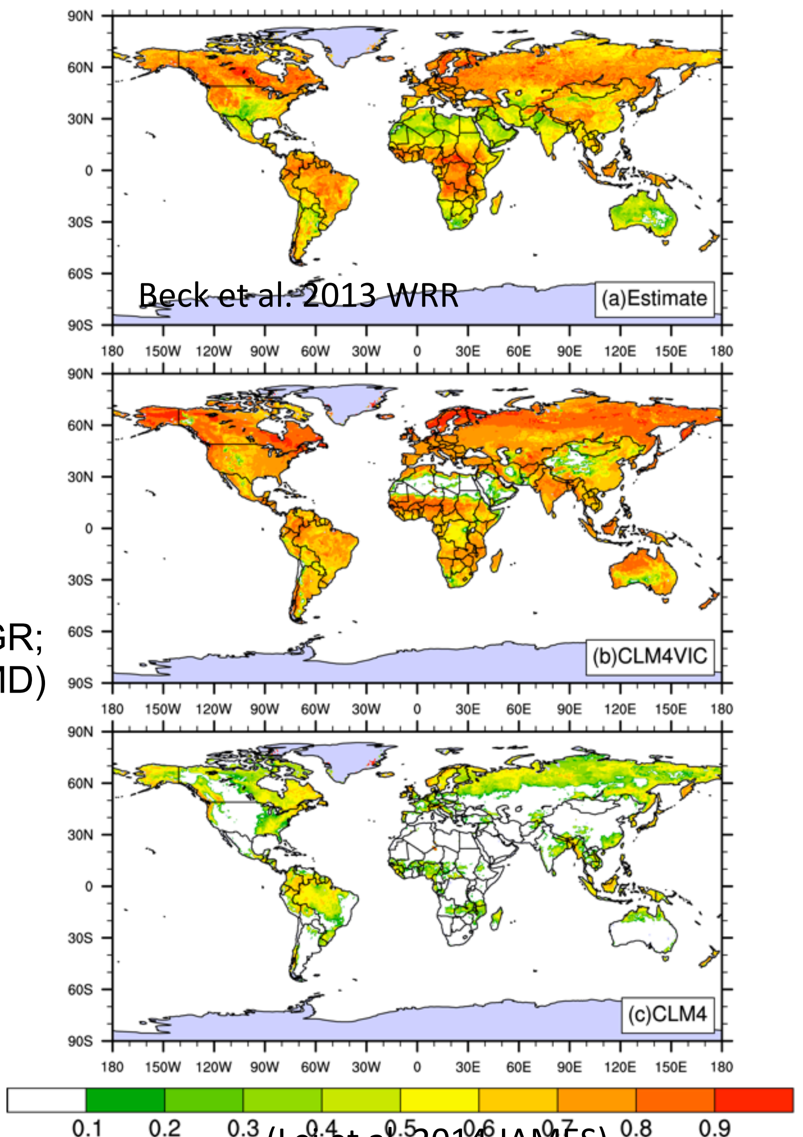
(Li et al. 2011 JGR)
(Oleson et al. 2013)

Spatial representation



(Tesfa et al. 2014 JGR;
Tesfa et al. 2014 GMD)

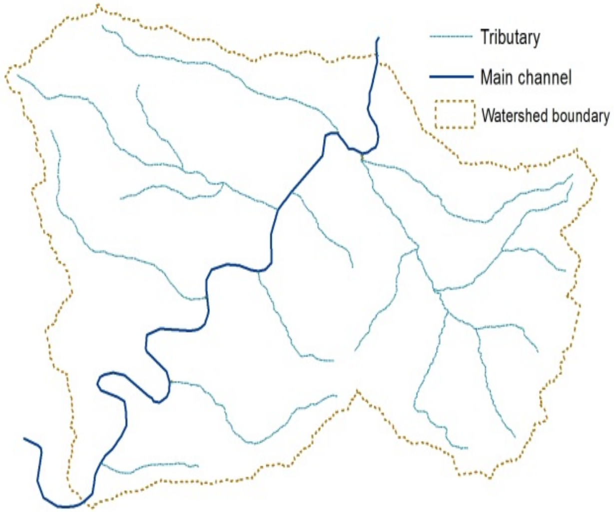
Observed / simulated baseflow index



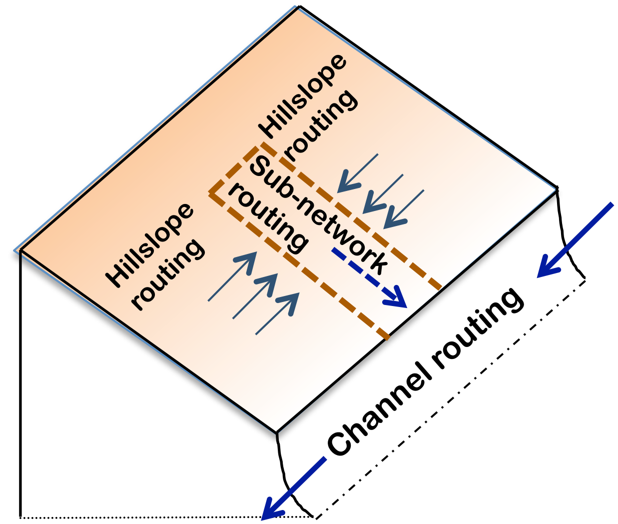
(Lei et al. 2014 JAMES)

Model for Scale Adaptive River Transport (MOSART): river transport

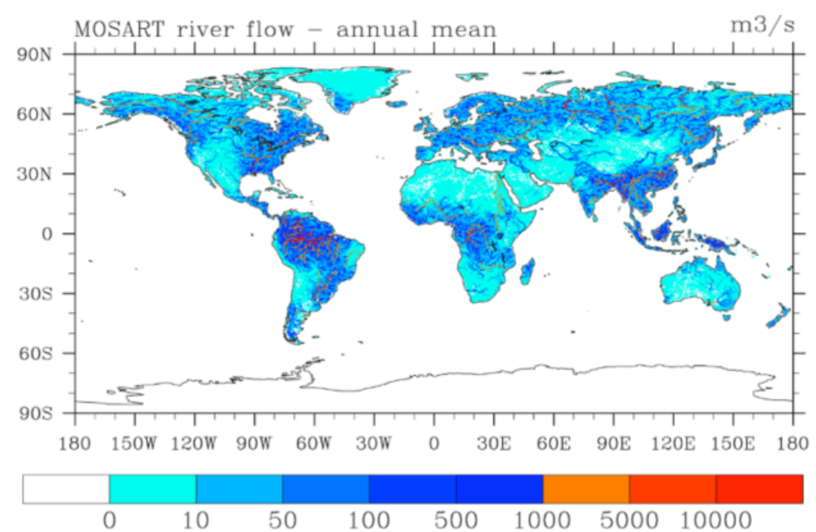
Real River Network



Conceptualized River Network of MOSART



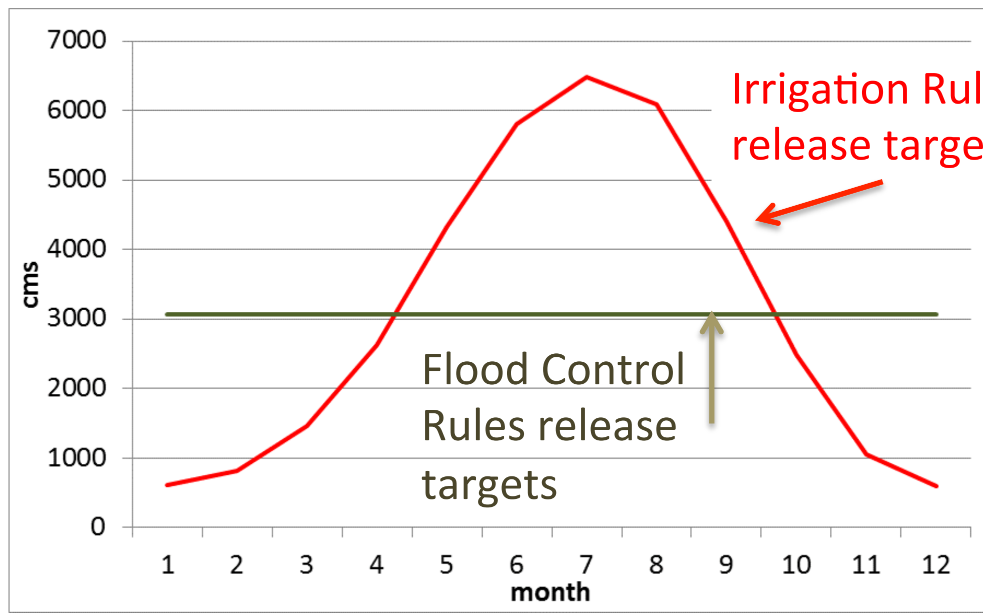
- Hillslope routing: account for impacts of overland flow on soil erosion, nutrient loading, etc.
- Sub-network routing: scale adaptive across different resolutions to reduce scale dependence
- Main channel routing: explicit estimation of in-stream conditions (velocity, water depth, etc.)



(Li et al. 2013 JHM)

WM: flow regulation by reservoir operations

- Generic operating rules (Voisin et al. HESS, 2013)
  - Each reservoir has multiple purposes:
    i) Flood control and other, ii) Irrigation, or iii) Joint irrigation and flood control
  - Generic Release targets and storage targets for each purpose
  - Configured independently for each reservoir based on hydro-climatological conditions and demand associated with the reservoir



Monthly release targets at Grand Coulee for different rules scenarios

Improvements through use of multi-objective rules

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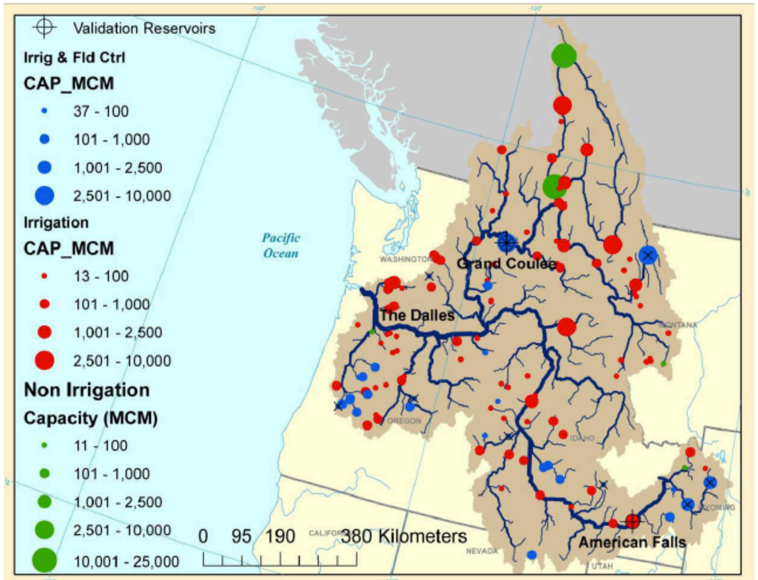
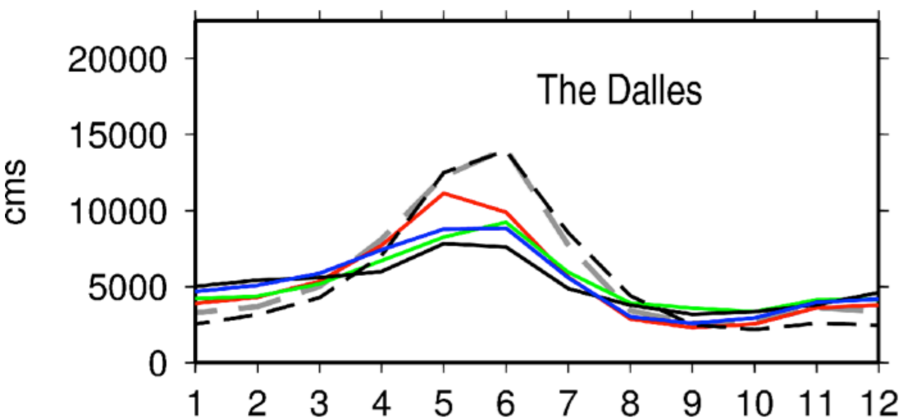
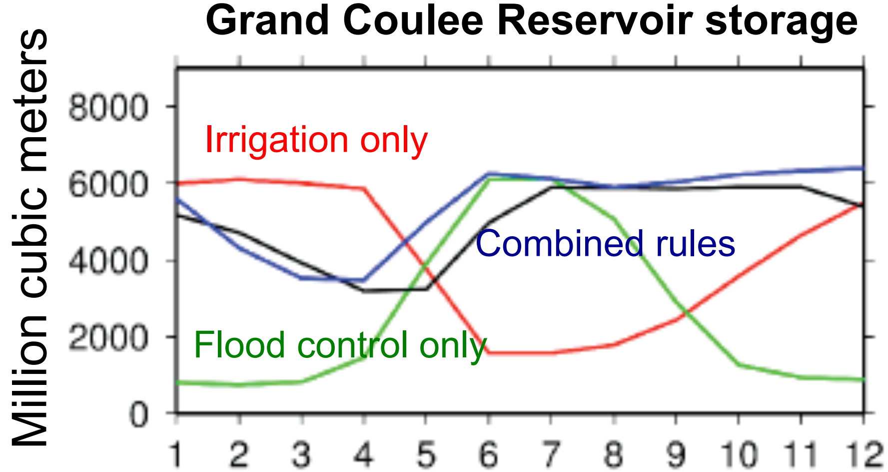
Columbia River Basin



1848 reservoirs represented in the U.S.

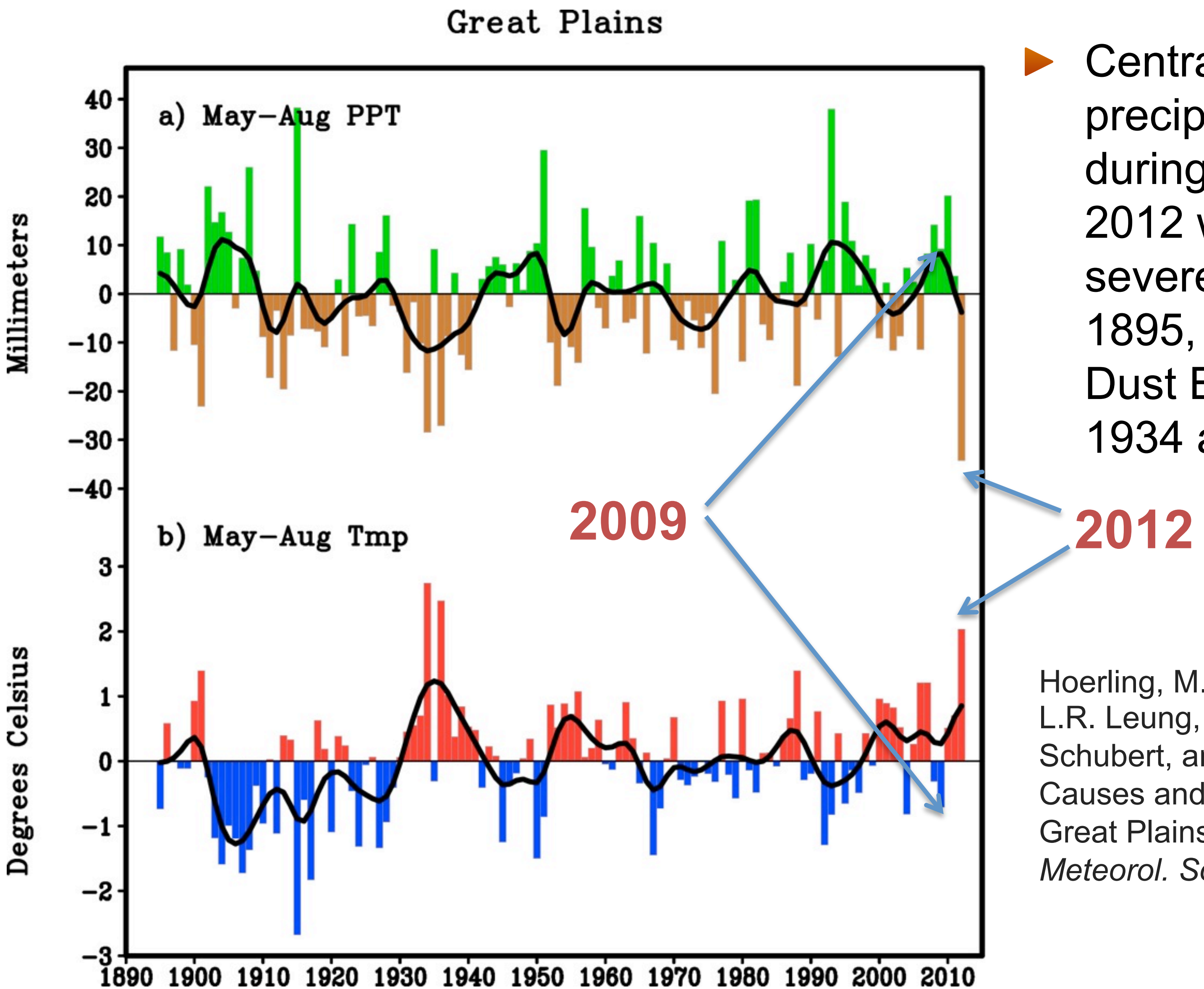


Grand Coulee Reservoir storage



(Voisin et al. 2013a HESS)

Model evaluation: case study of climate anomalies in contemporary record



- Central Great Plains precipitation deficits during May-August 2012 were the most severe since at least 1895, eclipsing the Dust Bowl summers of 1934 and 1936

Hoerling, M., J. Eischeid, A. Kumar, L.R. Leung, A. Mariotti, K. Mo, S. Schubert, and R. Seager, 2014: Causes and predictability of the 2012 Great Plains drought. *Bull. Amer. Meteorol. Soc.*, 95(2), 269-282.

Widespread and severe surface moisture deficits in summer 2012

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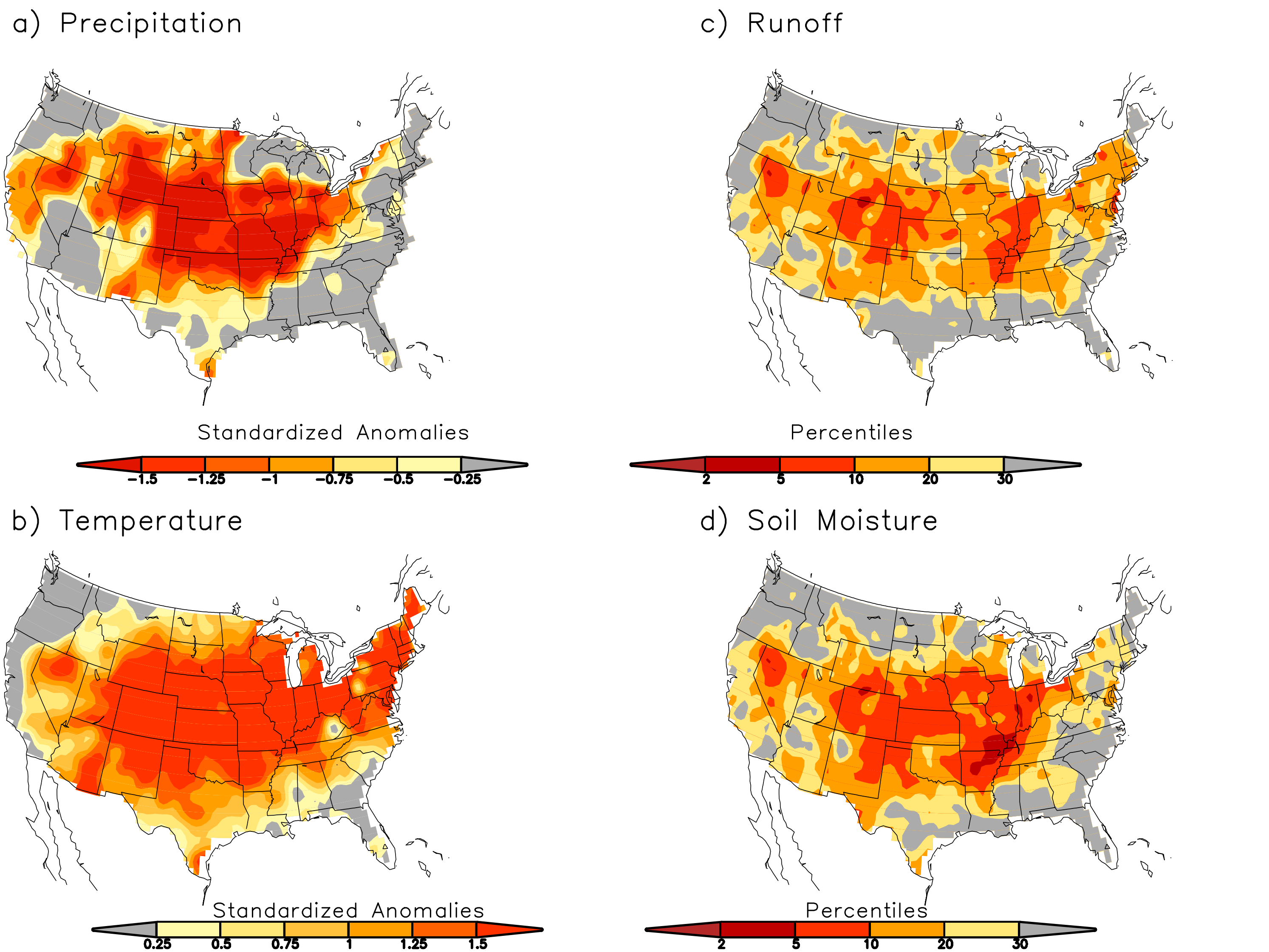
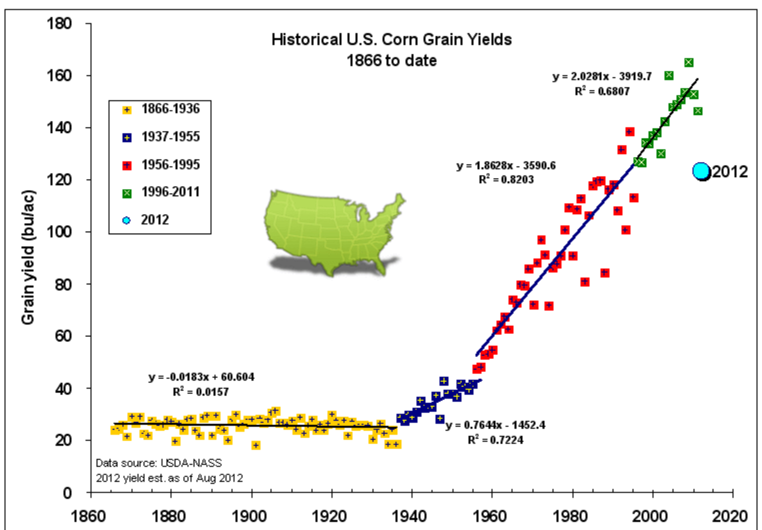


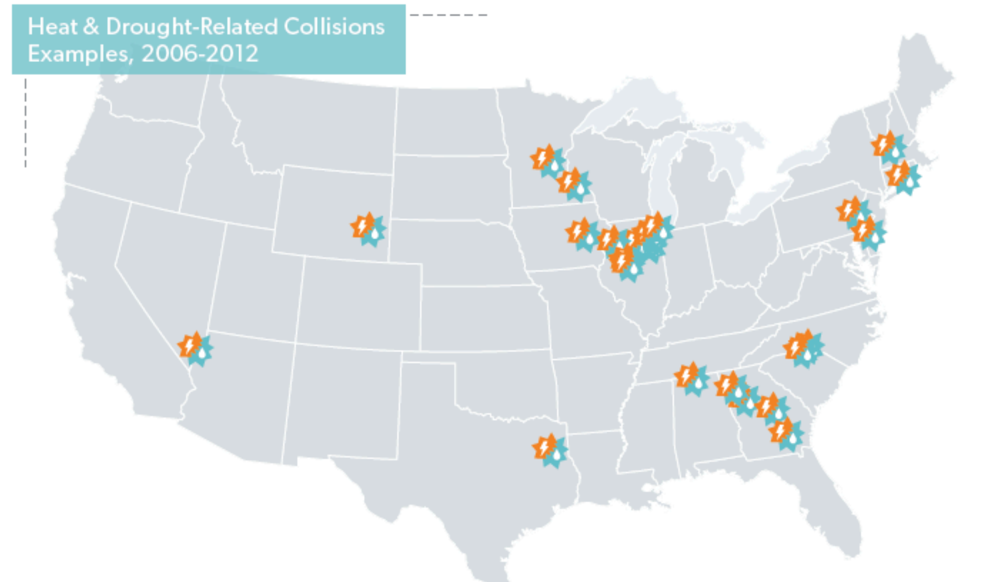
Record heat and drought led to low flows and power plant outages

A satellite view of the Mississippi



Impacts on crop yield

UCS Report: Power and Water at Risk



INCOMING WATER TOO WARM

- → Prairie Island nuclear plant, MN
- → LaSalle County nuclear plant, IL
- → Hope Creek nuclear plant, NJ
- → Limerick nuclear plant, PA
- → Dresden nuclear plant, IL
- → Hatch nuclear plant, GA
- → Millstone nuclear plant, CT
- → Powerton coal plant, IL

OUTGOING WATER TOO WARM

- → Quad Cities nuclear plant, IL
- → Monticello nuclear plant, MN
- → Harllee Branch coal plant, GA
- → GG Allen coal plant, NC
- → Riverbend coal plant, NC
- → Browns Ferry nuclear plant, AL
- → LaSalle County nuclear plant, IL
- → Braidwood nuclear plant, IL
- → ED Edwards coal plant, IL
- → Joliet coal plant, IL
- → Will County coal plant, IL
- → Dresden nuclear plant, IL

NOT ENOUGH WATER

- → Hammond coal plant, GA
- → Laramie River coal plant, WY
- → Yates coal plant, GA
- → Hoover Dam hydroelectric, NV
- → Martin Lake coal plant, TX
- → Vermont Yankee nuclear plant, VT
- → Duane Arnold nuclear plant, IA

Experiments: 2009 vs 2012 ensemble simulations

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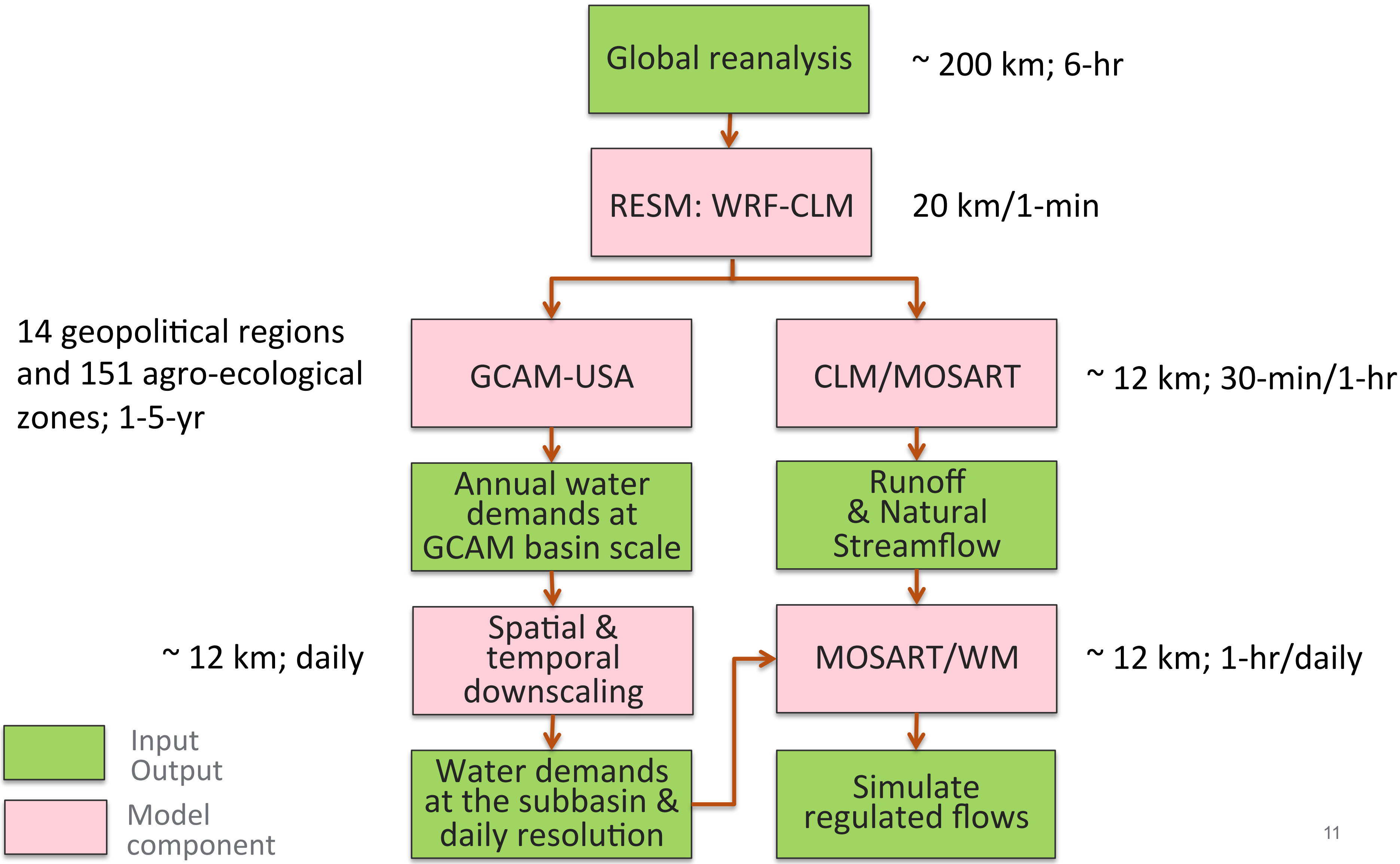
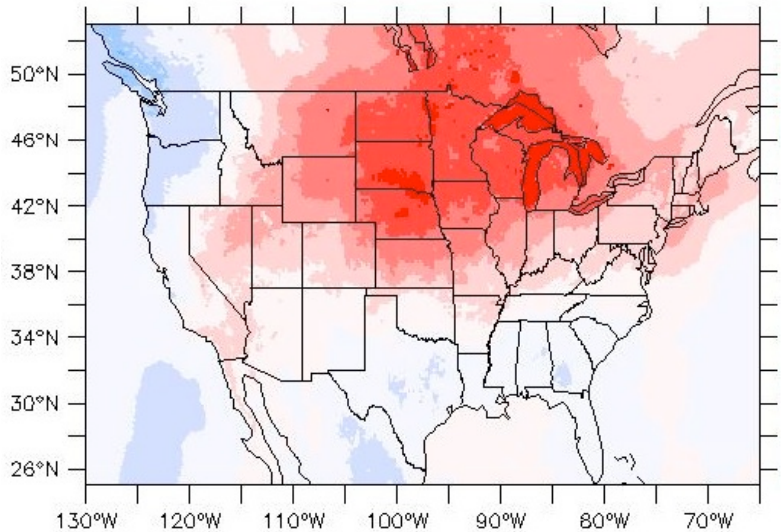
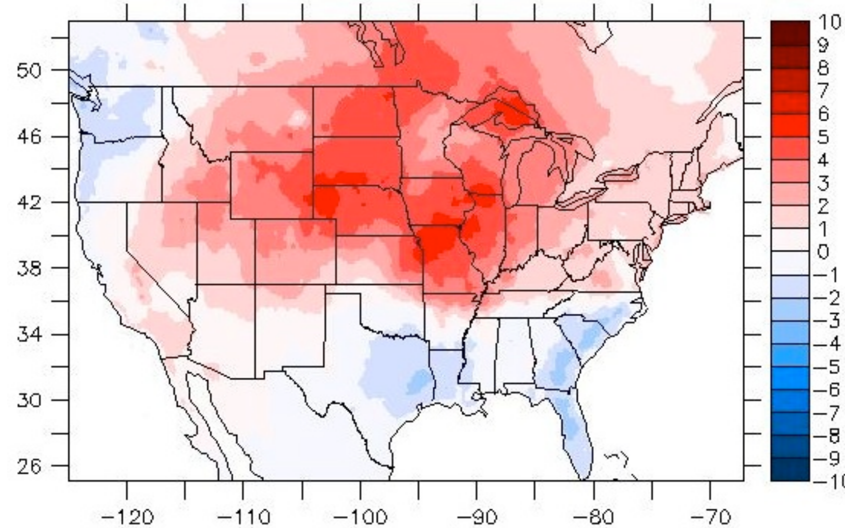


RESM captures the summer temperature and precipitation anomaly of 2012 compared to 2009

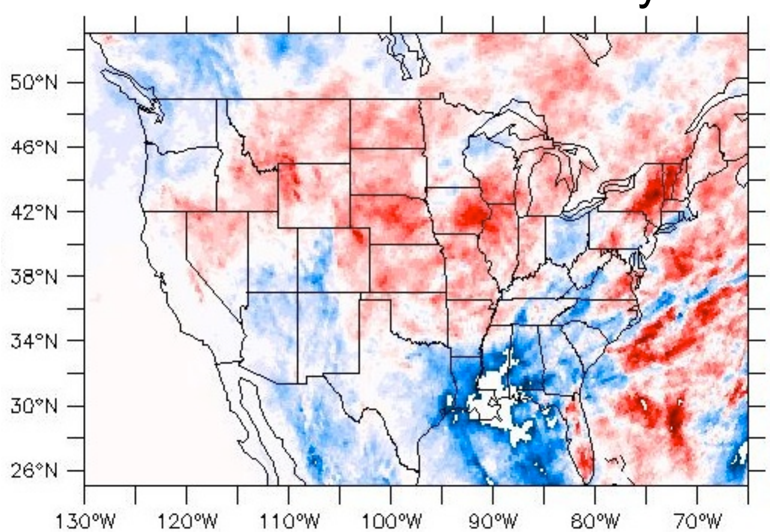
Simulated T anomaly



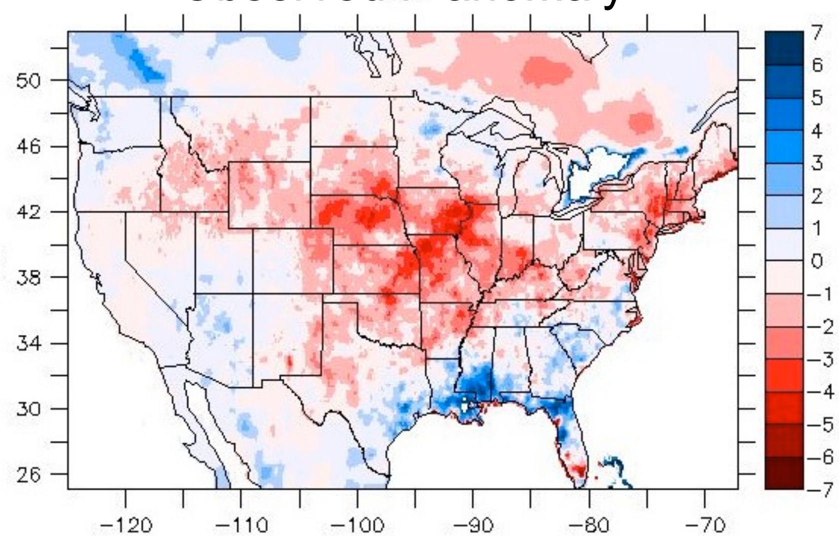
Observed T anomaly



Simulated P anomaly



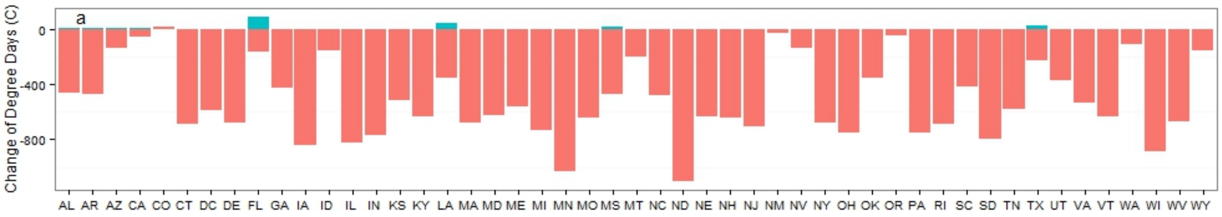
Observed P anomaly



Seasonal changes in HDD/CDD before, during, and after the summer drought

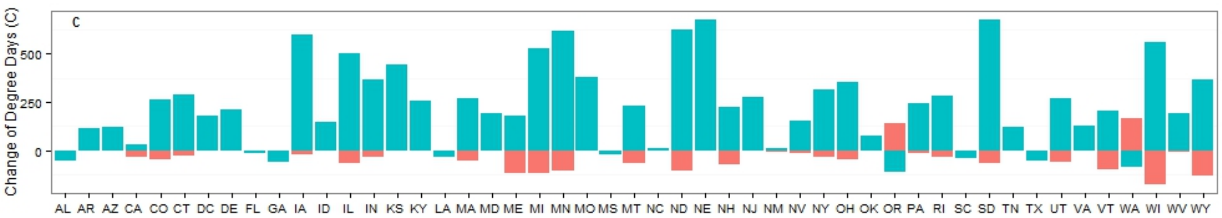
- Prior to the 2012 drought, winter and spring are warmer than 2009
- The 2012 drought is accompanied by large warming in the summer, but subsequent temperature anomalies in the fall is minor

DJF

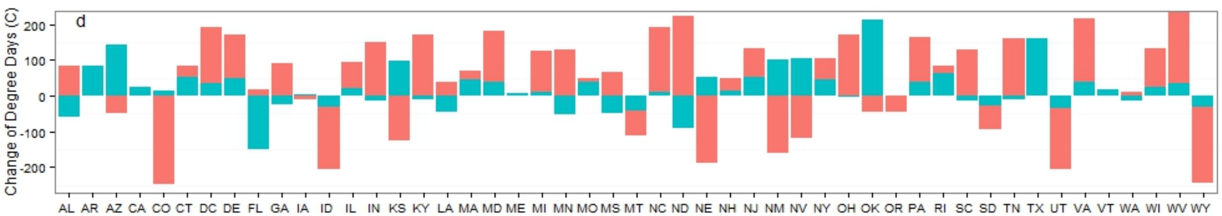


MAM

JJA

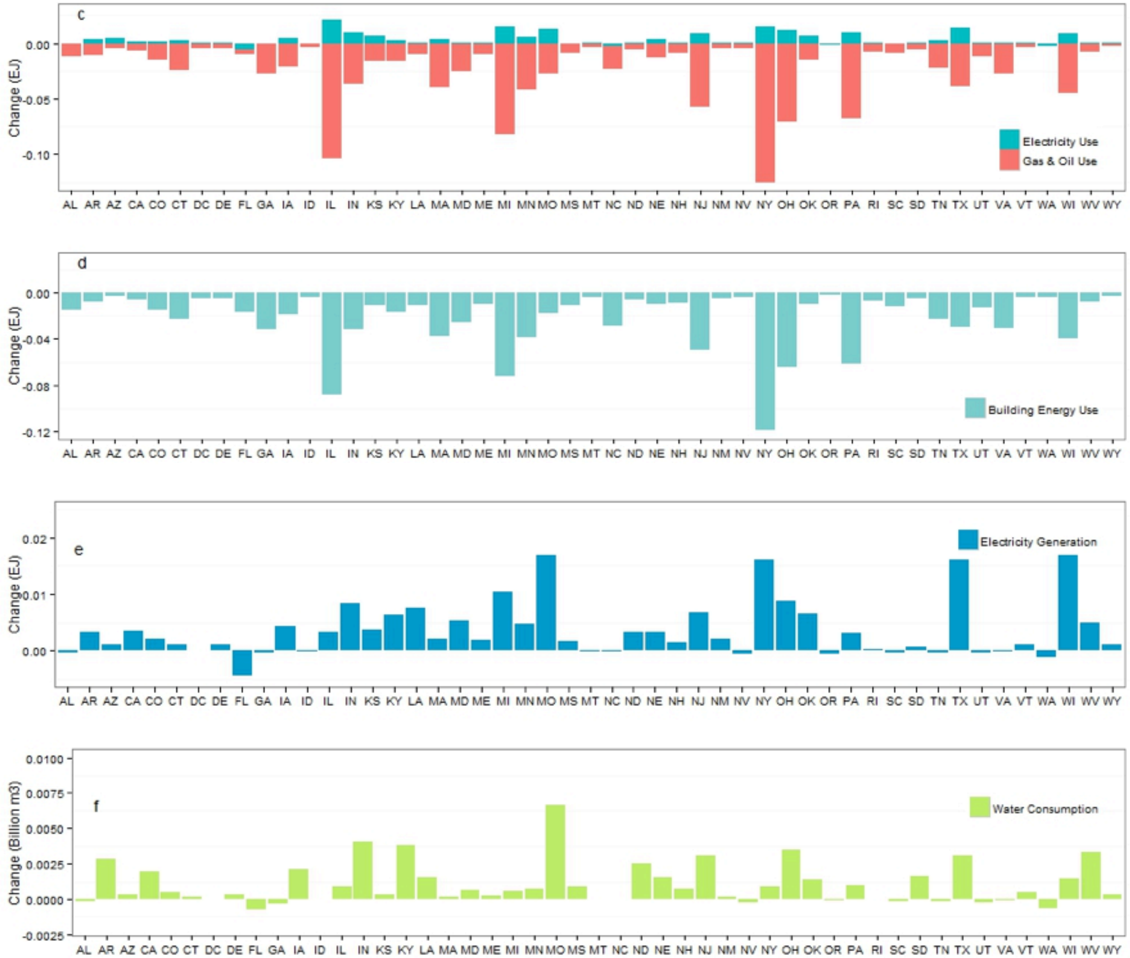


SON



Changes in HDD/CDD drive changes in energy use and water demand

- *Seasonal* changes in HDD/CDD drive changes in different energy sectors, with water demand mostly tied to electricity generation, which is influenced mainly by the summer warm anomaly – a common signature?



Changes in regulated flow simulated by CLM-MOSART-WM

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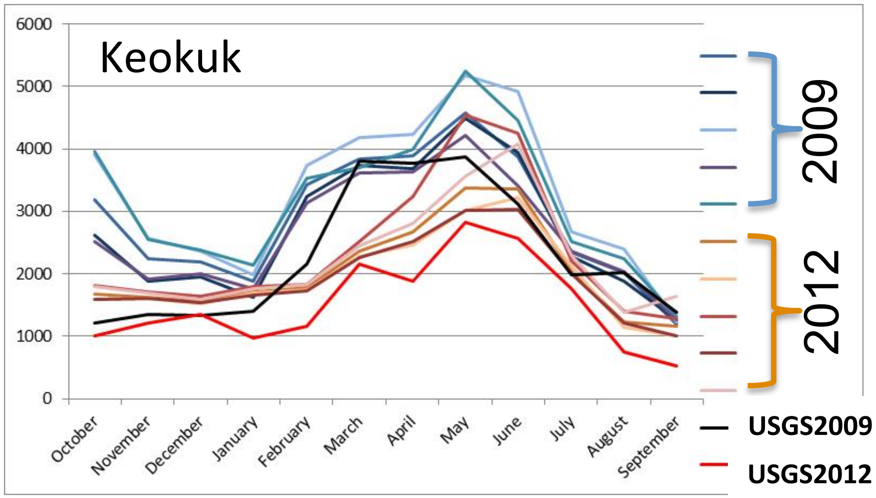
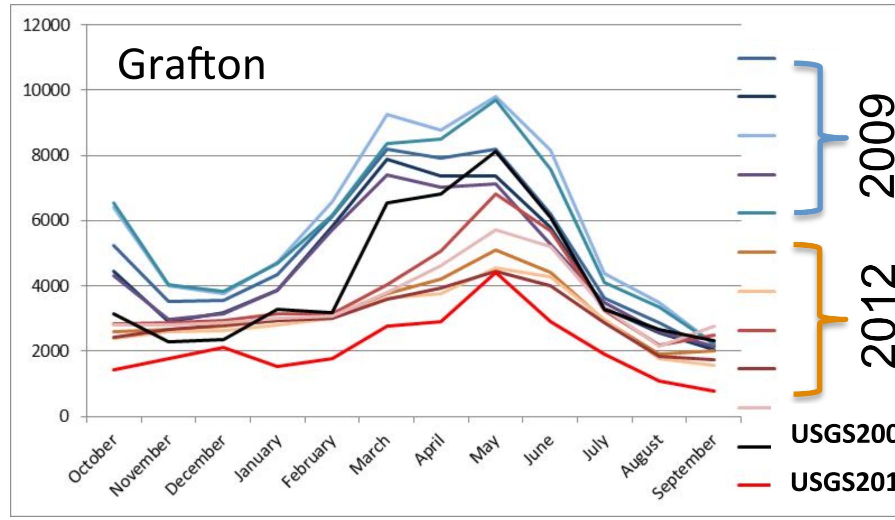
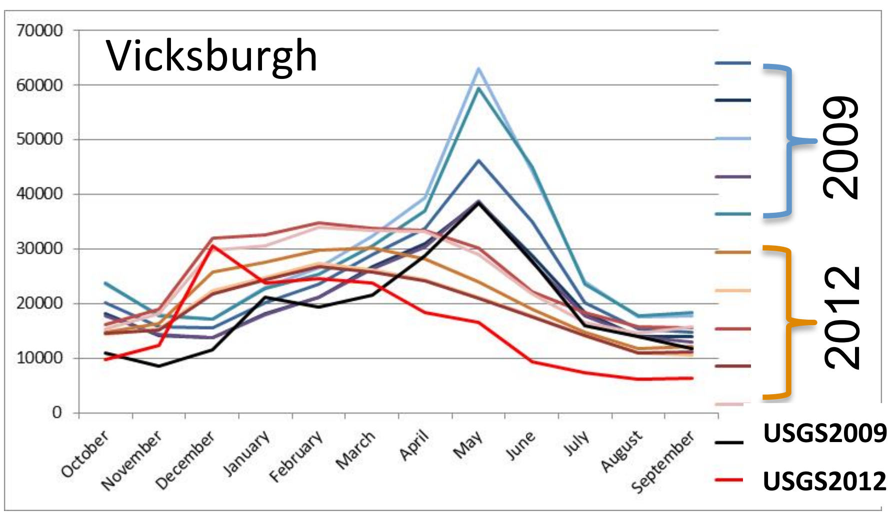
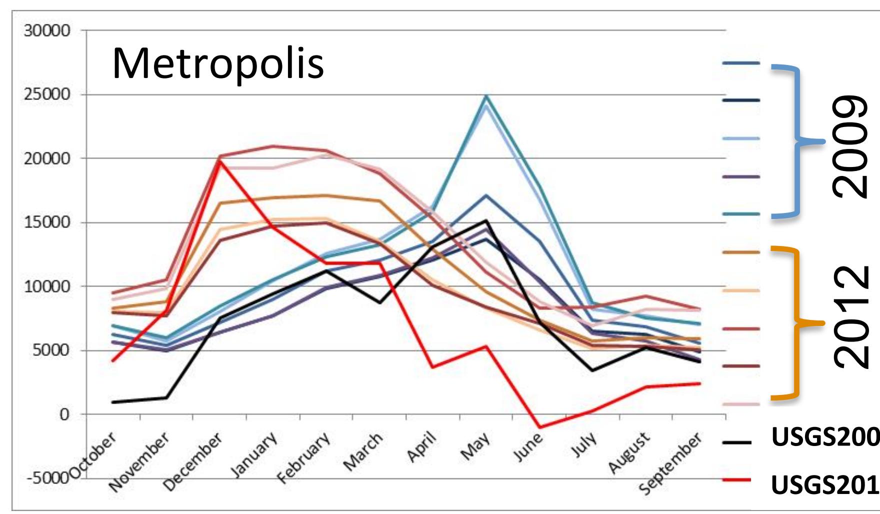
- Missouri and Upper Mississippi: Overall less precipitation and lower snowmelt





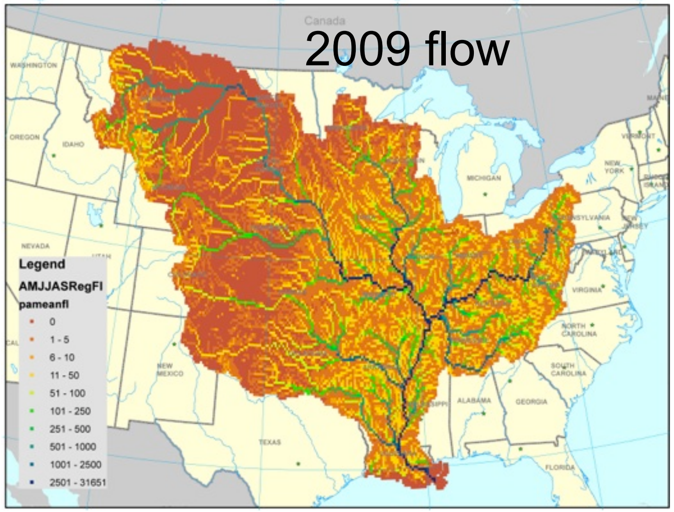
- Lower Mississippi, Ohio, and Tennessee: Much earlier snowmelt and lower summer flow

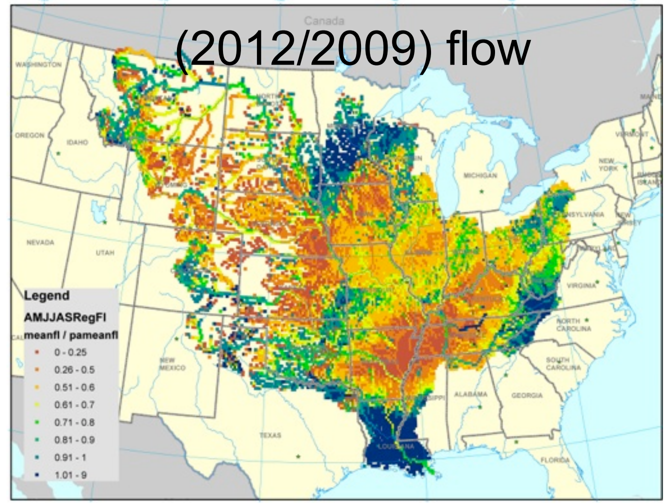




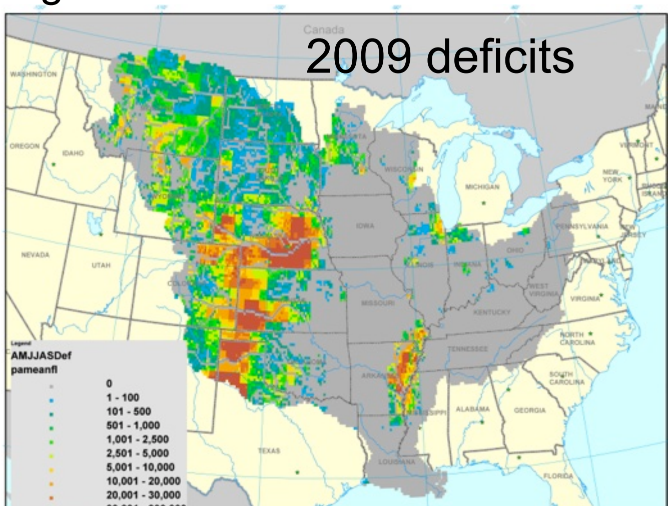
Models simulate flow reduction and water deficits

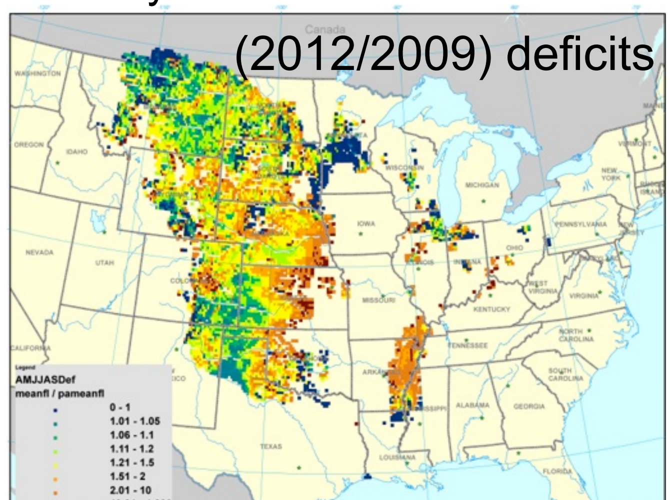
- Flow decrease is due to dry conditions in western Mississippi and warm but not dry winter in eastern Mississippi



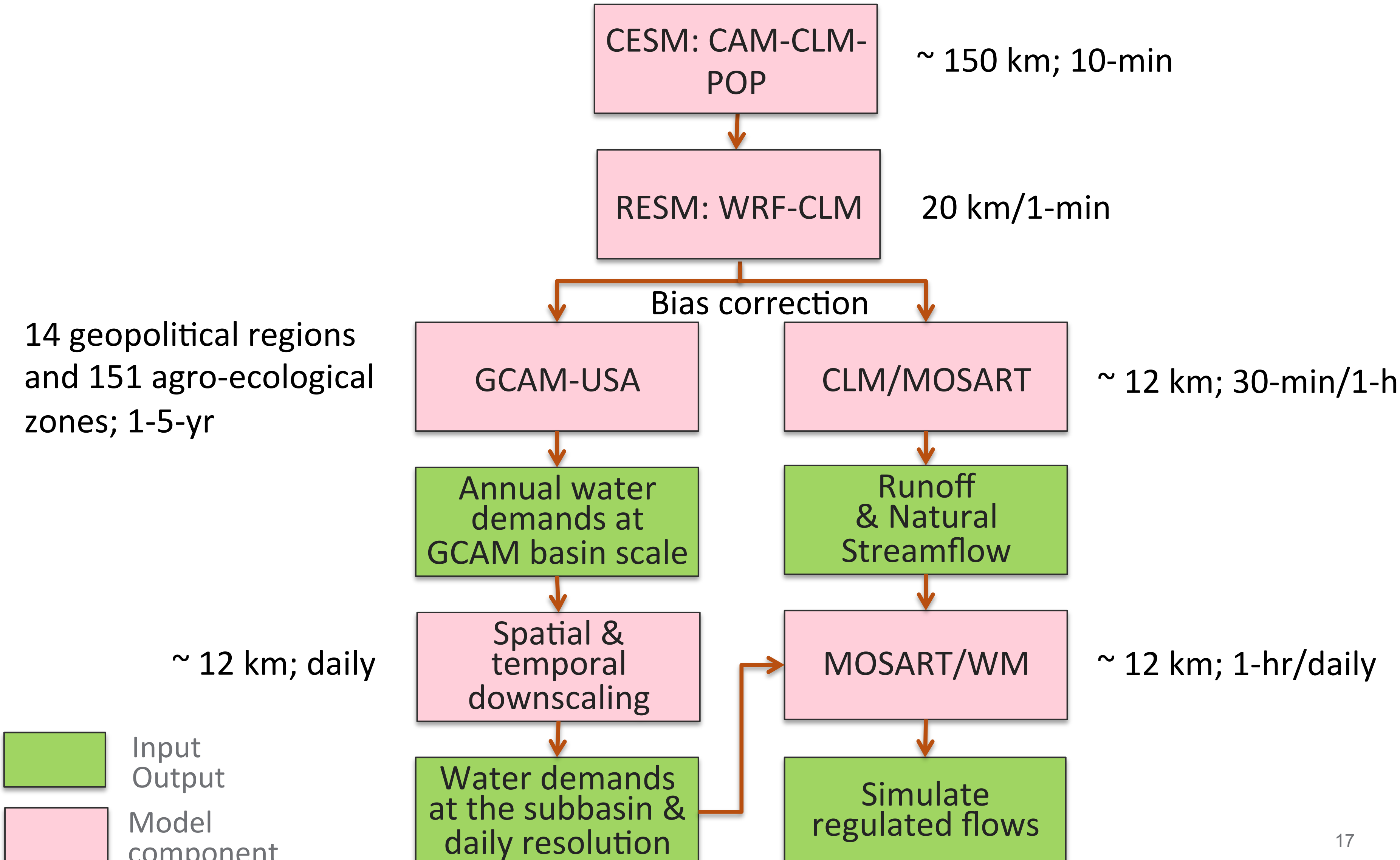


- Significant water deficit in the Mississippi driven by flow reduction and increased demand



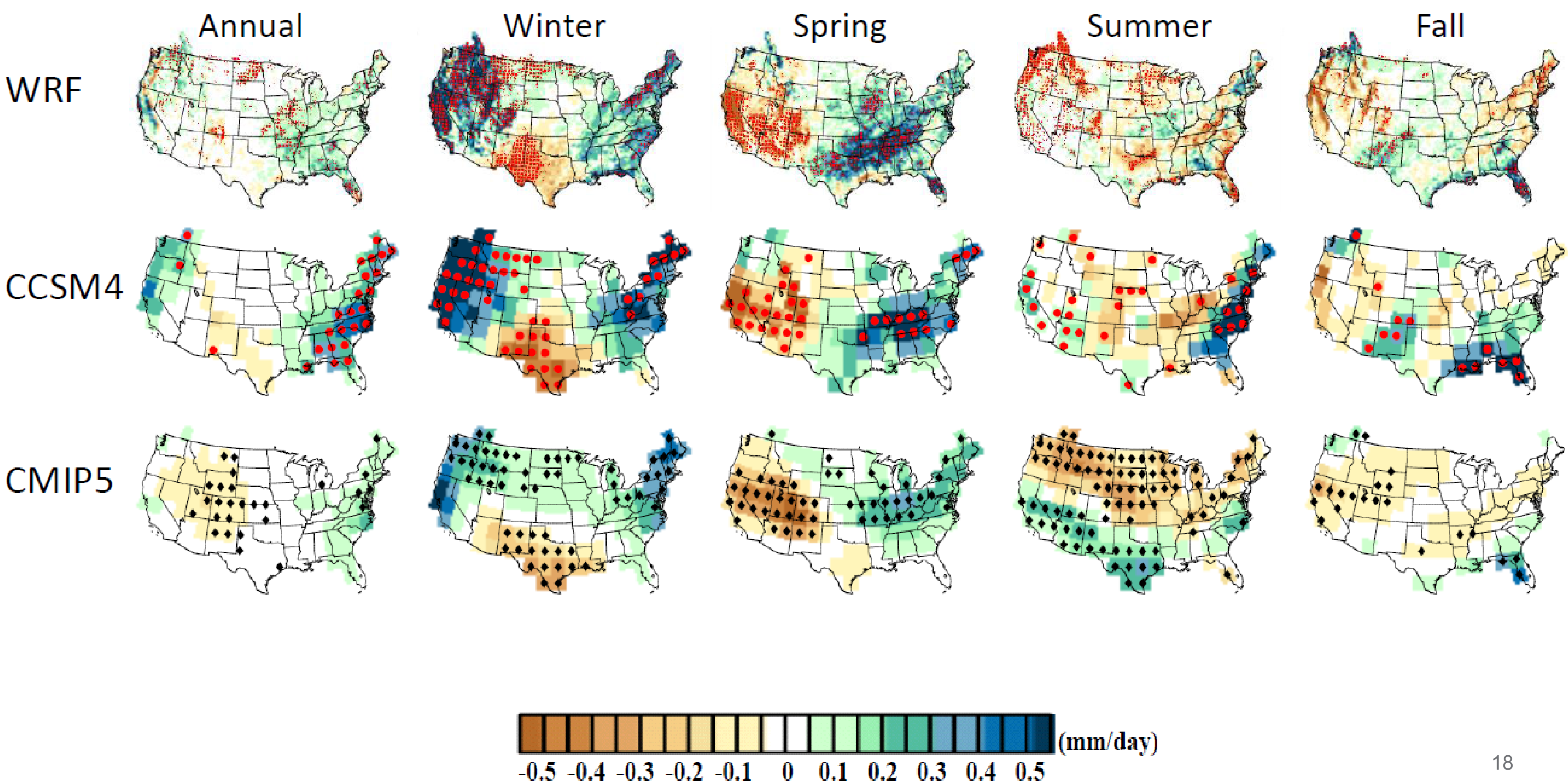


Experiments: 1975-2004 (historical) vs 2005-2100 (RCP4.5 and RCP8.5)



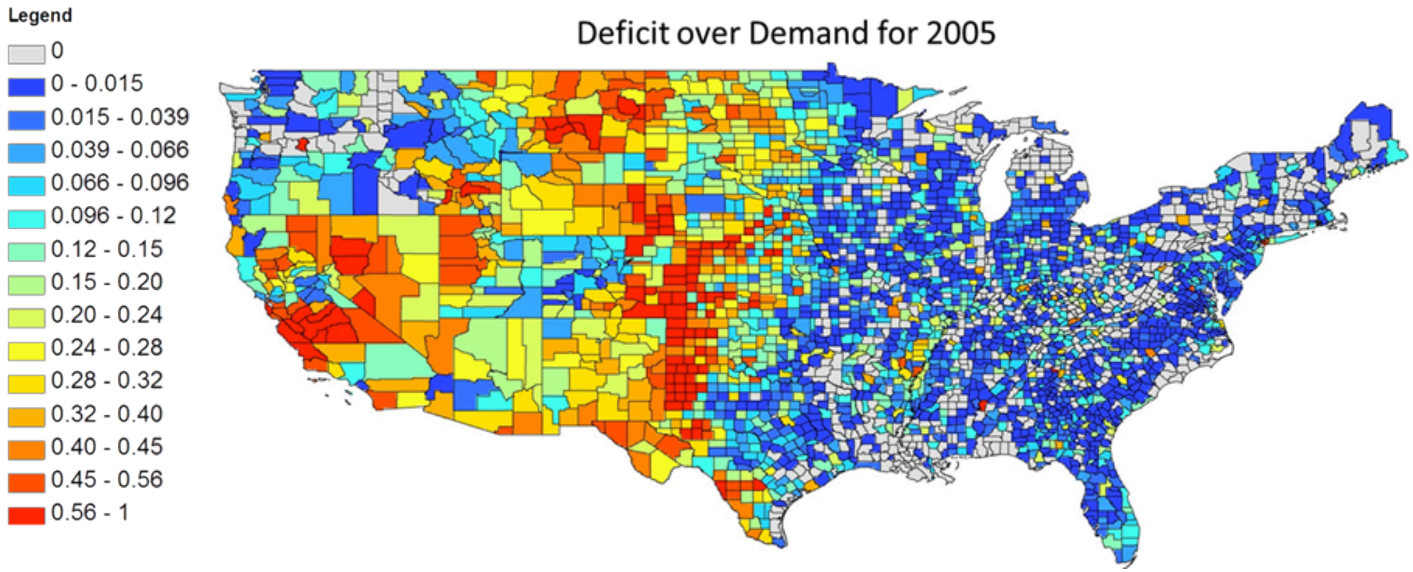
RESM projected changes in *seasonal* water availability are consistent with the CMIP5 multi-model ensemble

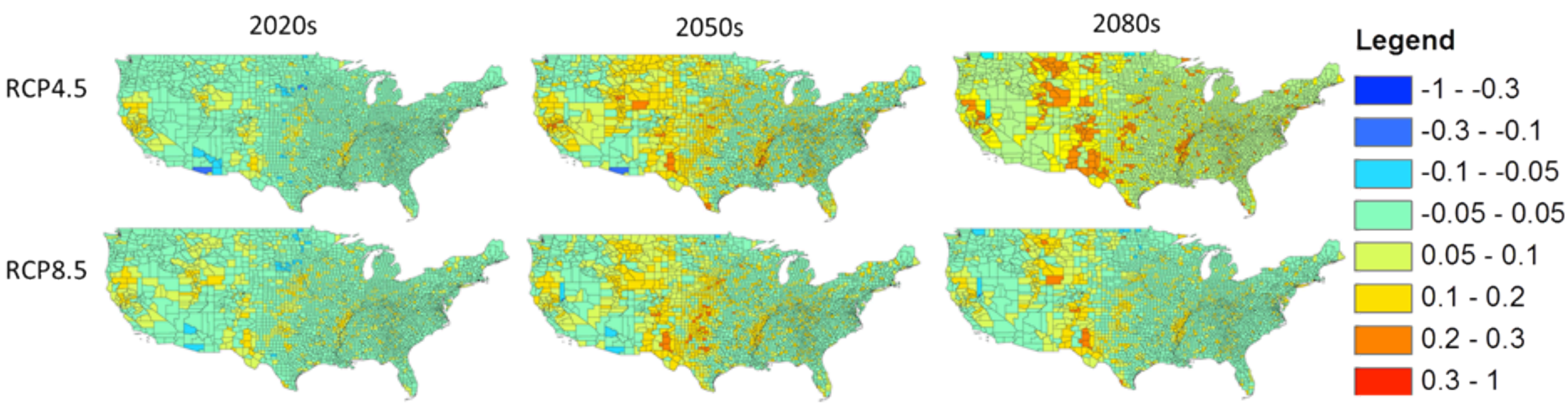
P – E changes comparing 2070 – 2099 with 1975 – 2004 for RCP8.5



Water deficit is projected to increase more with climate change mitigation

Annual county scale water deficit as a fraction of demand





The irrigation sector will experience most of the water deficit, particularly in the west

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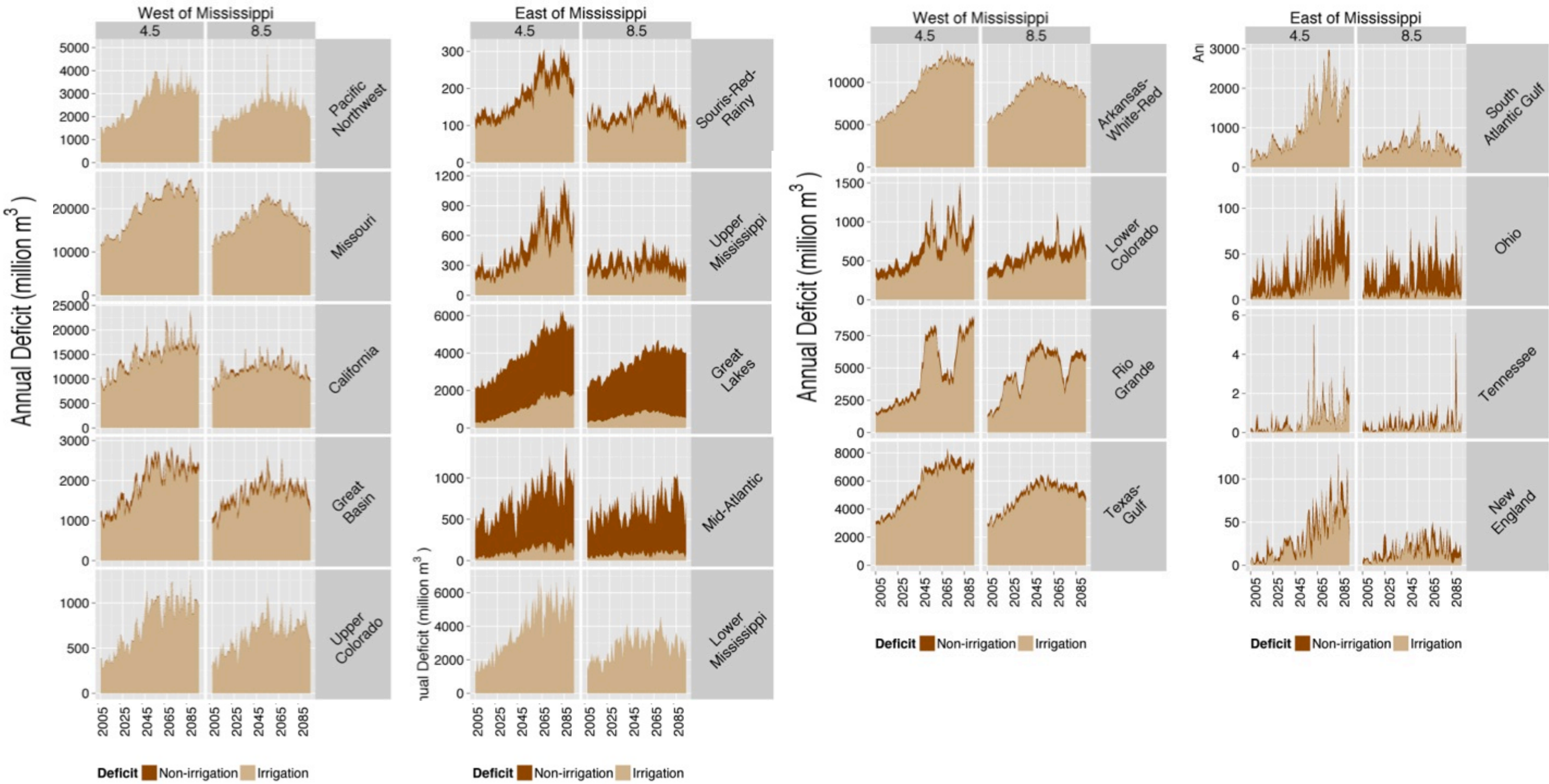

Water deficit hotspots are more severe in RCP4.5 than RCP8.5

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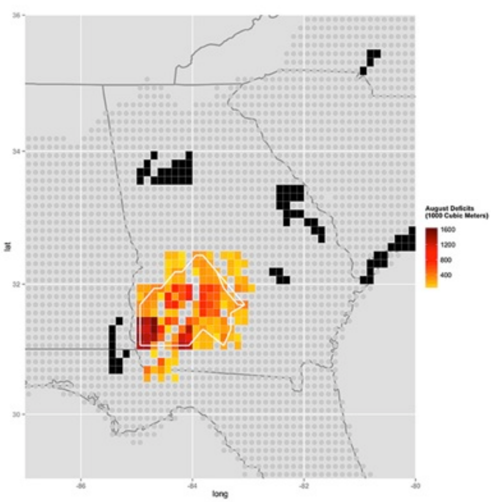
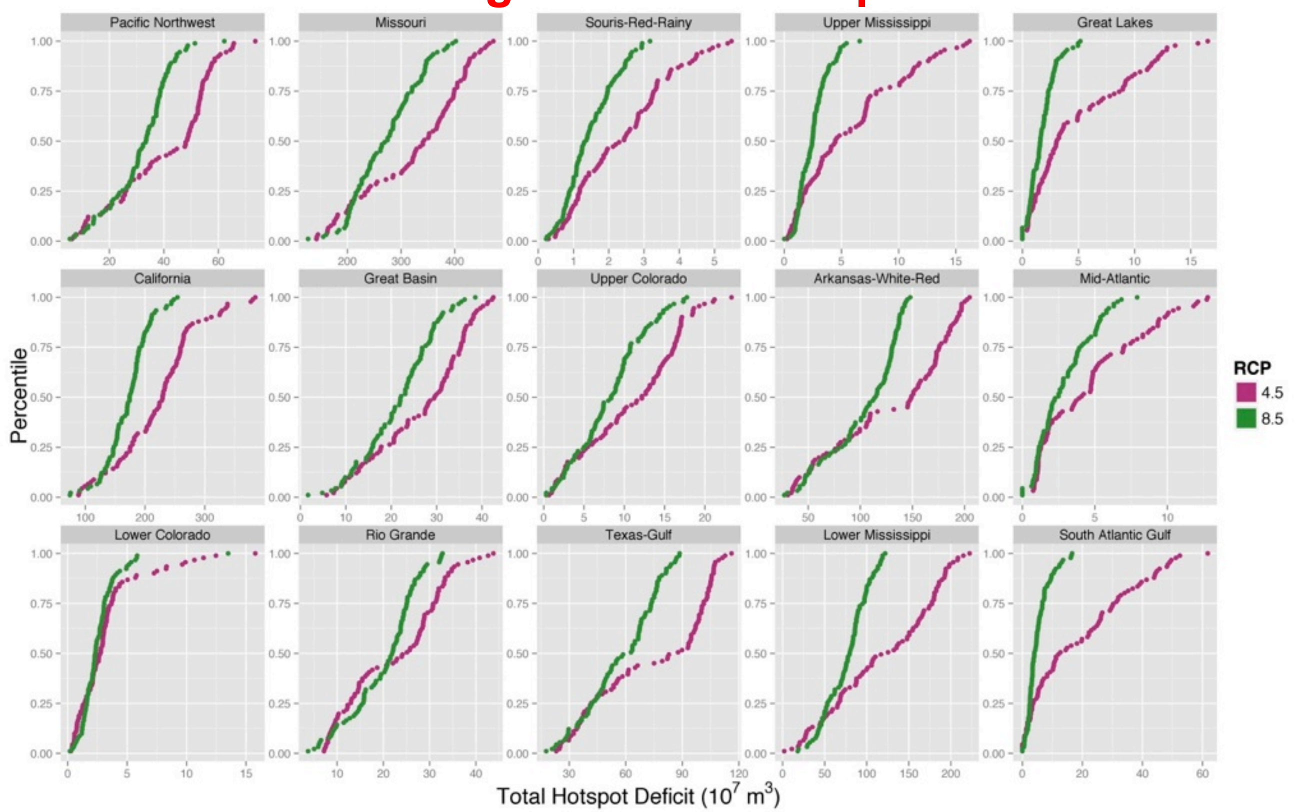
- A deficit hotspot is defined to be a group of adjacent cells each exceeding a deficit threshold, and is used to characterize the severity of water deficit in terms of magnitude, spatial extent, and temporal changes
- A minimum of four adjacent cells exceeding the deficit threshold defined as the 95th percentile from the distribution of deficit values, by basin

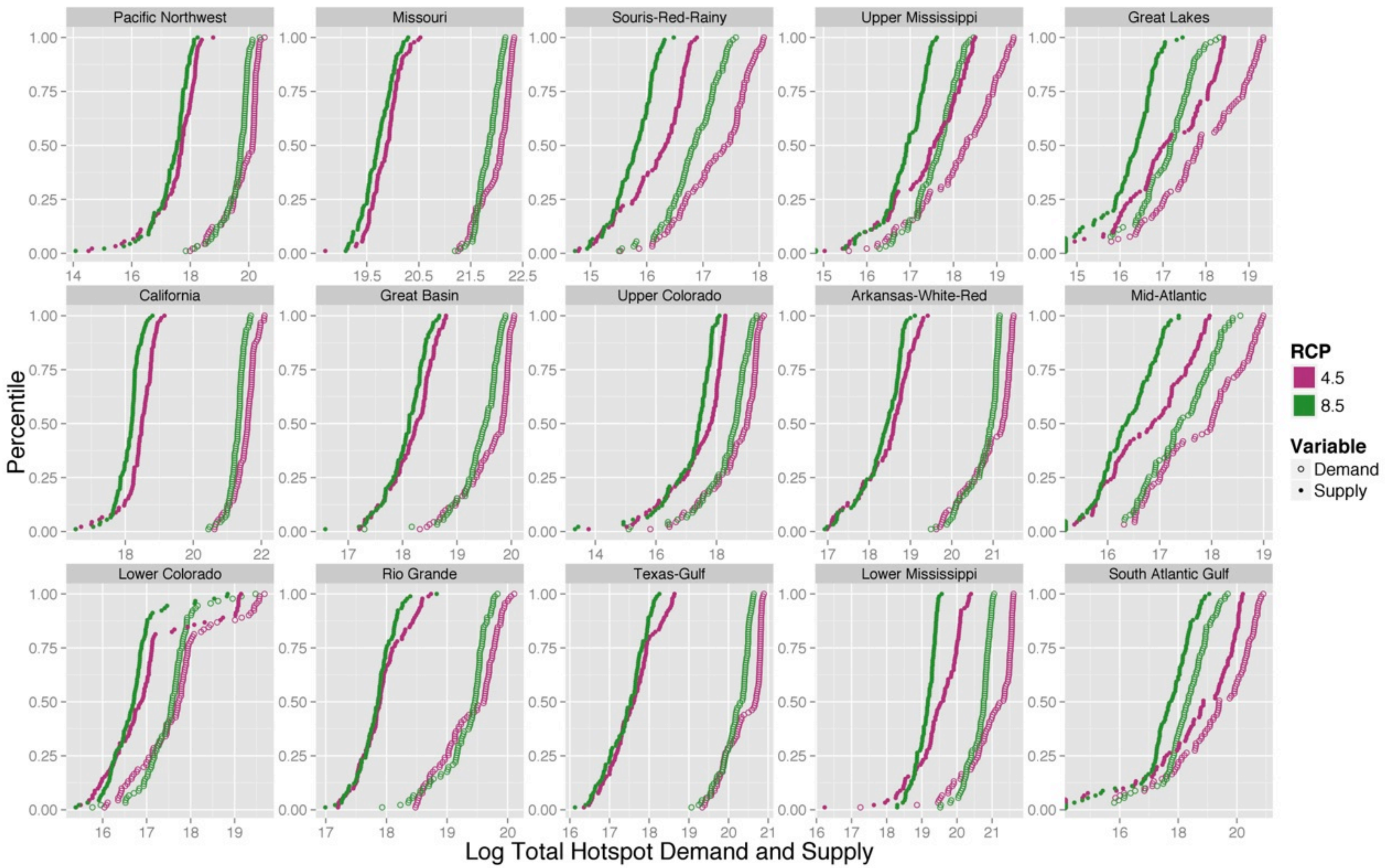


August deficit hotspots



Both supply and demand in the hotspots are higher in RCP4.5 than RCP8.5

- Climate mitigation reduces climate change impacts on water supply, but water demand is increased in order to achieve emission targets



Water deficit hotspot extent and number increase more significantly in RCP4.5 than RCP8.5

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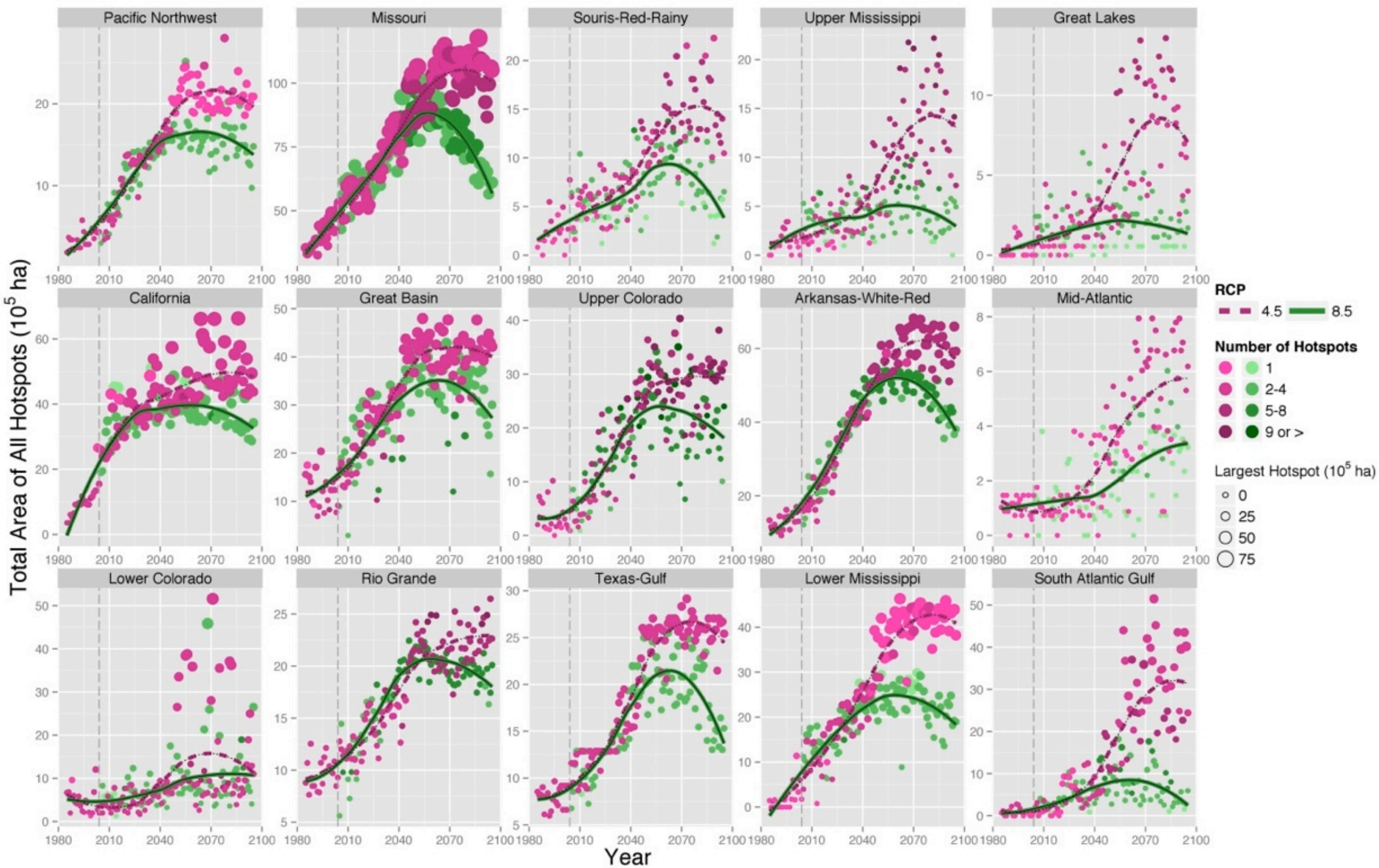
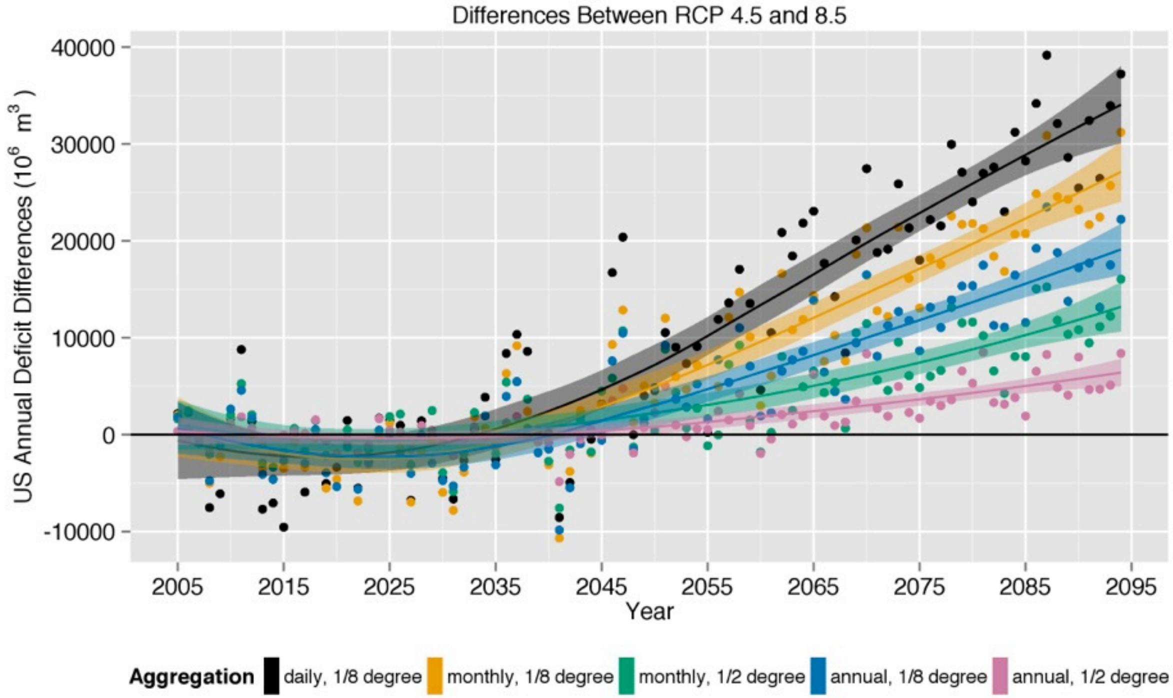
- Long term trends are driven primarily by population changes



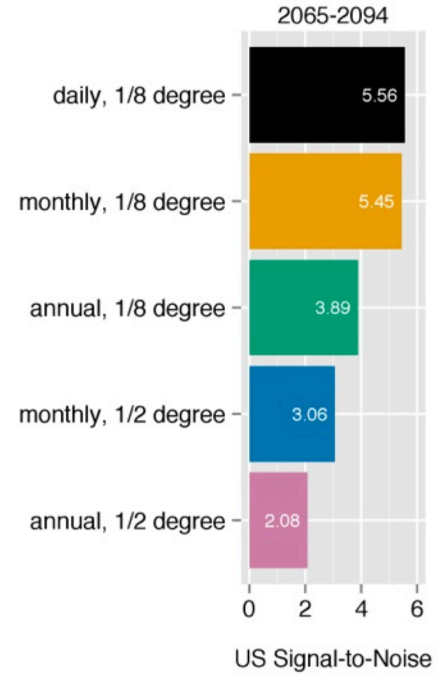
Higher resolution models simulate more robust differences in water deficit between RCP4.5 and RCP8.5

- By systematically aggregating the high resolution model outputs to coarser spatial and temporal resolutions, our analysis shows a systematic reduction in the water deficit difference between RCP4.5 and RCP8.5 compared to interannual variability (i.e., signal-to-noise ratio), demonstrating that high resolution modeling is key to projecting more robust impacts of carbon policy on regional water deficit

Difference in annual water deficits between RCP4.5 and RCP8.5 at multiple resolutions



Signal-to-noise ratio



Summary

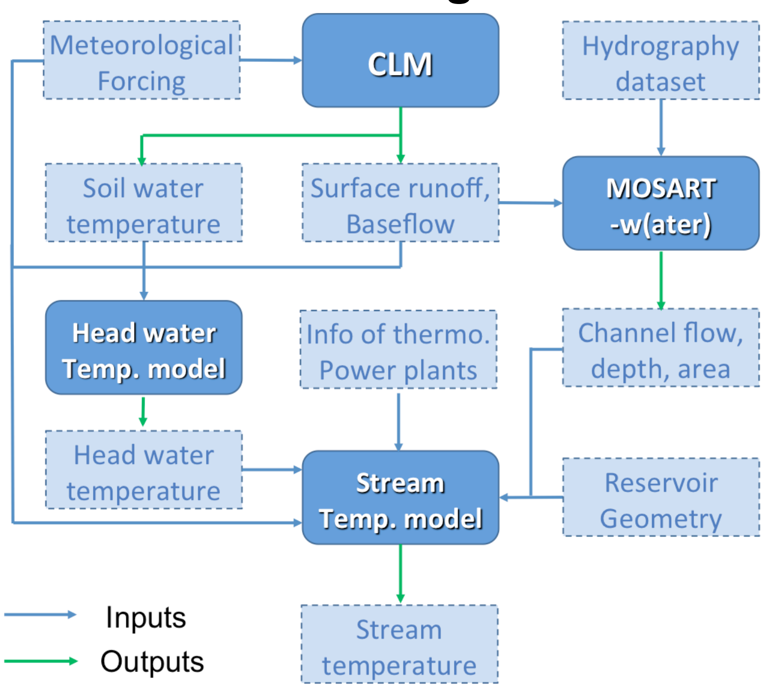
- A coupled modeling framework capable of simulating regional scale features has been developed to enable investigations of energy-water-land nexus, in the context of climate change mitigation, adaptation, and impacts
- The models reasonably capture the anomalous meteorological and hydrological conditions and energy use of 2012 (drought) compared to 2009 (normal), highlighting reduced flow, increased water demand for electricity and irrigation, and increased water deficits
- The models projected more severe water deficits in the future under RCP4.5 than RCP8.5, suggesting that emission mitigation (using bioenergy) may lead to more water deficits, despite climate change impacts on water supply are subdued

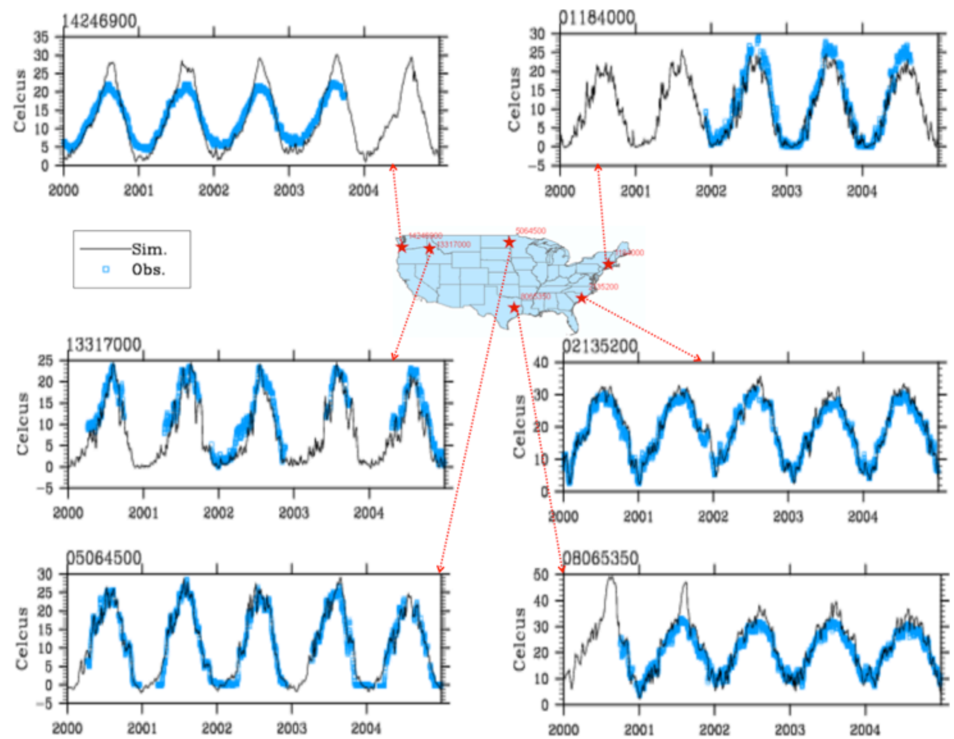
Next steps: Modeling stream temperature and inundation dynamics

- A stream temperature model has been developed based on MOSART coupled to CLM and WM
- Modeling inundation dynamics is important for simulating vulnerability of coastal energy infrastructure to floods and SW-GW interactions

Seasonally inundated river basins in central Amazon

MOSART modeling framework





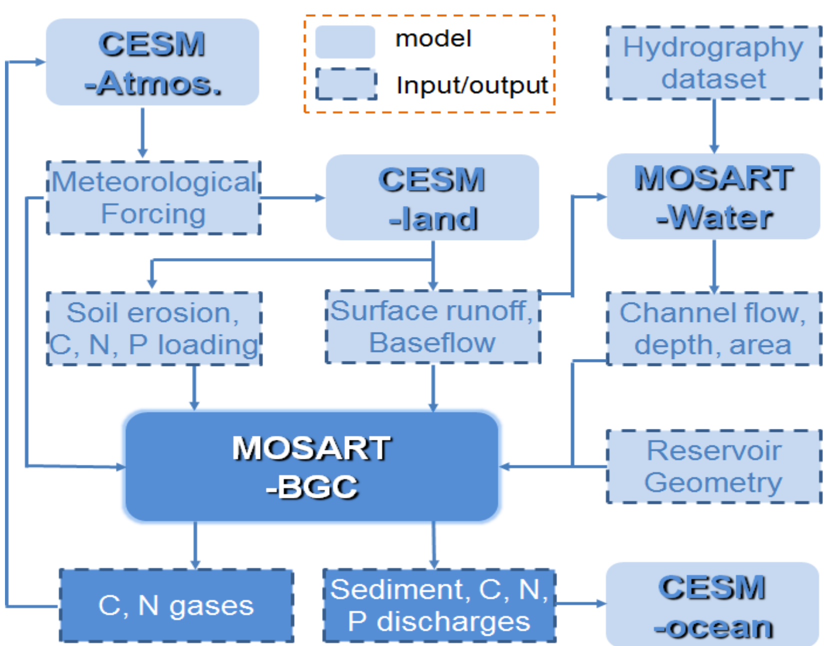
Next steps: Modeling river biogeochemistry linking land and ocean C, N, and P cycles

- In the US, CO_2 degassed from streams and rivers is up to 10% of the net ecosystem exchange (Butman and Raymond 2011)
- Nutrients and sediments transported by rivers to the ocean are important in linking terrestrial and ocean biogeochemistry

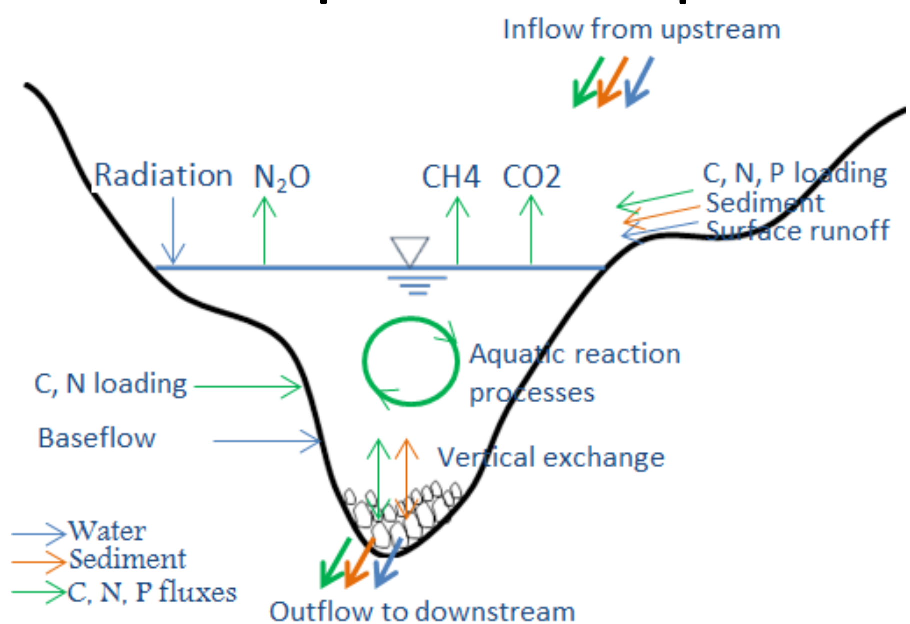
Table 1 | Drainage network CO_2 efflux estimates from other large river systems.

Region	Total C from CO_2 ($Pg\,yr^{-1}$)	Average efflux ($g\,C\,m^{-2}\,yr^{-1}$)	Source
Sweden	8.5×10^{-4}	1,850	(ref. 23)
Amazon basin*	0.5	830	(ref. 21)
Mississippi basin†	0.01	1,182	(ref. 8)
Xijiang river‡	2.22×10^{-4}	830–1,560	(ref. 20)
Globe	0.56	NA	(ref. 5)
Globe§	0.23	NA	(ref. 6)
Humid tropics‖	0.9	NA	(ref. 21)
Conterminous US	0.1	882–4,008¶	This study
Temperate zone	0.13	1,675	(ref. 5)
Temperate zone (25° N–50° N)	0.5	2,370#	This Study

Overall framework



Reach level processes description



Global modeling of reservoir regulations

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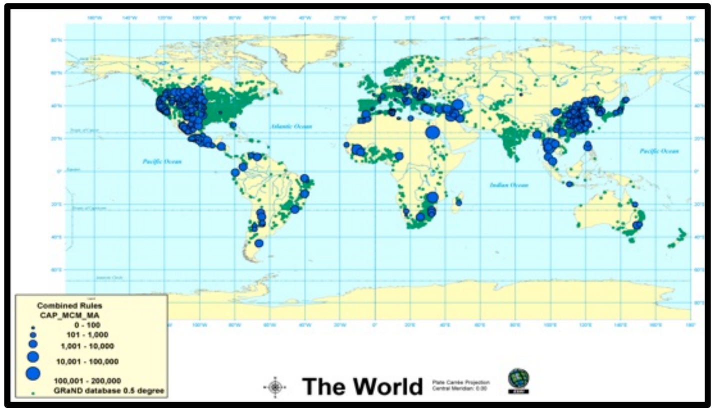
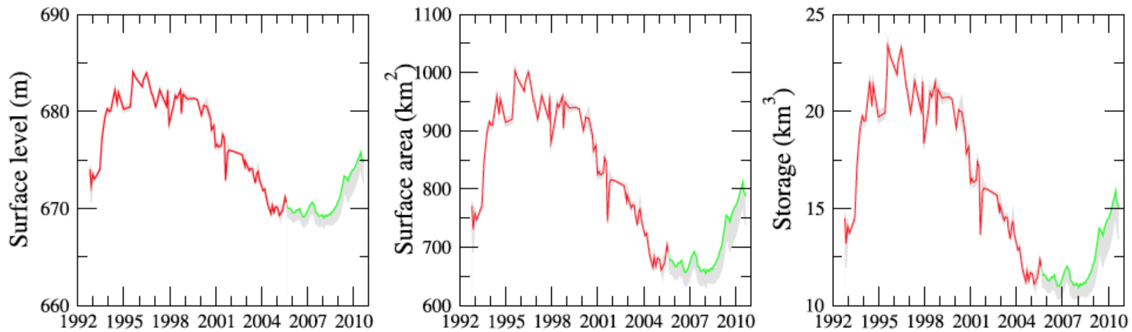
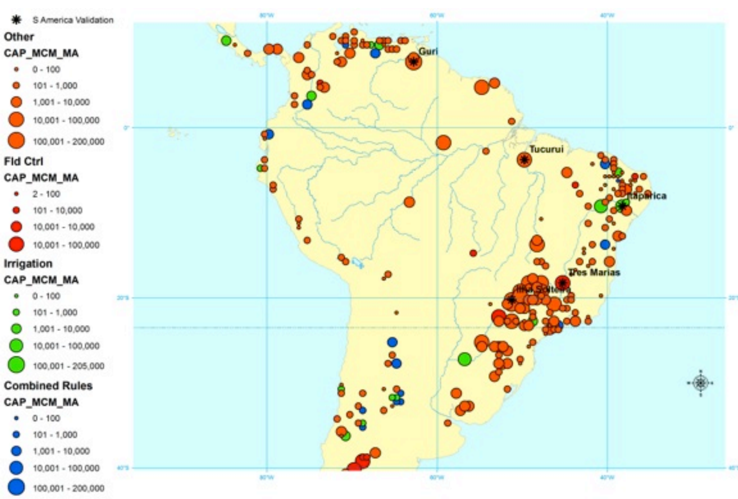
Reservoirs use for irrigation and flood control

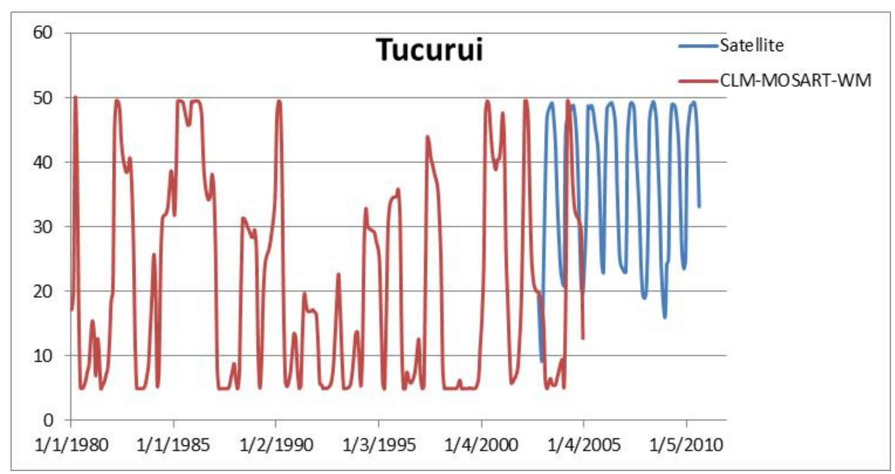


Gao et al. 2012 WRR



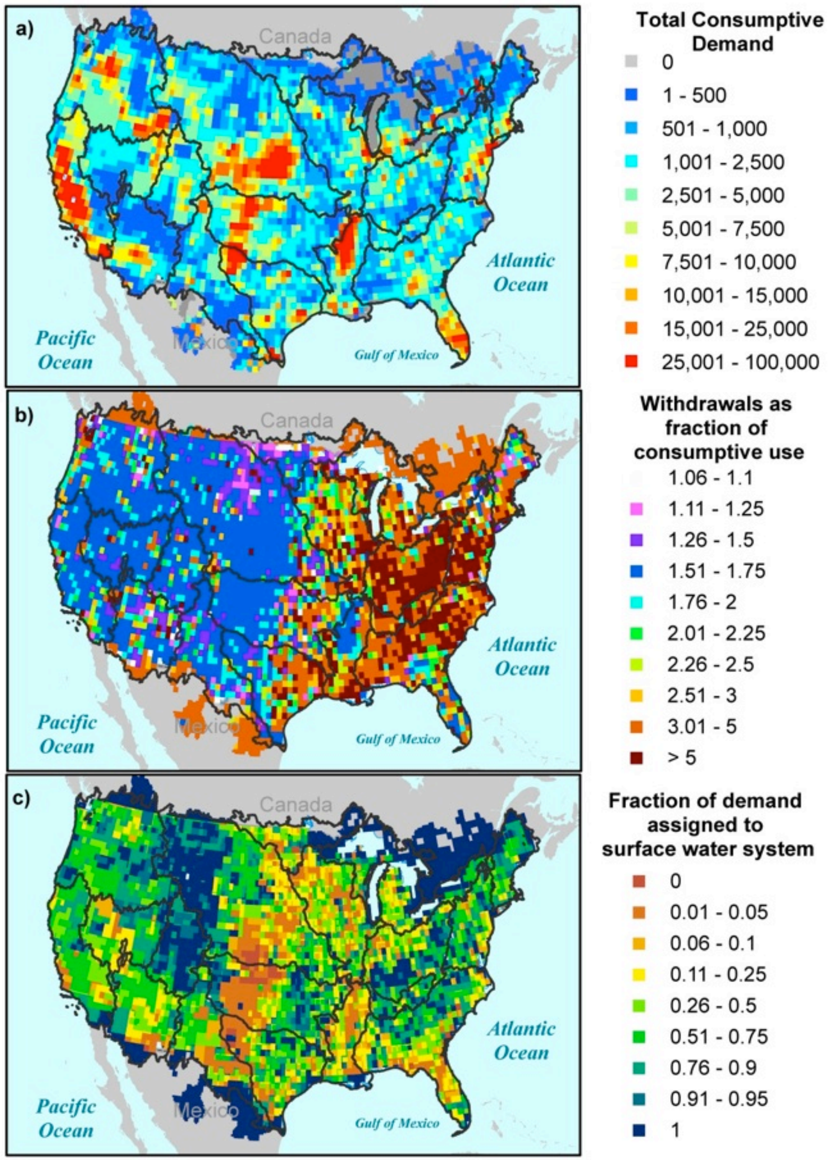
- Satellite retrievals of reservoir altimetry (ENVISAT) and surface area (MODIS) provide information about reservoir storage that can be used to constrain the operating rules in the WM model for more realistic simulation of regulated flow and reservoir storage

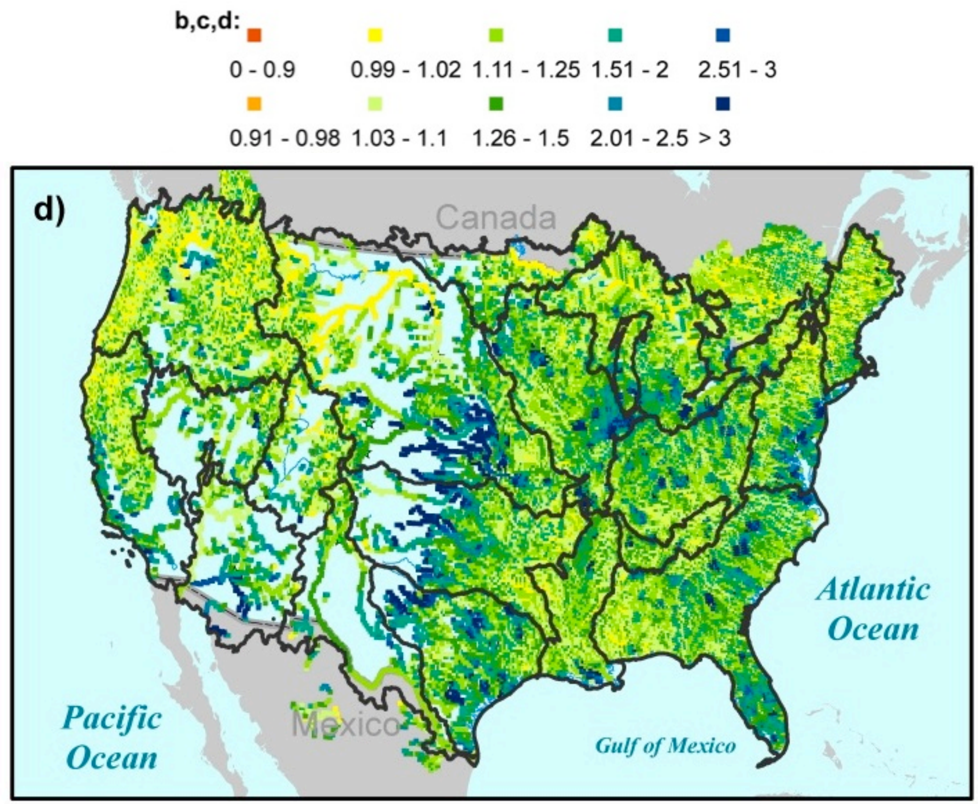




Modeling the resilience of the water system to climate and socio-economic changes

- Large east – west contrast in water consumption and withdrawal
- Large regional difference in groundwater use
- A modeling framework that accounts for groundwater use and return flow enables investigations of resilience of the water systems to climate change and socio-economic changes





Acknowledgments

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- DOE ESM and IAR support of the iESM project
  - development of MOSART-W and WM, and regional and global implementation
- DOE ESM support of the IMPACTS project
  - development of CLM
- DOE IAR support of the RIAM project
  - development of MOSART-H
- DOE ESM support of ACME
  - ongoing model development with CLM, MOSART, and WM
- DOE RGCM support of Scidac university collaboration
  - development of RESM – WRF coupling with ROMS
- PNNL PRIMA initiative
  - coupling CLM/MOSART/WM with GCAM; model evaluation and numerical experiments