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

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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

- CESM: CAM-CLM-POP
- Global/regional reanalysis
  - RESM: WRF-CLM-ROMS
  - 20 km/1-min
- GCAM-USA
  - Annual water demands at GCAM basin scale
  - Spatial & temporal downscaling
- CLM/MOSART
  - Runoff & Natural Streamflow
- MOSART/WM
  - Simulate regulated flows

- ~ 150 km; 10-min
- ~ 30 - 200 km; 6-hr
- 14 geopolitical regions and 151 agro-ecological zones; 1-5-yr
- ~ 12 km; 30-min/1-hr
- ~ 12 km; daily
- ~ 12 km; 1-hr/daily
Community Land Model (CLM): soil hydrology

CLM hydrology
- Precipitation → Transpiration → Surface runoff → Aquifer recharge → Water table
- Throughfall → Evaporation → Sublimation → Melt
- Soil saturated fraction
- Saturation excess runoff → Infiltration excess runoff

Observed / simulated baseflow index
- Beck et al. 2013 WRR (a) Estimate
- CLM4 VIC (b) CLM4 VIC
- CLM4 (c) CLM4

VIC formulation
- Grid cell vegetation coverage
- Canopy layer energy and moisture fluxes
- Layer 0, 1, 2
- ARNO baseflow curve
- (Li et al. 2011 JGR)
- (Tesfa et al. 2014 JGR; Tesfa et al. 2014 GMD)

Spatial representation
- Transpiration
- Throughfall
- Evaporation
- Sublimation
- Melt
- Precipitation
- Aquifer recharge
- Water table
- Saturated fraction
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)
Generic operating rules

- 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

(Voisin et al. HESS, 2013)
Improvements through use of multi-objective rules

Columbia River Basin

1848 reservoirs represented in the U.S.

Grand Coulee Reservoir storage

(Voisin et al. 2013a HESS)
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.

Widespread and severe surface moisture deficits in summer 2012

a) Precipitation

b) Temperature

c) Runoff

d) Soil Moisture
Record heat and drought led to low flows and power plant outages.

A satellite view of the Mississippi

UCS Report: Power and Water at Risk

Heat & Drought-Related Collisions Examples, 2006-2012

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

Impacts on crop yield
Experiments: 2009 vs 2012 ensemble simulations

14 geopolitical regions and 151 agro-ecological zones; 1-5-yr

~ 12 km; daily

Global reanalysis

~ 200 km; 6-hr

RESM: WRF-CLM

20 km/1-min

GCAM-USA

Annual water demands at GCAM basin scale

~ 12 km; 30-min/1-hr

CLM/MOSART

Runoff & Natural Streamflow

~ 12 km; 1-hr/daily

Spatial & temporal downscaling

MOSART/WM

Simulate regulated flows

Water demands at the subbasin & daily resolution

Input
Output
Model component

Model component

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

- 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)

- **CESM: CAM-CLM-POP**
  - ~150 km; 10-min

- **RESM: WRF-CLM**
  - 20 km/1-min

**Bias correction**

- **GCAM-USA**
  - Annual water demands at GCAM basin scale
  - ~12 km; daily

- **CLM/MOSART**
  - Runoff & Natural Streamflow
  - ~12 km; 30-min/1-hr

**Spatial & temporal downscaling**

- **MOSART/WM**
  - Simulate regulated flows
  - ~12 km; 1-hr/daily

- **Input**
- **Output**
- **Model component**

14 geopolitical regions and 151 agro-ecological zones; 1-5-yr
RESM projected changes in seasonal water availability are consistent with the CMIP5 multi-model ensemble.

Water deficit is projected to increase more with climate change mitigation.
The irrigation sector will experience most of the water deficit, particularly in the west.
Water deficit hotspots are more severe in RCP4.5 than RCP8.5

- 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

- 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.
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

```mermaid
graph TD
    MOSART -w(ater)[5] --> CLM[2]
```

**CLM**

- Meteorological Forcing
- Soil water temperature
- Surface runoff, Baseflow
- MOSART -w(ater)
- Info of thermo. Power plants
- Channel flow, depth, area
- Reservoir Geometry

**Outputs**

- Stream temperature

**Inputs**
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

Overall framework

<table>
<thead>
<tr>
<th>Region</th>
<th>Total C from CO$_2$ (Pg yr$^{-1}$)</th>
<th>Average efflux (g C m$^{-2}$ yr$^{-1}$)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>$8.5 \times 10^{-4}$</td>
<td>1.850</td>
<td>(ref. 23)</td>
</tr>
<tr>
<td>Amazon basin*</td>
<td>0.5</td>
<td>830</td>
<td>(ref. 21)</td>
</tr>
<tr>
<td>Mississippi basin†</td>
<td>0.01</td>
<td>1.182</td>
<td>(ref. 8)</td>
</tr>
<tr>
<td>Xijiang river*</td>
<td>$2.22 \times 10^{-4}$</td>
<td>830-1.560</td>
<td>(ref. 20)</td>
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<tr>
<td>Globe</td>
<td>0.56</td>
<td>NA</td>
<td>(ref. 5)</td>
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<tr>
<td>Globe*</td>
<td>0.23</td>
<td>NA</td>
<td>(ref. 6)</td>
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<tr>
<td>Humid tropics‖</td>
<td>0.9</td>
<td>NA</td>
<td>(ref. 21)</td>
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<tr>
<td>Conterminous US</td>
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<td>This study</td>
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<td>Temperate zone</td>
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<td>1.675</td>
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<tr>
<td>Temperate zone (25° N-50° N)</td>
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<td>2.370*</td>
<td>This Study</td>
</tr>
</tbody>
</table>
Global modeling of reservoir regulations

Reservoirs use for irrigation and flood control

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

- 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