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Integrated multi-scale, multi-sector modeling of climate impacts, responses, and feedbacks

Ian Kraucunas

JGCRI 2015 Integrated Assessment Workshop and GCAM Community Modeling Meeting

Session: Multi-Model Approaches to Energy-Water-Land Linkages

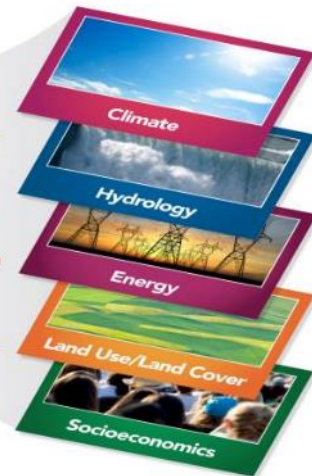
Two integrated modeling activities that address the climate-energy-water-land nexus

► Platform for Regional Integrated Modeling and Analysis (PRIMA)

- PNNL initiative (2010-2014)
- Developed a flexible platform for simulating complex multi-scale interactions among human and natural systems
- Extensive stakeholder engagement and uncertainty characterization

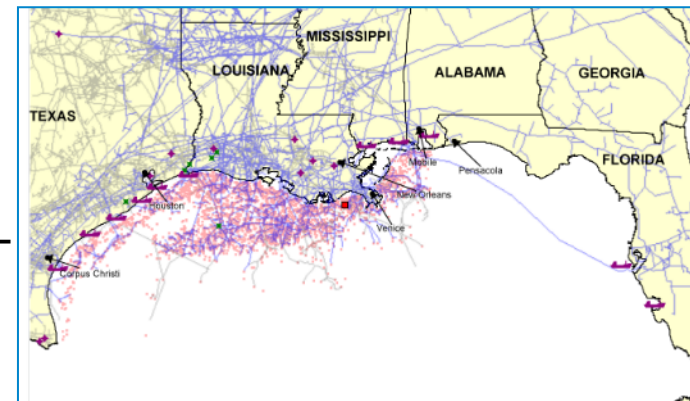


Regional Human –
Earth System
Modeling Integration



► Developing a Framework for Regional Integrated Assessment Modeling (“RIAM”)

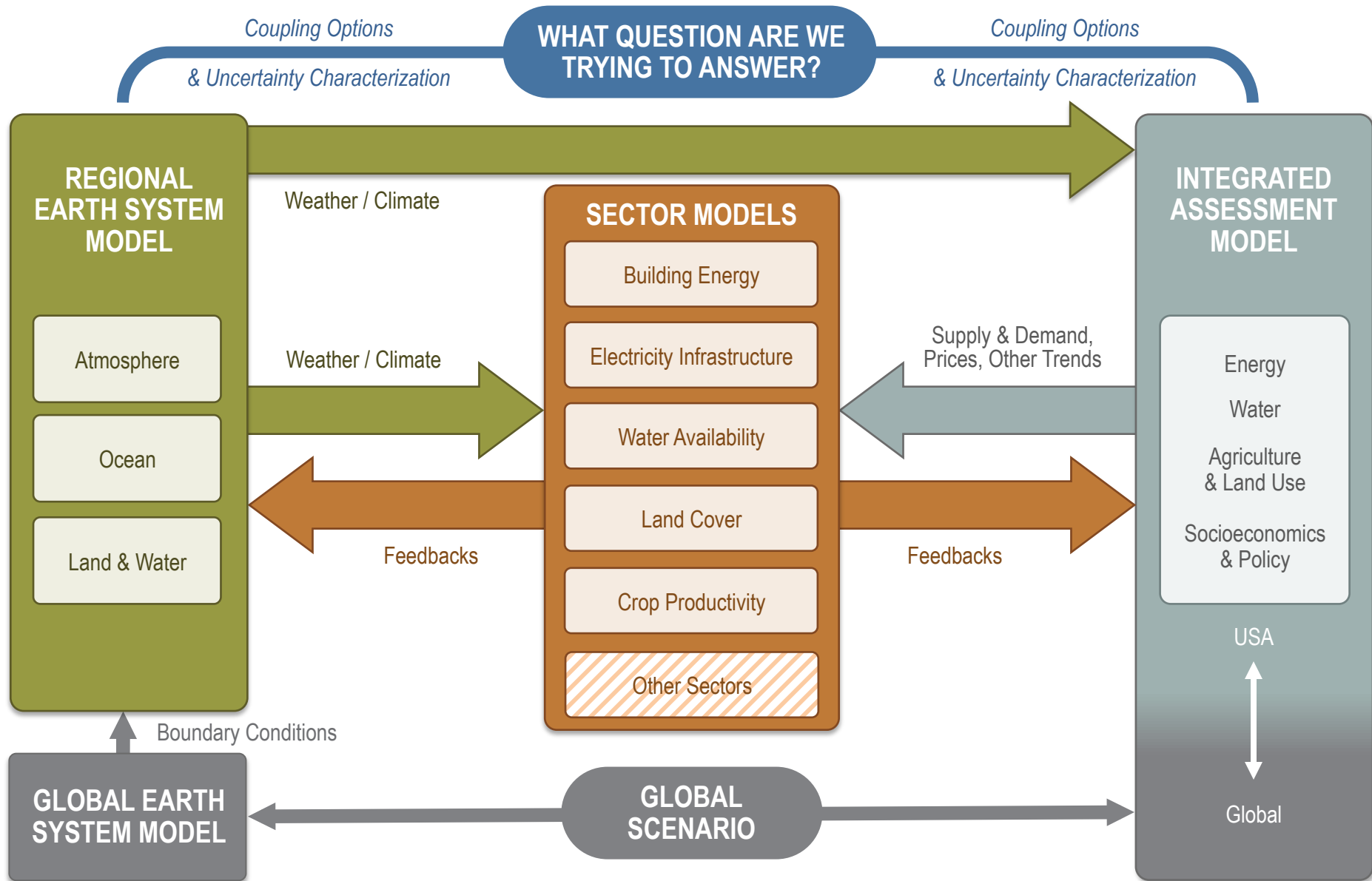
- Joint PNNL/ORNL project funded by DOE-IARP
- Investigate the vulnerability of integrated human-natural systems to climate change, especially extreme events, and evaluate response options
- Characterize the benefits and challenges of integrated multi-scale modeling approaches



Energy Infrastructure, electric transmission, LNG, natural gas, oil, petroleum. (http://www.eia.gov/special/gulf_of_mexico/)

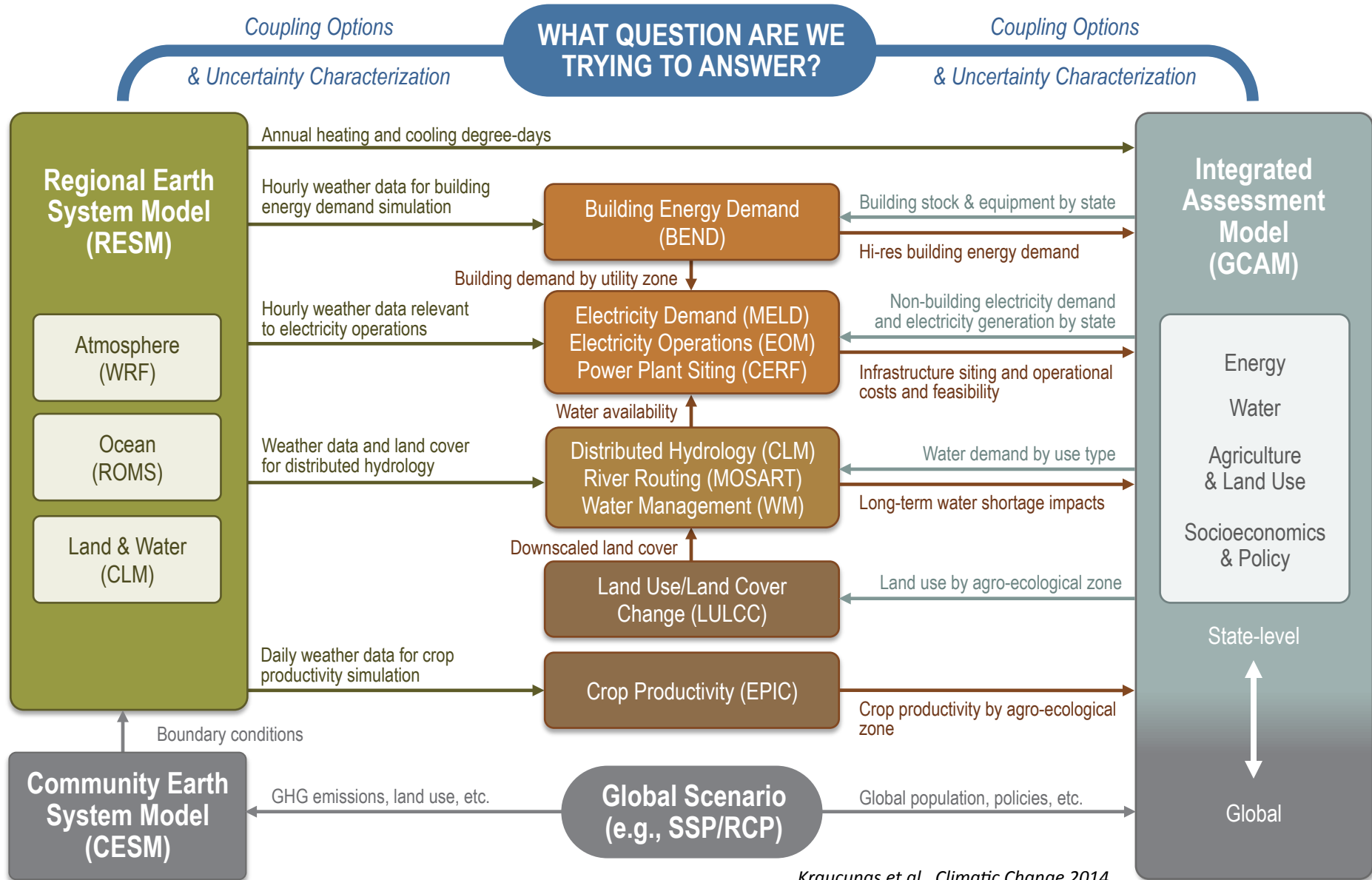
Platform for Regional Integrated Modeling and Analysis (PRIMA)

Regional Integrated Assessment Modeling (RIAM)



Platform for Regional Integrated Modeling and Analysis (PRIMA)

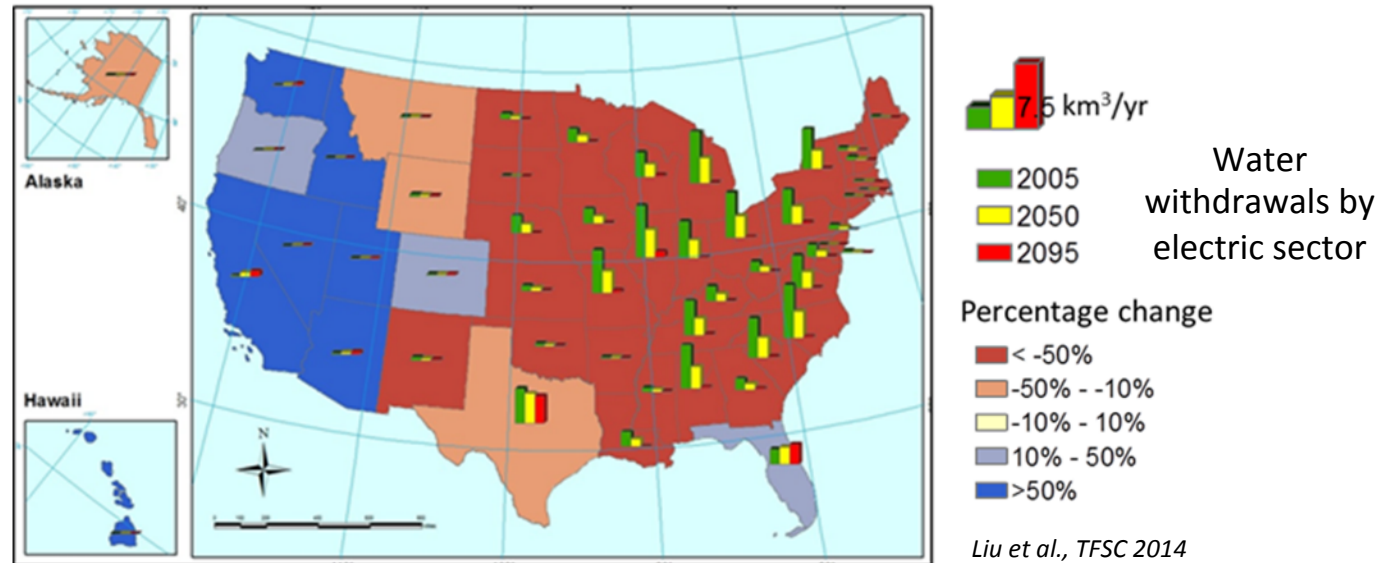
Regional Integrated Assessment Modeling (RIAM)



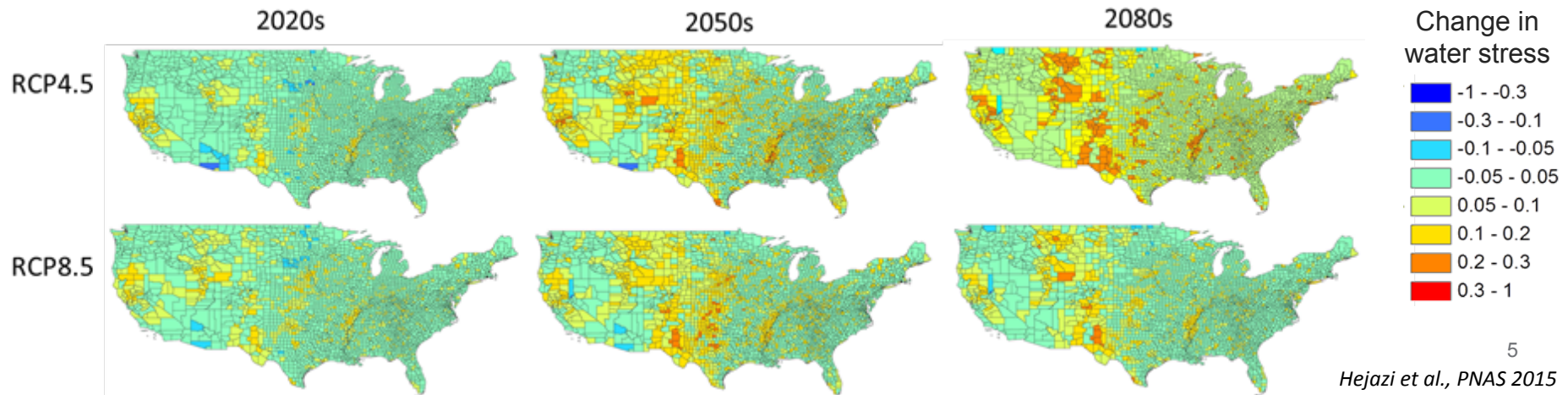
Integrated modeling can be used to study energy-water tradeoffs

Implications of cooling technology changes (GCAM)

Mohamad Hejazi
will provide
additional details
and results



Implications of biomass-heavy mitigation strategy (GCAM+WRF+CLM+WM)



Land use/land cover change can also have significant effects on surface hydrology

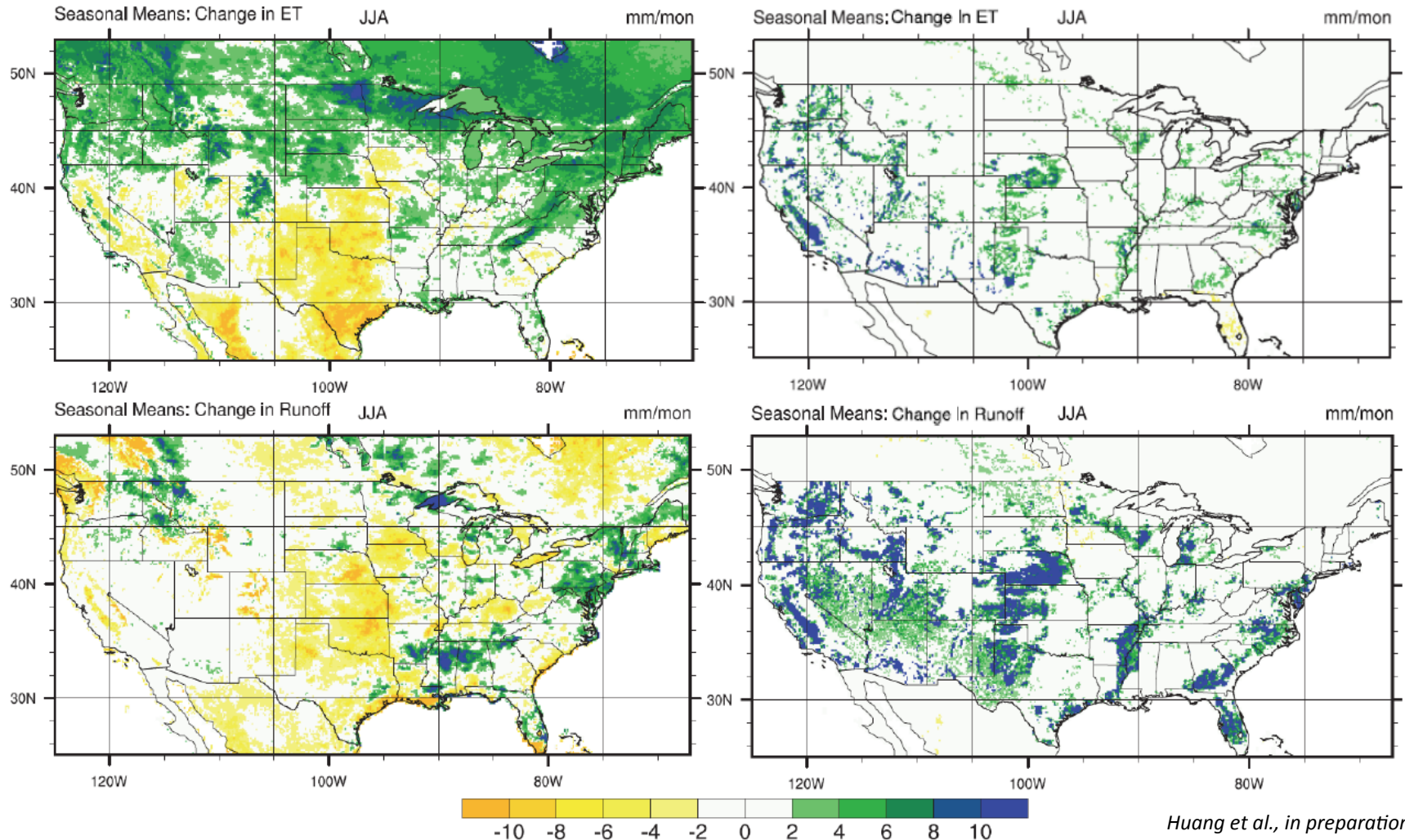
RESM and GCAM LULCC downscaling used to drive CLM

Climate effect, RCP4.5

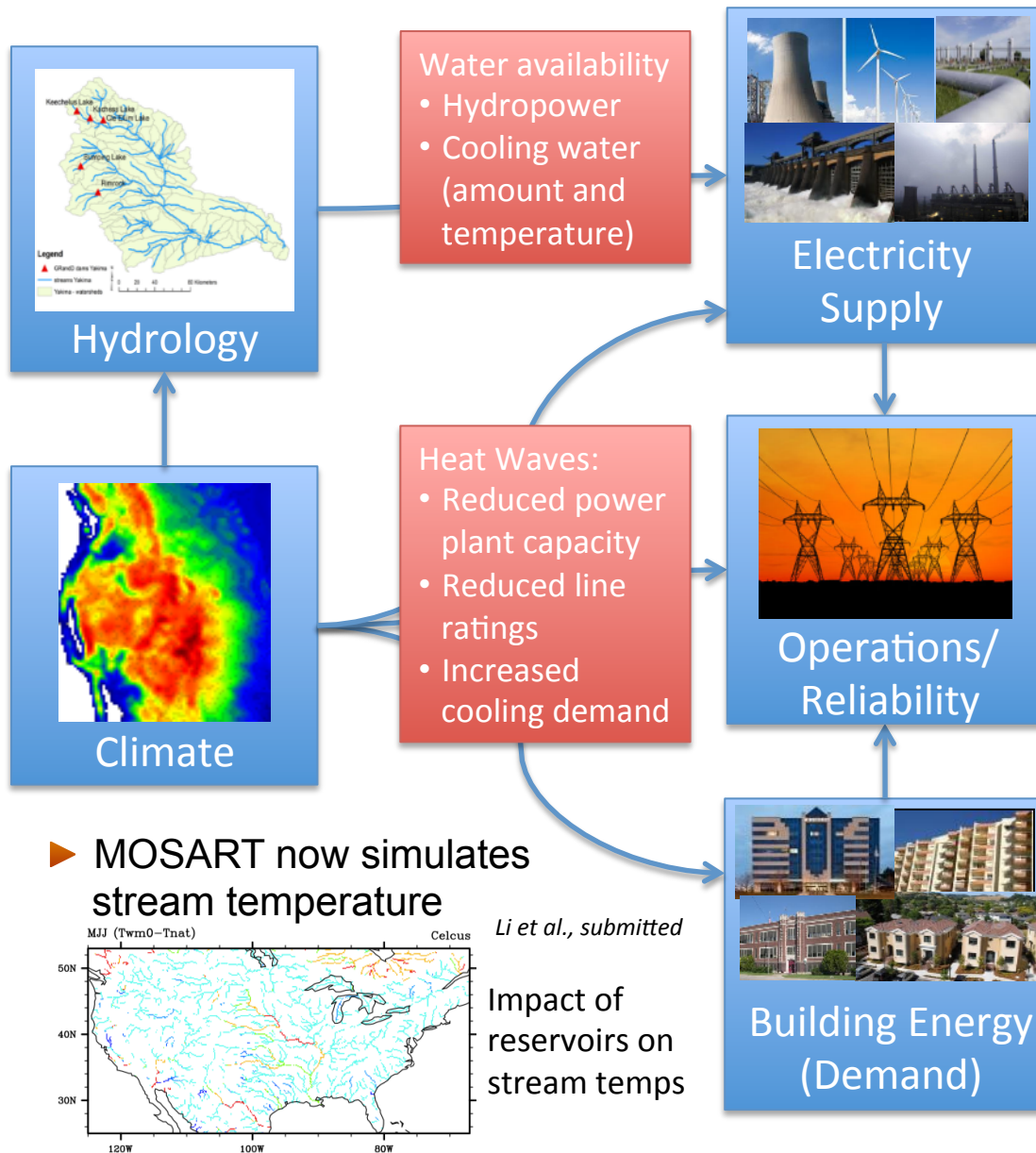
LULCC effect, RCP4.5

Summer evapotranspiration

Summer runoff

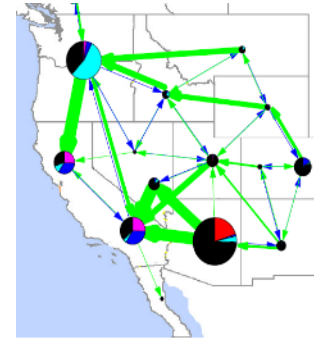


Simulating heat wave and drought impacts on electricity supply, demand, and operations



- Added air temperature and water-related deratings to two production cost models (PROMOD and EOM)

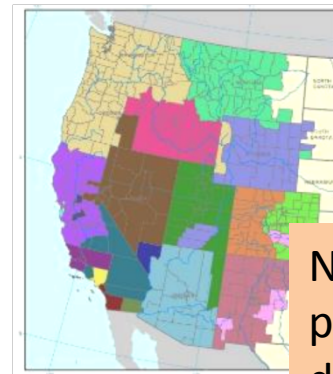
Ke et al., in review



Drought-related capacity derating and power flows

- Developed regional/zonal building energy demand model (BEND) by combining EnergyPlus with a geostatistical analysis

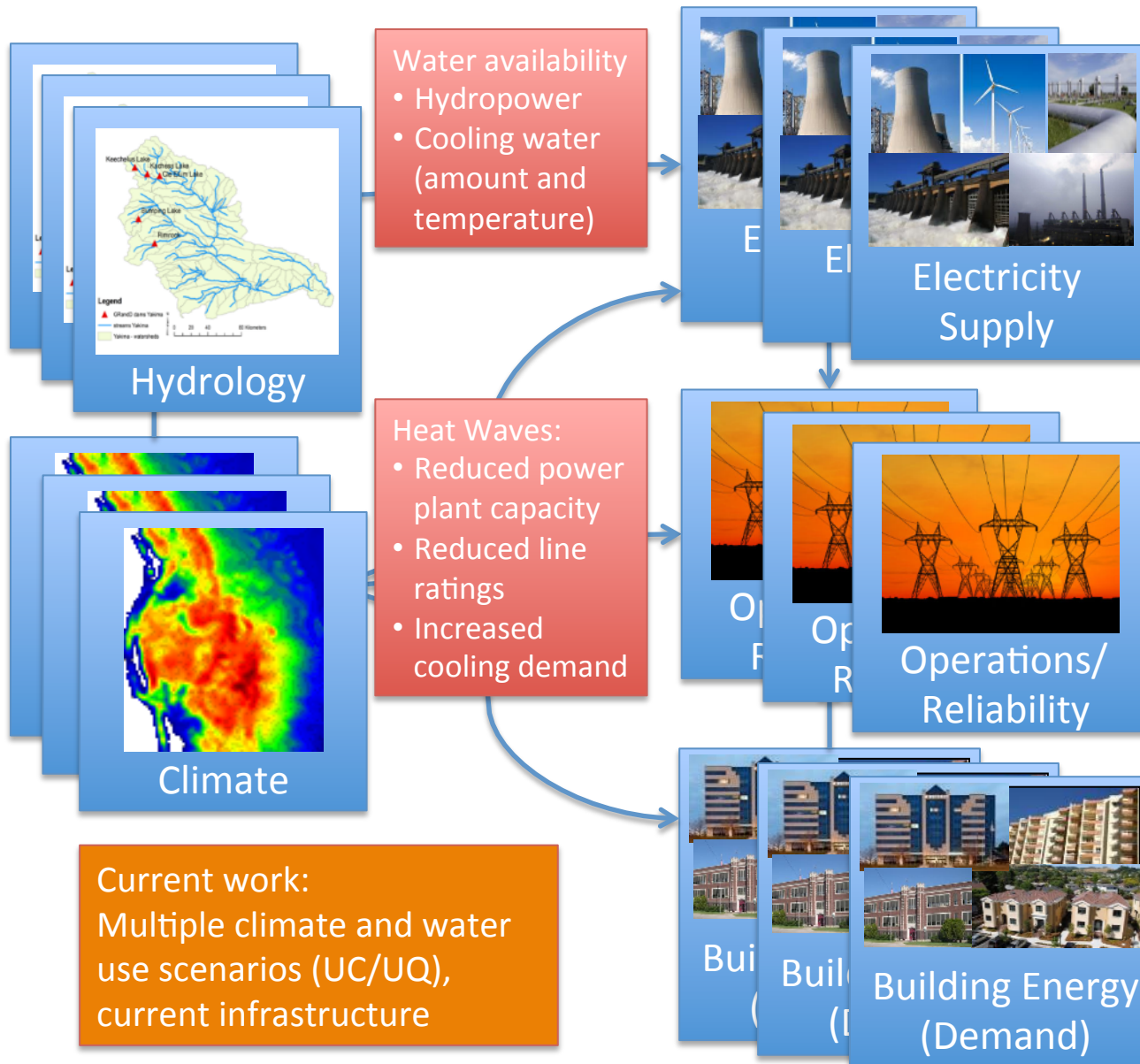
Dirks et al., 2015



Western Interconnection load regions

Nathalie Voisin will provide additional details and results

Simulating heat wave and drought impacts on electricity supply, demand, and operations



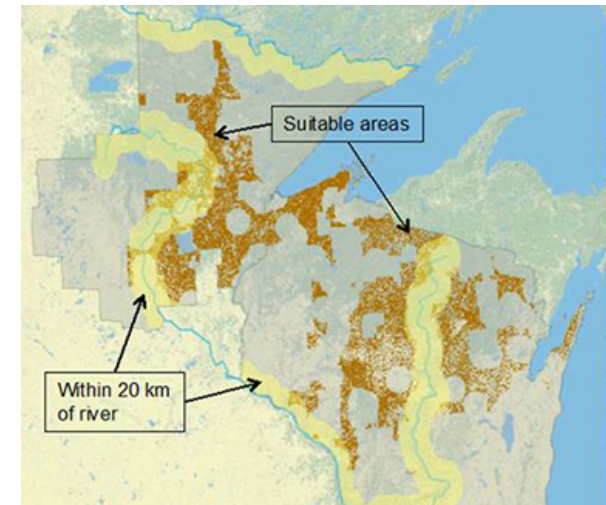
Next Steps:
Analyze Multiple Policy Options and Response Scenarios

- Will future infrastructure be more or less vulnerable?
- Will other constraints emerge (e.g., limits related to power plant siting)?
- How will human responses feed back to climate and/or hydrology?

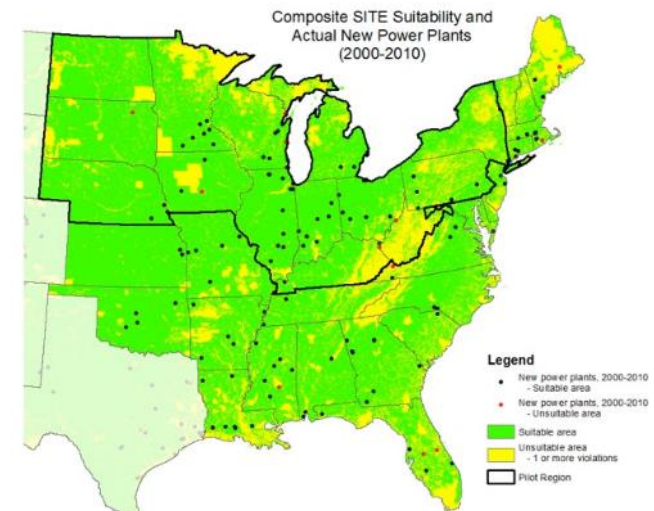
Capacity Expansion Regional Feasibility (CERF) Model

- ▶ GIS-based power plant siting model (1 km² resolution) that combines:
 - Technology-specific siting suitability criteria (e.g., Clean Water Act 316b streamflow requirements)
 - Extensive database of terrain, land use restrictions, and existing infrastructure
 - Natural resource availability information (e.g., water, wind, etc.)
 - An economic algorithm to address relative locational values in siting (e.g., LMPs, grid interconnection costs)

- ▶ **CERF provides a mechanism for testing whether capacity expansion plans (e.g., from GCAM) are technically and economically feasible “on the ground”**

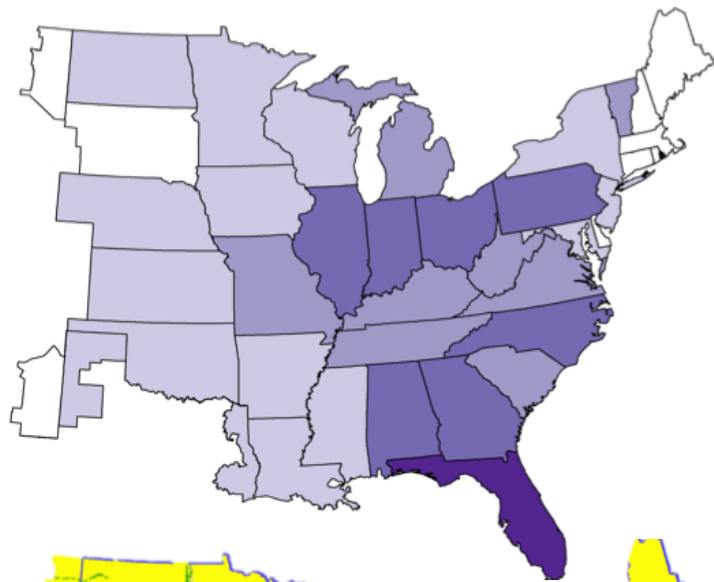


Example of a CERF siting analysis

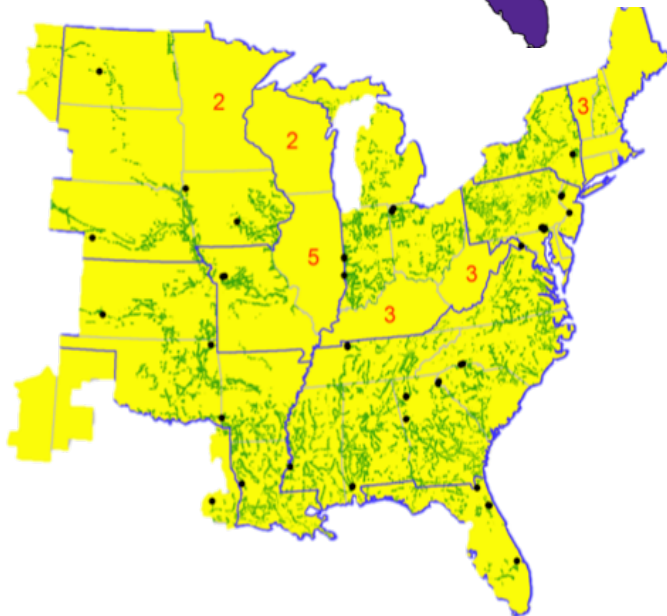
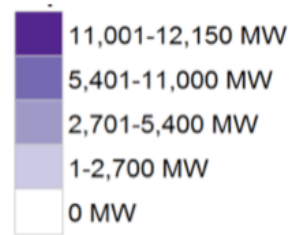


Validation against historical siting decisions

Using CERF (high-resolution siting model) to constrain GCAM capacity expansion projections



New nuclear capacity called for by GCAM under RCP4.5

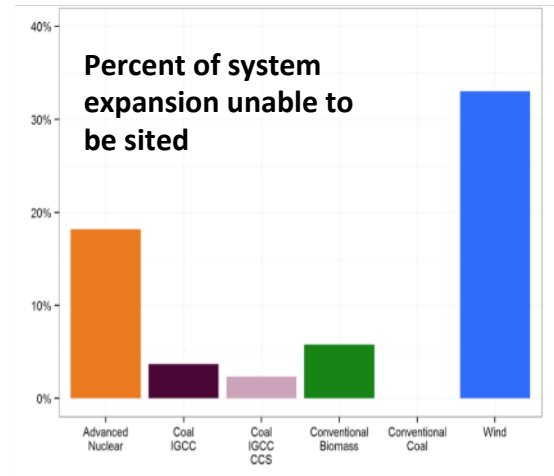


CERF suitability results for nuclear



Sited nuclear plants (2005-2050)

of unsited plants in states with nuclear moratoria



Next step: re-run GCAM with nuclear moratoria imposed and with more stringent wind resource availability

Future work: additional constraints (e.g., next-gen biomass, CCS locations, grid operability,...)

Exposure of energy facilities to hurricane storm surge in the Gulf Coast

- ▶ Evaluated exposure to Katrina-like surges under different scenarios of storm intensity, sea level rise, and land subsidence

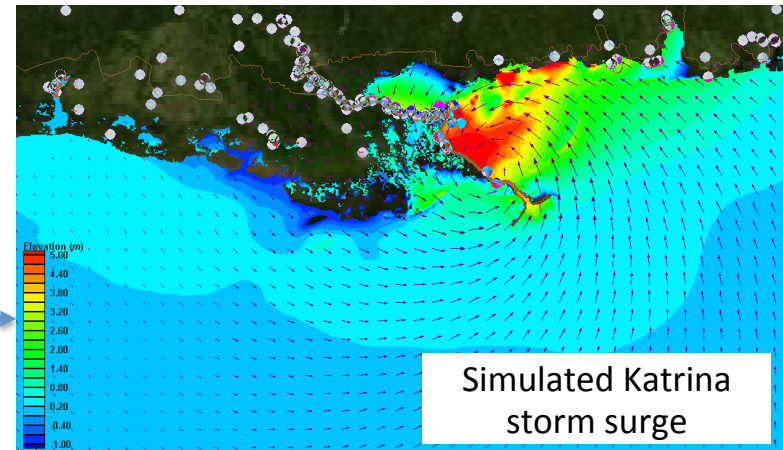
- Regional climate model (WRF)
- Hi-res storm surge model (FVCOM)
- GIS-based exposure analysis

- ▶ New/current work:

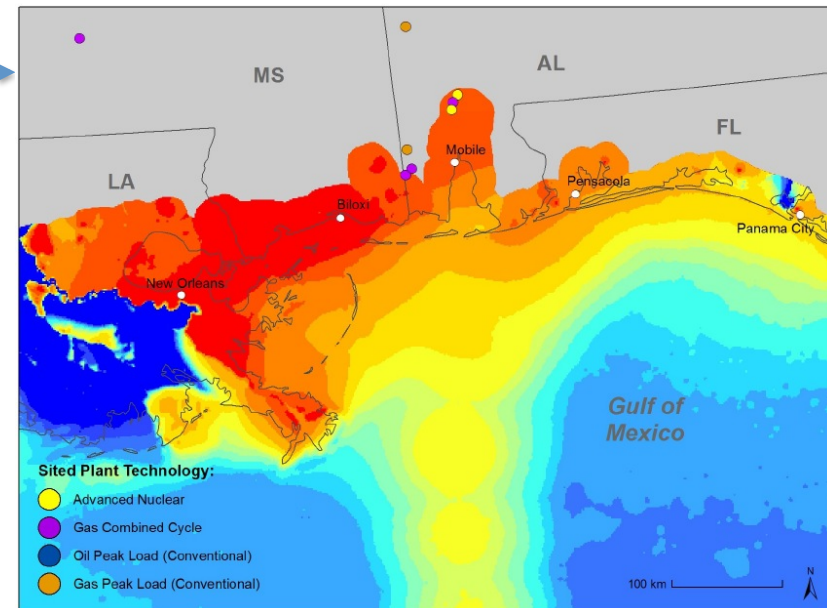
- Evaluate potential impacts on power plant siting (using GCAM-CERF results)

- ▶ Knowledge gaps/future work:

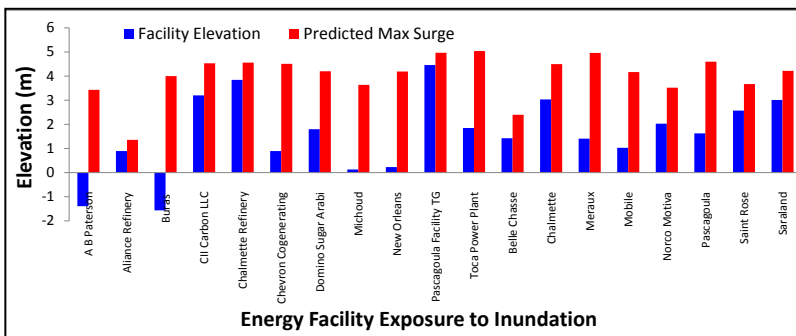
- Translating exposure into impacts (both short-term and long-term)



Yang et al., 2014



Vernon et al., in preparation



Summary and Concluding Thoughts

- ▶ Integrated, multi-sector, multi-scale modeling systems can provide unique insights into how human and Earth systems interact
 - Development to date has focused on developing systematic approaches to model coupling with steadily increasing complexity (crawl → walk → run)
 - Results have highlighted how climate change can enhance or constrain certain scenarios/responses, and vice versa
- ▶ Key next steps include:
 - Determining when higher spatial, temporal, and/or process resolution is warranted
 - Developing more robust representations of climate impacts on key sectors of interest (requires data as well as modeling)
 - Working towards more flexible, interoperable frameworks that take advantage of individual model strengths



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Thank you!

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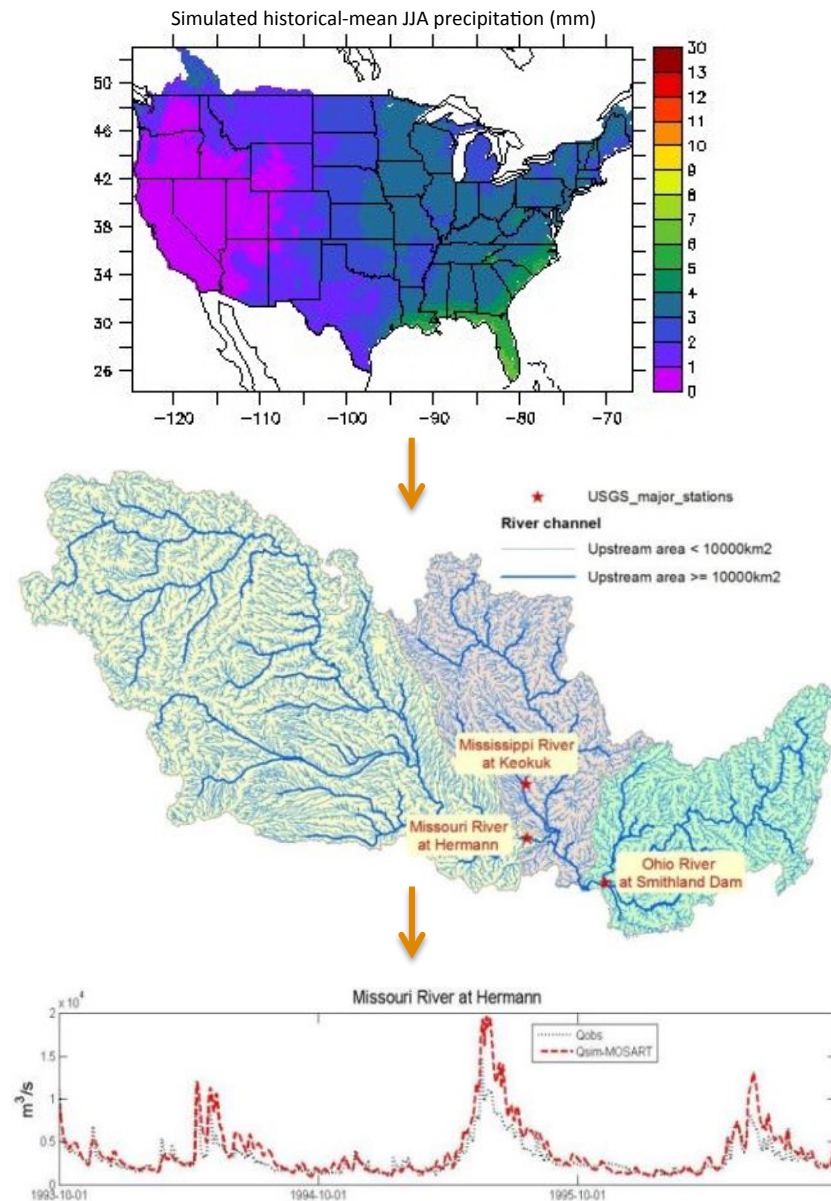
PRIMA/RIAM Natural Systems Models

Regional Earth System Model (RESM)

- ▶ High-resolution (~15km) dynamically downscaled climate information
- ▶ Integration of atmosphere, land, and ocean models captures key regional processes (e.g., Southwest Monsoon)
- ▶ Modular framework: Other climate models/data can be substituted

Regional Water/Hydrology Models

- ▶ Sub-basin extension to the Community Land Model (“SCLM”)
- ▶ New scalable, physically based river routing model (MOSART)
- ▶ Water Management (WM) model includes generic representation of regional reservoir operations & regulated flows (facilitates coupling with GCAM)



Model of Scale Adaptive River Transport (MOSART) now simulates stream temperature

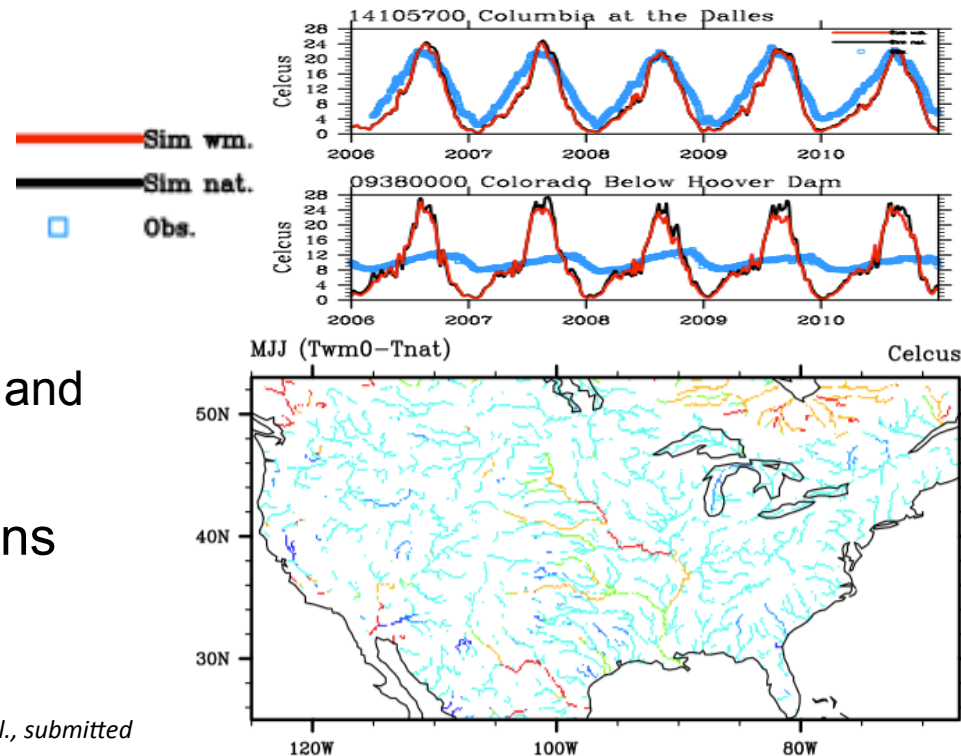
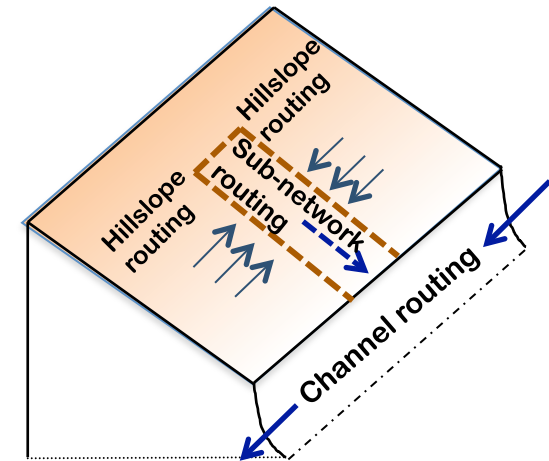
MOSART characteristics:

- Explicit, physically based, scale-consistent subgrid and channel routing
- Also simulates channel water depth and velocity—needed for future modeling of in-stream biogeochemistry, sediment transport, and floods

In-stream temperatures include:

- Channel heat balance
- Effects of river routing
- Power plant heat discharges
- Impacts of reservoirs (regulation and impoundment)

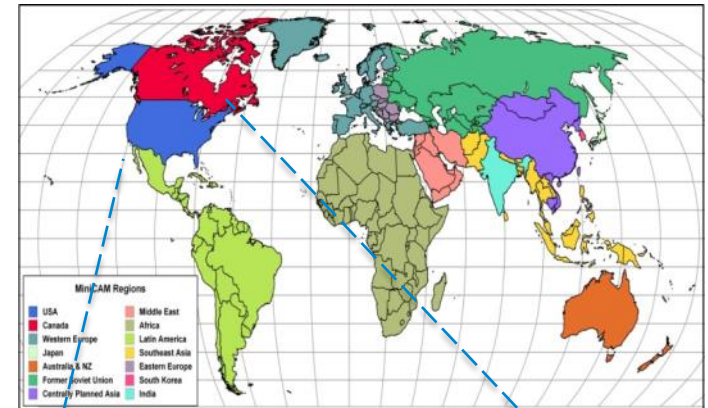
Results show that reservoir operations have strongest impact on in-stream temperatures



Adding sub-national detail to GCAM facilitates coupling with sector models

- ▶ To facilitate coupling with detailed sector models, we have added subnational detail to GCAM (version name: GCAM-USA):
 - 50-state climate-dependent building energy
 - 50-state electricity generation mix
 - Increased spatial and technological resolution for agriculture and land use
 - Water supply and demand at major watershed scale
 - Additional sectors now being added (e.g., state-level natural gas supply and demand)
- ▶ The rest of the model operates normally, thus providing global constraints and context (i.e., GCAM-USA is GCAM)

Standard GCAM: 37 Geo-Political Regions



GCAM-USA: Subnational Detail



GCAM-USA Building Energy Demand: Results

Increases in summer cooling demand are more than offset by reduced winter heating

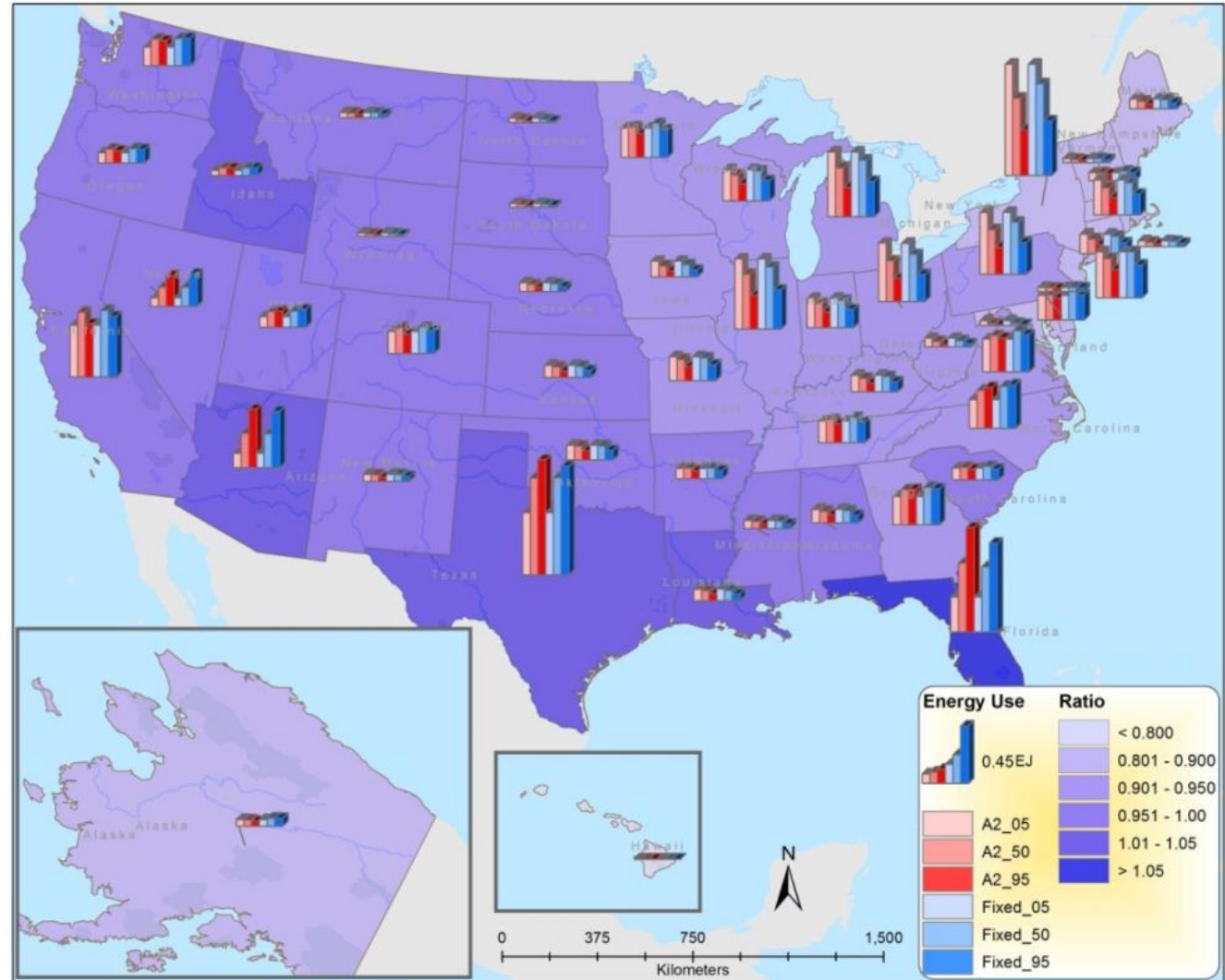


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Projected building energy use in 2005, 2050, and 2095 driven by CASCade A2 statically downscaled climate scenario (red bars) versus fixed 2005 climate (blue bars).

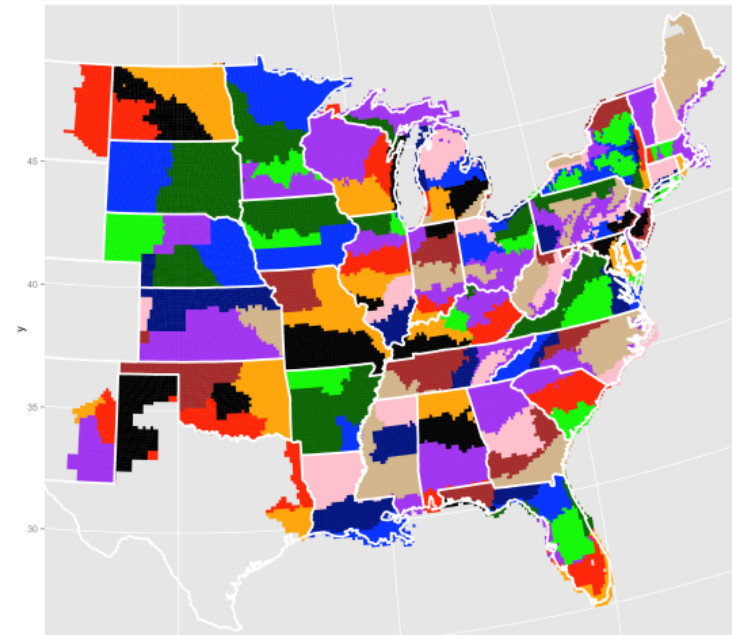
Purple shading denotes ratio of cumulative 21st century building energy use for A2 scenario versus no climate forcing (i.e., versus a scenario that only includes changes in population, building floor space, building technologies, GDP, and other socioeconomic trends)



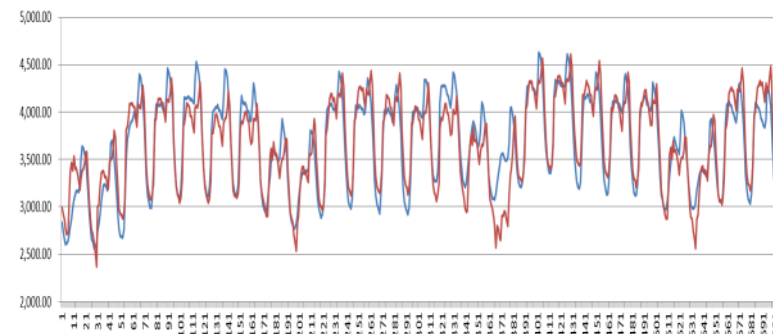
Building Energy Demand (BEND) Model

BEND simulates climate-dependent building energy demand at high spatial, temporal, and technological resolution

- ▶ Combines DOE's EnergyPlus model (for individual buildings) with a geostatistical analysis of regional climate, population, and building types and technologies
- ▶ Resolution as fine as 1/8 degree (~12 km); results can be aggregated to any geographic region (e.g., utility zone)
- ▶ Uses GCAM input (population-driven floor space growth, technology turnover) to drive future building stock changes
- ▶ Uses RESM or other hourly weather/climate input (9 variables!) to simulate changes in building energy demand
- ▶ Can also be used to model demand response, smart charging, etc.



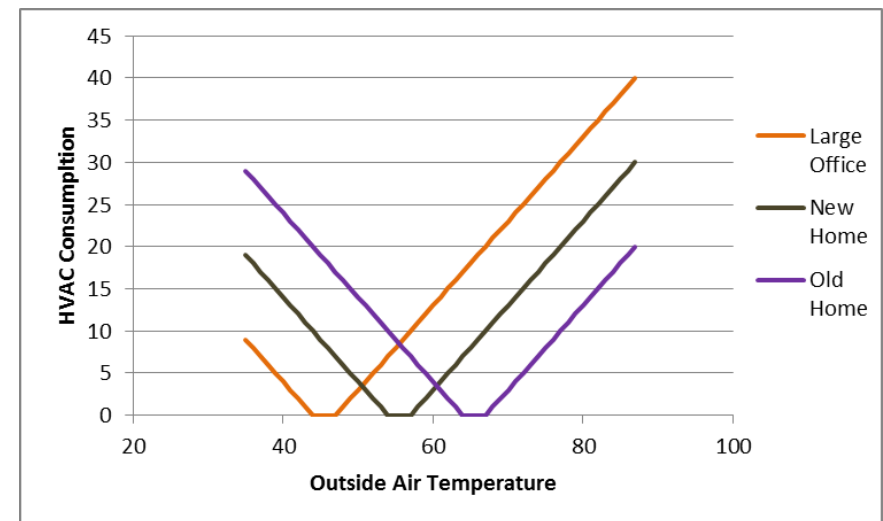
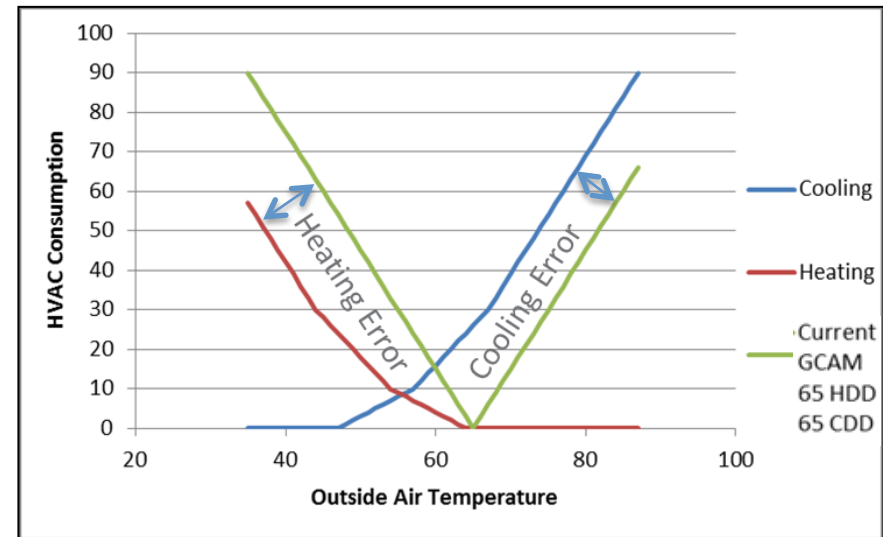
Climate similar regions in the Eastern Interconnection



Sample BEND output/validation for a single utility zone

Using insights from high-resolution modeling to improve the GCAM buildings model

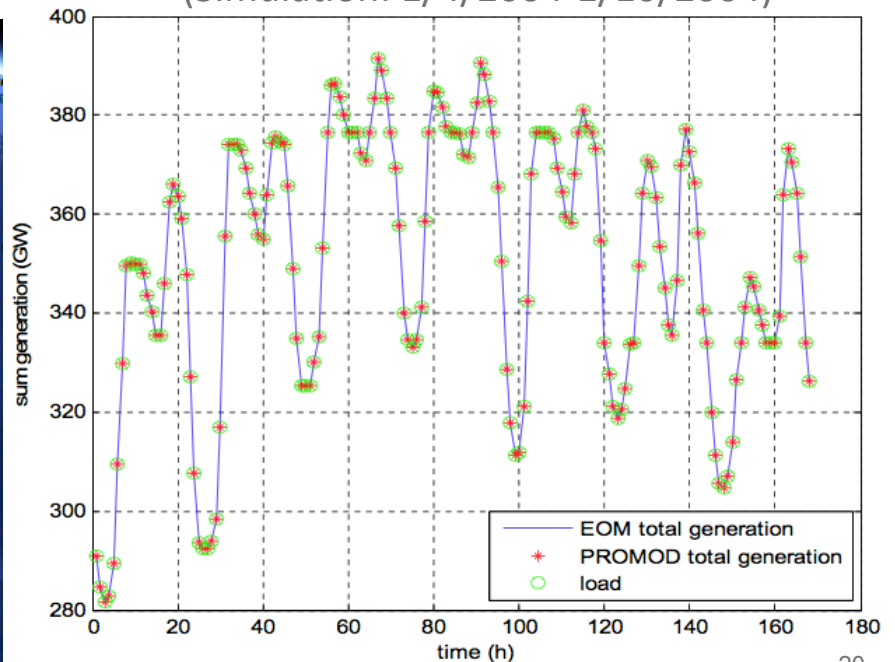
- ▶ Current GCAM buildings model
 - 2 Building classes
 - residential
 - commercial
 - Heating and cooling loads determined based on heating degree days (HDD) and cooling degree days (CDD) with 65°F/18.3°C base
- ▶ Possible GCAM building model enhancements
 - Heating and cooling loads determined based on multiple HDD and CDD
 - heating degree days
 - ◆ 65°F/18.3°C, 55°F/12.8°C, 45°F/7.2°C
 - cooling degree days
 - ◆ 75°F/23.9°C, 65°F/18.3°C, 55°F/12.8°C
 - 6 Building types
 - residential: single family and multi-family
 - commercial: office, retail, institutional, warehouse/storage.



- ▶ Hourly unit commitment and economic dispatch model with zonal transmission constraints
- ▶ Unique capability: Hourly climate-dependent capacity rating (can account for air temperature and cooling water availability)
- ▶ Open source; Validated against PROMOD

Validation for Eastern Interconnection

Good agreement with PROMOD
(Simulation: 1/4/2004-1/10/2004)



PNNL-SA-100133

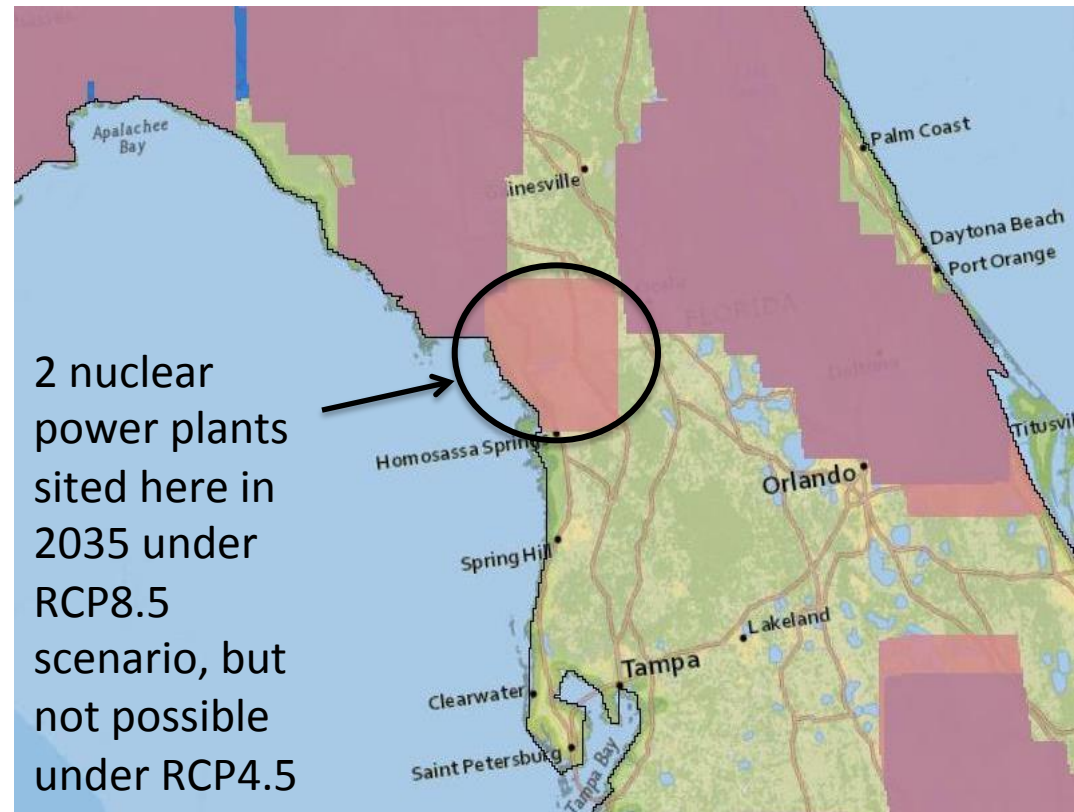
How do climate change and climate policy constrain capacity expansion planning?

► Models used:

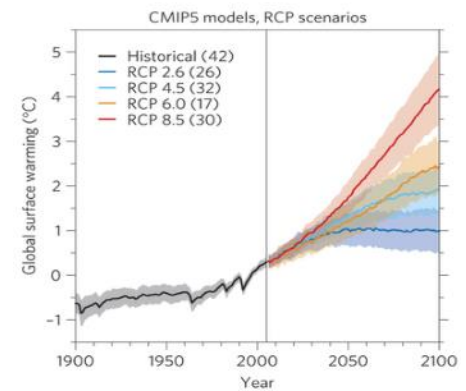
- Regional Earth System Model
→ *water availability*
- Global Change Assessment Model
→ *basin-scale water demand, state-level energy demand and system expansion*
- Capacity Expansion Regional Feasibility Model
→ *high-resolution power plant siting*

► Results and outcomes

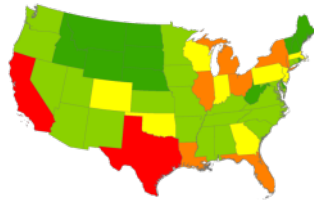
- Changes in water availability (due to climate, climate policy, and/or changes in regional water demands) may constrain siting of baseload power plants in some locations, **but water availability constraints were notably smaller than other constraints.**



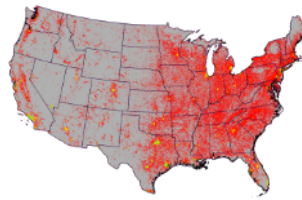
Sufficient cooling water for advanced nuclear
Pink = RCP 8.5;
Blue = RCP 4.5;
Purple = both RCPs



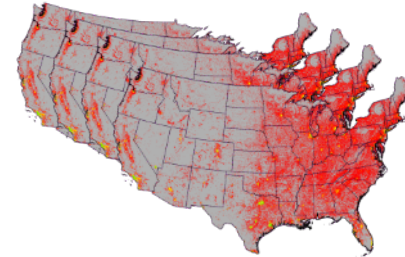
Coupling GCAM with infrastructure models: Implications of rapid changes in natural gas



GCAM-USA natural
gas demand scenario
and supply estimates

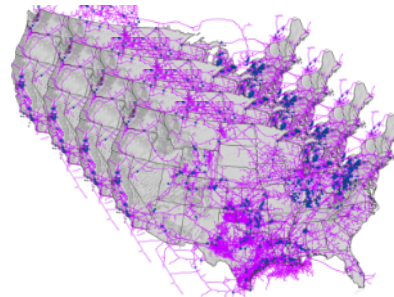


Allocate projected
demand changes to
neighborhood cells

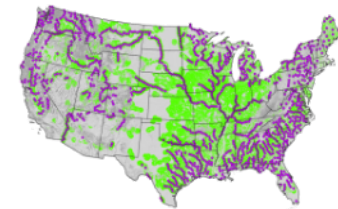


Create ensemble of demand
maps under varying
assumptions and policy options

**How do extreme weather events
(e.g., cold snaps) interact with gas
infrastructure under different
policy futures (e.g., LNG exports)
to create vulnerabilities?**



Perform vulnerability
analysis under different
assumptions, policies,
and scenarios



Use natural gas system
model to identify required
pipeline growth, storage
sites, etc.

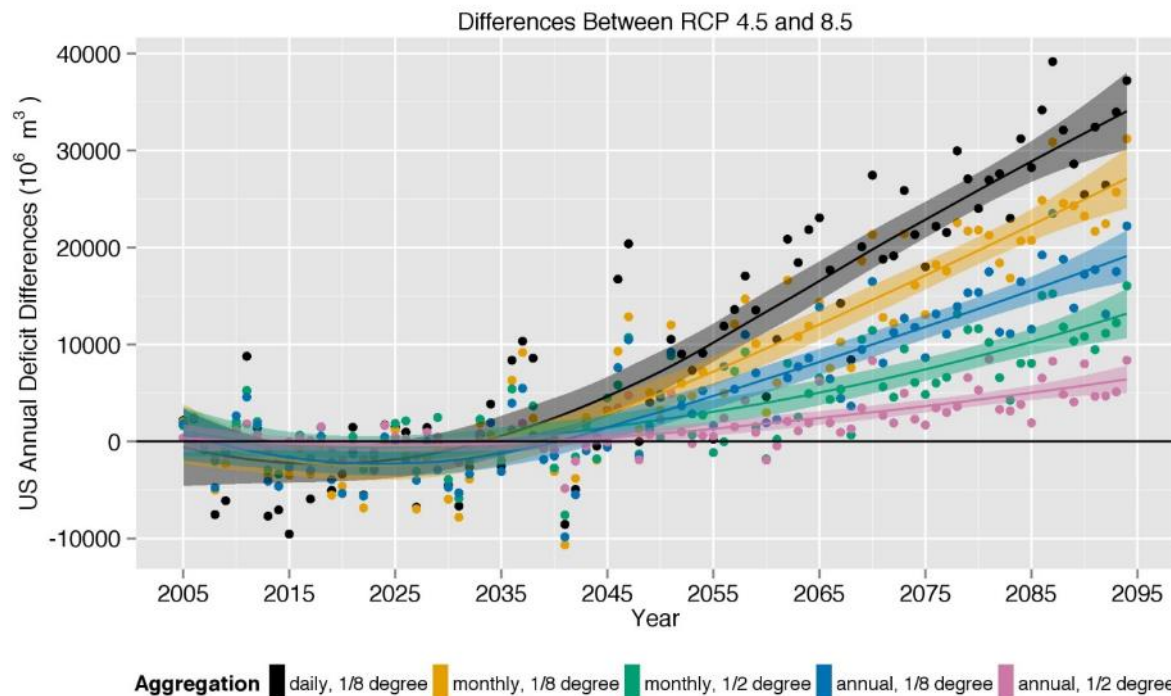
Key challenges:

- Reconciling GCAM assumptions with natural gas system model assumptions
- Vulnerability/impact analysis (short-term and long-term)

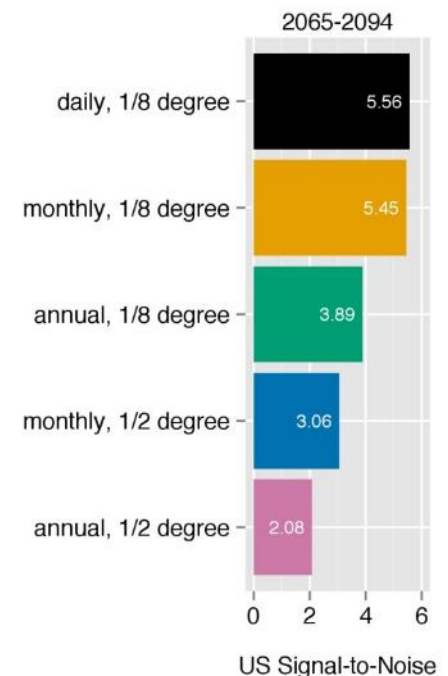
Higher resolution models simulate more robust differences in water deficit between RCP4.5 and RCP8.5

- 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

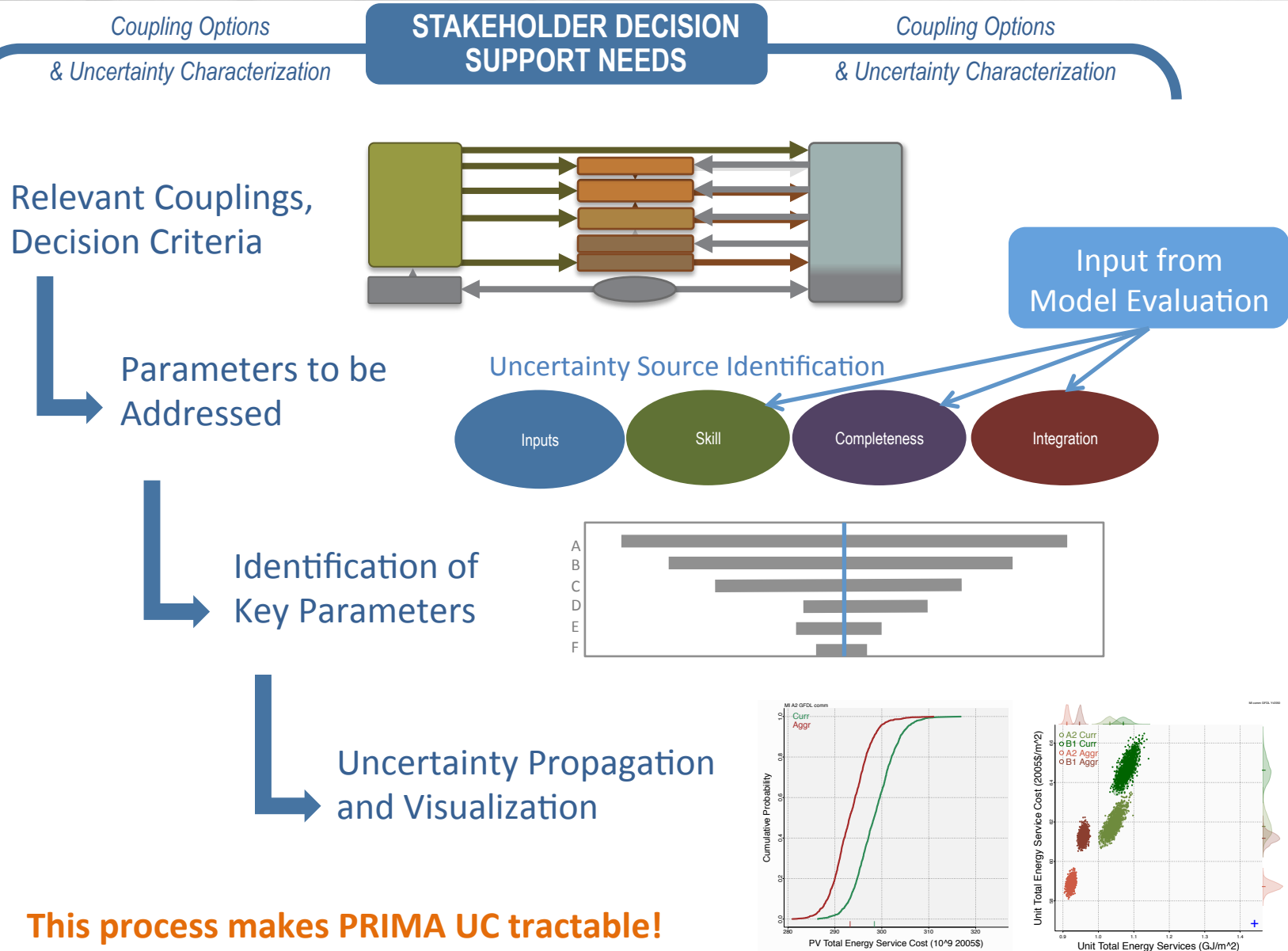
Difference in annual water deficits between RCP4.5 and RCP8.5 at multiple resolutions



Signal-to-noise ratio

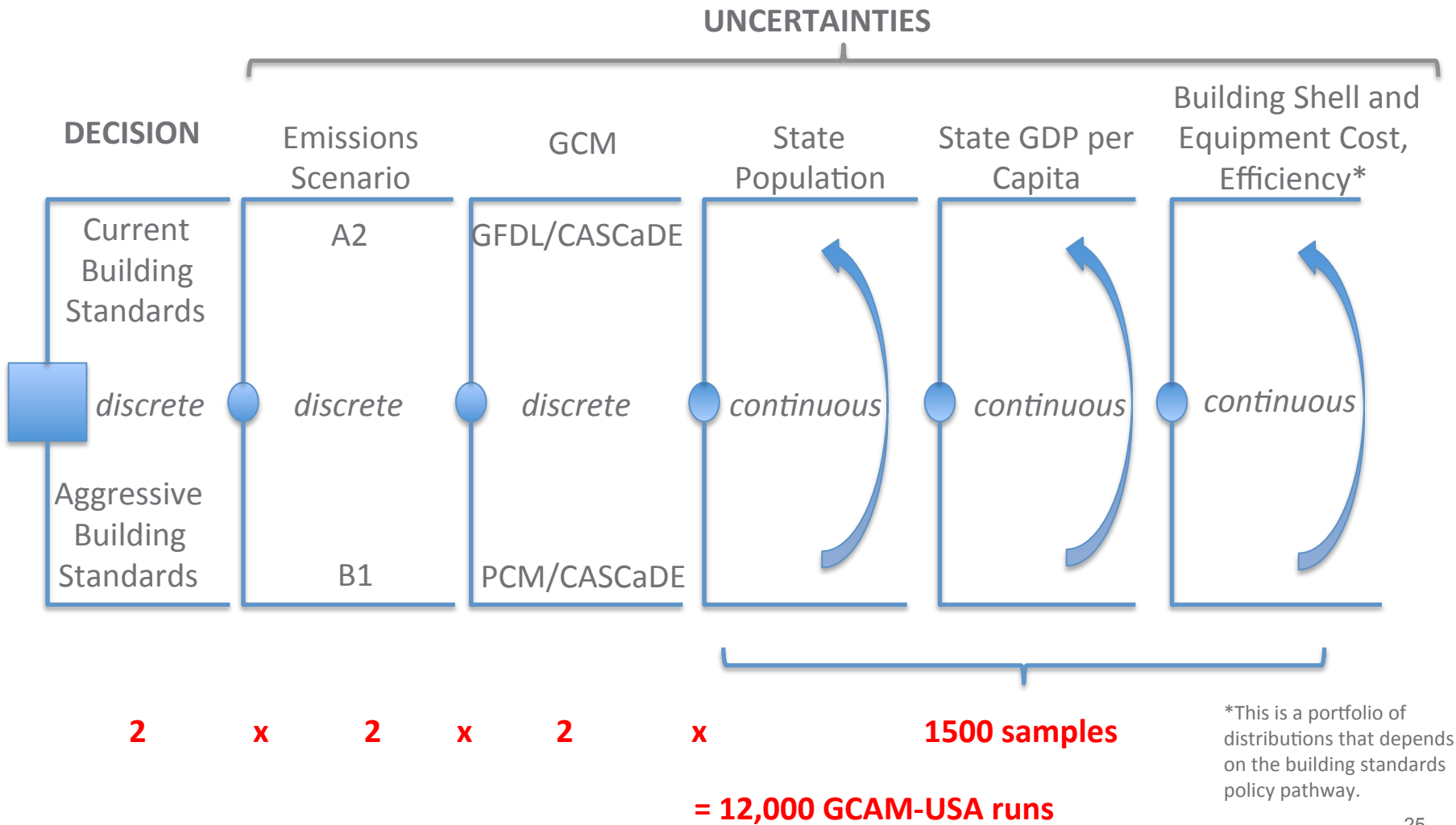


PRIMA Uncertainty Characterization Process

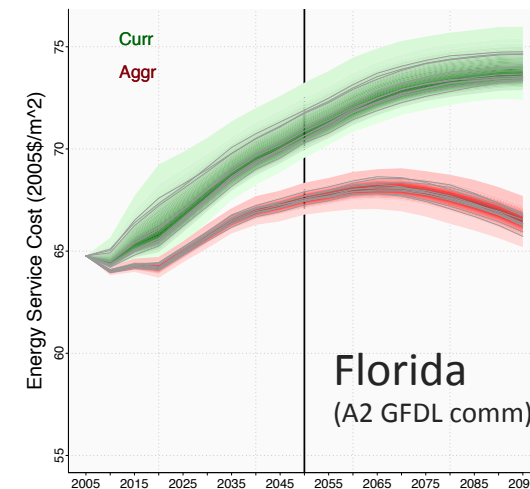
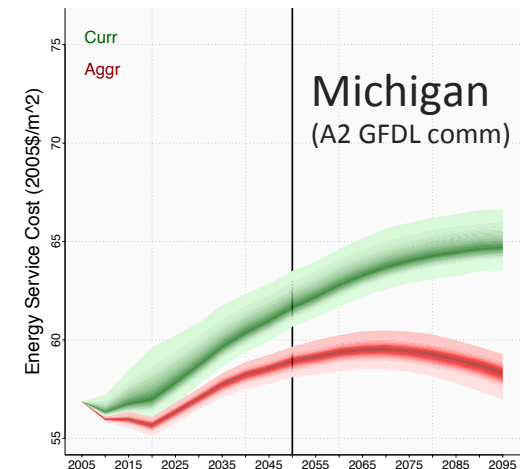
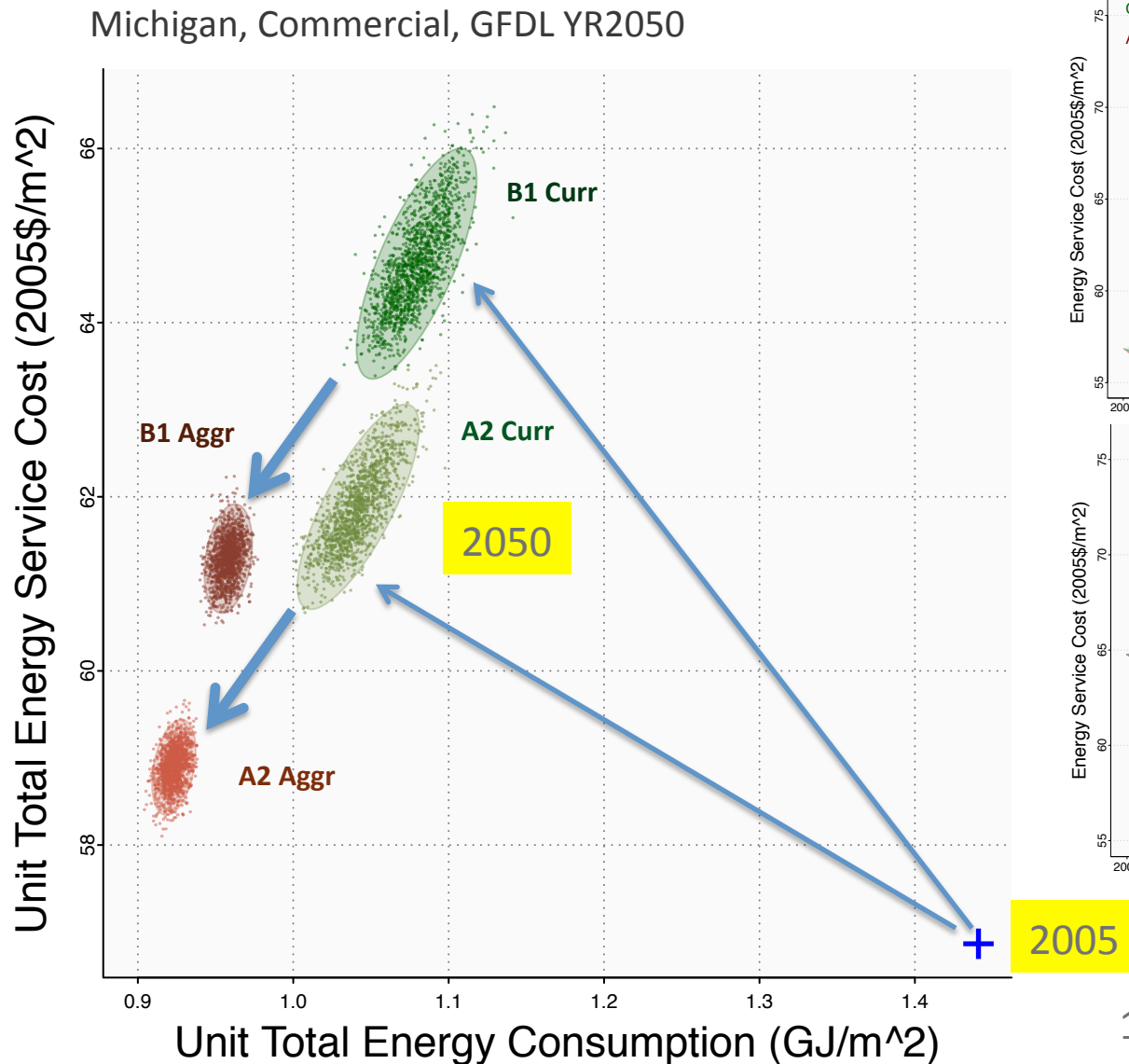


PRIMA Uncertainty Characterization: Initial Experiment Using GCAM

Decision: whether to adopt aggressive building standards in each state



Aggressive Standards Reduce Costs in all Scenarios, Years, States, & Models



1 GJ = 0.95 MBtu