Advancing process-based hydrologic models for climate risk assessments

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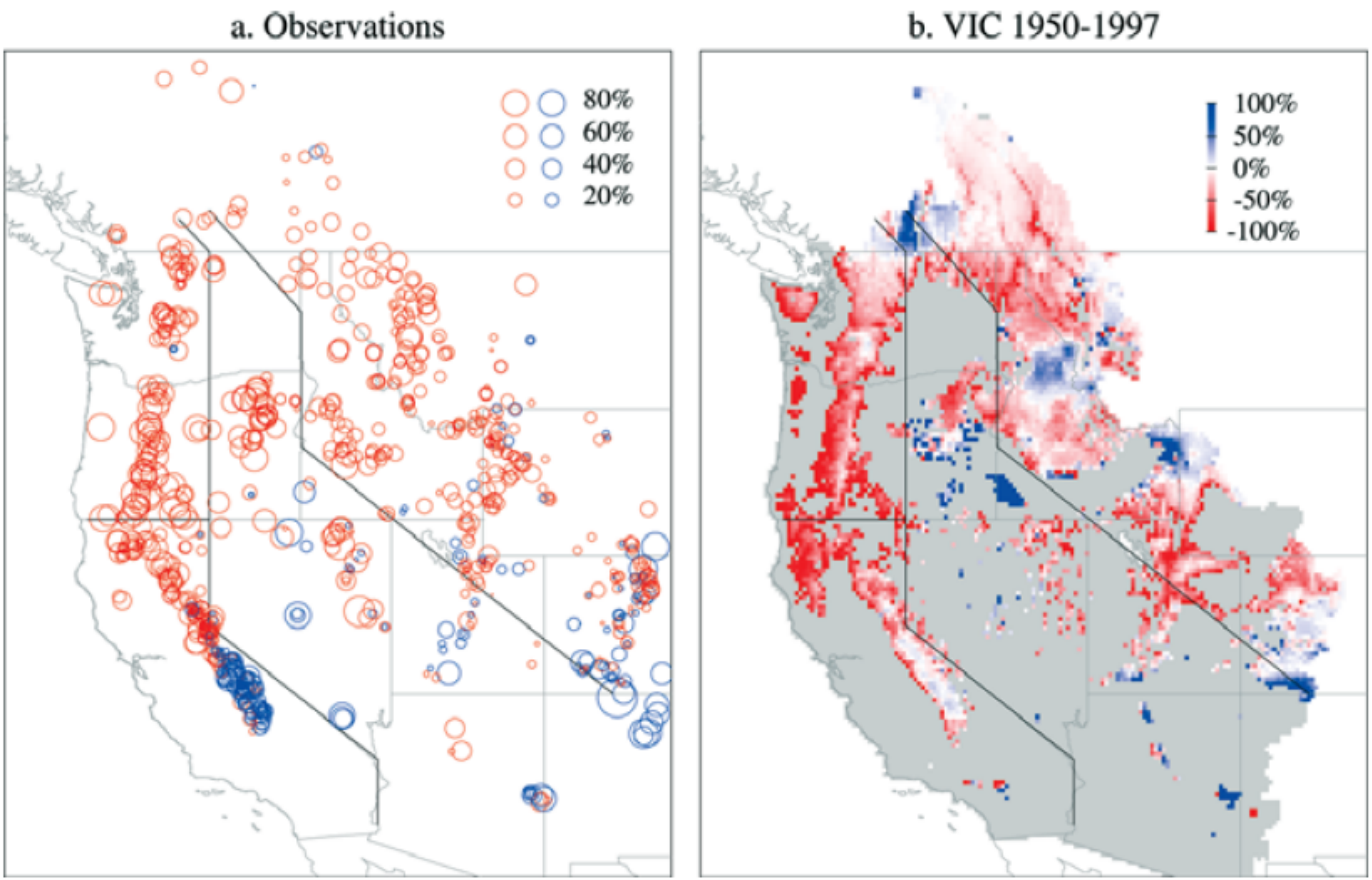
Support from NASA-AIST

Outline

- Motivation
  - Water security
  - Need to explore wide range of futures in water resources planning
- "Revealing" uncertainties in climate impact assessments
  - Emission scenarios
  - Climate model simulations (model, initial conditions)
  - Climate downscaling (statistical, dynamical)
  - Hydrologic modeling
- Model development activities
  - Climate downscaling
  - Hydrologic modeling
- Summary and outlook

Declining snowpack:
Trends in end-of-winter snow accumulation



Mote et al., BAMS, 2005

Changes in seasonality:
Trends in runoff timing

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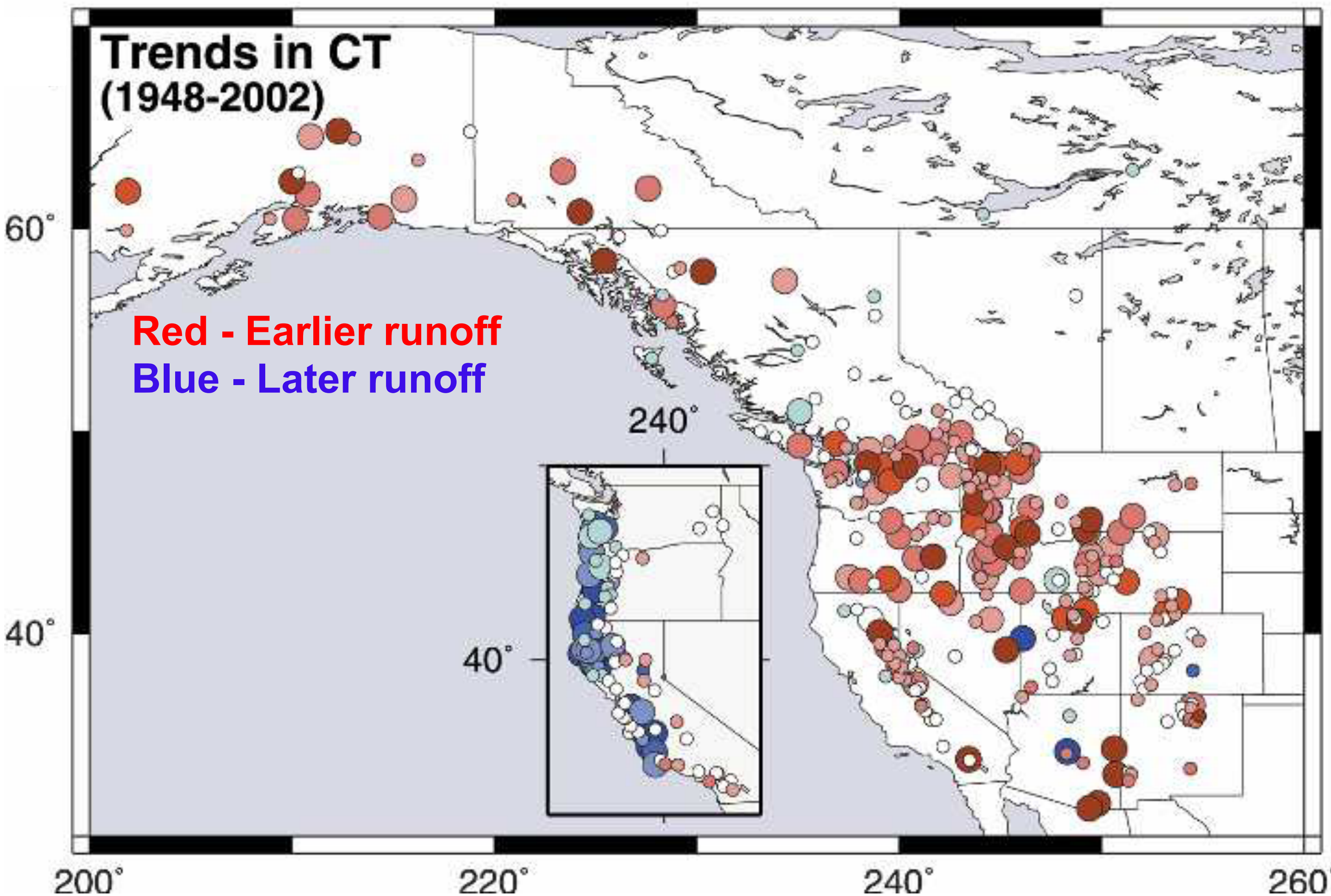

Stewart et al., J. Climate, 2005

…controversial questions

When will Lake Mead go dry?

Tim P. Barnett[1] and David W. Pierce[1]

Comment on "When will Lake Mead go dry?" by T. P. Barnett and D. W. Pierce

Joseph J. Barsugli,[1,2] Kenneth Nowak,[1,3] Balaji Rajagopalan,[1,3] James R. Prairie,[4]

Water supply risk on the Colorado River: Can management mitigate?

Balaji Rajagopalan,[1,2] Kenneth Nowak,[1] James Prairie,[3] Martin Hoerling,[4] Benjamin Harding,[5] Joseph Barsugli,[2,4] Andrea Ray,[4] and Bradley Udall[2,4]

Received 14 December 2008; revised 3 June 2009; accepted 1 July 2009; published 21 August 2009.

[1] Population growth and a changing climate will tax the future reliability of the Colorado River water supply. Using a heuristic model, we assess the annual risk to the Colorado River water supply for 2008–2057. Projected demand growth superimposed upon historical climate variability results in only a small probability of annual reservoir depletion through 2057. In contrast, a scenario of 20% reduction in the annual Colorado River flow due to climate change by 2057 results in a near tenfold increase in the probability of annual reservoir depletion by 2057. However, our analysis suggests that flexibility in current management practices could mitigate some of the increased risk due to climate change–induced reductions in flows.

Citation: Rajagopalan, B., K. Nowak, J. Prairie, M. Hoerling, B. Harding, J. Barsugli, A. Ray, and B. Udall (2009), Water supply risk on the Colorado River: Can management mitigate?, *Water Resour. Res.*, *45*, W08201, doi:10.1029/2008WR007652.

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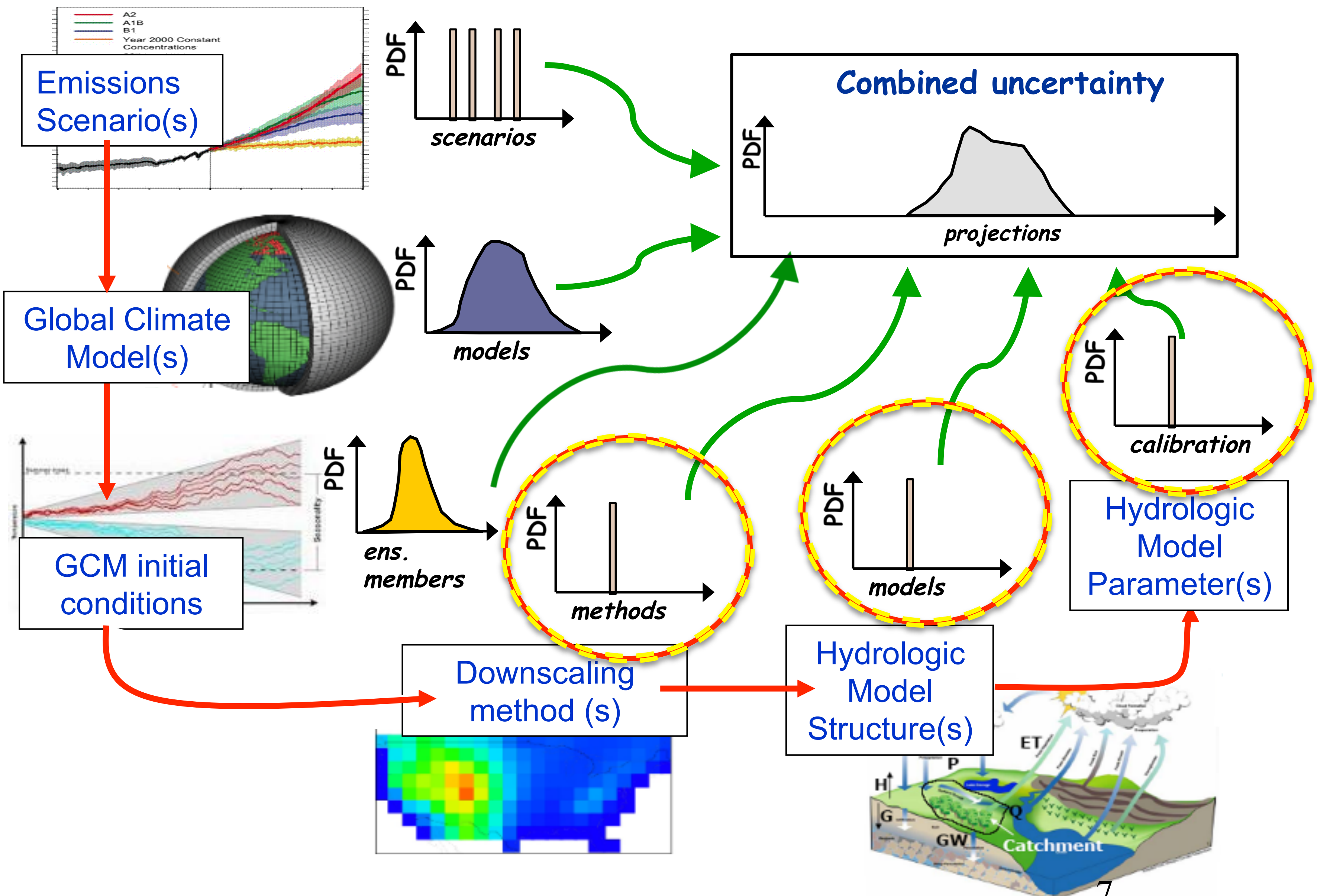
“Revealing” uncertainties



“Revealing” uncertainties

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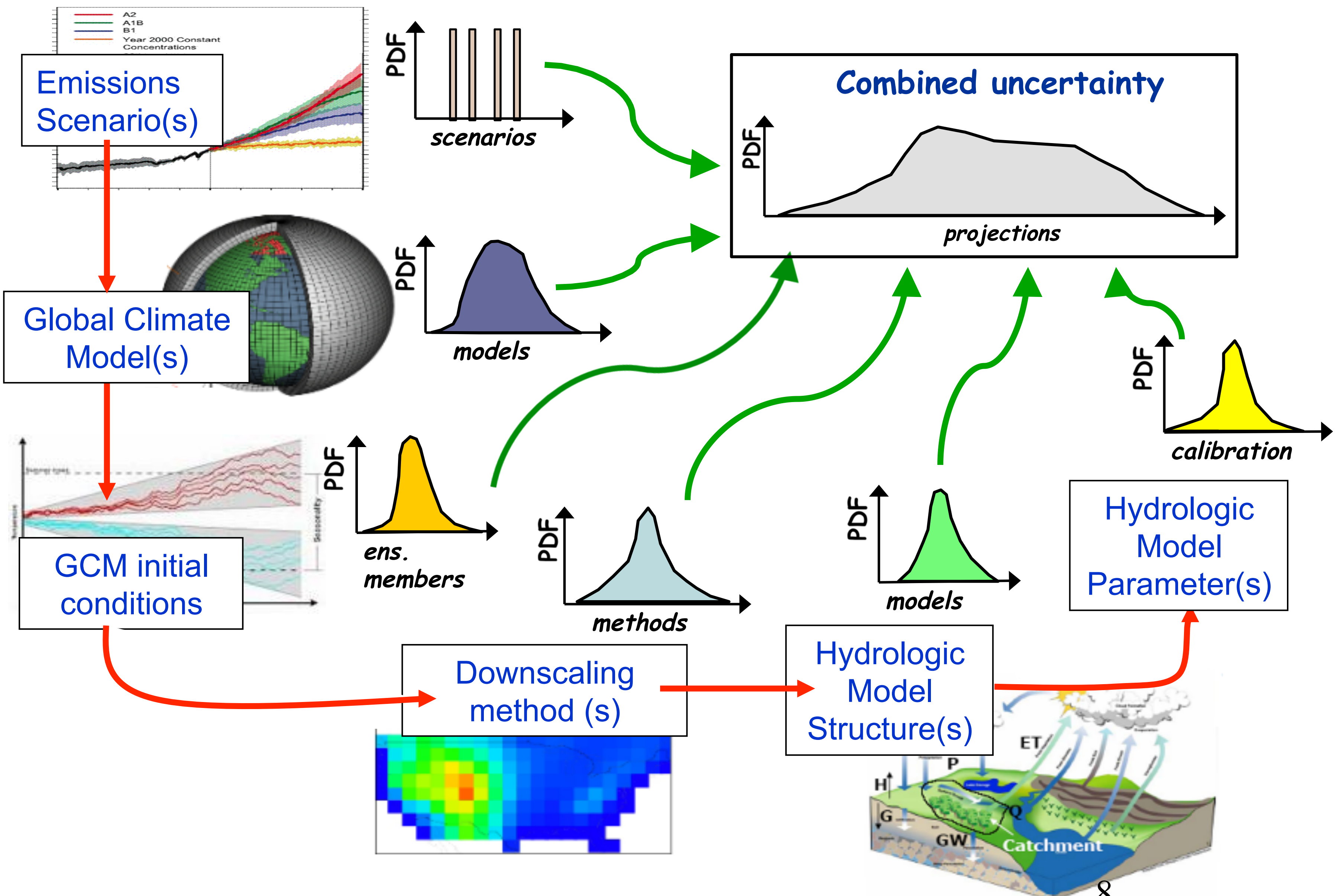
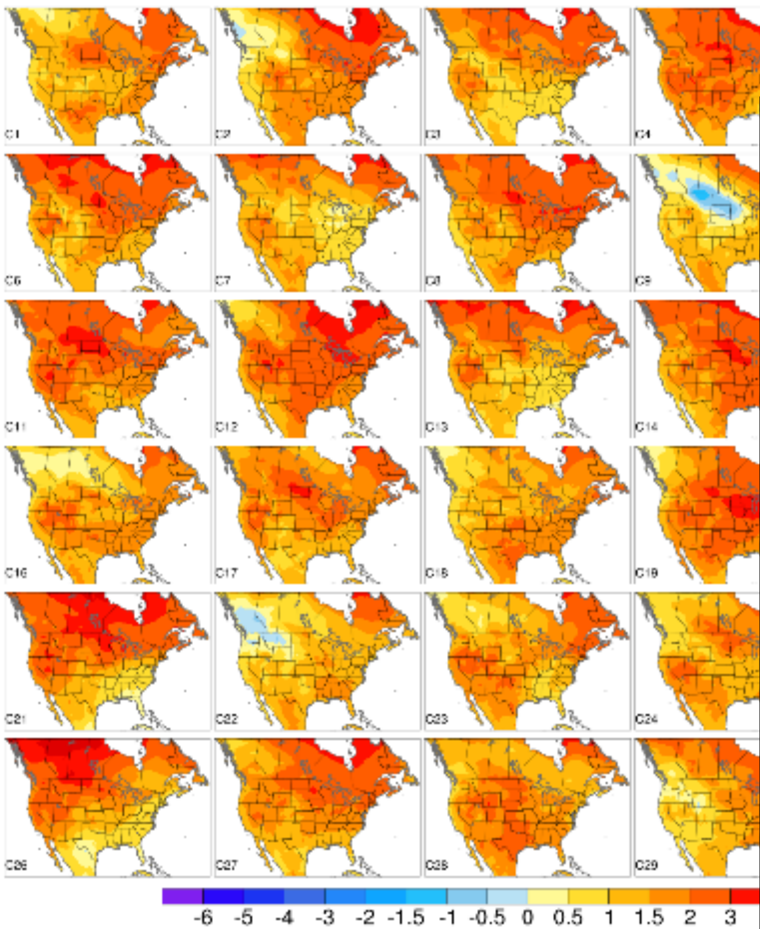
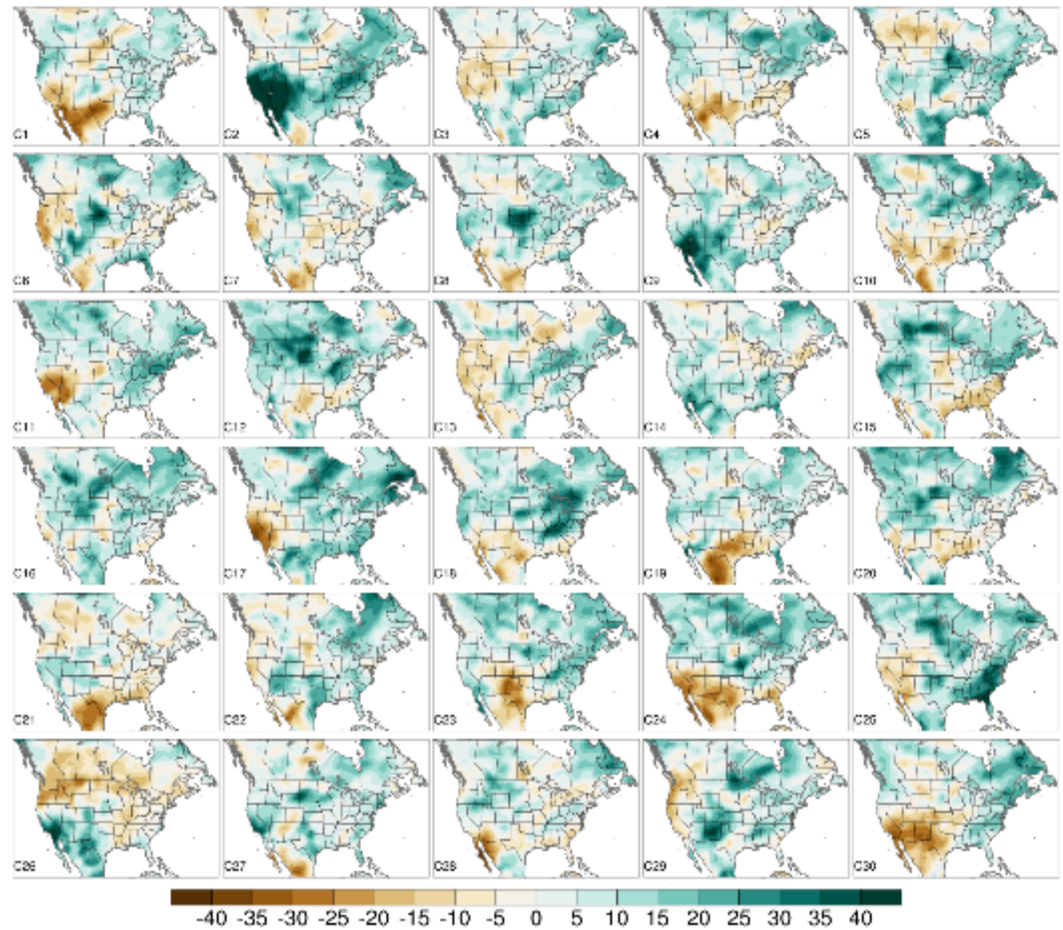


Climate model uncertainty

The role of internal variability



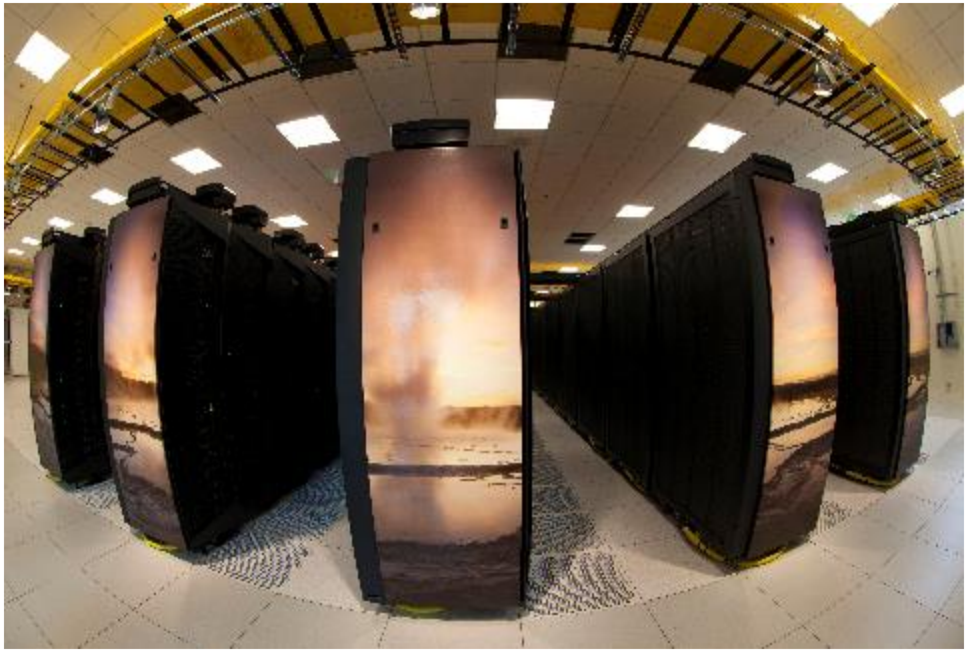
Change in air temperatur

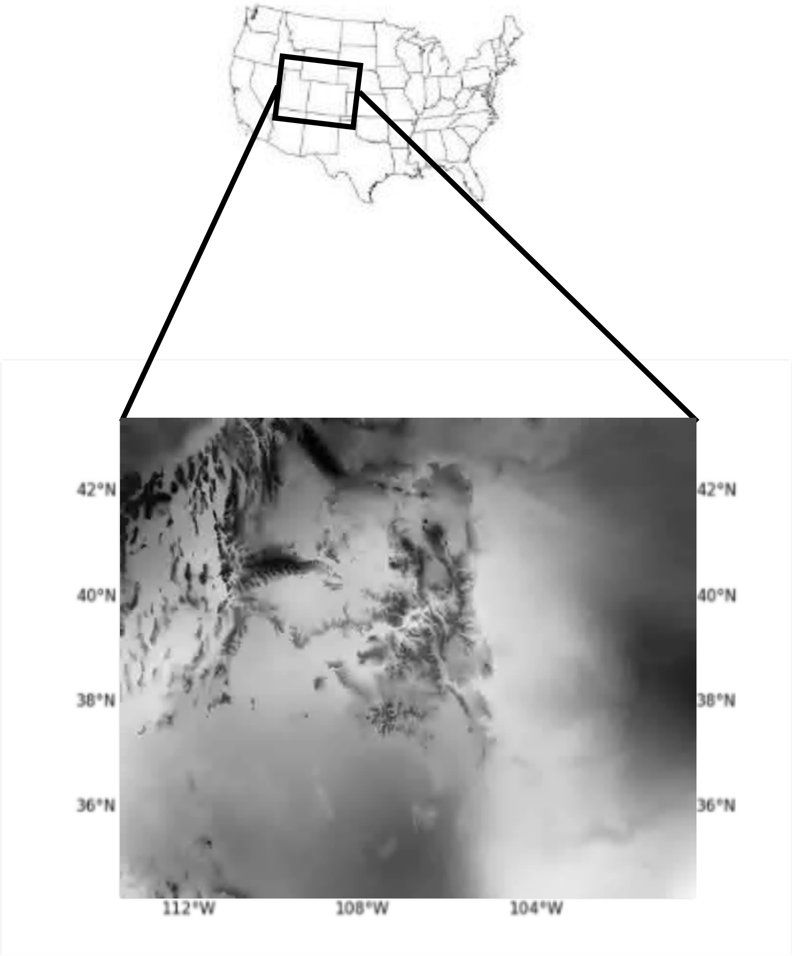


Change in precipitation

Downscaling climate models

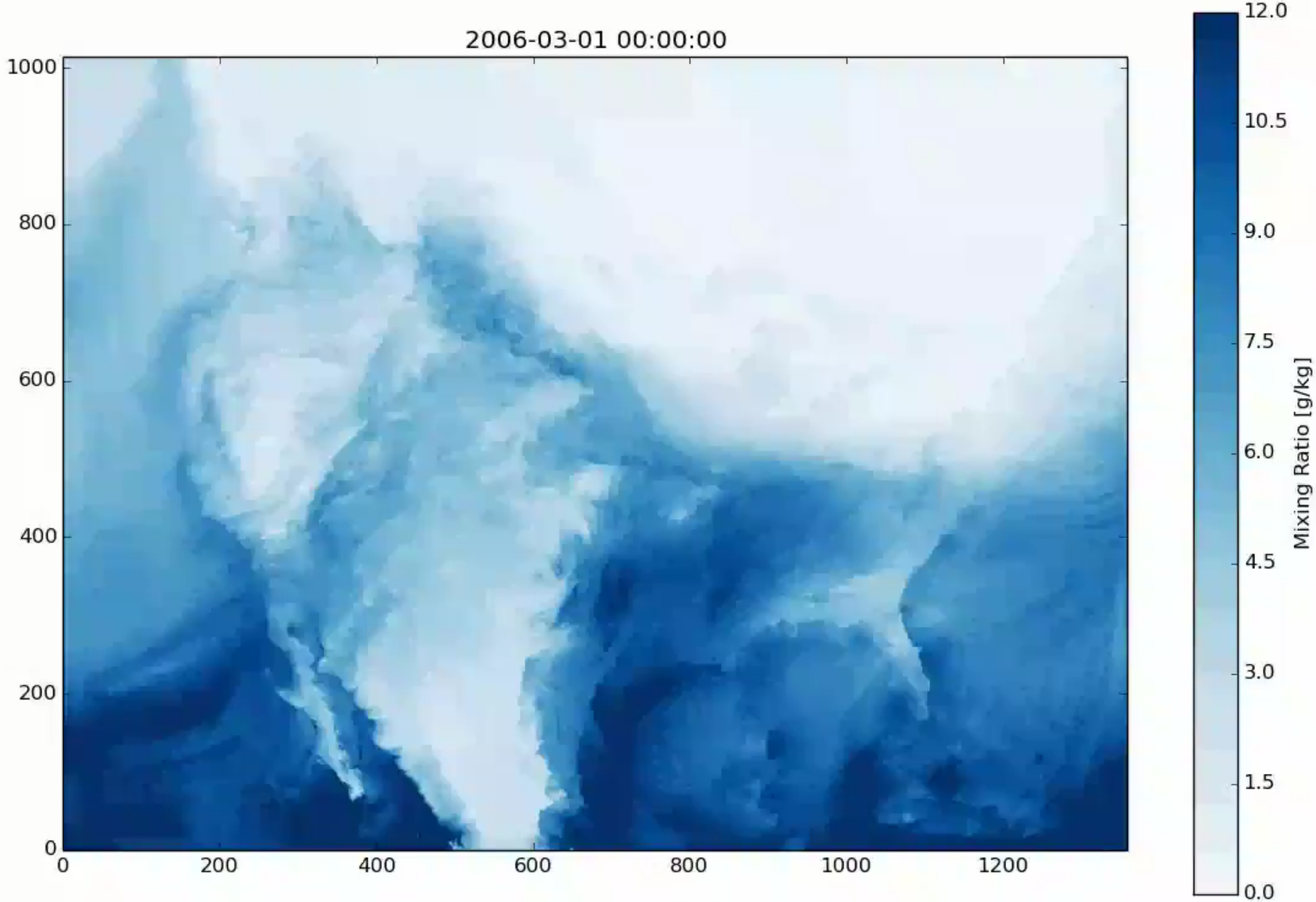
- High-resolution Regional Climate Model



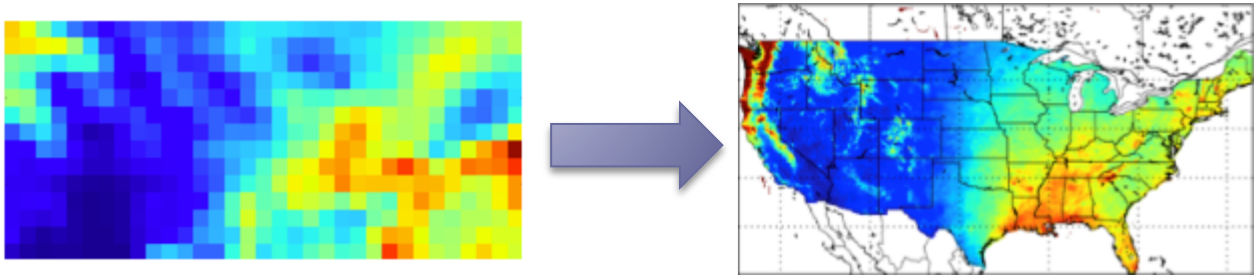


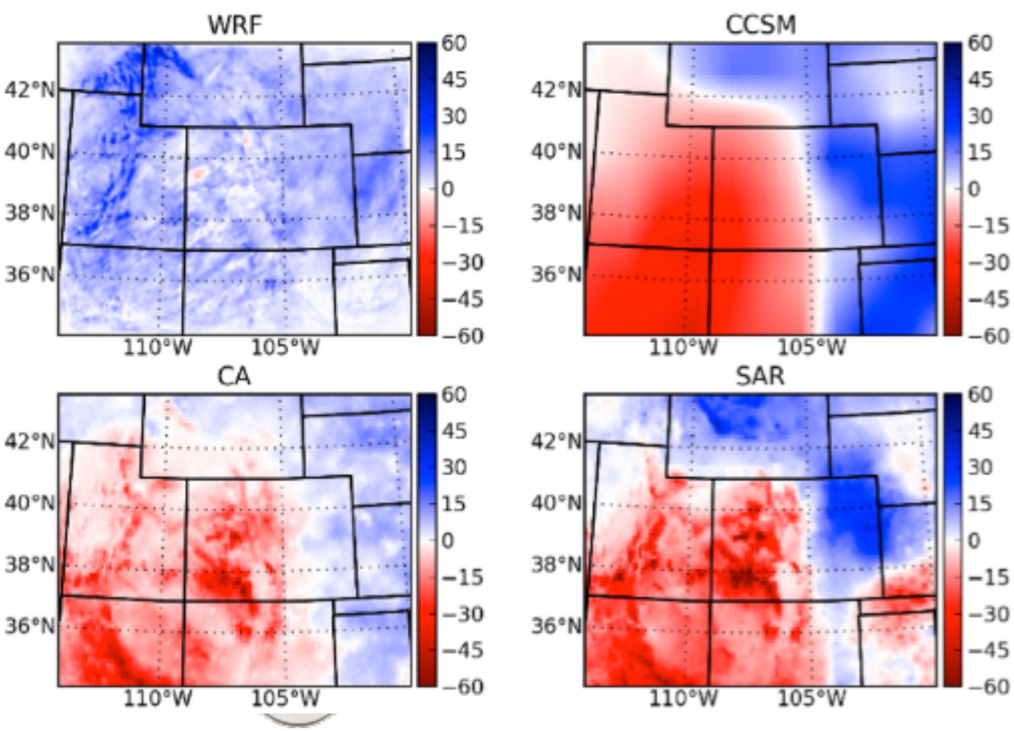
WRF simulations

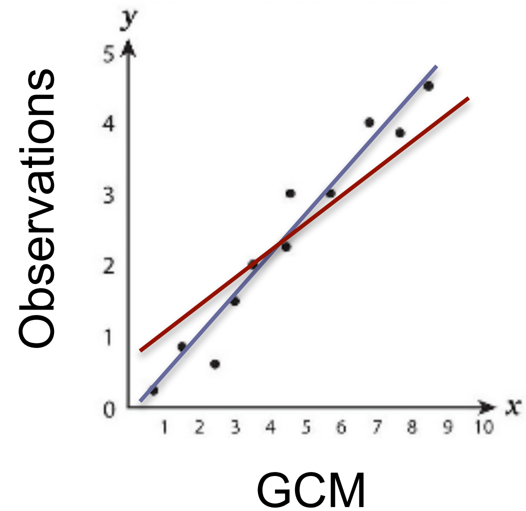
- Water vapor simulation



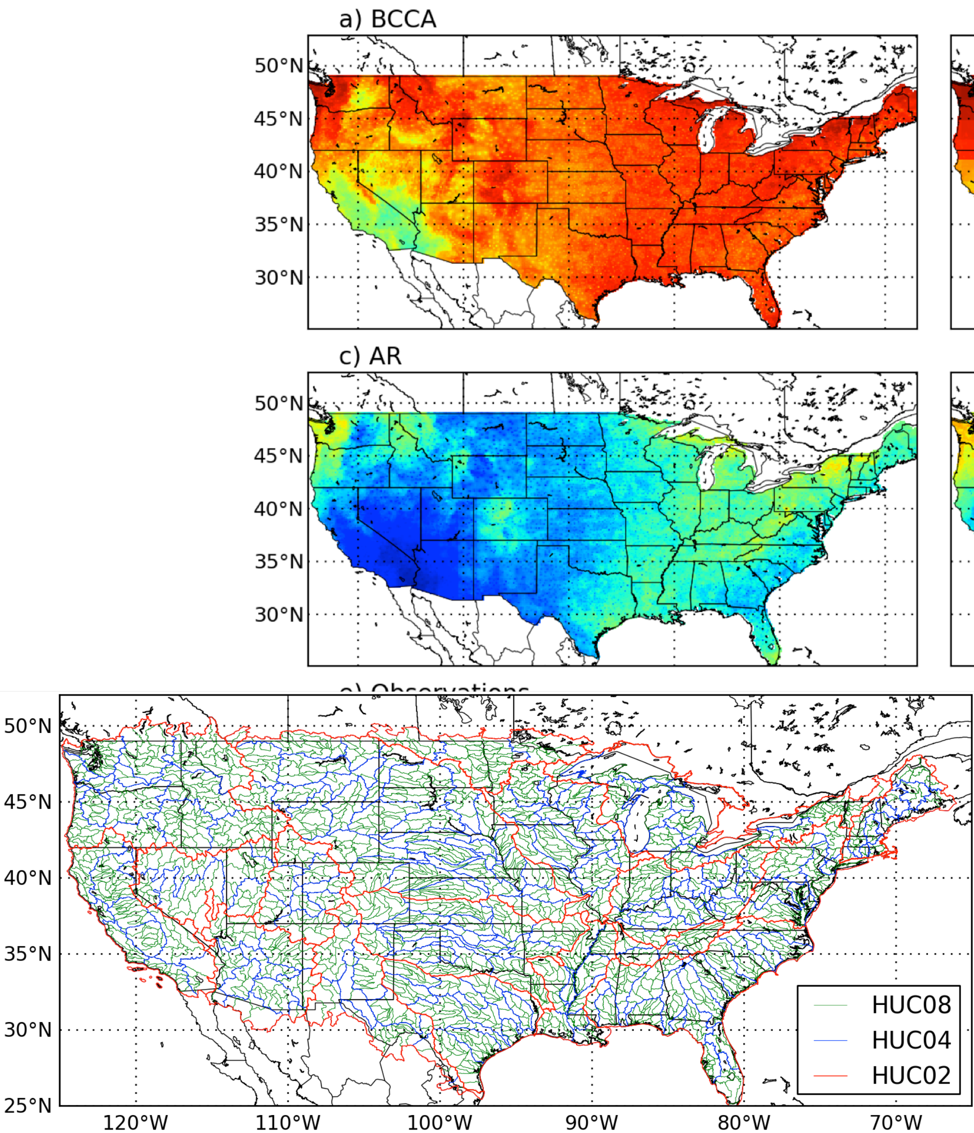
Statistical Downscaling

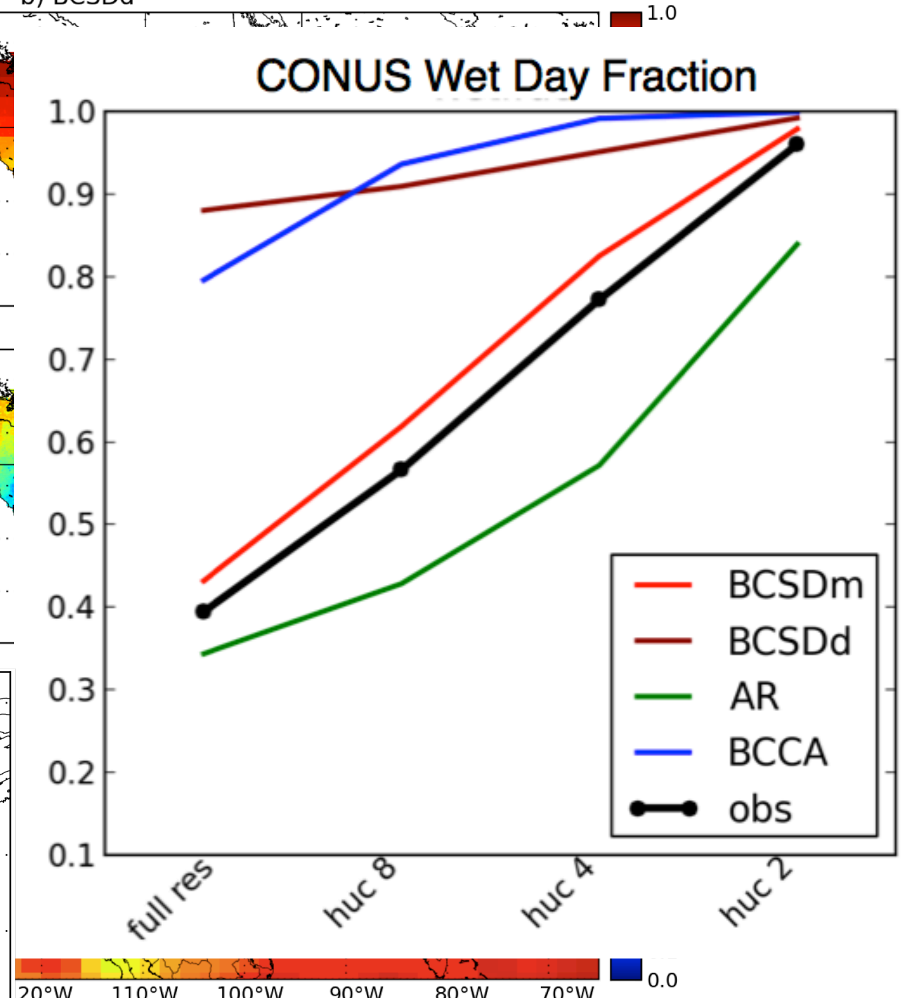






Statistical downscaling: Wet day fraction

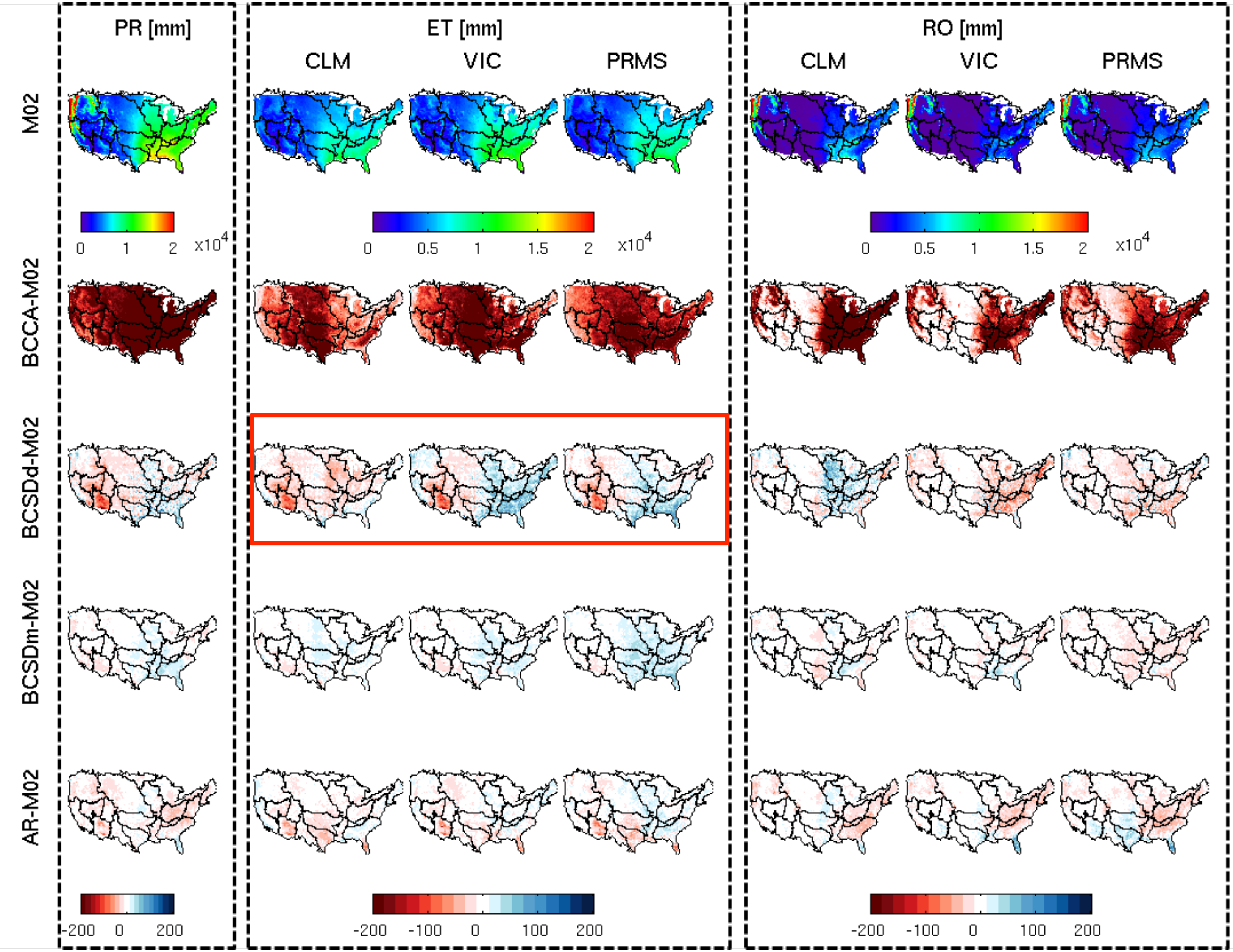




Gutmann et al., WRR 2014

Impact on Annual water balance

Statistical downscaling methods and hydrologic models



Mizukami et al., JHM 2015

Key Findings

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- The choice of GCM and ensemble members matters
- The choice of *meteorological forcings* used in defining current hydroclimate can have as large an impact on projected hydrologic outcomes as the climate change signal.
- The choice of *statistical versus dynamical downscaling* is important, and the resolution used in dynamical downscaling matters.
- The choice of *statistical downscaling technique*, if any, matters
- The choice of *hydrologic model* also affects projection outcomes, though less so if a hydrology model is well calibrated.
- Finally, outcomes depend significantly on subjective decisions made in calibrating hydrologic models
  - the choice of forcing data
  - the choice of calibration scheme and objective

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Climate downscaling advances

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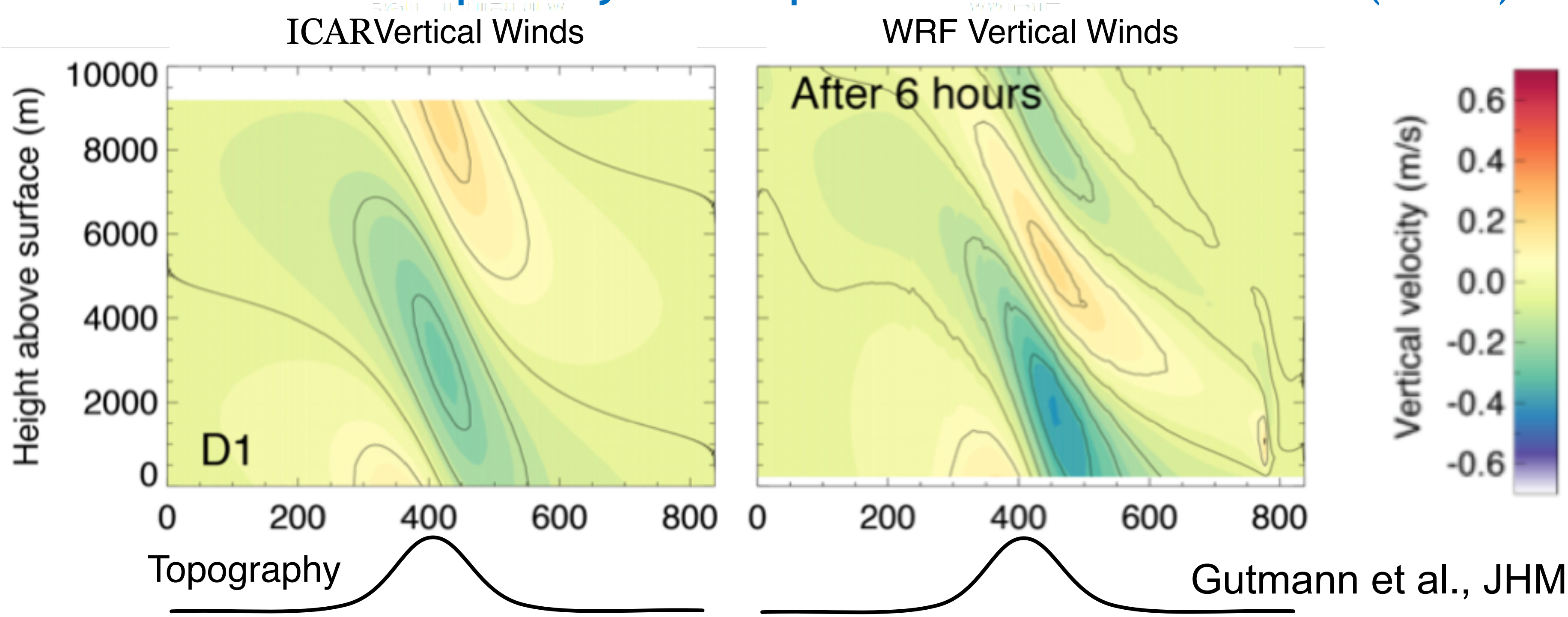
Dichotomous end-members:

- Statistical downscaling is computationally efficient (no physics)
- Dynamical downscaling has loads of physics (too expensive)

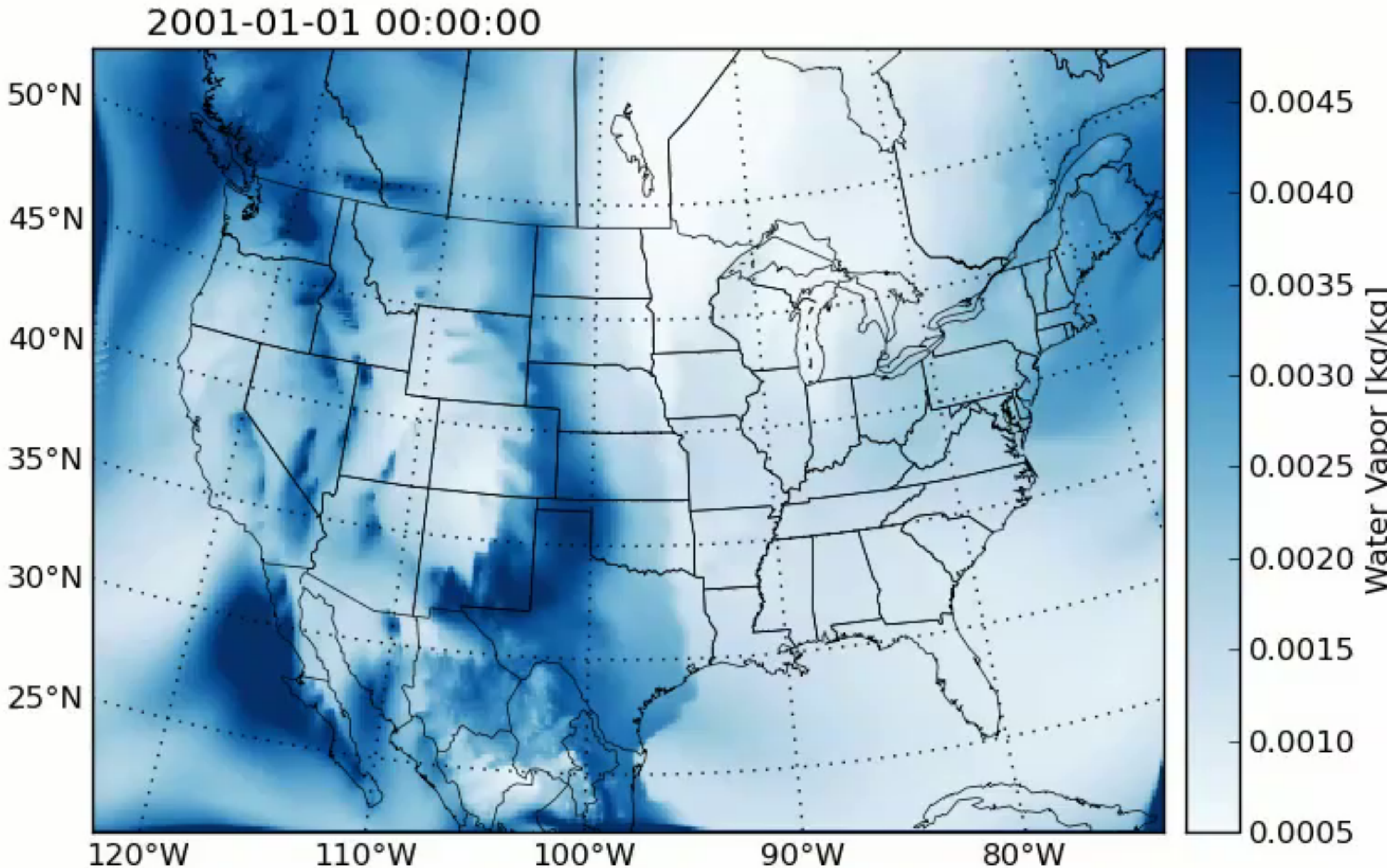
Identify the key physics and develop a simple model
GOAL: >90% of the information for <1% of the cost

Intermediate Complexity Atmospheric Research model (ICAR)

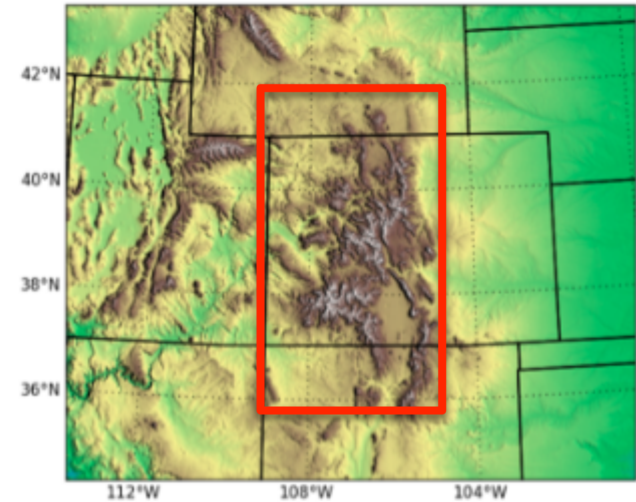


Gutmann et al., JHM

ICAR water vapor simulation



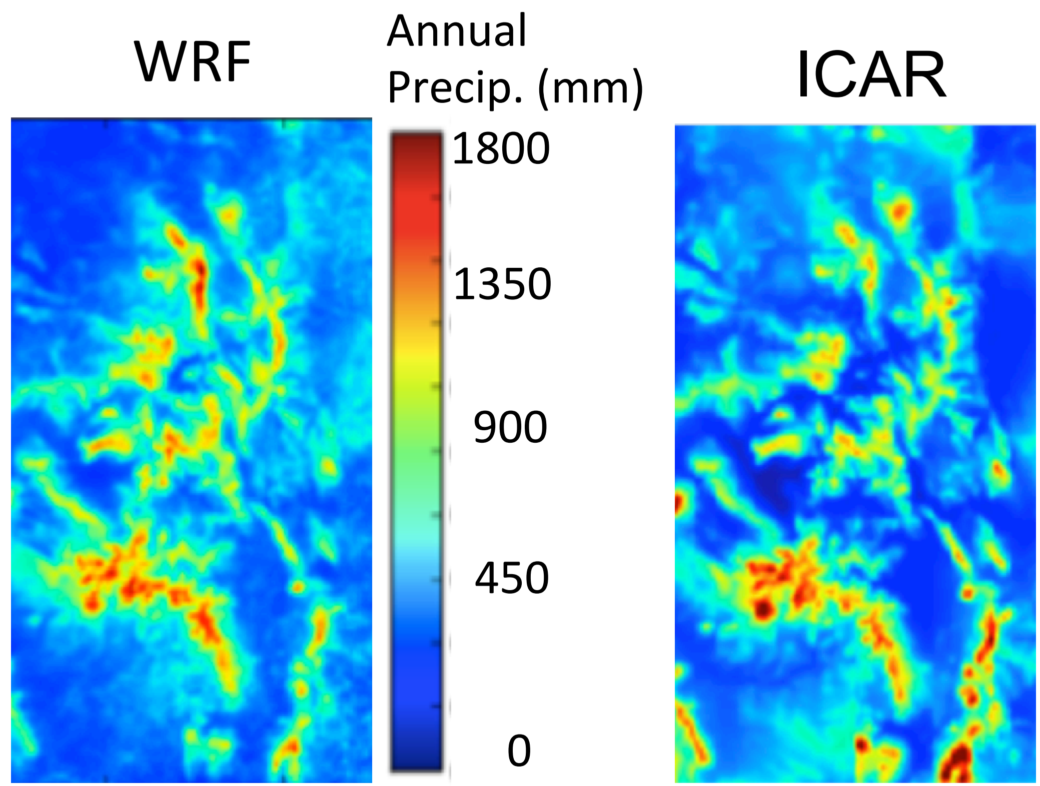
ICAR Precipitation Simulation



WRF and ICAR have very similar precipitation distributions.

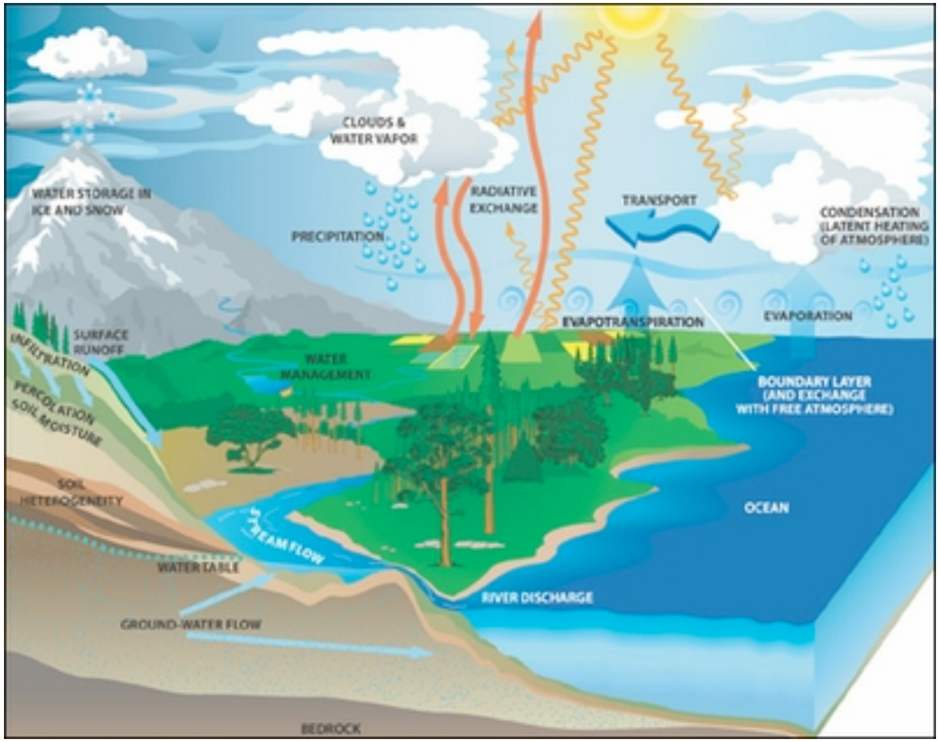
ICAR requires ~1% of the computational effort of WRF.

This enables a pseudo-dynamical downscaling for a wide variety of GCM / scenario combinations



(pre-bias correction)

Unifying process-based hydrologic models



General schematic of the terrestrial water cycle, showing dominant fluxes of water and energy

Conceptual basis:

1. Most modelers share a common understanding of how the dominant fluxes of water and energy affect the time evolution of model states

2. Differences among models relate to
   a) the spatial discretization of the model domain;
   b) the approaches used to parameterize individual fluxes (including model parameter values); and
   c) the methods used to solve the governing model equations.

The Structure for Unifying Multiple Modeling Alternatives (SUMMA):

Defines a single set of conservation equations for land biogeophysics, with the capability to use different spatial discretizations, different flux parameterizations and model parameters, & different time stepping schemes

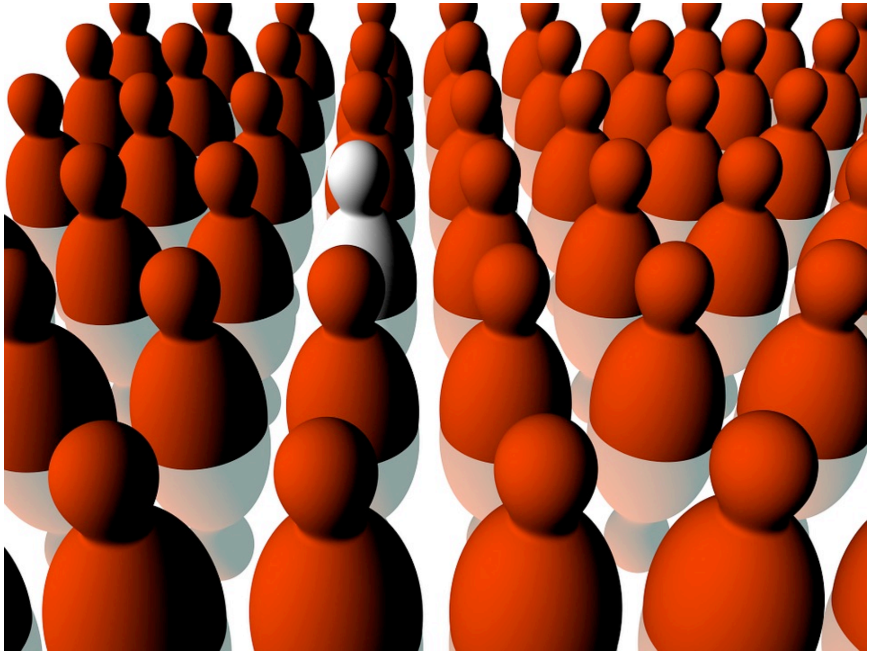
Clark et al. (WRR 2011); Clark et al. (WRR 2015a; 2015b)

Need to unify hydrologic models

- **Model proliferation**: Every hydrologist has their own model, making different decisions at different points in the model development process

- **The shantytown syndrome**: Ad-hoc approach to model development

- Model proliferation & the shantytown syndrome make it difficult to test underlying hypotheses and identify a clear path to model improvement



The Structure for Unifying Multiple Modeling Alternatives (SUMMA)

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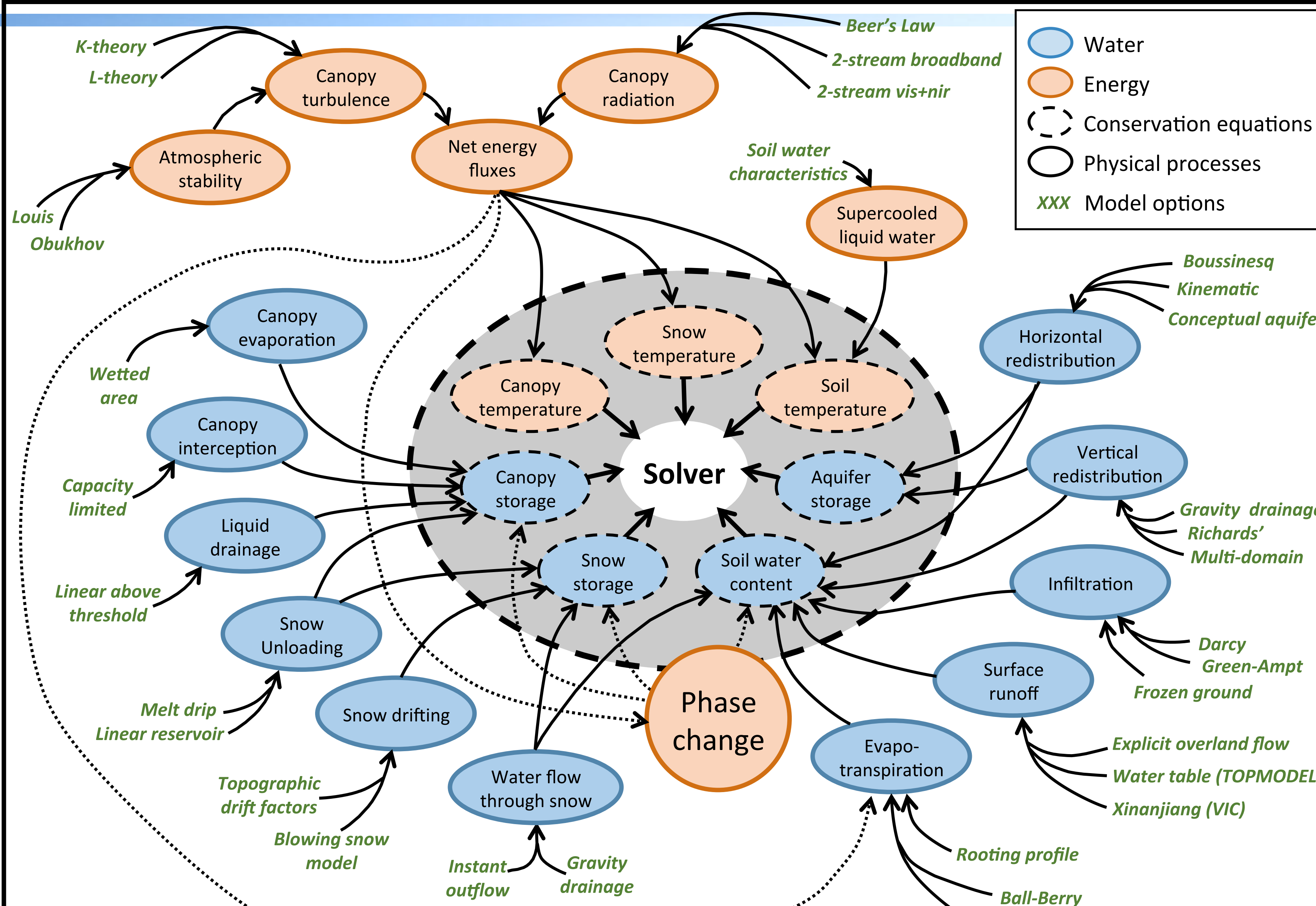
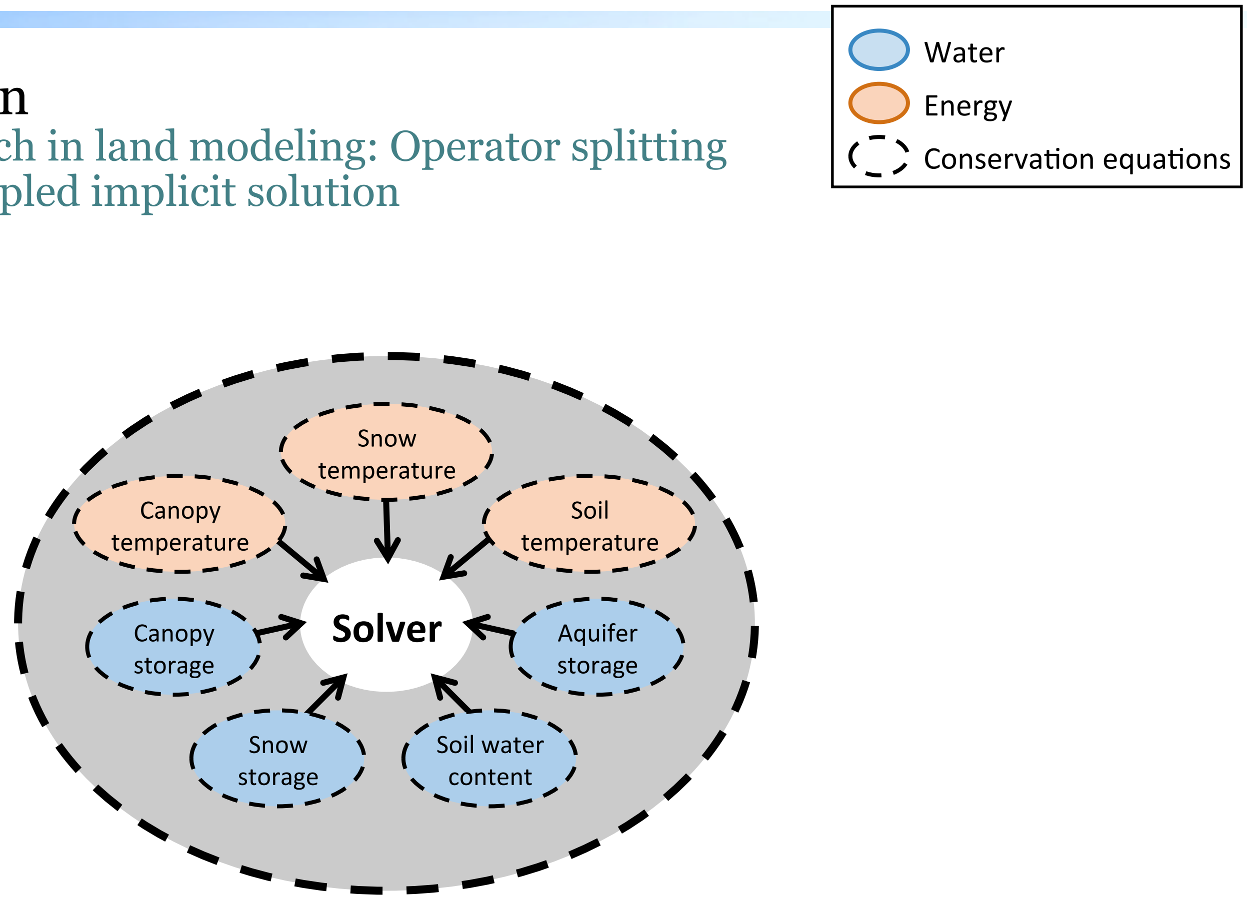


Clark et al. (WRR 2015a)

Model construction

- Numerical solution
  - Traditional approach in land modeling: Operator splitting
  - SUMMA: Fully coupled implicit solution



Model construction

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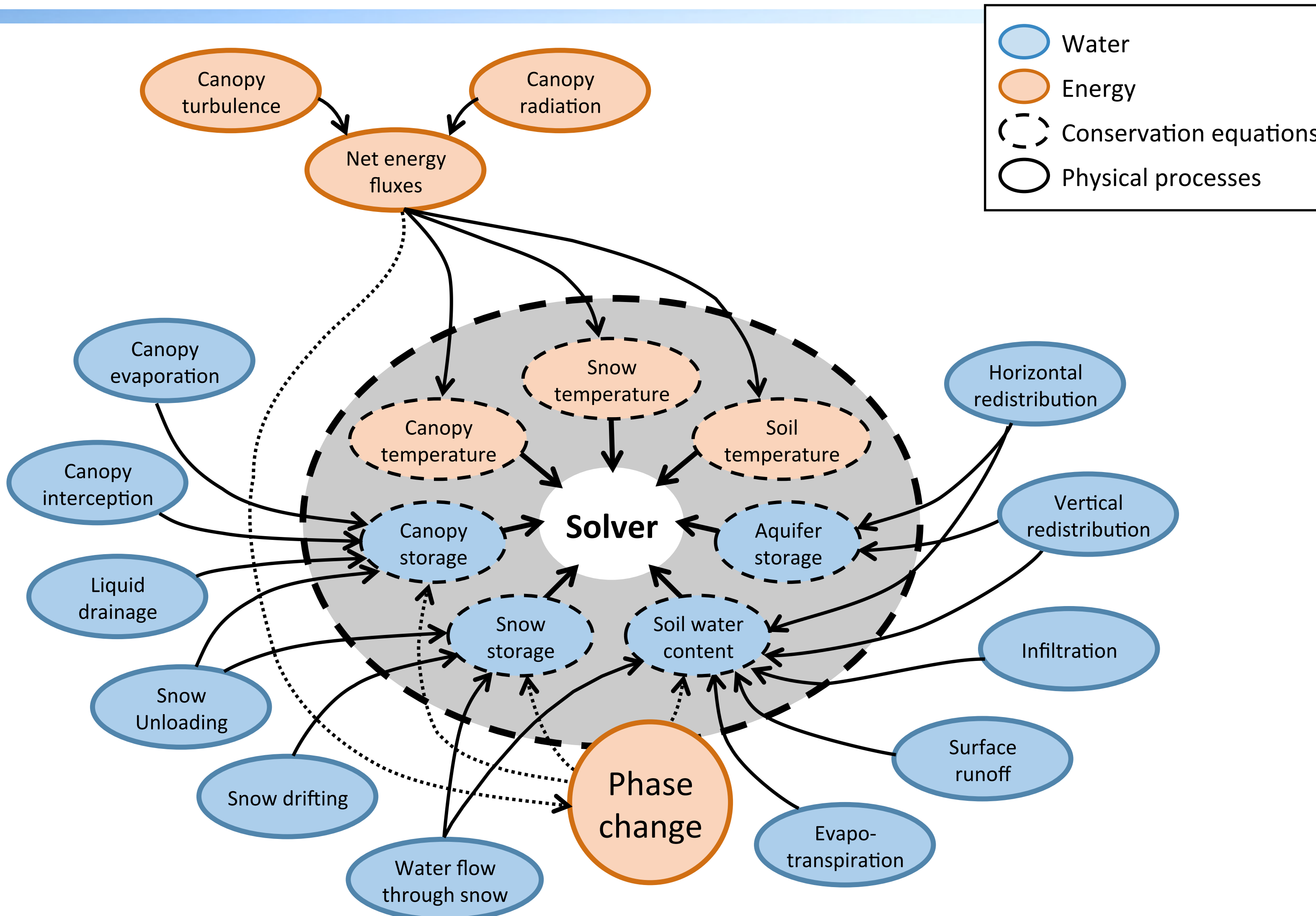
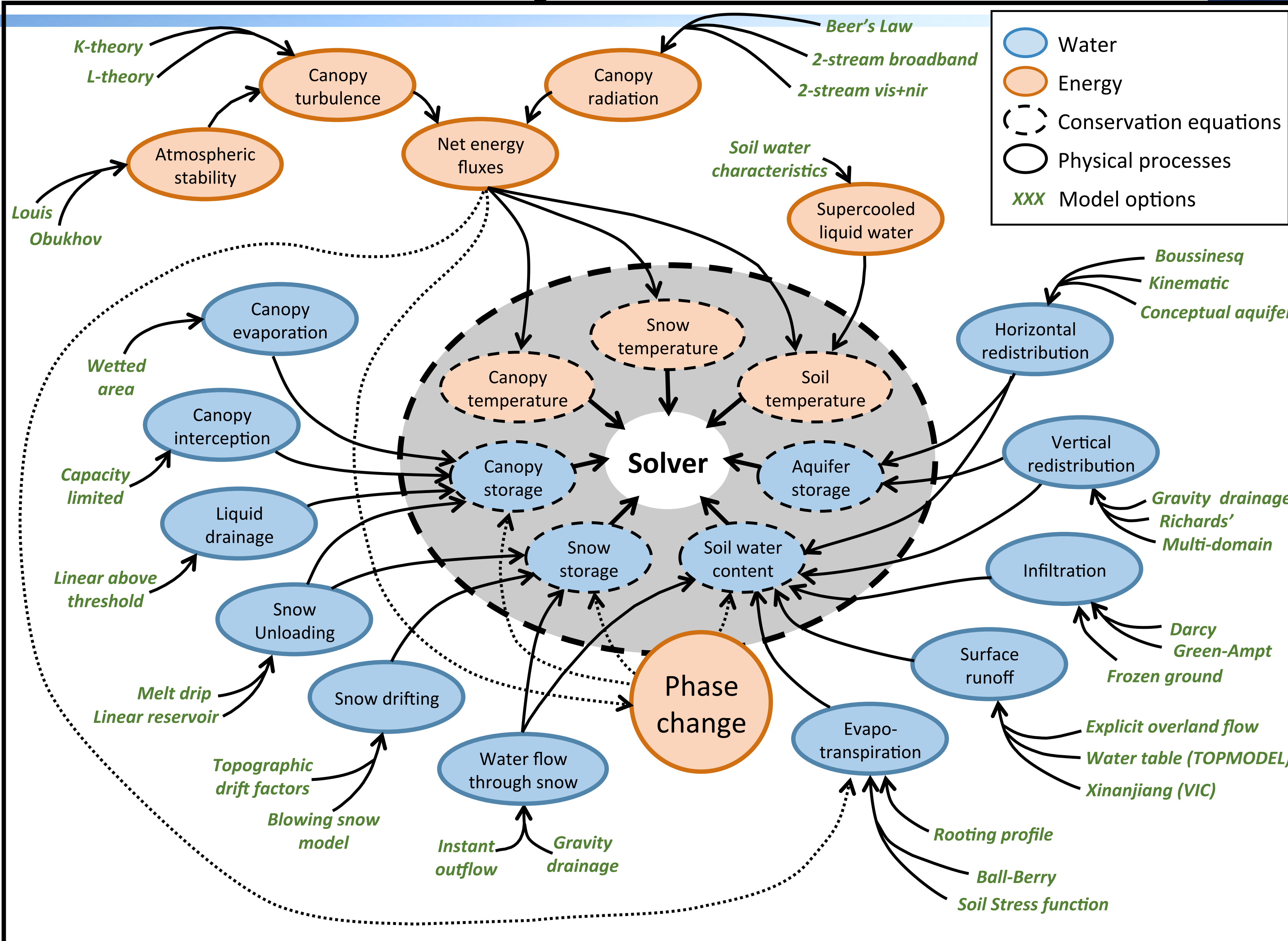
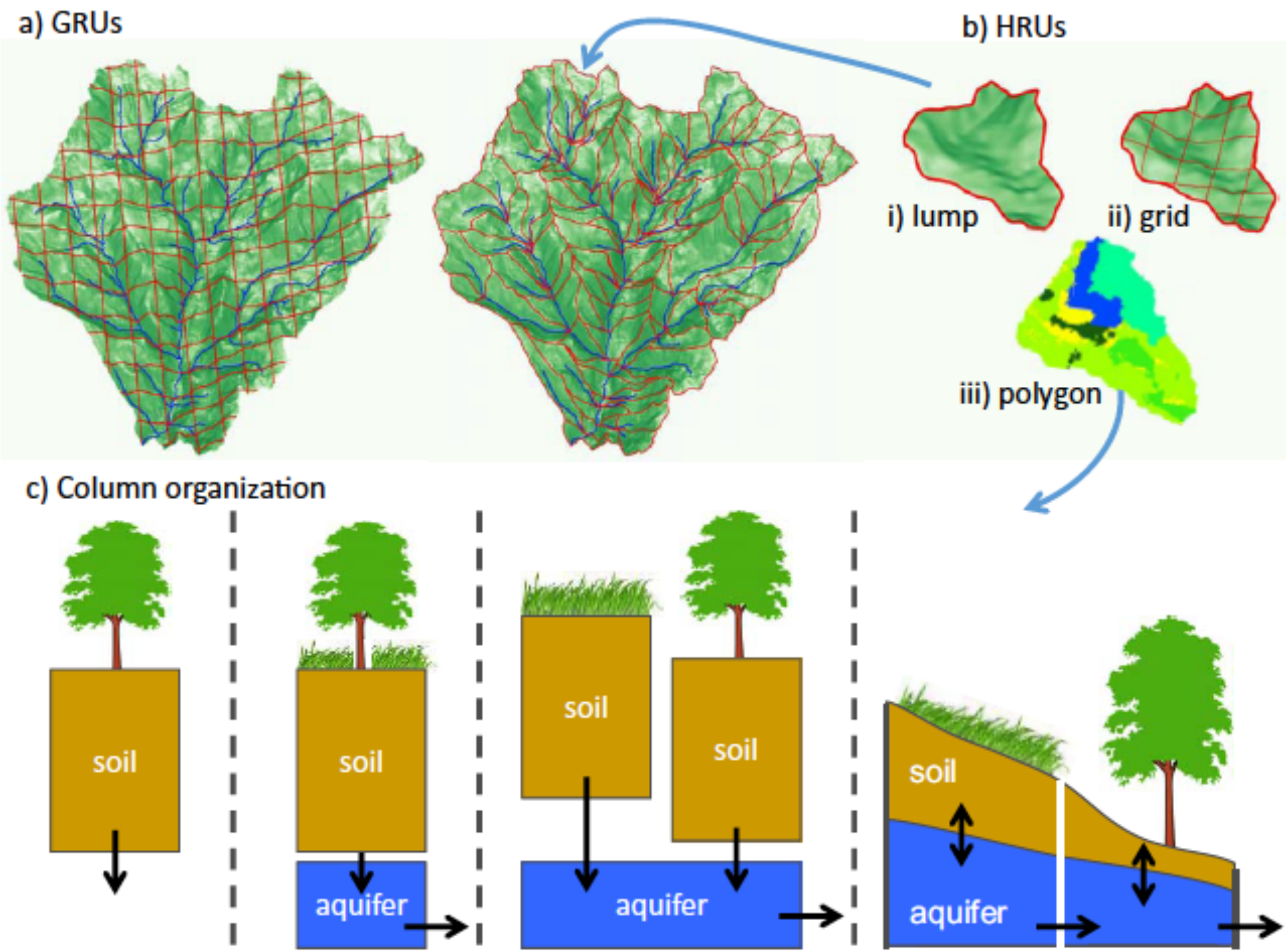


- Modularity
  - Modularity at the level of individual fluxes
  - Separation of physical processes and the numerical solution greatly simplifies adding new modeling options

Process flexibility



Spatial flexibility



Modeling requirements

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- Scientific requirements
  - Process flexibility
  - Spatial flexibility
  - Numerical flexibility
- User requirements
  - Can be configured to meet a broad range of requirements
  - Can be configured to minimize run time, and enable use of ensembles and extensive model analysis
  - Easy to modify
- Existing multiple hypothesis frameworks meet these requirements to varying degrees
  - JULES, CLM, Noah-MP, etc.

Land Information System (LIS)

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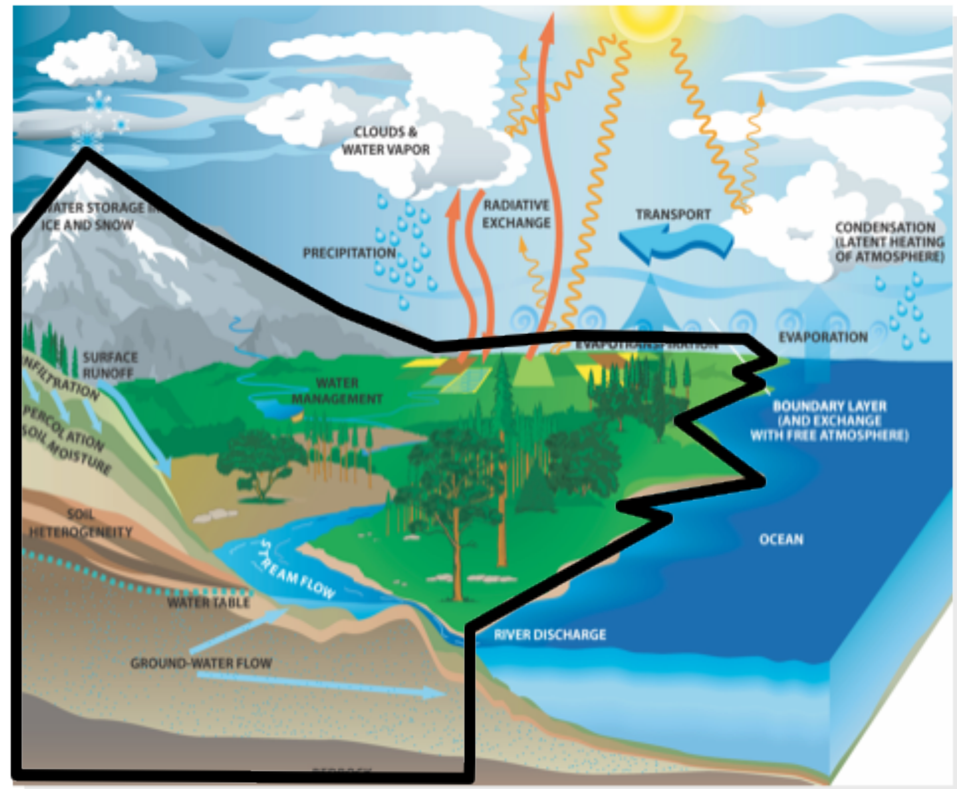
- A system to study land surface processes and land-atmosphere interactions
  - *Integrates satellite- and ground-based observational data products with land surface modeling techniques*
  - *Capable of modeling at different spatial scales*

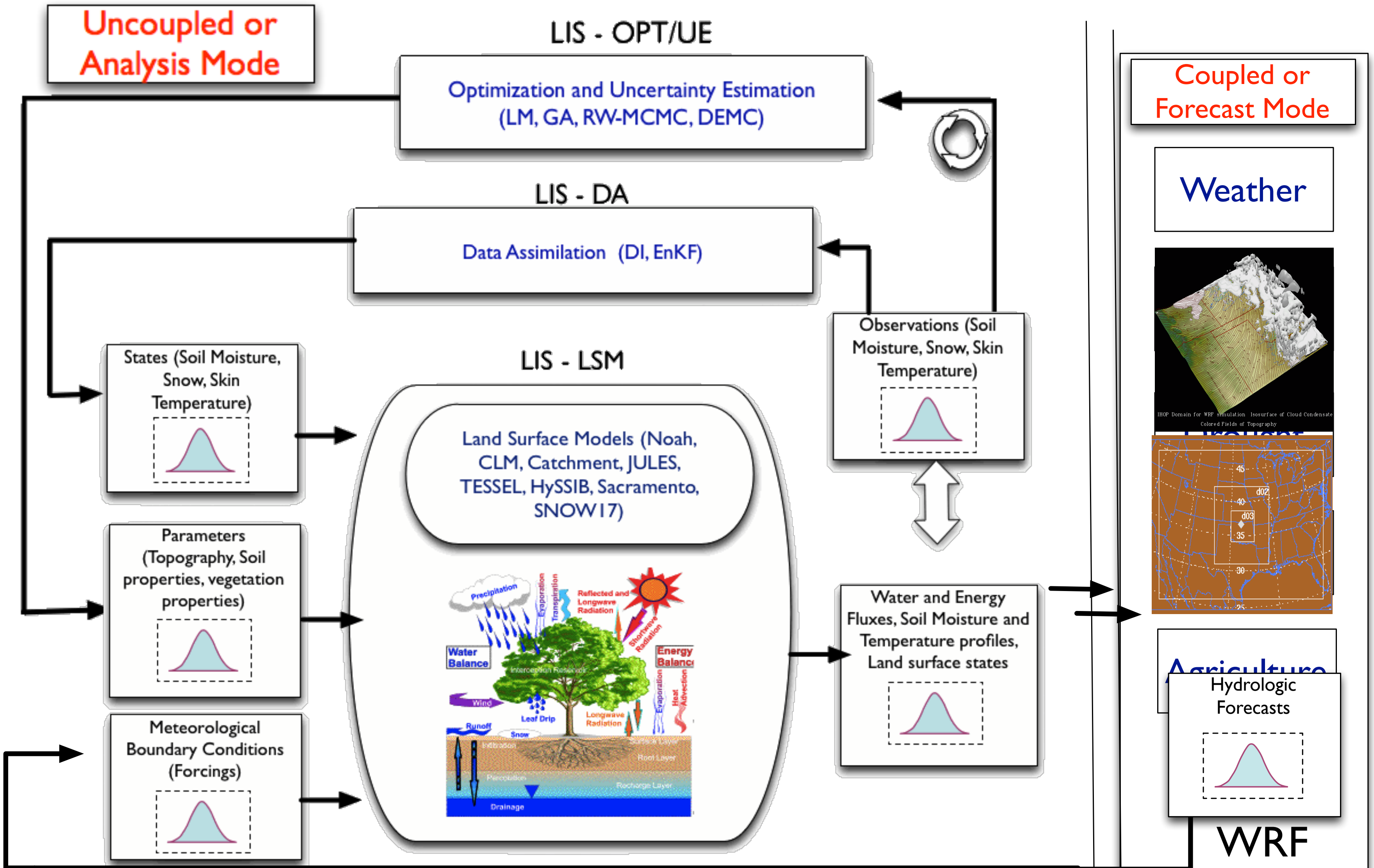


✓ NASA's 2005 software of the year award

✓ An OSSE environment for hydrology mission studies has been developed as part of an AIST-2011 project

http://lis.gsfc.nasa.gov

LIS modes of operation



Kumar et al. (2006), Env. Modeling and Software, Peters-Lidard et al (2007), Innovations in Systems and Software Engineering

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Summary and outlook

- Uncertainties in climate impacts "revealed"
  - Uncertainties have always been there; just understanding them now
  - Possible that previous climate impact studies were over-confident

- Work ongoing to improve representation of uncertainties
  - Climate downscaling
    - Computationally efficient and physically realistic
    - Apply to a wide range of scenarios; better depiction of nonstationarity
  - Hydrologic modeling
    - More thoroughly explore hydrologic modeling alternatives
    - Improve model fidelity; depart from model democracy

- Outlook
  - Explore the "full" space of likely futures
  - Develop "hydrologic storylines" – a representative set of scenarios useful for water resources planning

Explicitly characterize uncertainty through the hydrologic prediction chain

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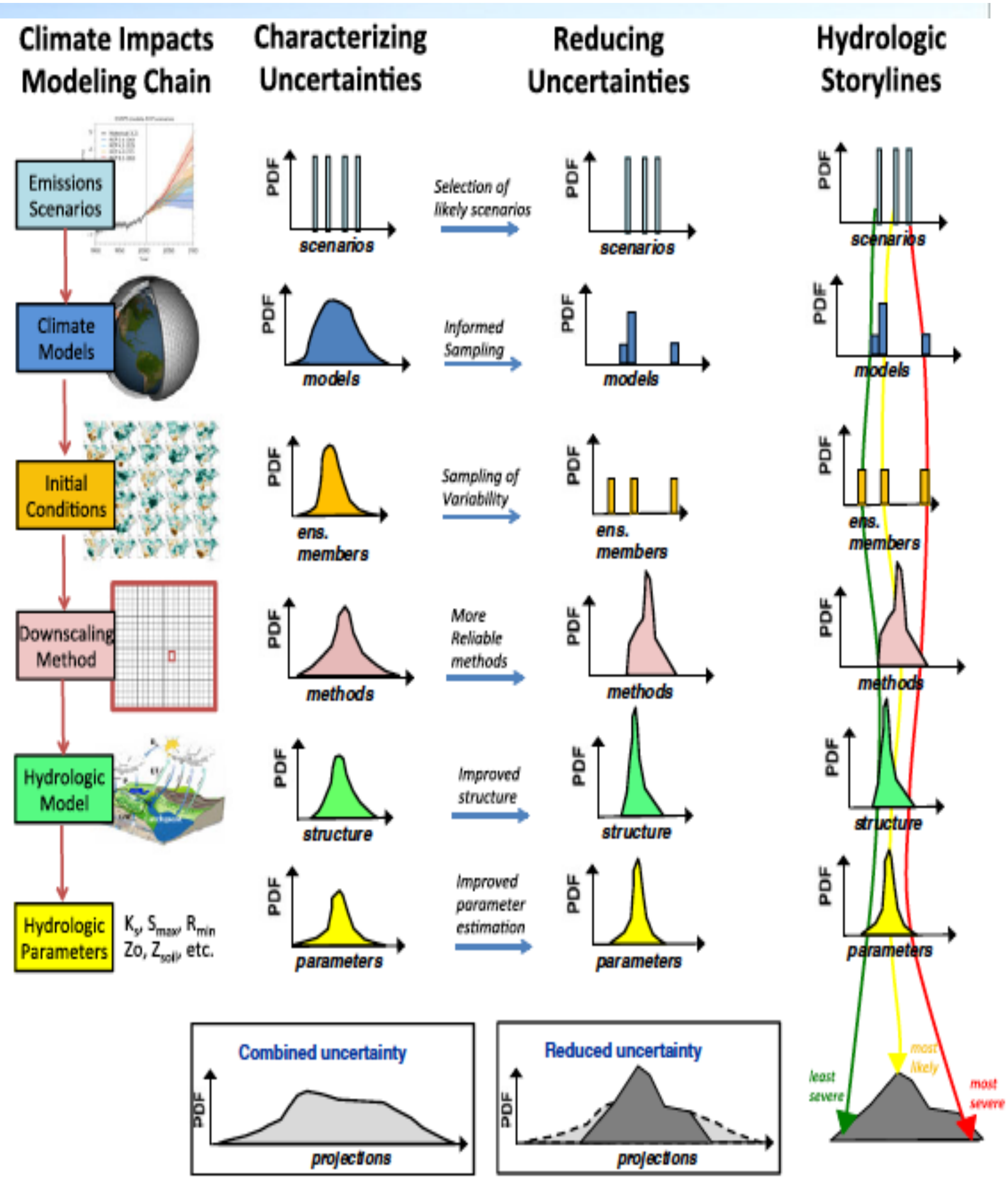
- Approach
  - Characterize uncertainty: "full" coverage of model hypothesis space
  - Reduce uncertainty: cull bad models and methods



Clark et al., WRR 2015; Clark et al., Current Climate Change Reports 2016

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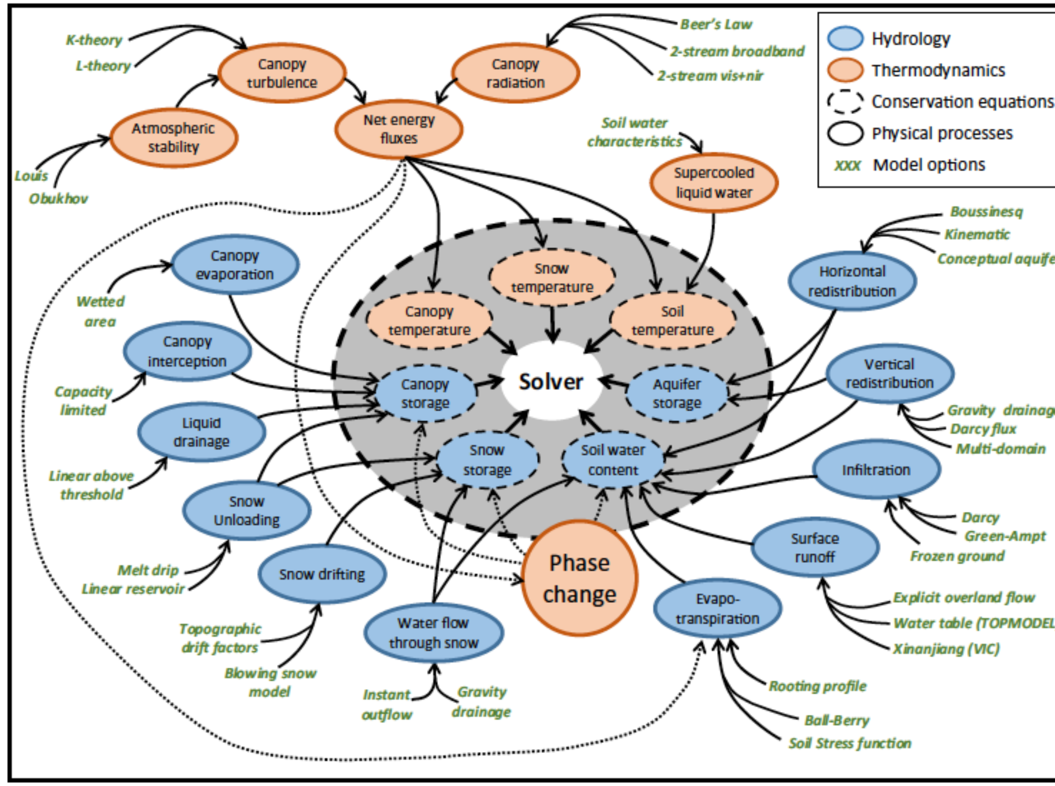

- *Move from "ad-hoc" small ensemble systems, to ensemble systems deliberately designed to encapsulate defensible modeling approaches*

Clark et al., WRR 2015; Clark et al., Current Climate Change Reports 2016

Publications resulting from these efforts

NCAR UCAR

- Clark, M. P., B. Nijssen, J. Lundquist, D. Kavetski, D. E. Rupp, E. Gutmann, A. Wood, L. Brekke, J. R. Arnold, D. Gochis, and R. Rasmussen (2015a), A unified approach to hydrologic modeling: Part 1. Modeling concept, *Water Resources Research, 51, doi:*10.1002/2015WR017198
- Clark, M. P., B. Nijssen, J. Lundquist, D. Kavetski, D. E. Rupp, E. Gutmann, A. Wood, D. Gochis, R. Rasmussen, D. Tarboton, V. Mahat, G. Flerchinger, and D. Marks (2015b), A unified approach to hydrologic modeling: Part 2. Model implementation and case studies, *Water Resources Research, 51, doi:* 10.1002/2015WR017200
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- Gutmann, E., R. M. Rasmussen, C. Liu, K. Ikeda, D. J. Gochis, M. P. Clark, J. Dudhia, and G. Thompson (2012), A comparison of statistical and dynamical downscaling of winter precipitation over complex terrain, *Journal of Climate*, *25*(1), 262-281.
- Gutmann, E., T. Pruitt, M. P. Clark, L. Brekke, J. R. Arnold, D. A. Raff, and R. M. Rasmussen (2014), An intercomparison of statistical downscaling methods used for water resource assessments in the United States, *Water Resources Research*, *50*(9), 7167-7186
- Mendoza, P. A., B. Rajagopalan, M. P. Clark, K. Ikeda, and R. Rasmussen (2014a), Statistical post-processing of High-Resolution Regional Climate Model Output, *Monthly Weather Review*, in press.
- Mendoza, P. A., B. Rajagopalan, M. P. Clark, G. Cortés, and J. McPhee (2014b), A robust multimodel framework for ensemble seasonal hydroclimatic forecasts, *Water Resources Research*, *50*(7), 6030-6052.
- Mendoza, P. A., M. Clark, M. Barlage, B. Rajagopalan, L. Samaniego, G. Abramowitz, and H. Gupta (2014c), Are we unnecessarily constraining the agility of complex process-based models?, *Water Resources Research* doi: 10.1029/2014WR015820.
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Publications resulting from these efforts (cont.)

NCAR UCAR

- Mizukami, N., M. P. Clark, A. G. Slater, L. D. Brekke, M. M. Elsner, J. R. Arnold, and S. Gangopadhyay (2014), Hydrologic implications of different large-scale meteorological model forcing datasets in mountainous regions, *Journal of Hydrometeorology*, *15*(1), 474-488.
- Mizukami, N., M. Clark, E. Gutmann, P. A. Mendoza, A. Newman, B. Nijssen, B. Livneh, J. R. Arnold, L. Brekke, and L. Hay (2015), Implications of the methodological choices for hydrologic portrayals over the Contiguous United States: statistically downscaled forcing data and hydrologic models, *Journal of Hydrometeorology (accepted pending revisions)*
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- Newman, A., M. Clark, K. Sampson, A. Wood, L. Hay, A. Bock, R. Viger, D. Blodgett, L. Brekke, and J. Arnold (2014b), Development of a large-sample watershed-scale hydrometeorological dataset for the contiguous USA: dataset characteristics and assessment of regional variability in hydrologic model performance, *Hydrology and Earth System Sciences Discussions*, *11*(5), 5599-5631.
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- Wood, A., T. Hopson, A. Newman, J. R. Arnold, L. Brekke, and M. Clark (2015), Using a variational ensemble streamflow prediction analysis to understand seasonal hydrologic predictability, *Journal of Hydrometeorology (accepted pending revisions)*