NCAR research activities in support of water resource planning and management
Part 1: Assessing the assessment methods

Andy Wood[1], Martyn Clark[1], Ethan Gutmann[1], Andy Newman[1], Naoki Mizukami[1], Pablo Mendoza[1], Levi Brekke[2], and Jeff Arnold[3]

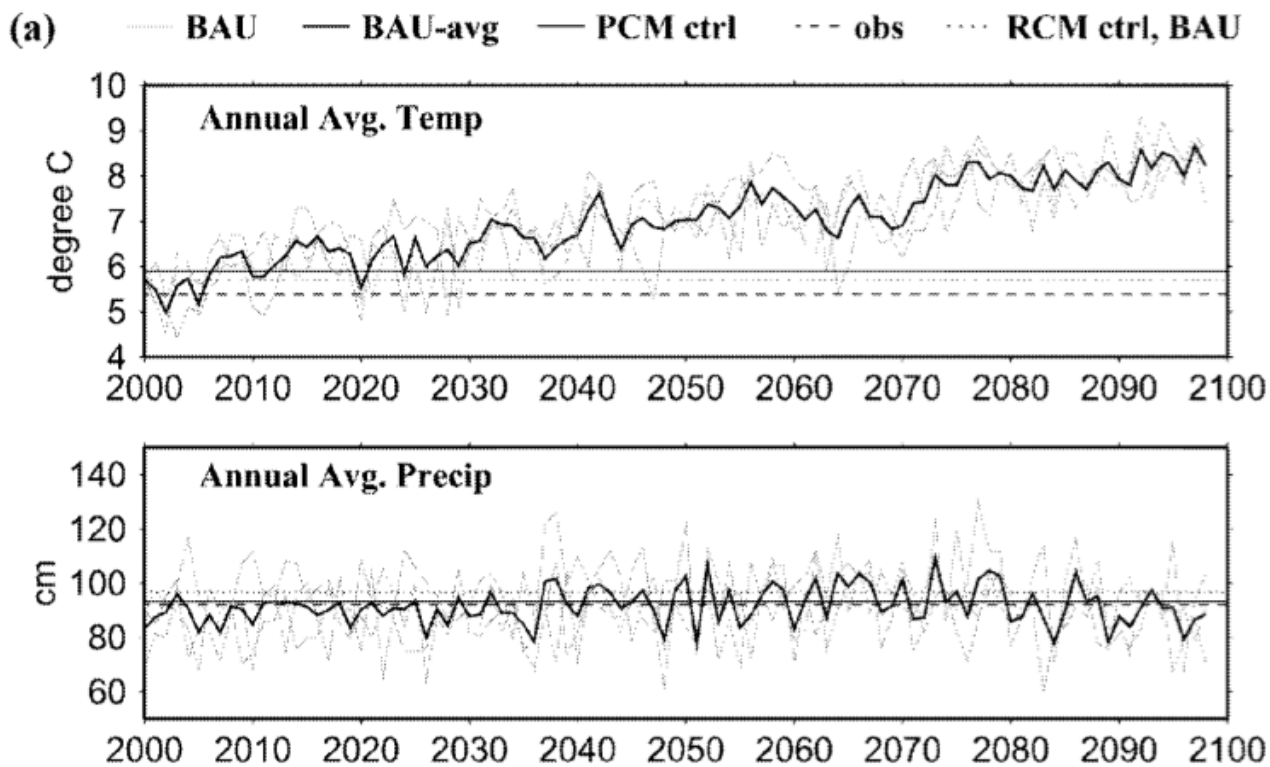
1. NCAR
2. Bureau of Reclamation
3. US Army Corps of Engineers

WWCRA Workshop: Climate Science to Engineering Operations for Watershed Management
Seattle, Washington, 25 August 2015

We've learned much in a decade

10 years ago, a PNW climate change assessment used:

- 1 emissions scenario ('business-as-usual')
- 3 ensemble members
- 2 downscaling methods (BCSD vs MM5)
- 1 hydrology model (VIC, ¼ degree)



Payne et al (2004)

Mitigating the effects of climate change on the water resources of the Columbia river basin

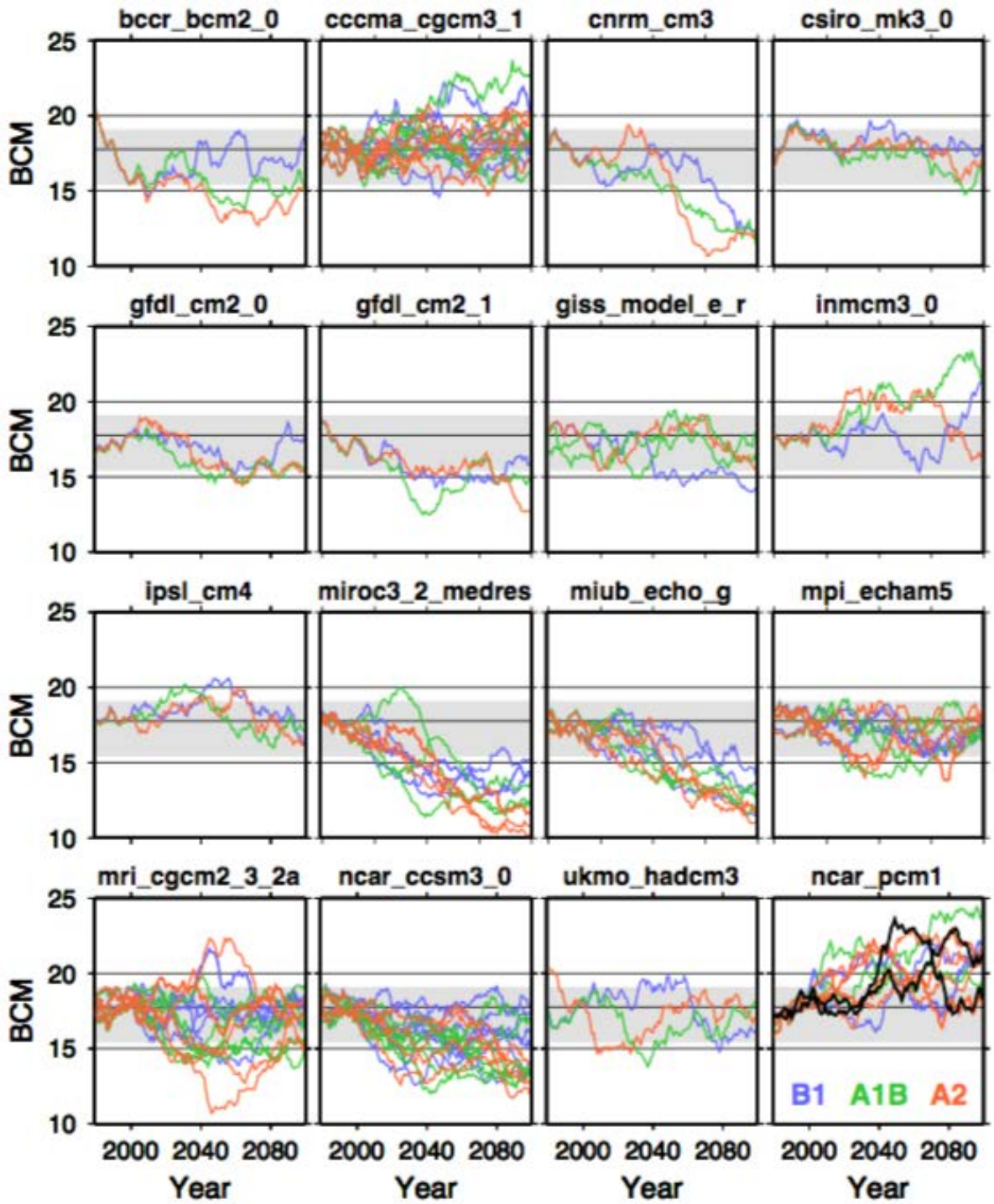
(DOE Accelerated Climate Prediction Initiative)

	Hydropower revenues [a] (%)	Sustainable firm power [a] (%)	Flood damages [b] ($M)	McNary deficits [a] (%)	McNary reliability [c] (%)
Period 1					
Current operations	*95.5*	*93*	1.033	*131*	43.8
15% Reallocation	*95.5*	*94*	1.033	*131*	43.8

Advances

Since then, impact assessment has mainly advanced by:

- using many more GCMs and ensembles (97 proj. in latest LLNL archive)
- larger domains at higher resolutions (CONUS at up to 1 km, global at 1 km)
- proliferation of statistical methods
  (CA>BCCA->LOCA, AR, MACA, SDSM?)
- **getting serious about exploring uncertainties**

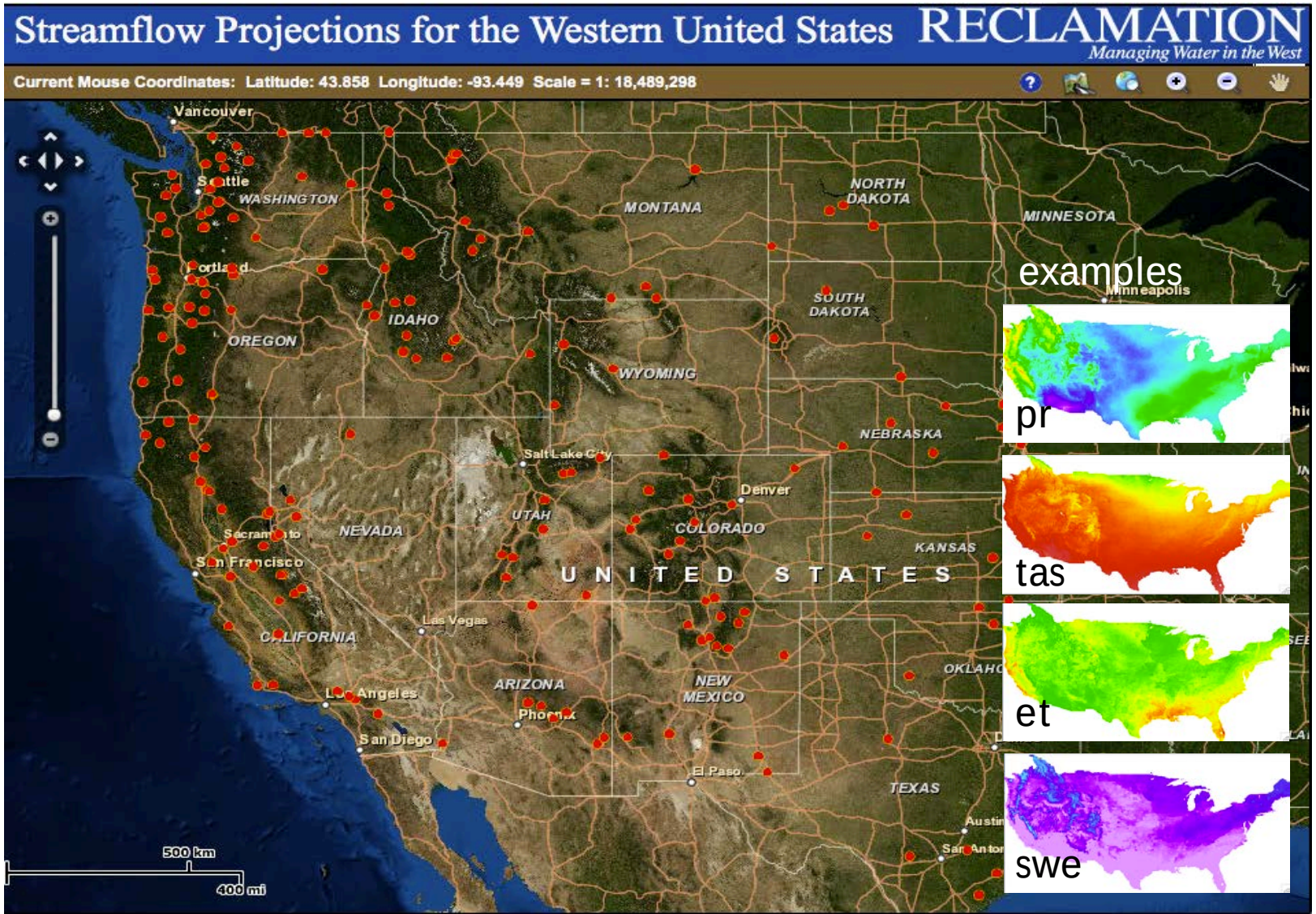


Lees Ferry 30-year mean streamflow projections
Harding et al (2012) HESS

Maintaining baselines: CONUS BCSD5 runs

CMIP5 BCSD VIC Conus Runs

- NCAR generated 97 CMIP5 scenario BCSD-based daily forcings and VIC CONUS hydrology datasets, together with a ~500 routed streamflows



Supports assessing broad-scale CC implications & local scale studies

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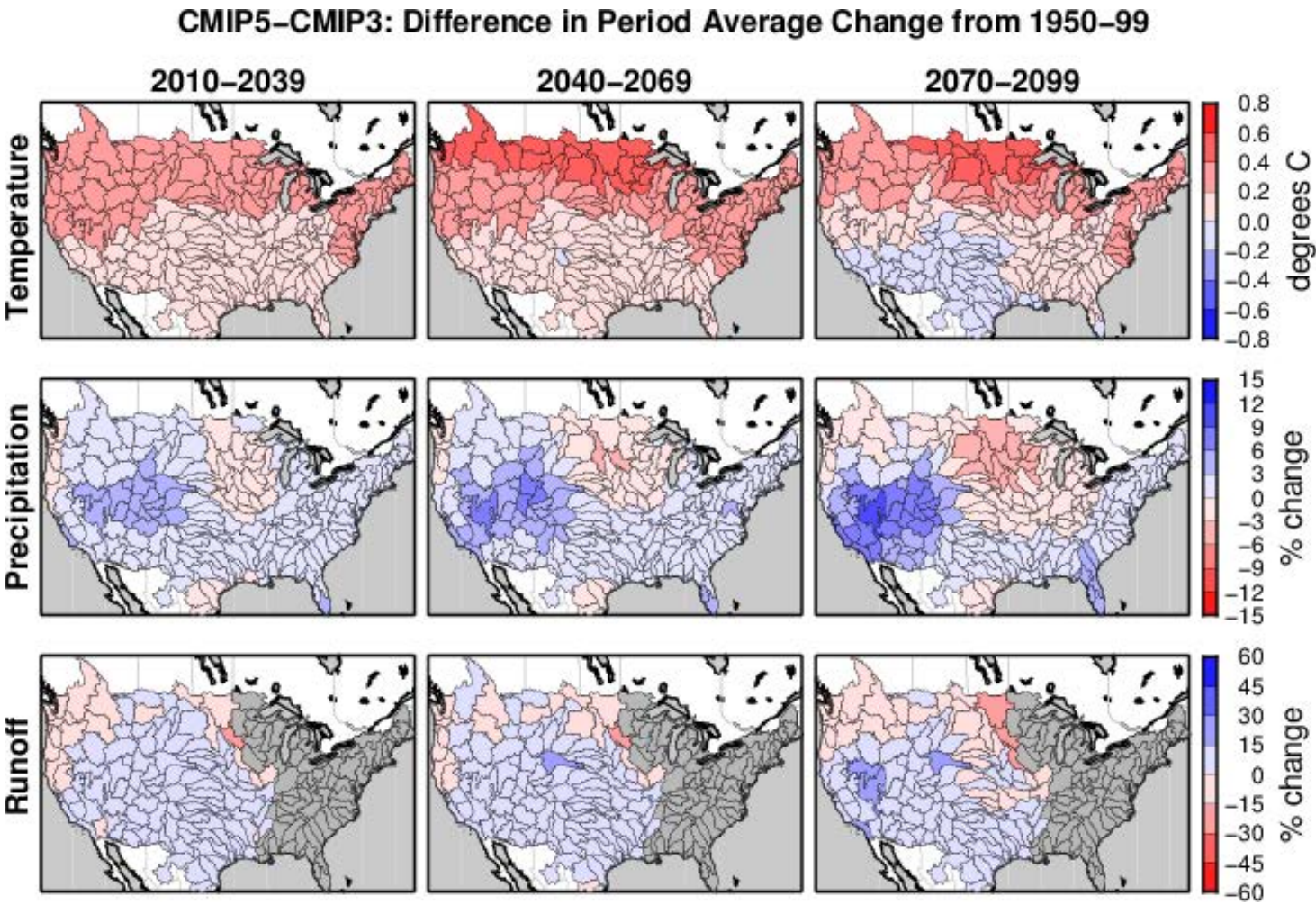
Example: difference in Change in Annual hydroclimate (CMIP5 - CMIP3)

T (ºC, -0.2 to +0.6)

P (%, -6 to +12)

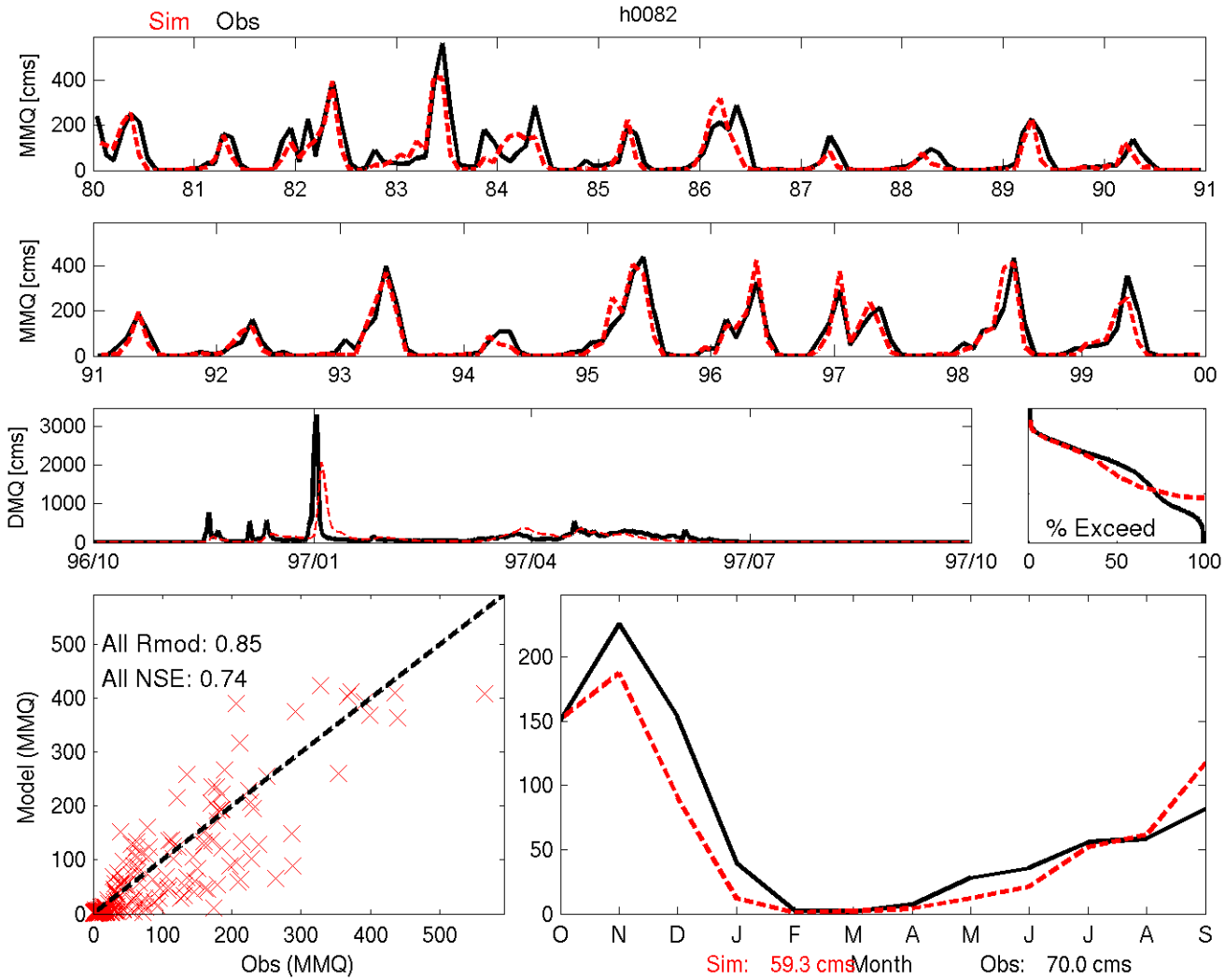
Q (%, -30 to +45)**



Source: Reclamation 2014

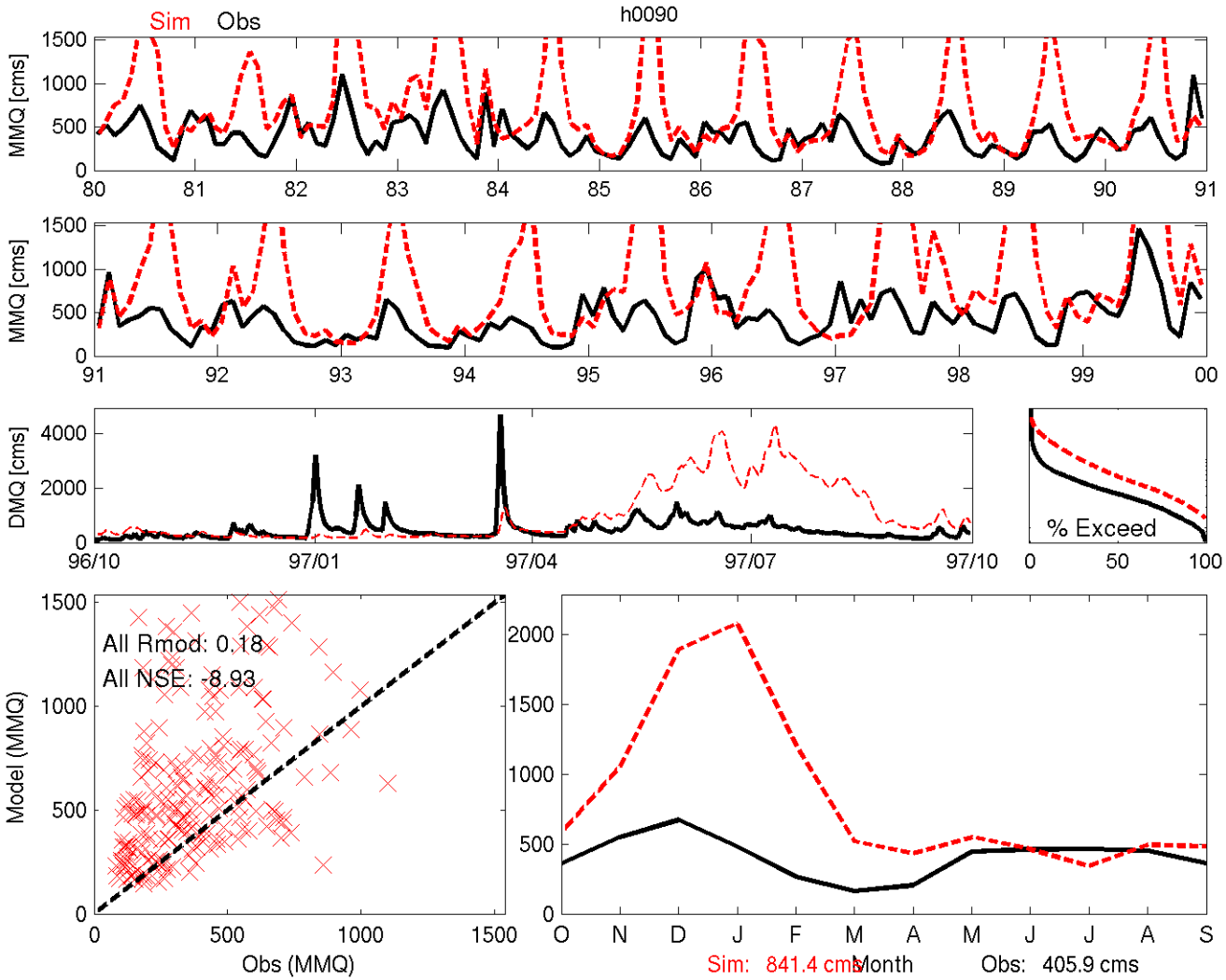
Sample small site calibrations (existing)

Ranged from decent…



Sample small site calibrations (existing)

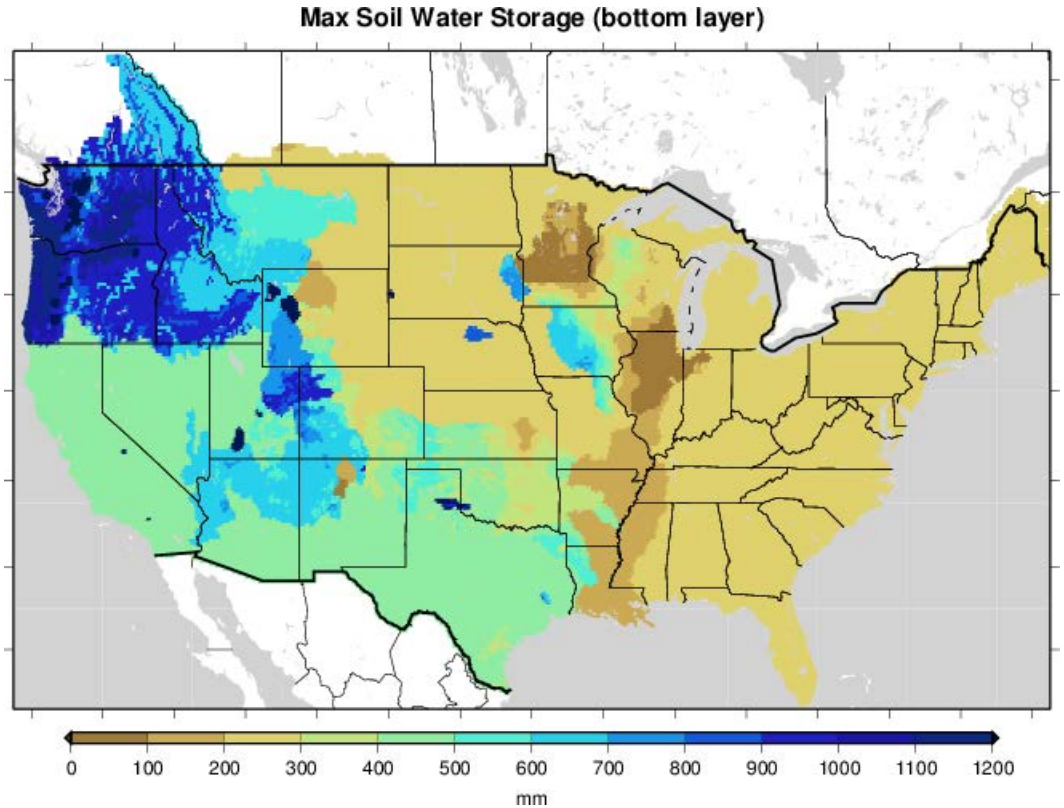
… to poor.



Current parameter estimations in large scale modeling

- A- priori (base) parameter estimations + basin-wide calibrations (i.e. basin-wide multipliers) (e.g., SAC/SNOW17 – NWS River Forecast, VIC- USBR- climate change assessment)

- Issues
  - Discontinuity in spatial distributions of model parameters.
  - Transferability of calibrated parameters to the other basins?
  - Not accounting for sub-grid variability of soil properties.



For example, the nationwide VIC simulations used for water security assessments based on a single model with spatially inconsistent parameter estimates

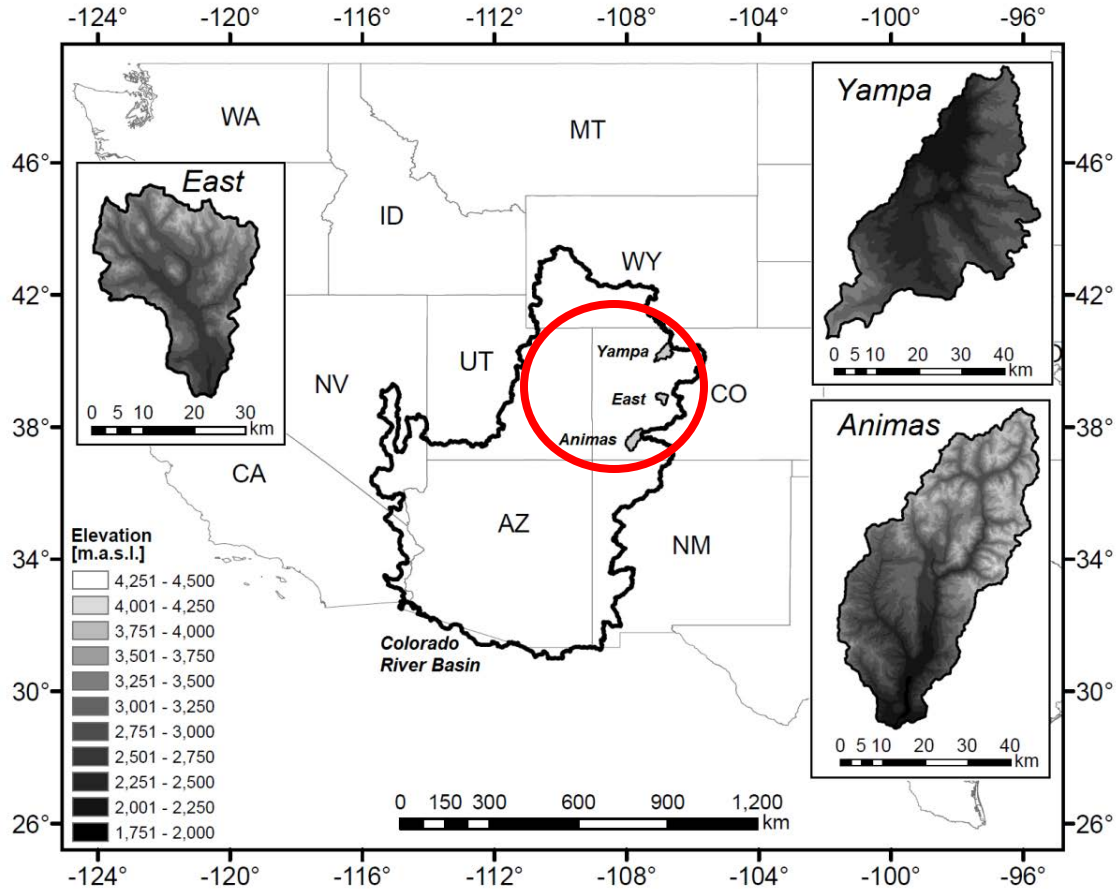
Investigating Uncertainties

- downscaling method
- model choice
- parameter estimation
- input forcings

Exploring parameter effects at the watershed scale

The Colorado Headwaters Region offers a major renewable water supply in the southwestern United States, with approximately 85 % of the streamflow coming from snowmelt. Hence, we conduct this research over three basins located in this area:

- **Yampa at Steamboat Springs**
- **East at Almont**
- **Animas at Durango**



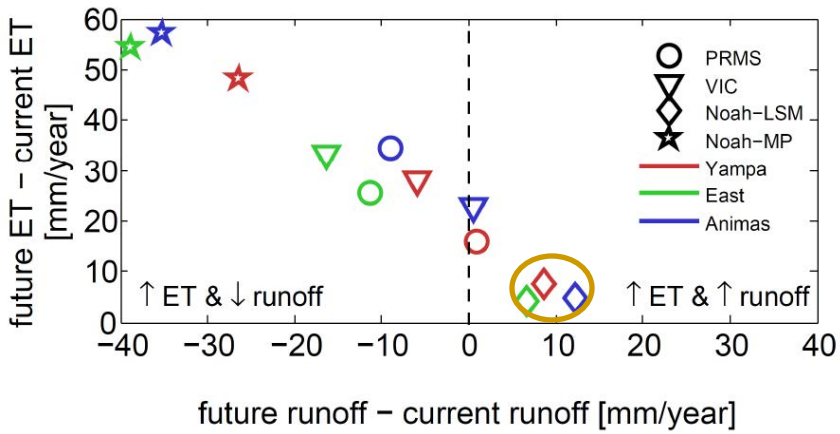
Basins of interest for this study

Mendoza et al., JHM 2015

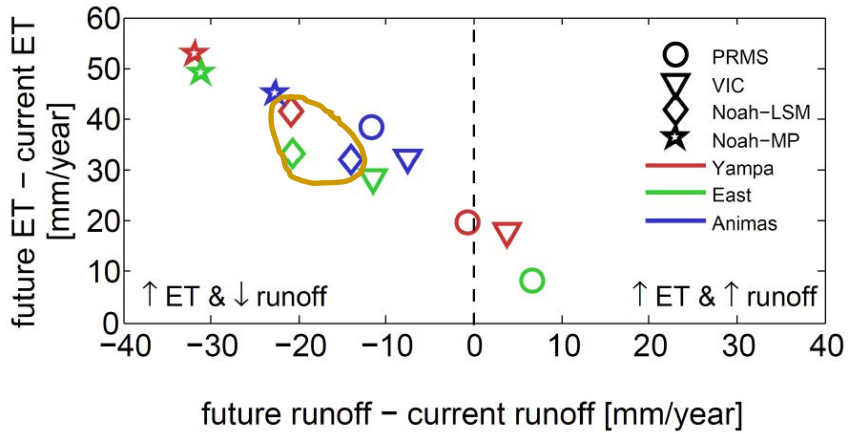
Looking at the hydrologic 'change signals'

Role of hydrologic model choice and calibration?

Uncalibrated model simulations



Calibrated model simulations



- Uncalibrated models: Hydrologic change signal in Noah (↑ET and ↑Runoff) differs from the rest of models (↑ET and ↓Runoff).
- After calibration, signal direction from Noah-LSM switches to ↑ET and ↓Runoff.
- Inter-model agreement does not necessarily improve in terms of magnitude and direction.

Mendoza et al., JHM 2015

Climate downscaling uncertainty

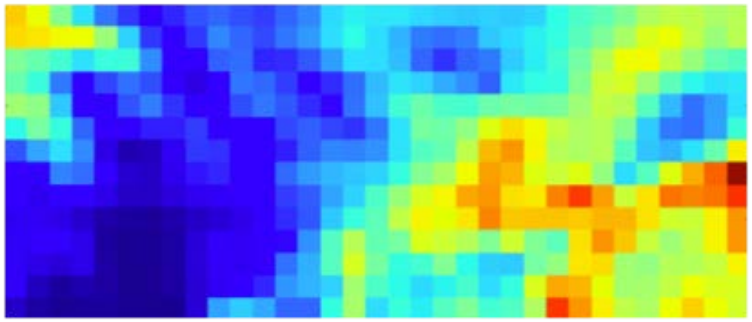
Choice of statistical downscaling methods

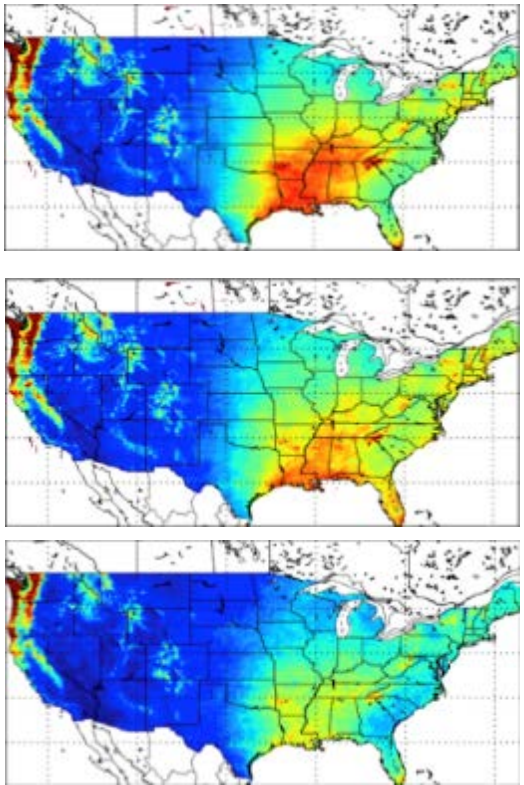
- Widely used and newer methods
  - BCSD-monthly Wood et al (2004)
  - BCSD-daily Thrasher et al (2012)
  - BCCA Hidalgo et al (2008)
  - Asynchronous Regression Stoner et al (2013)

- All simply rescale or shift GCM outputs

Test Downscaling

NCEP/NCAR Reanalysis





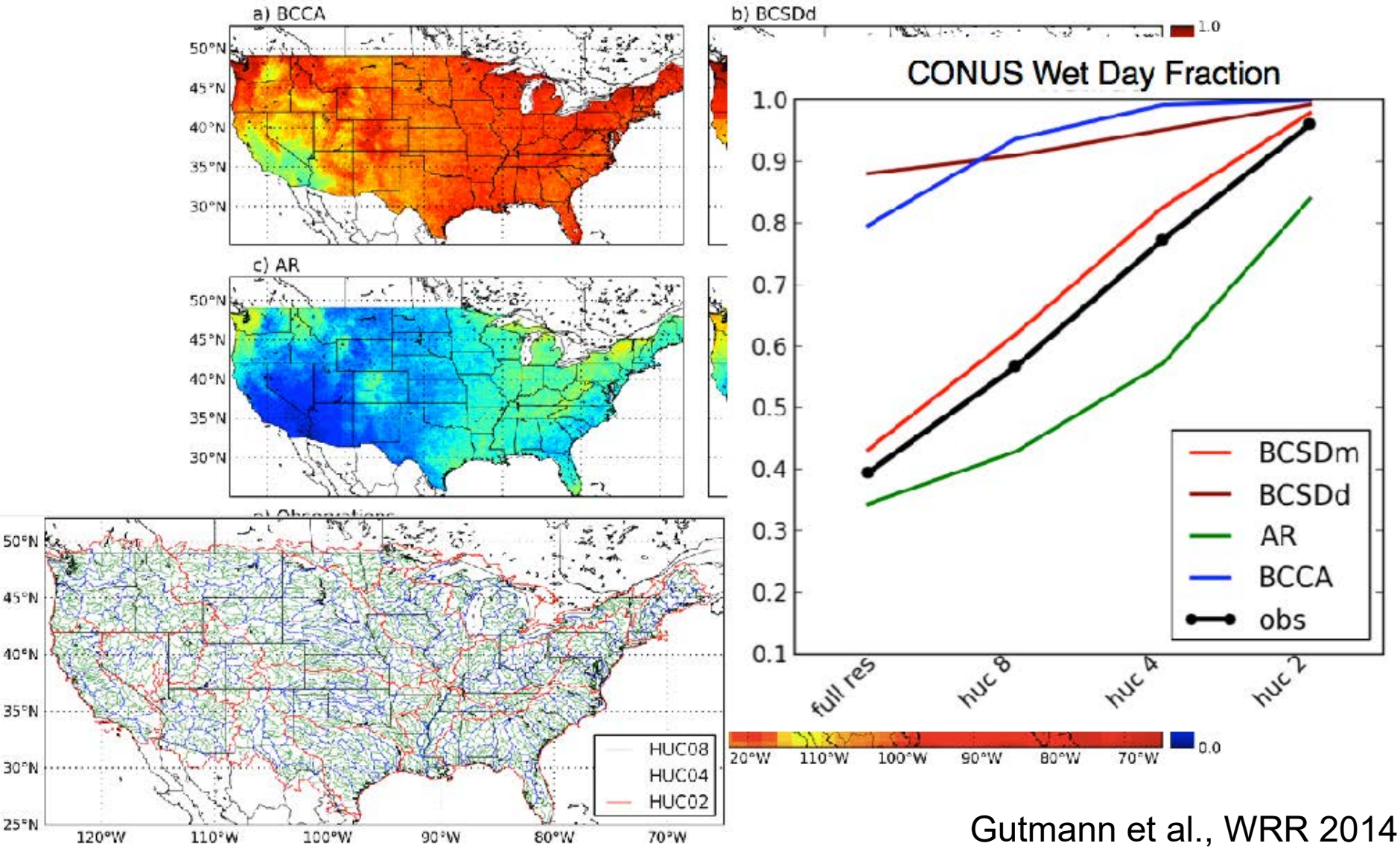
AR

BCSD

BCCA

Gutmann et al., WRR 2014

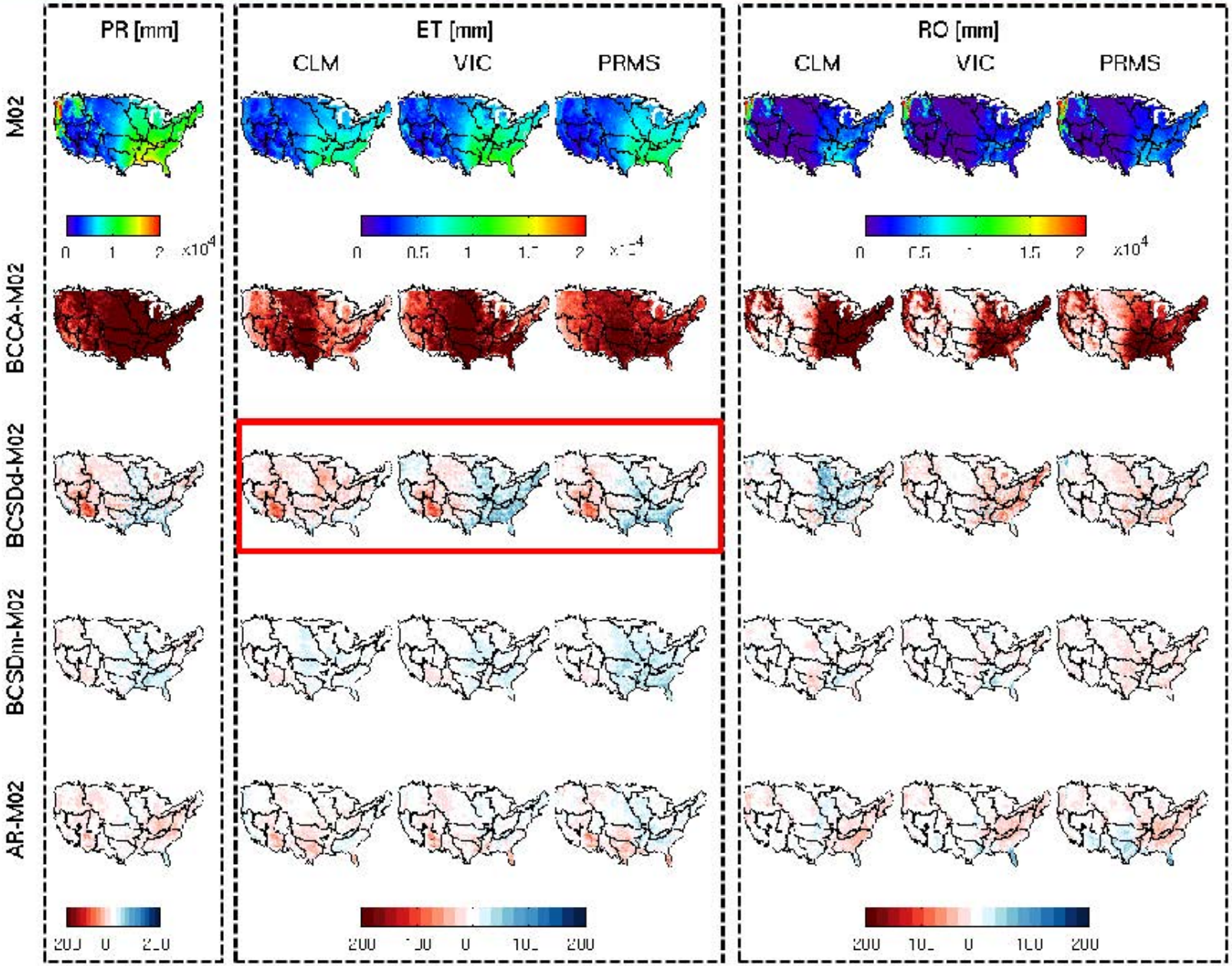
Statistical downscaling: Wet day fraction



Gutmann et al., WRR 2014

Impact on Annual water balance

Statistical downscaling methods and hydrologic models

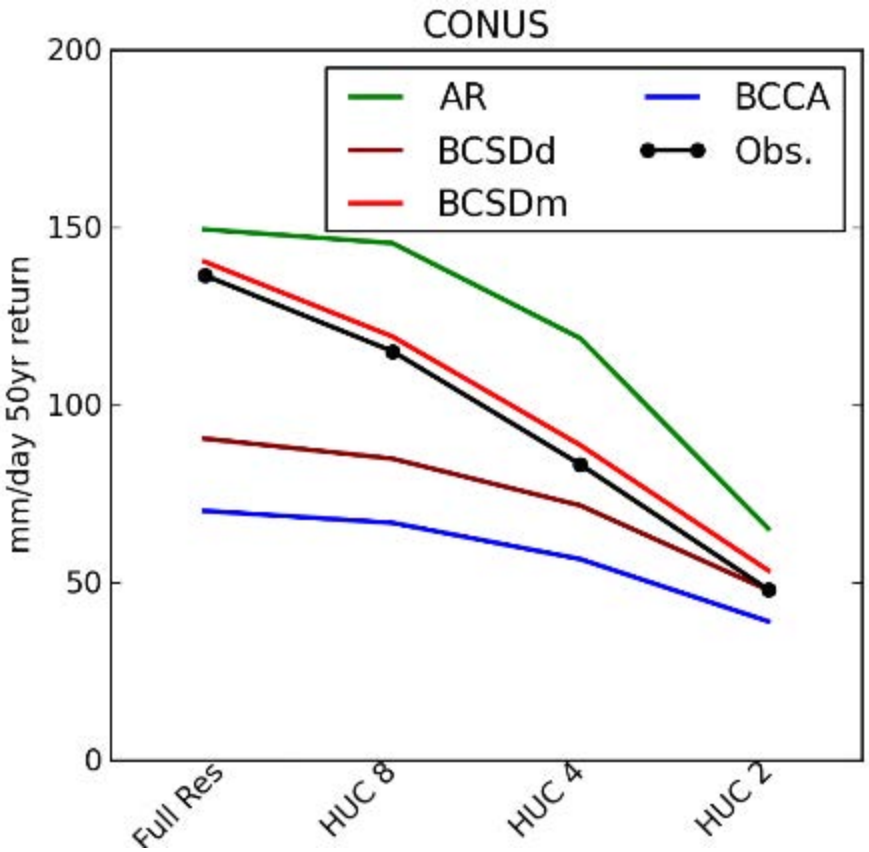


Mizukami et al., JHM 2015

Effects of Scale on Extreme Events

For 50-yr return rainfall:

- BCCA and BCSDd severely underestimate extreme events.
- BCSDm represents observed extreme event distribution for the training period.
- AR, BCCA, and BCSDd do not represent spatial scaling appropriately.

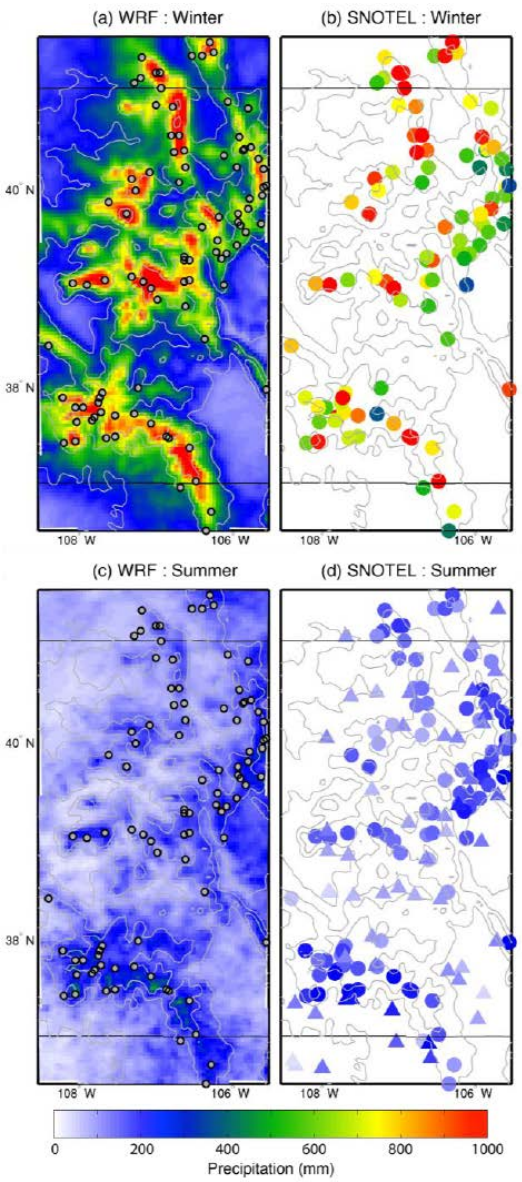


aggregate to larger spatial scales →

Gutmann et al (2014)

Using dynamically downscaled forcings

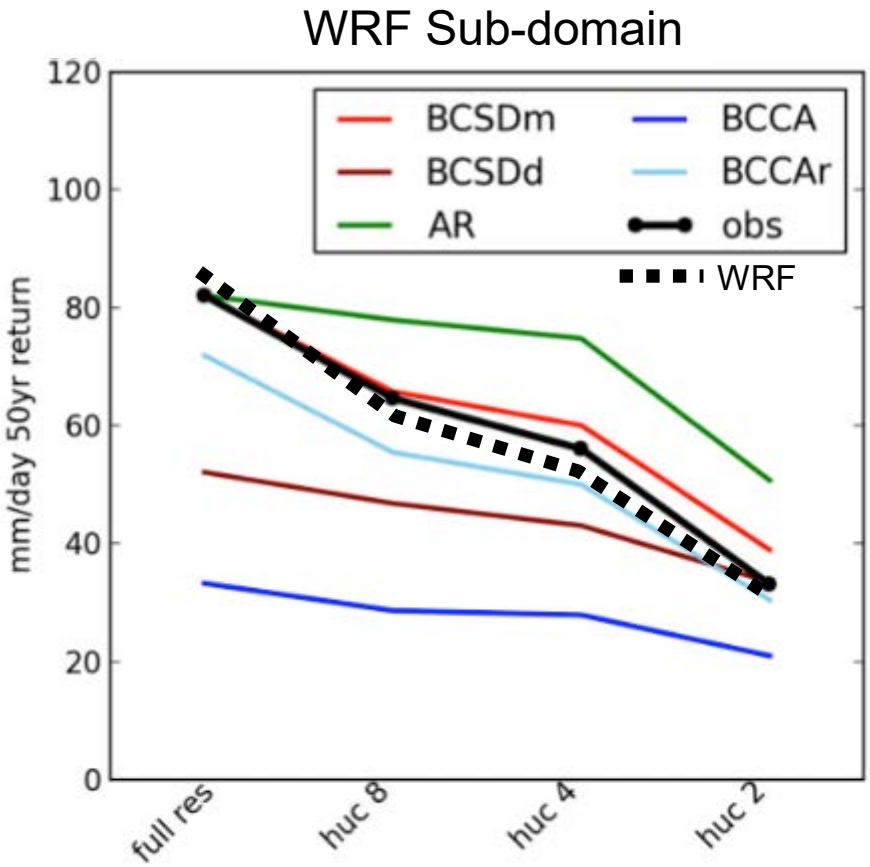
- Outputs from WRF
- WRF **historical** runs and **Pseudo Global Warming** (PGW) simulations described in **Rasmussen et al. (2014)**.
- **PGW**: **add a mean climate perturbation** to the initial and 3-hourly boundary conditions of the North American Regional Reanalysis (NARR).
- Data available at three resolutions: 4 km, 12 km and 36 km for an **8-yr period (Oct/2000- Sep/2008)**.



Wintertime and summertime precipitation amounts from 4 km-resolution simulations (Rasmussen et al., 2014)

Effects of Scale on Extreme Events

- The headwaters WRF runs also represented multi-scale extreme rainfall well.



aggregate to larger spatial scales →

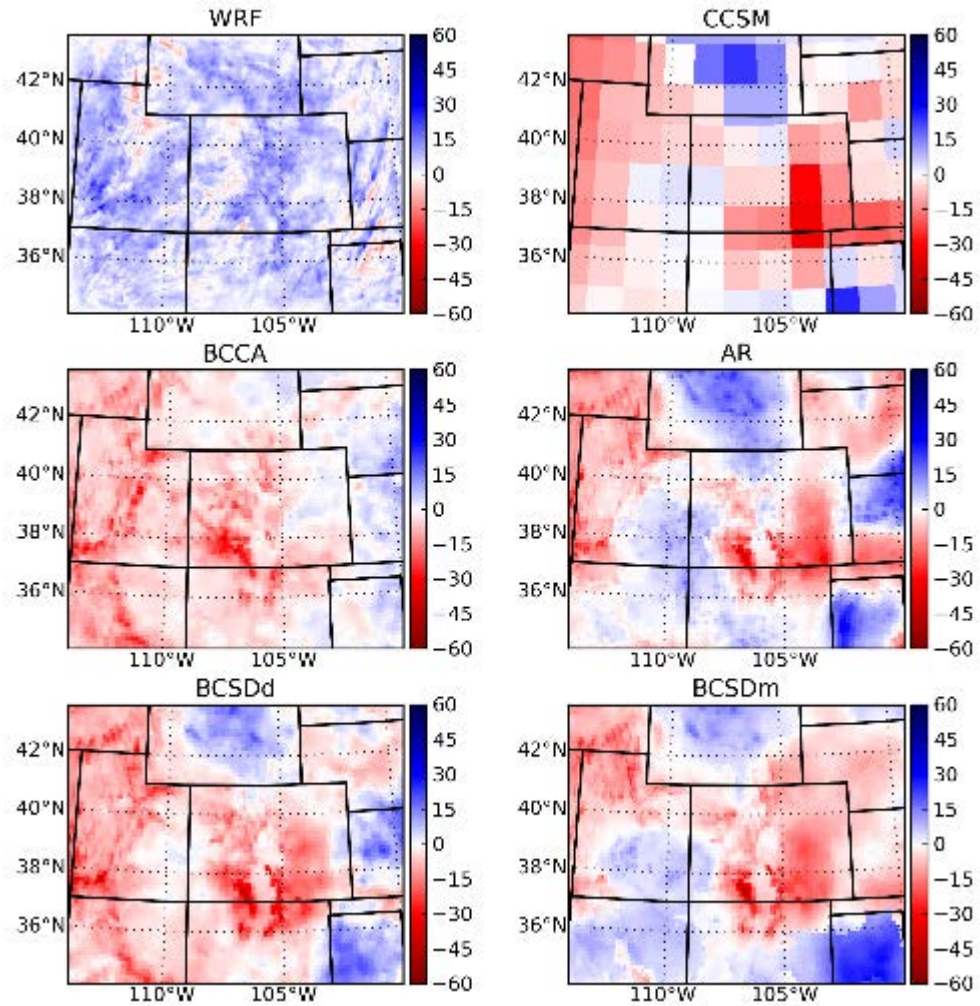
Gutmann et al. WRR (2014)

Representation of climate change

Precipitation

- Climate change in mean annual precipitation in the statistical methods (mostly) looks like CCSM
- WRF has more increase in Western Mountains, more decreases on Eastern plains
- Differences at the monthly scale are more drastic
- Orographically driven changes may be predictable…

Mean March Change

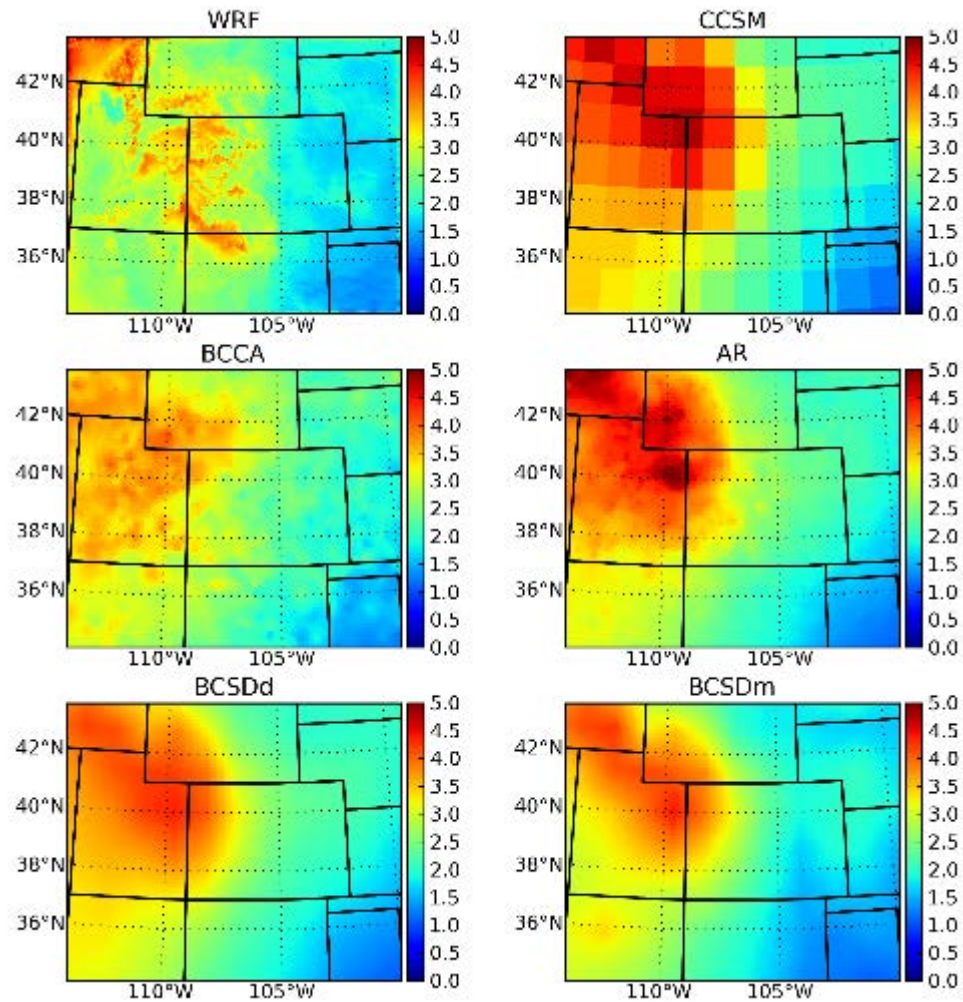


Representation of climate change

Temperature

- Temperature changes are slightly more consistent between methods
- WRF has distinct patterns related to snow cover
- These terrain-forced physically understandable patterns should be predictable…

Mean March Change



Key Findings

- Known: choice of GCM and ensemble members matters
- The choice of *downscaling method* is important, and the resolution used in dynamical downscaling matters.
- The choice of *hydrologic model* also affects projection outcomes, though less so if a hydrology model is well calibrated.
- Hydrologic *model calibration* is critically important, but often receives relatively little attention (even in model comparison studies).
- Finally, outcomes depend significantly on subjective decisions made in calibrating hydrologic models
  - the choice of forcing data
  - the choice of calibration objectives

NCAR research activities in support of water resource planning and management
Part 2: Advancing impact assessments

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WWCRA Workshop: Climate Science to Engineering Operations for Watershed Management
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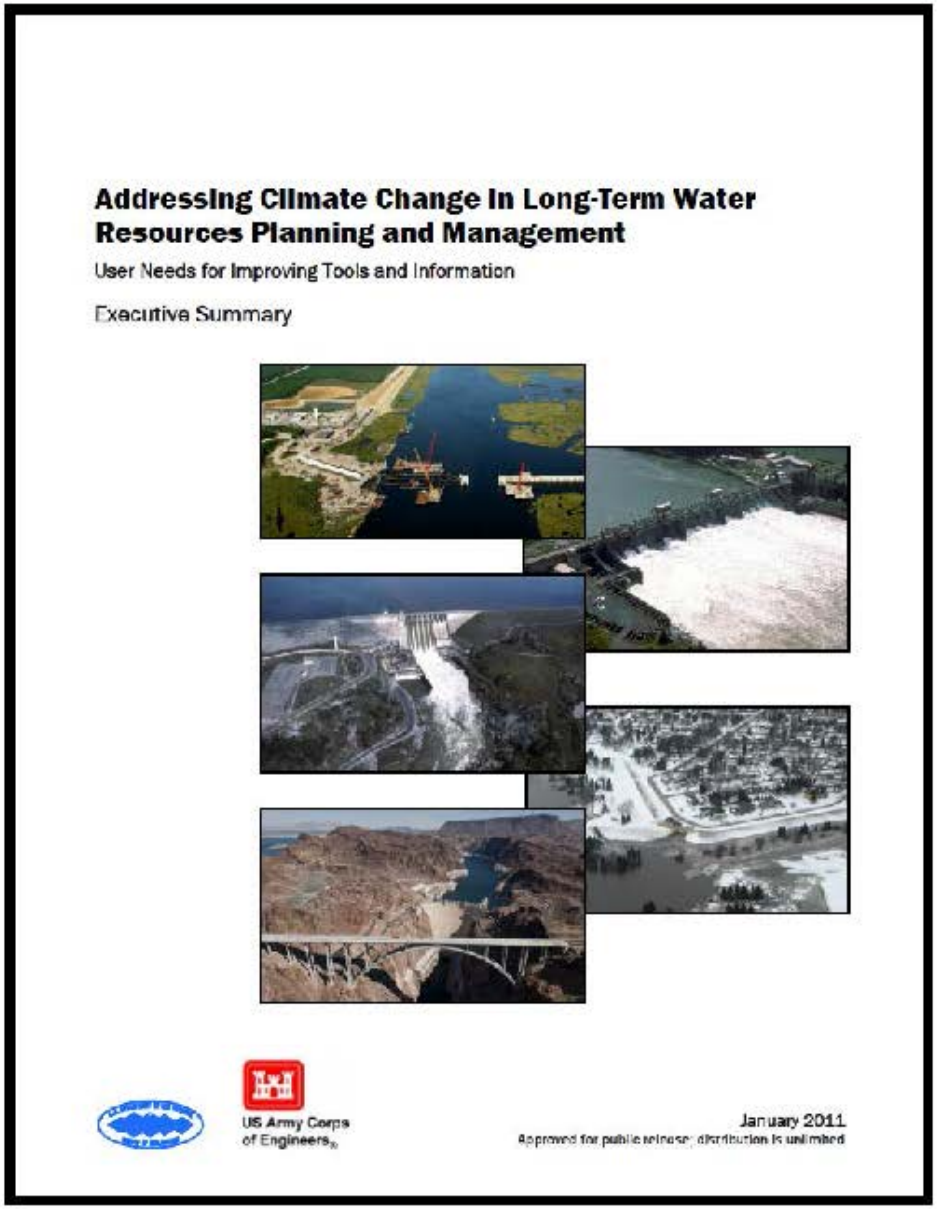
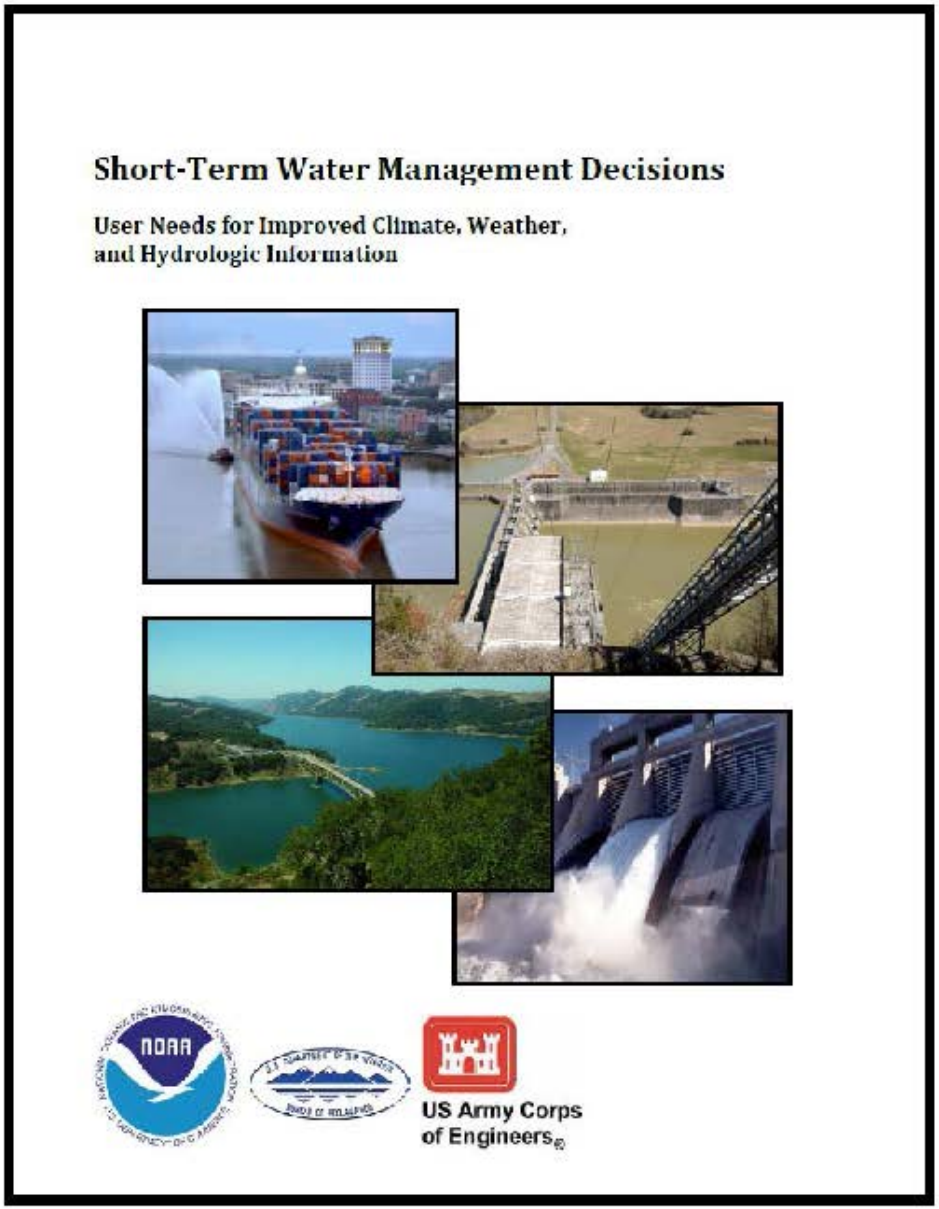
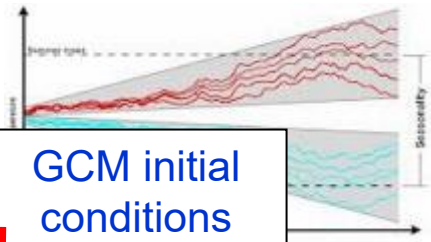
Key reports


Addressing Climate Change in Long-Term Water Resources Planning and Management
User Needs for Improving Tools and Information
Executive Summary
US Army Corps of Engineers
January 2011

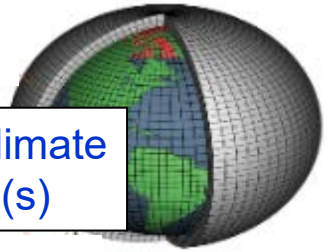

Short-Term Water Management Decisions
User Needs for Improved Climate, Weather, and Hydrologic Information
NOAA
US Army Corps of Engineers

LT-Doc: Possible targeted science response

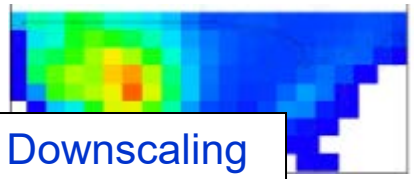
NCAR UCAR



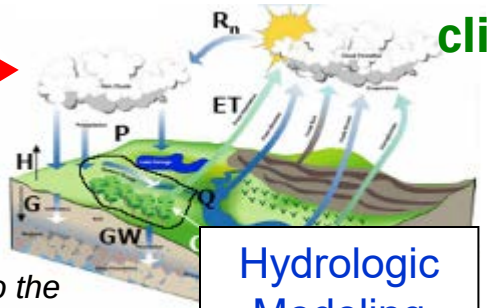
GCM initial conditions



Global Climate Model(s)



Downscaling method(s)



Hydrologic Modeling

Key research/agency needs

Evaluate multi-GCM screening and combination approaches

Improve understanding of the predictable changes in climate and the role of internal vs forced variability

Evaluate/improve downscaling methods across the continuum of methodological complexity

Understand/quantify uncertainty in downscaling models and methods

Assess the capability of downscaling methods to reproduce non-stationarity & actionable information

Improve understanding of predictable changes in climate on hydrology (e.g., declining snowpack)

Evaluate/improve hydrologic model simulations

Quantify hydrologic model uncertainty

Provide information to the broader community

Note: *The official science response to the LT-Doc is not yet public*

ST-Doc: Possible targeted science response

NCAR UCAR

Key research/agency needs

Monitoring

Analyze and quantify uncertainty in meteorological and hydrologic observations

Develop CONUS+ ensemble hyper-resolution meteorological and hydrologic reanalysis

Forecasting

Implement hydrologic model improvement strategies

Develop integrated data assimilation system

Improve flow forecasting at sub-daily time scales

Improve flow forecasting for sub-seasonal to seasonal lead times (including post-processing methods)

Test-beds

Understand the sources of hydrologic predictability and the benefits of advanced forecast techniques

Assess the value of hydrologic models of varying complexity

Demonstrate the value of automated forecasting that is compatible with science + data advances

Note: *The official science response to the ST-Doc is currently being developed by a group of scientists from NOAA, NASA, and NCAR*

Integration of research elements

NCAR UCAR

Land surface meteorological forcing dataset

A high quality high resolution ensemble land surface forcing dataset, regularly updated, to support assessments in hydroclimate variability and infrastructure design

National-domain hydrologic modeling

A national modeling infrastructure to support basin and regional studies

Hydrologic storylines to support water resources planning

Develop robust storylines of possible changes in hydrology to enable robust planning under a changing climate

Hydrologic monitoring & prediction to support water resources management

A nationwide water prediction capability to enhance capacity for adapting to climate change increasing resilience to extremes

To address LT-Doc and ST-Doc needs, NCAR is conducting prototypical research and development designed to advance capabilities and/or expand capacities of end-user services like NWS and NRCS

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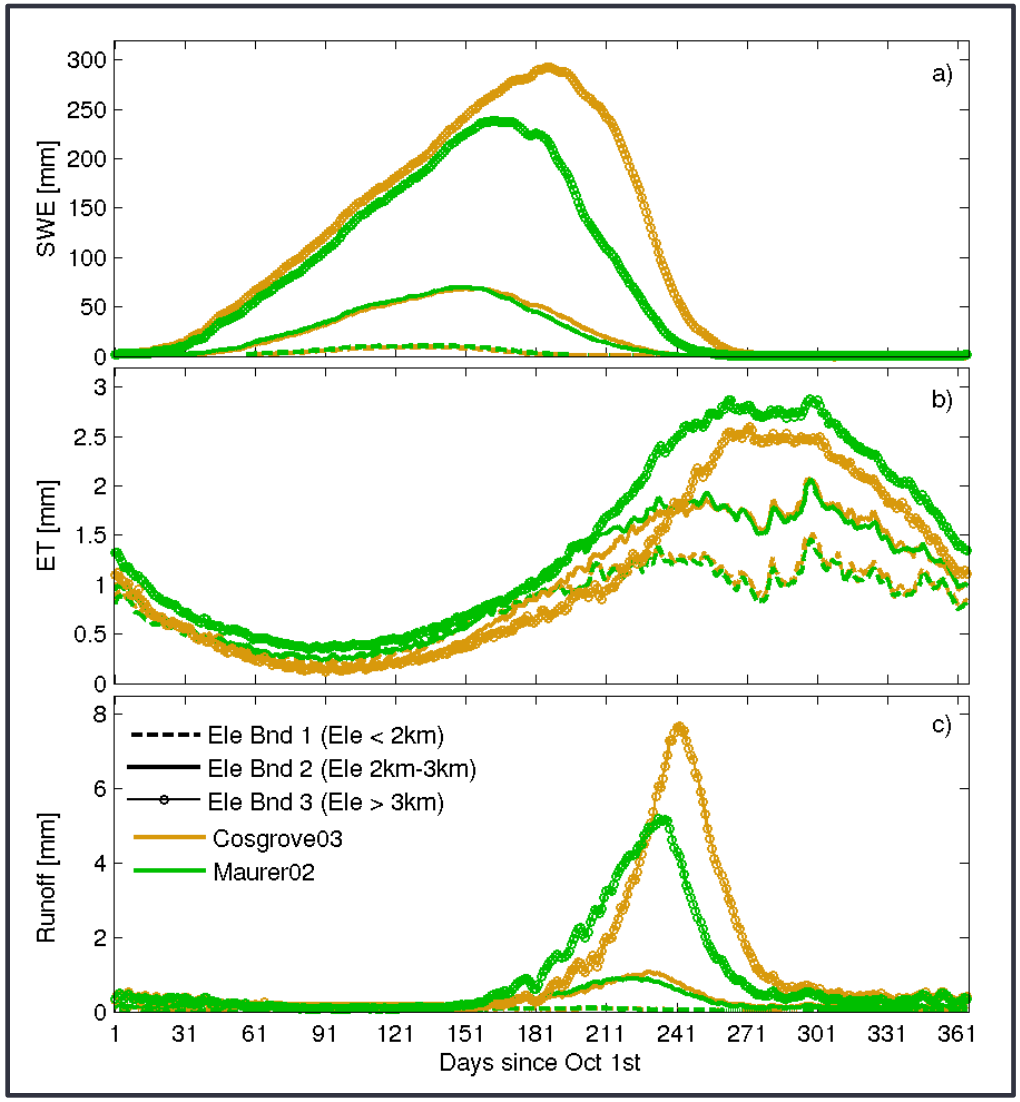
Uncertainties in model forcing data

- N-LDAS vs. Maurer
  - Gridded meteorological forcing fields (12-km grid) across the CONUS, 1979-present
- Opportunities to improve these products
  - Make more extensive use of data from stations (additional networks) and NWP models (finer spatial resolution) in a formal data fusion framework
  - Provide quantitative estimates of data uncertainty (ensemble forcing)

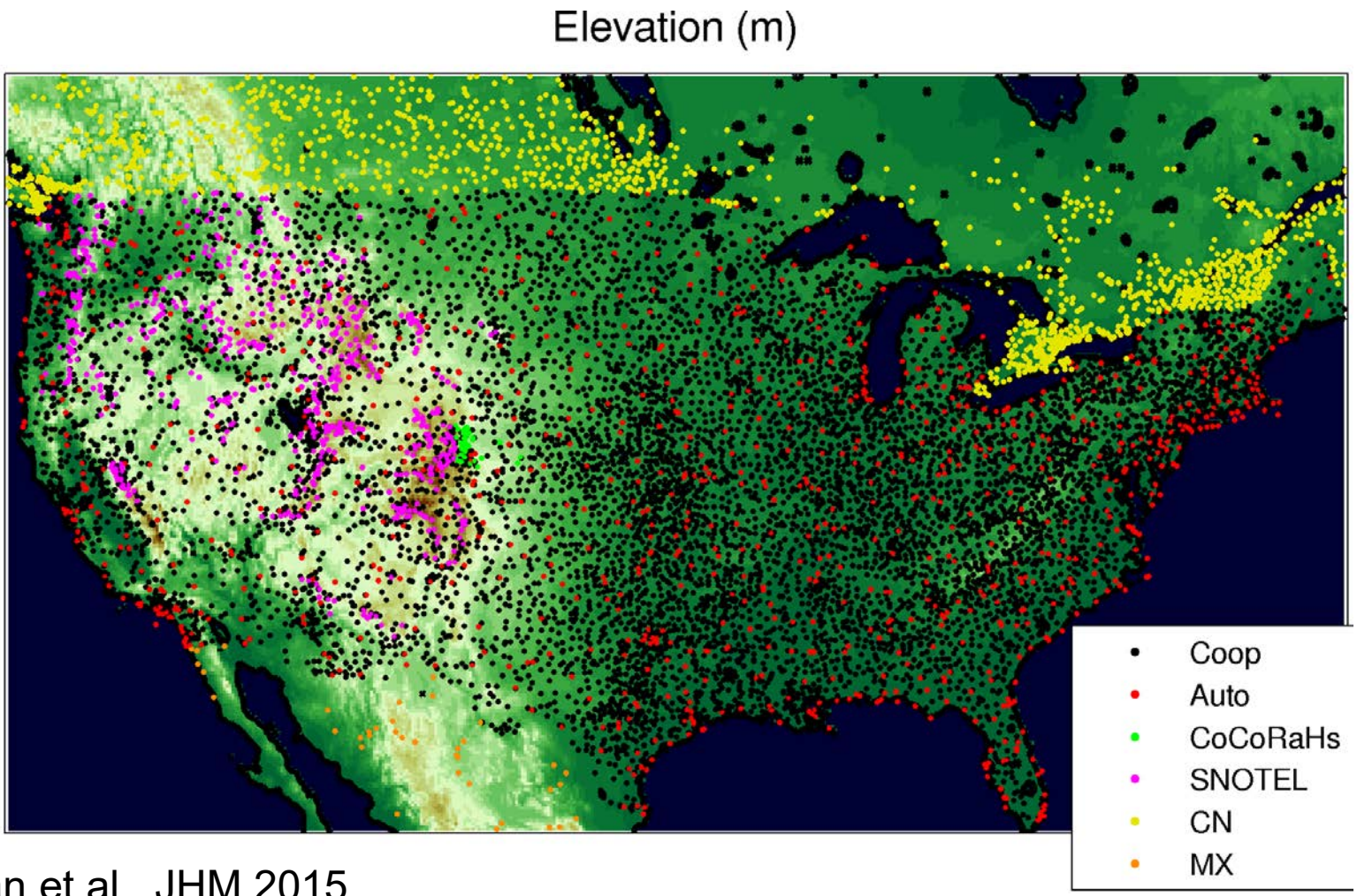


CLM simulations over the Upper Colorado River basin for three elevation bands, using two different meteorological forcing datasets

Mizukami et al. (JHM, 2014)

CONUS-domain probabilistic forcing

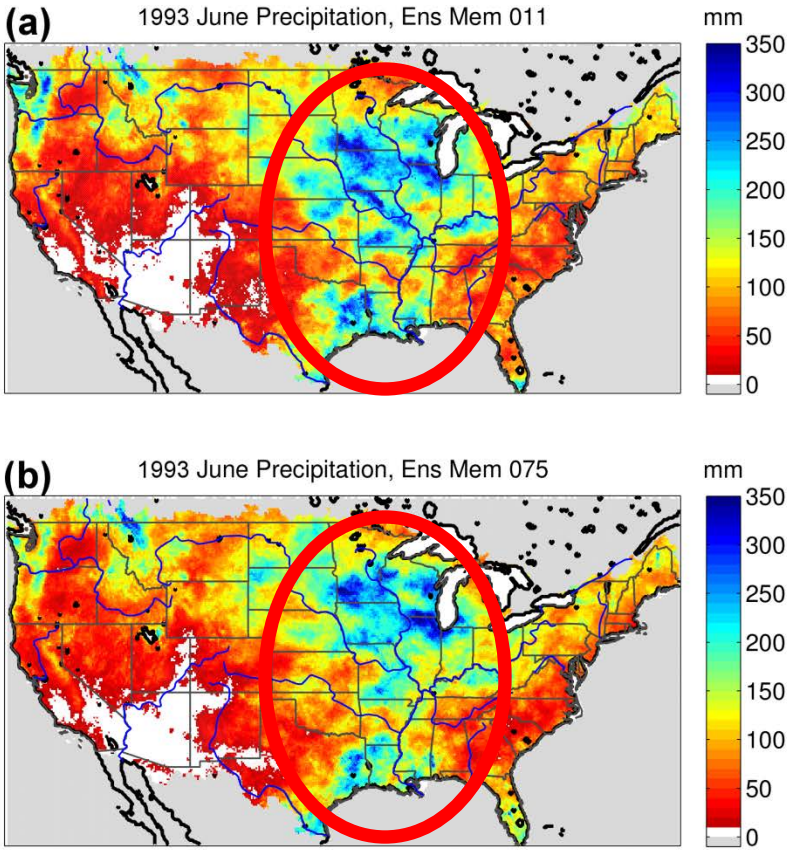
- 12,000+ stations with serially complete data
- Precipitation, temperature or both



Newman et al., JHM 2015

Example grids

- Central US Flood of 1993
  - *June 1993 total precipitation*



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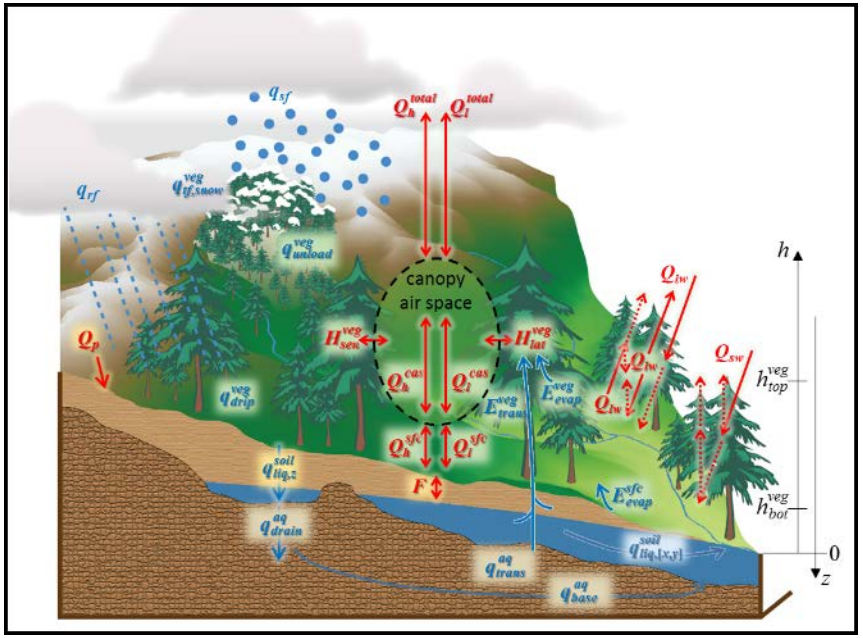
Hydrologic modeling
Revealing impacts of model choice



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

Propositions:

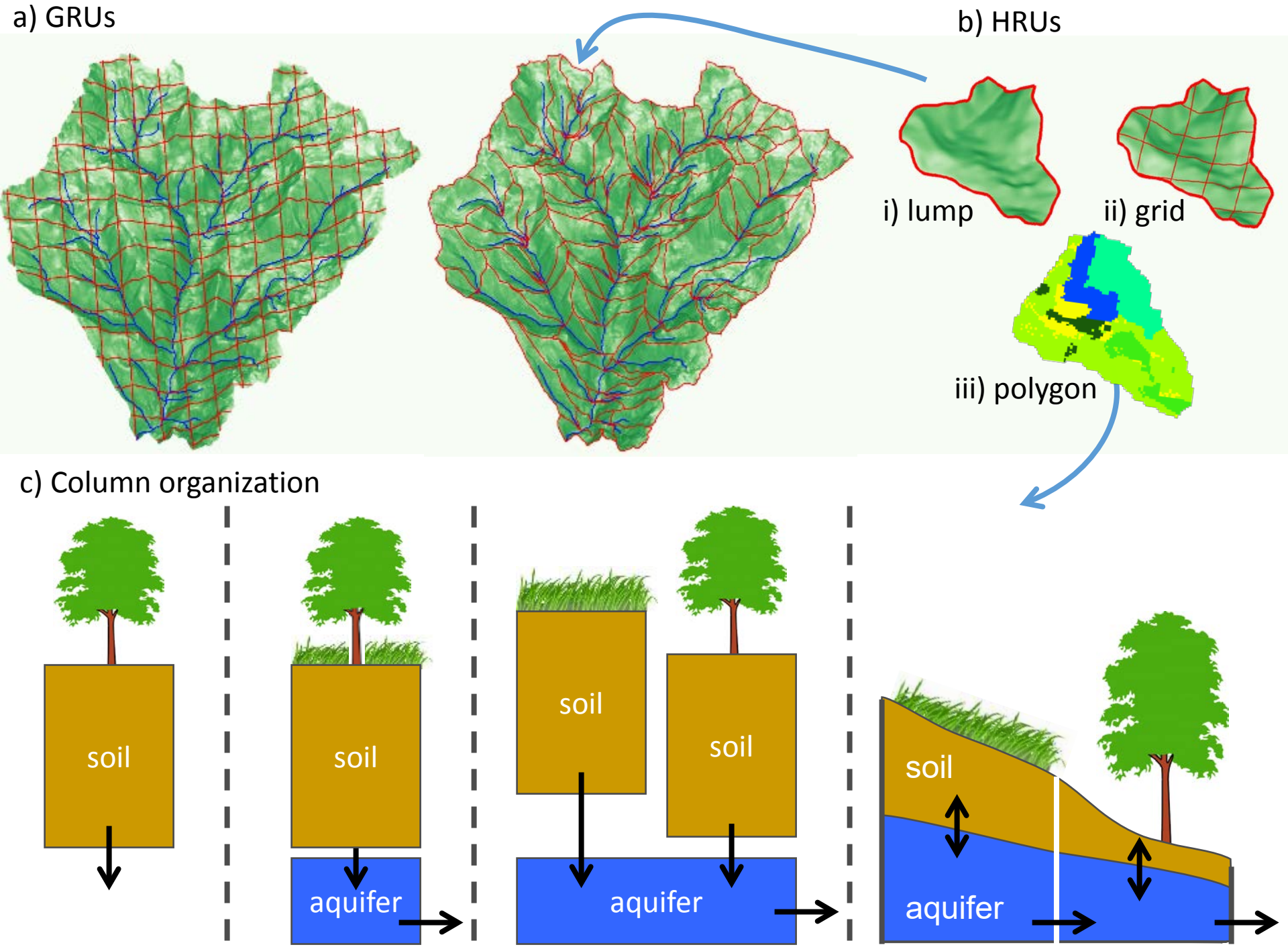
1. Most hydrologic modelers share a common understanding of how the dominant fluxes of water and energy affect the time evolution of thermodynamic and hydrologic states
   - The *collective understanding of the connectivity of state variables and fluxes* allows us to formulate general conservation equations in different sub-domains
   - The conservation equations are scale-invariant

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.

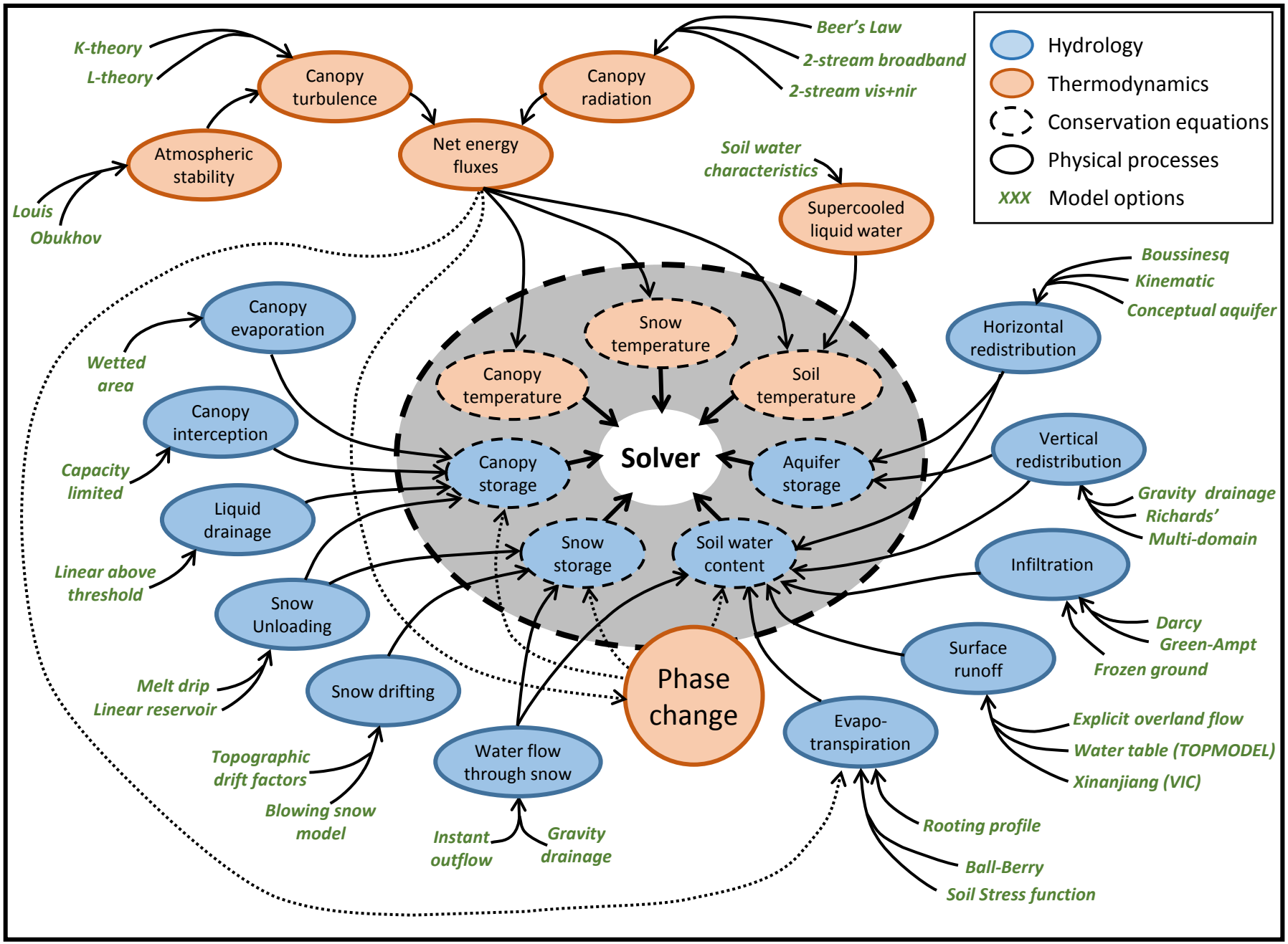
Given these propositions, ***it is possible to develop a unifying model framework***

For example, by defining a single set of conservation equations, with the capability to use different spatial discretizations (e.g., multi-scale grids, HRUs; connected or disconnected), different flux parameterizations and model parameters, and different time stepping schemes

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


a) GRUs
b) HRUs
i) lump
ii) grid
iii) polygon
c) Column organization
soil
soil
aquifer
soil
soil
aquifer
soil
aquifer

The Structure for Unifying Multiple Modeling Alternatives (SUMMA)



Parameter estimation in large-domain model applications

NCAR UCAR

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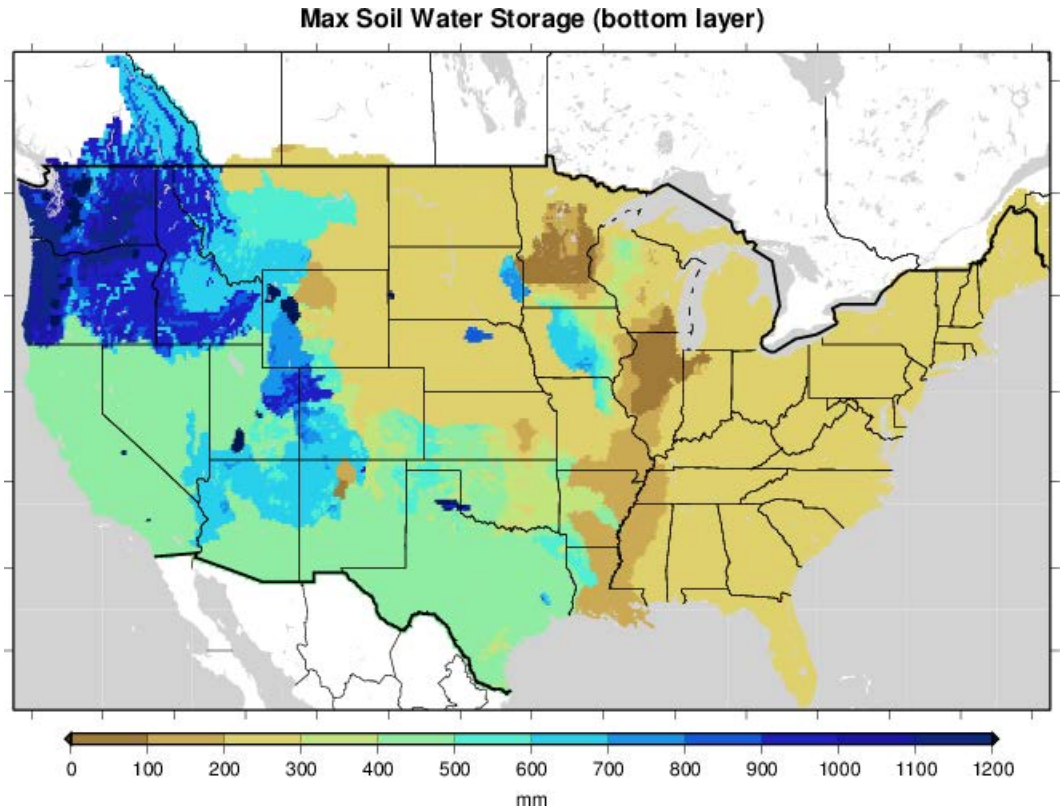
  - Not counting for sub-grid variability of soil properties.



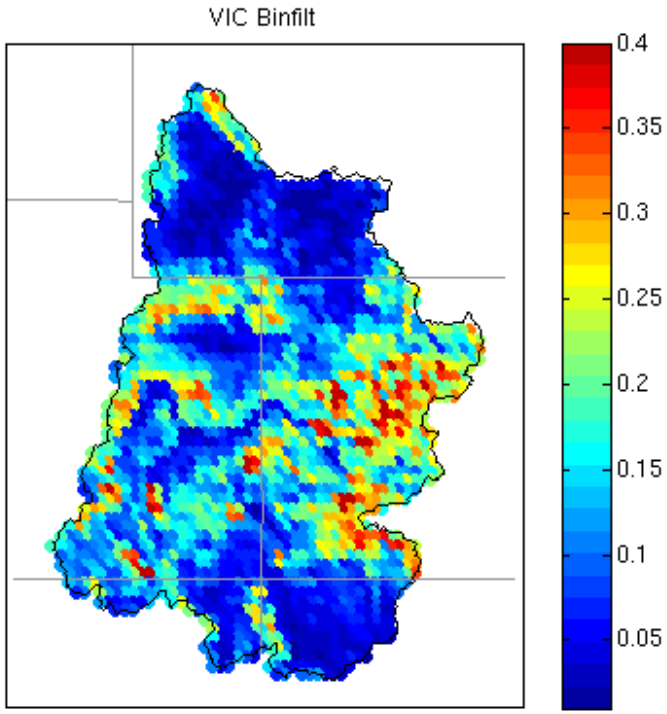
For example, the nationwide VIC simulations used for water security assessments based on a single model with spatially inconsistent parameter estimates

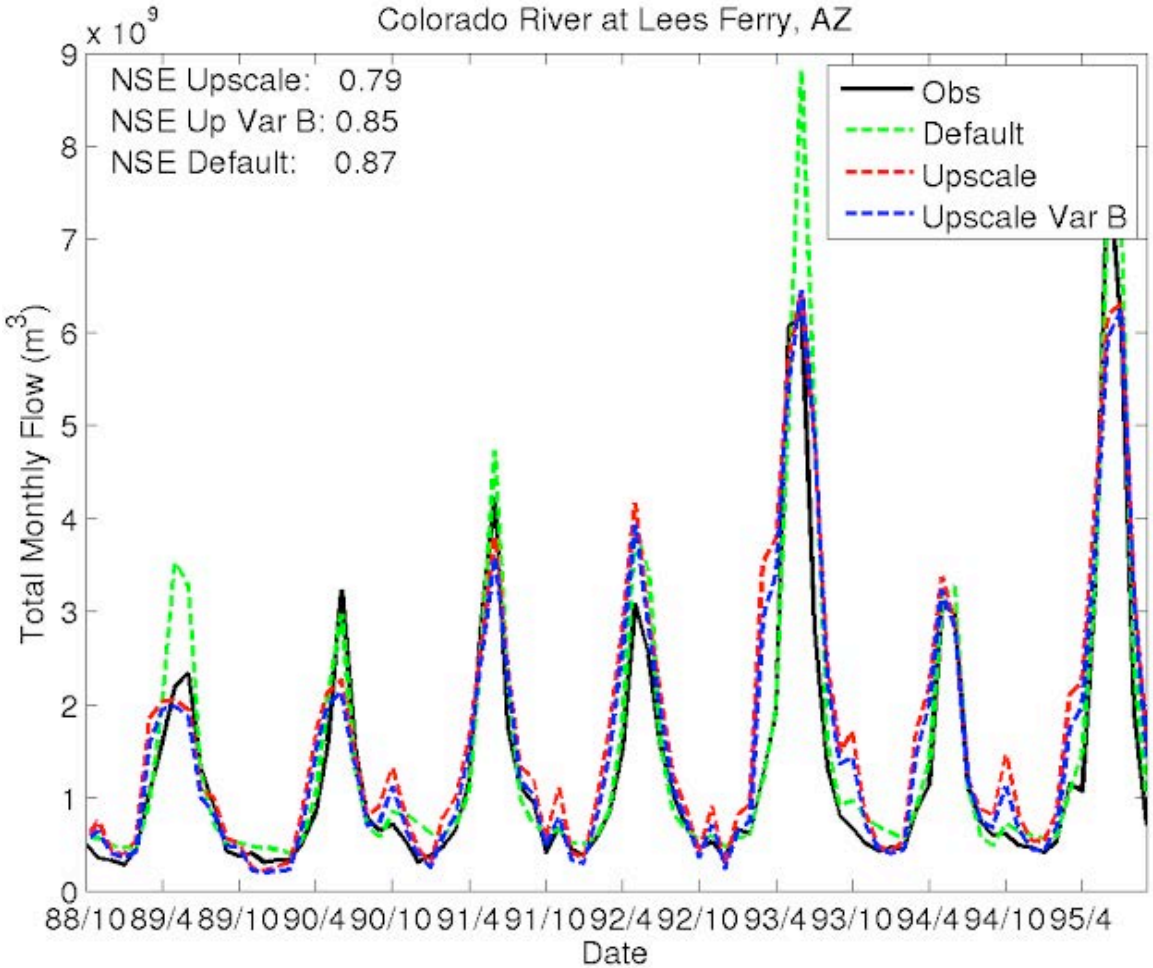
Goal and approach

- Improve continental parameter estimates for multiple hydrologic models.
- Initial work: Parameter estimation for the Upper Colorado River basin using streamflow from headwater basins

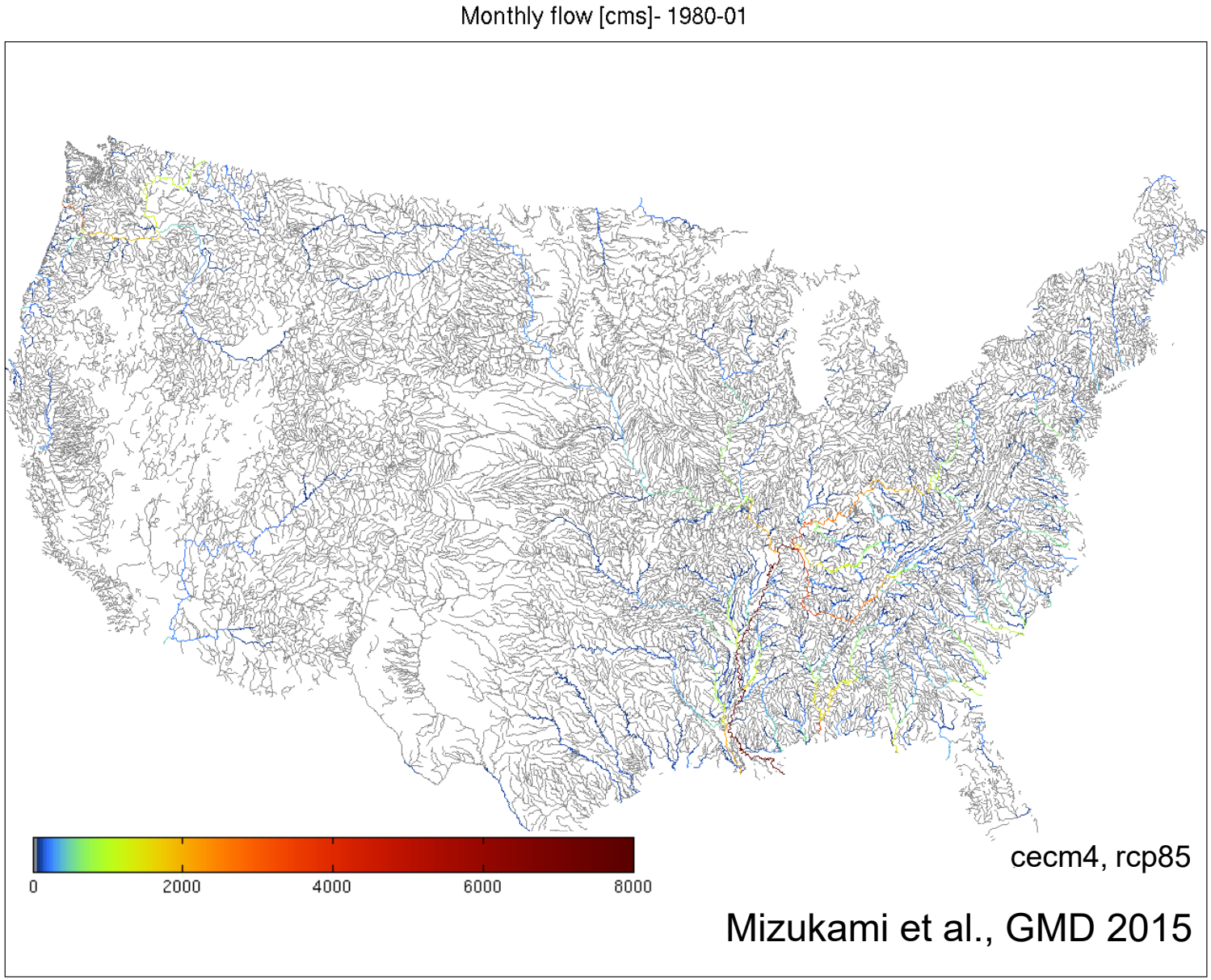
Initial results are encouraging

- Parameter fields show greater connection with grid-scale variability in terrain or soil properties
- Results at larger and separate flow locations are on par with manually calibrated results





Routed flow for the CONUS



Integration of research elements

NCAR UCAR

Land surface meteorological forcing dataset

A high quality high resolution ensemble land surface forcing dataset, regularly updated, to support assessments in hydroclimate variability and infrastructure design

National-domain hydrologic modeling

A national modeling infrastructure to support basin and regional studies

Hydrologic storylines to support water resources planning

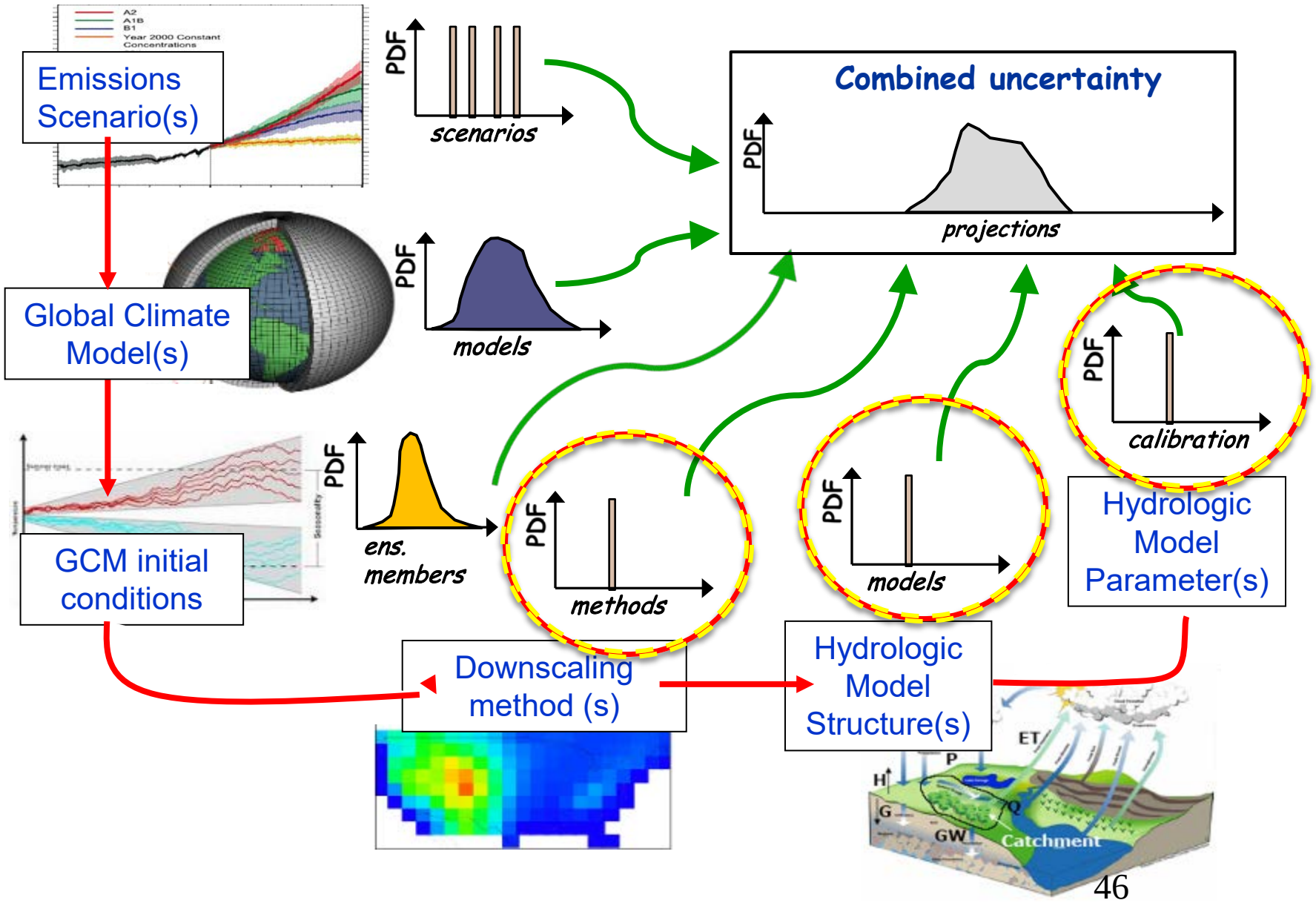
Develop robust storylines of possible changes in hydrology to enable robust planning under a changing climate

Hydrologic monitoring & prediction to support water resources management

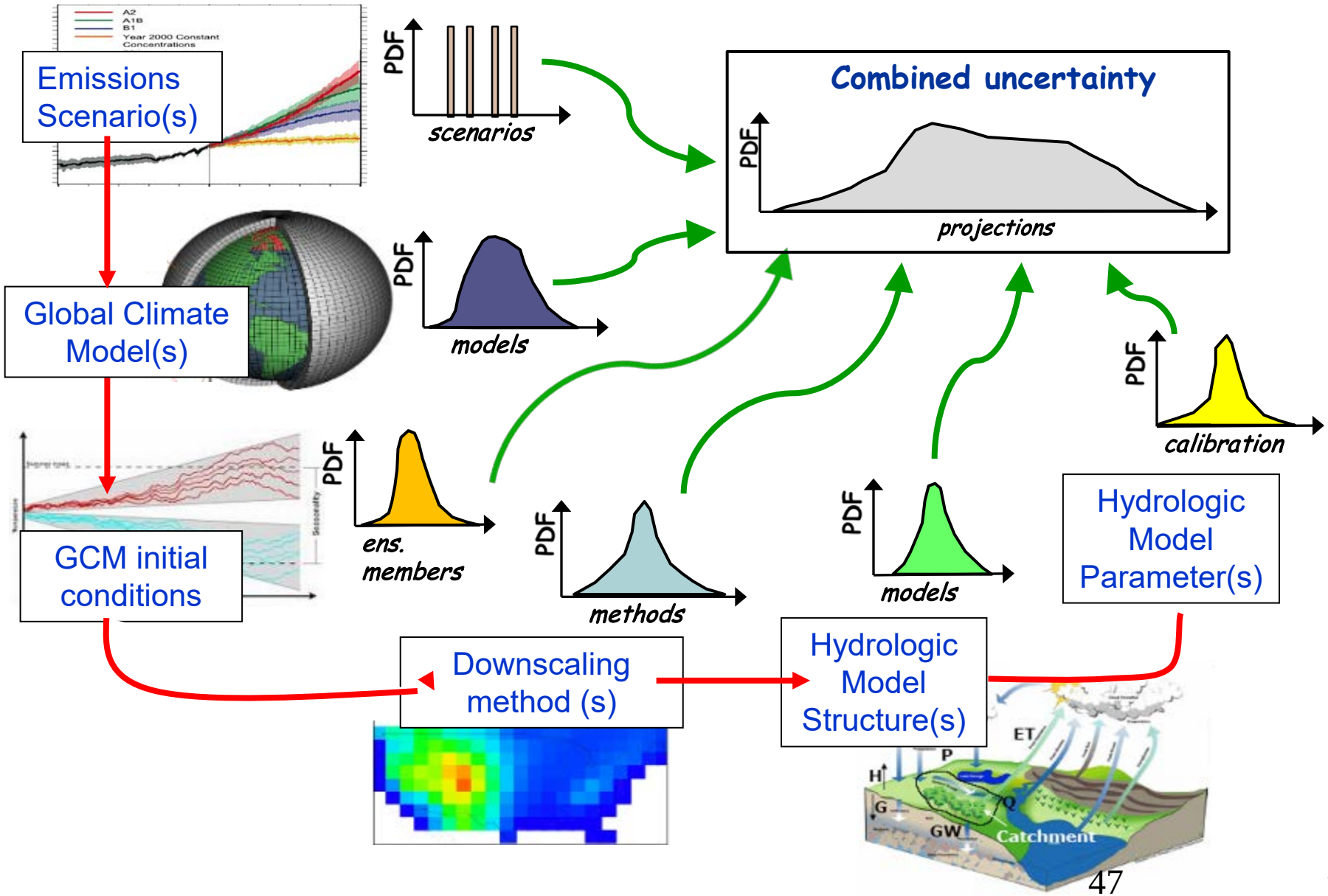
A nationwide water prediction capability to enhance capacity for adapting to climate change increasing resilience to extremes

To address LT-Doc and ST-Doc needs, NCAR is conducting prototypical research and development designed to advance capabilities and/or expand capacities of end-user services like NWS and NRCS

"Revealing" uncertainties



"Revealing" uncertainties



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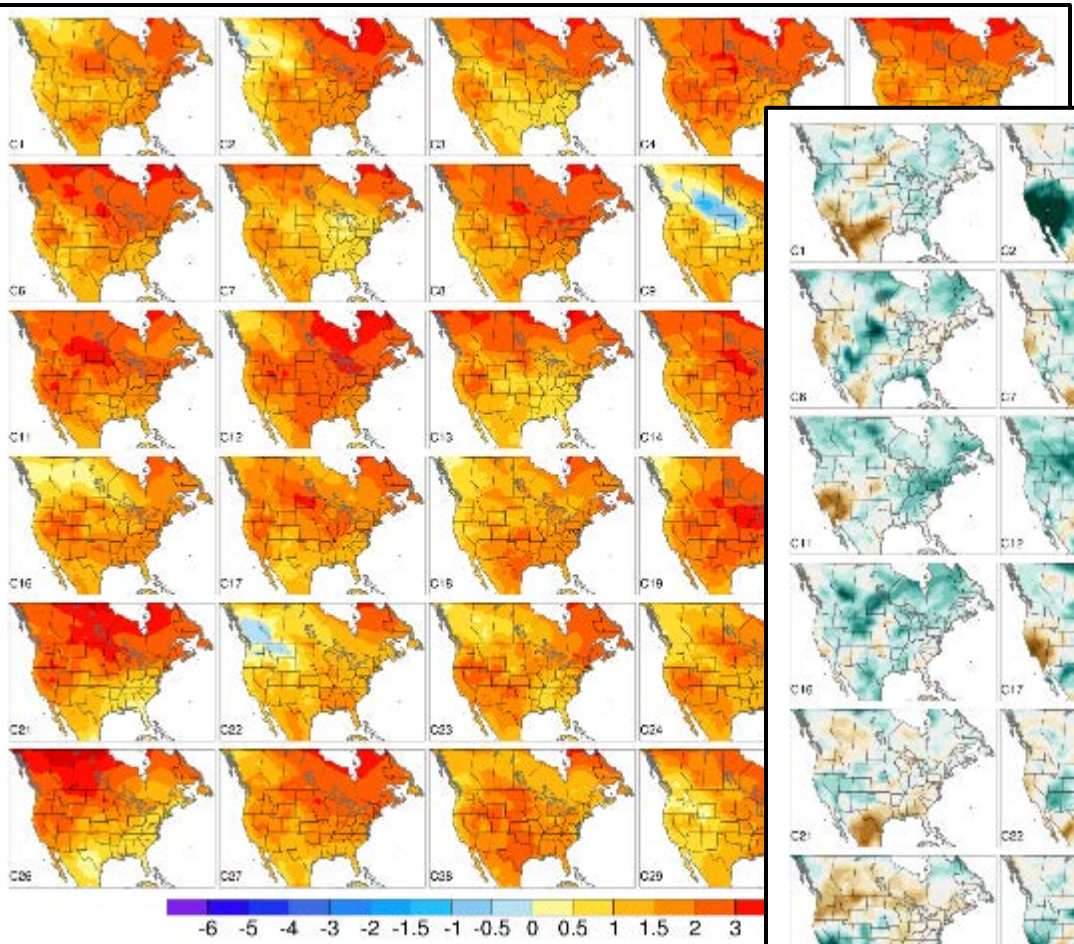
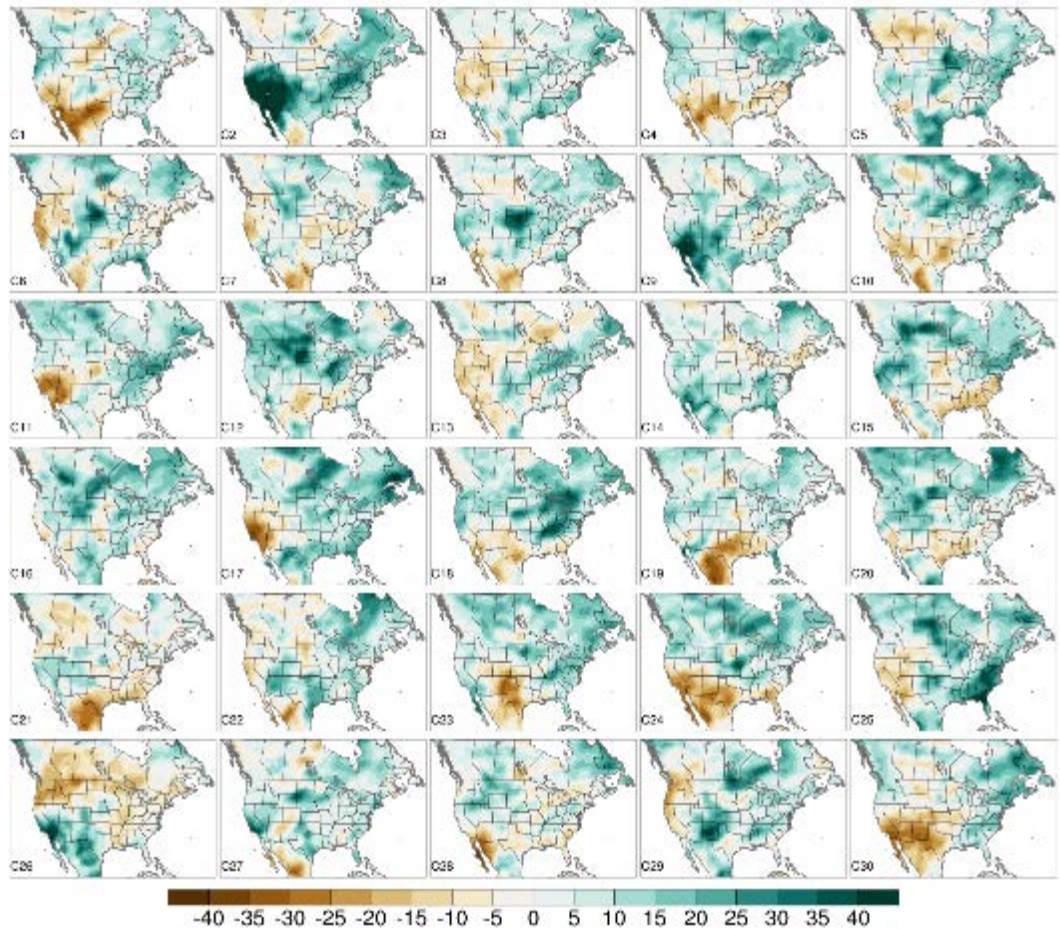
Climate model uncertainty

The role of internal variability



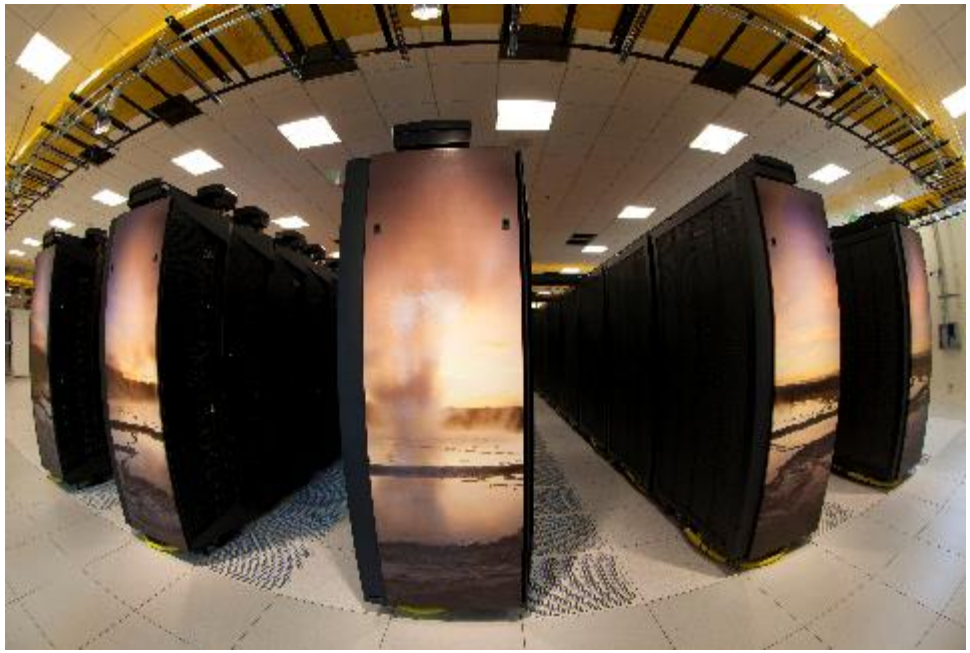
Change in air temperatu

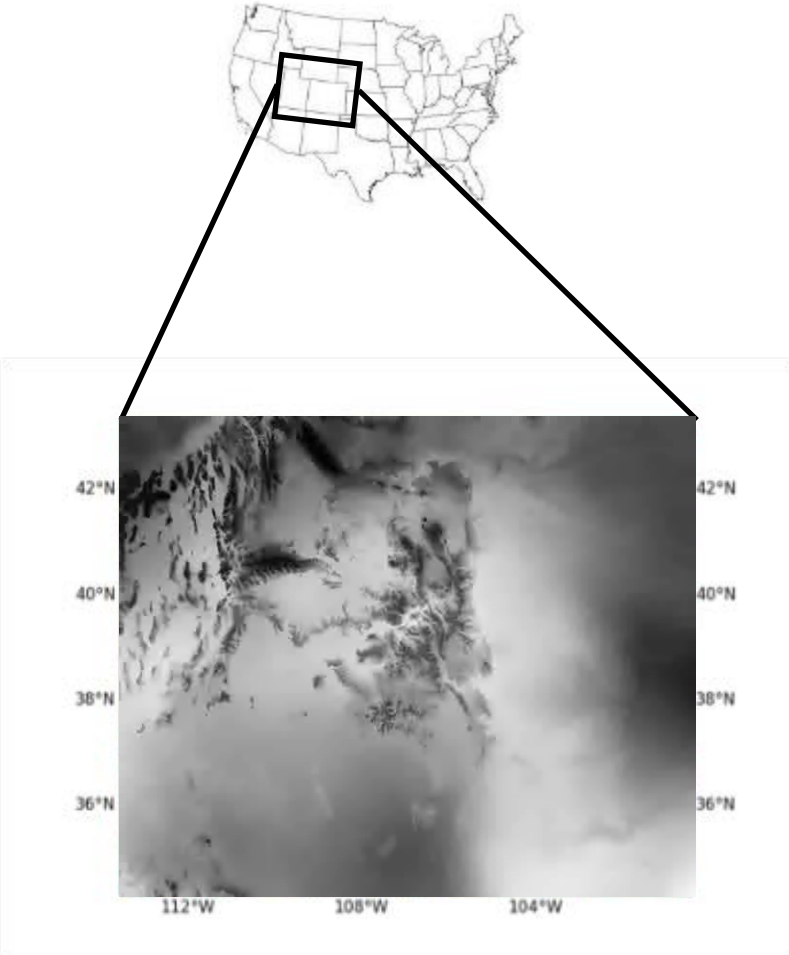


Change in precipitation

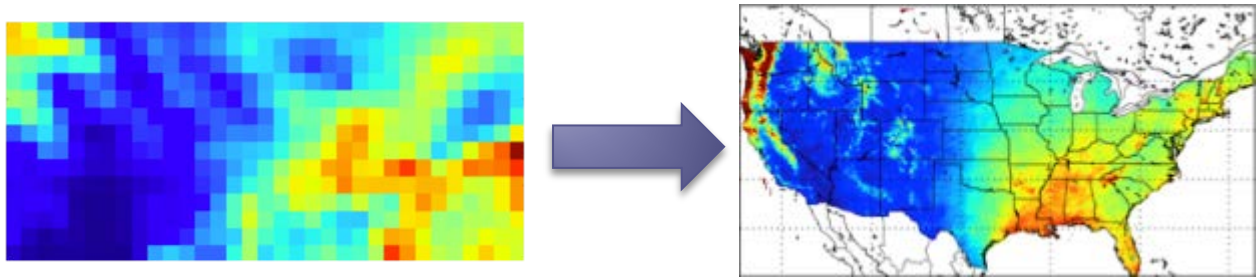
Dynamic Downscaling

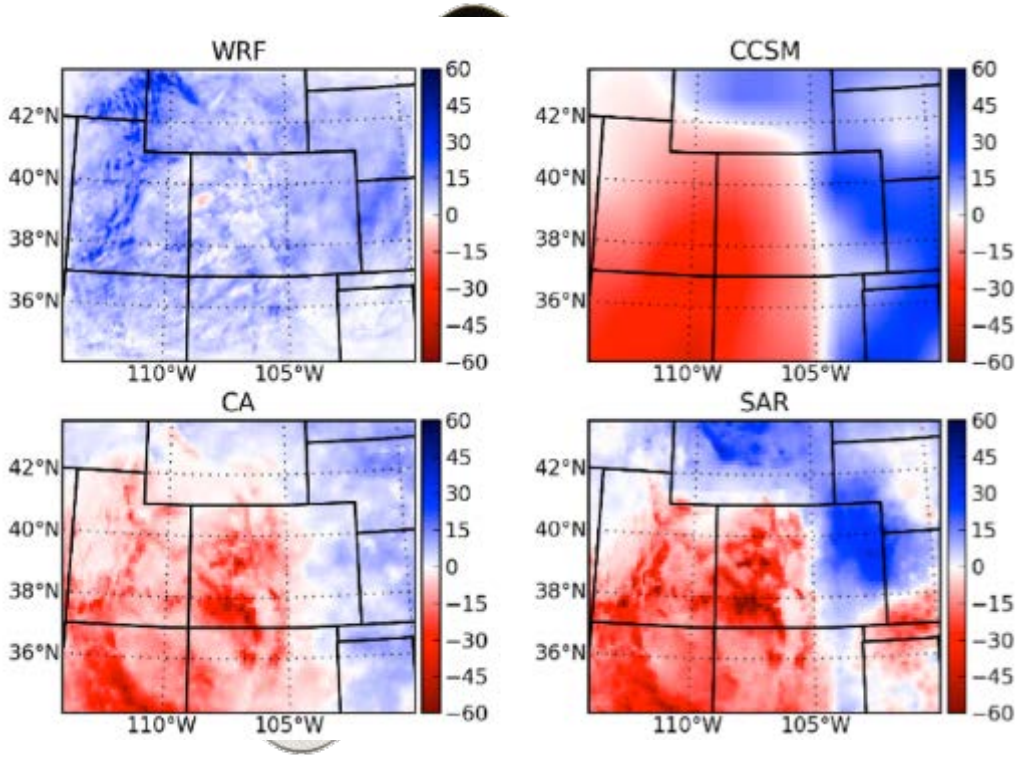
- High-resolution Regional Climate Model

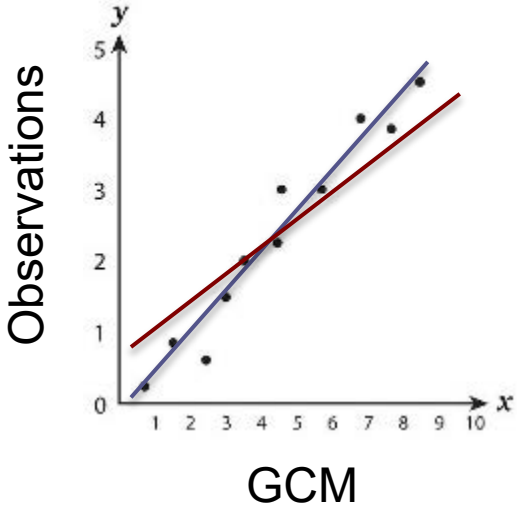




Statistical Downscaling







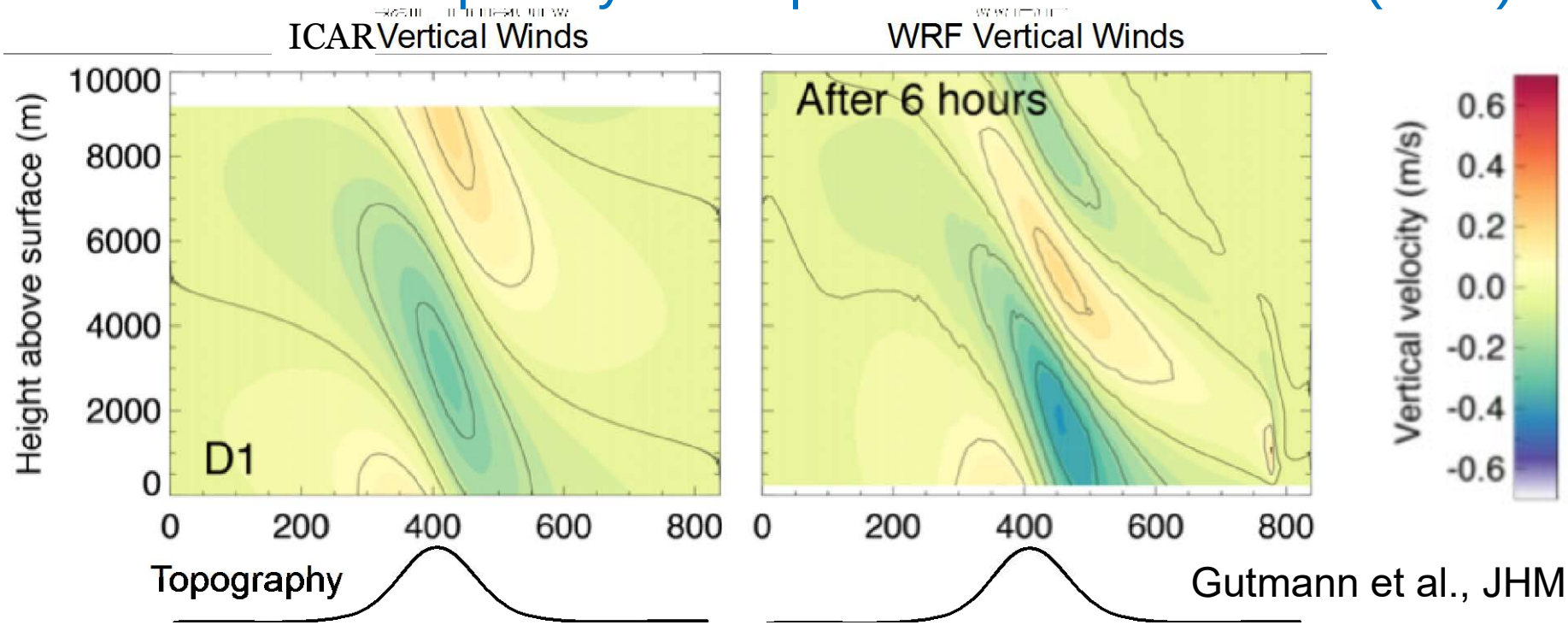
Pseudo-dynamical Downscaling

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

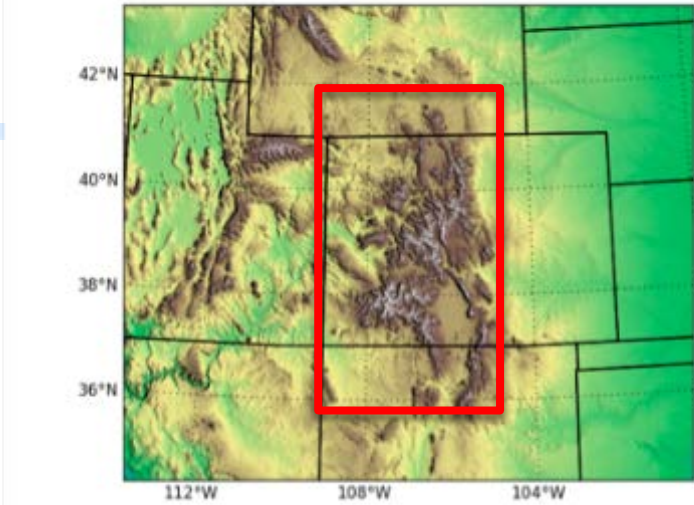
Intermediate Complexity Atmospheric Research model (ICAR)



Gutmann et al., JHM

ICAR water vapor simulation

ICAR Precipitation Simulation

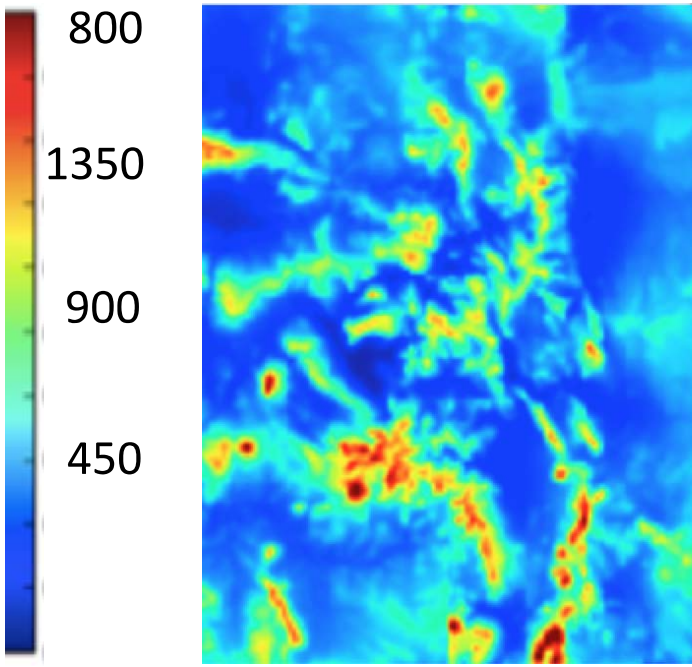


WRF and ICAR have very similar precipitation distributions.

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

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

ICAR



(pre-bias correction)

Summary

- 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

Publications resulting from NCAR 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
- Elsner, M. M., S. Gangopadhyay, T. Pruitt, L. Brekke, N. Mizukami, and M. Clark (2014), How does the Choice of Distributed Meteorological Data Affect Hydrologic Model Calibration and Streamflow Simulations?, *Journal of Hydrometeorology*(2014), 1384–1403, doi: 10.1175/JHM-D-13-083.1.
- 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.
- Mendoza, P. A., M. Clark, N. Mizukami, A. Newman, M. Barlage, E. Gutmann, R. Rasmussen, B. Rajagopalan, L. Brekke, and J. Arnold (2015), Effects of hydrologic model choice and calibration on the portrayal of climate change impacts, *Journal of Hydrometeorology, in press*

Publications resulting from NCAR 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)*
- Newman, A., M. Clark, A. Winstral, D. Marks, and M. Seyfried (2014a), The use of similarity concepts to represent sub-grid variability in hydrologic and land-surface models: case study in a snowmelt dominated watershed, *Journal of Hydrometeorology*, *15*, 1717–1738, doi: 10.1175/JHM-D-13-038.1.
- 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.
- Newman, A., M. P. Clark, J. Craig, B. Nijssen, A. Wood, E. Gutmann, N. Mizukami, L. Brekke, and J. R. Arnold (2015), Gridded ensemble precipitation and temperature estimates for the contiguous United States, *Journal of Hydrometeorology (accepted pending revisions)*
- Prein, A. F., G. J. Holland, R. M. Rasmussen, J. Done, K. Ikeda, M. P. Clark, and C. H. Liu (2013), Importance of regional climate model grid spacing for the simulation of heavy precipitation in the Colorado headwaters, *Journal of Climate*, *26*(13), 4848-4857.
- Rasmussen, R., K. Ikeda, C. Liu, D. Gochis, M. Clark, A. Dai, E. Gutmann, J. Dudhia, F. Chen, and M. Barlage (2014), Climate change impacts on the water balance of the Colorado Headwaters: High-resolution regional climate model simulations, *Journal of Hydrometeorology*, *15*, 1091–1116, doi: 10.1175/JHM-D-13-0118.1.
- 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)*