NCAR

High Resolution Regional Climate Simulations over the Contiguous United States (CONUS) Including Potential Climate Change Scenarios

Presented by Roy Rasmussen, NCAR

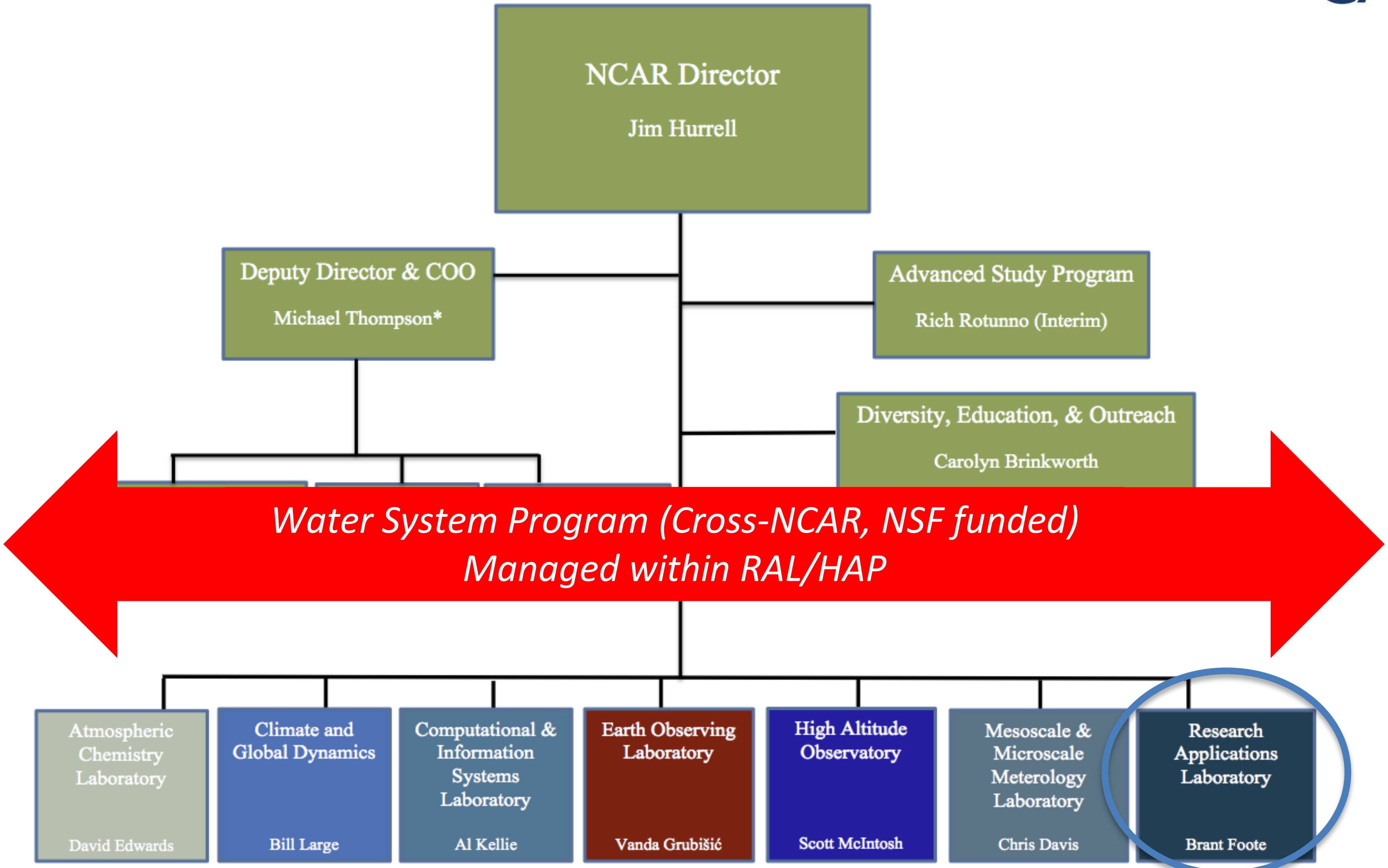
Director, Hydrometeorology Applications Program

Team members:

Changhi Liu, Kyoko Ikeda, Roy Rasmussen, Mike Barlage, Fei Chen, Martyn Clark, Aiguo Dai, Jimy Dudhia, David Gochis, Ethan Gutmann, Kyoko Ikeda, Changhai Liu, Andrew Newman, Andreas Prein, Gregory Thompson, David Yates, and University Collaborators

Sponsored by NCAR Water System Program funded by the National Science Foundation

NCAR Organization



*Currently Serving as Interim President of UCAR

Updated July 2015

Martyn Clark: Numerical modeling and prediction of hydrologic processes

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- Research background
  - Coupling of hydrology and climate models
  - Development of spatially distributed hydrologic models
  - Development of methods for hydrologic data assimilation
  - Development of methods to quantify hydrologic model uncertainty.
- Current research
  - Developing a unified approach for process-based hydrologic modeling
  - Developing methods to improve streamflow forecasts
  - Understanding the impacts of climate change on regional water resources
- Recent publications
  - Clark et al., 2015: A unified approach to hydrologic modeling: Part 1. Modeling concept. *Water Resources Research* **51**, doi: 10.1002/2015WR017198.
  - Clark et al., 2015: Improving the representation of hydrologic processes in Earth System Models. *Water Resources Research*, **51**, doi: 10.1002/2015WR017096.
  - Clark et al., 2016: Characterizing uncertainty of the hydrologic impacts of climate change. *Current Climate Change Reports*, 1-10, doi: 10.1007/s40641-016-0034-x

David Yates: Regional climate downscaling, Water Resources, Water Evaluation And Planning (WEAP) model

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- Research background
  - Downscaling of climate models
  - Water Evaluation and Planning (WEAP) model application and development
  - Water resources in a future climate

- Current research
  - Developing the WEAP model
  - Investigating the impact of climate change on water resource management (Denver Water, California)
  - Climate downscaling in South America

- Recent publications
- **Yates, D.**, B. Quan Luna, R. Rasmussen, D. Bratcher, L. Garrè, F. Chen, M. Tewari, and P. Friis-Hansen, 2014, Stormy weather: Assessing climate change hazards to electric power infrastructure: A Sandy Case Study, *Institute of Electrical and Electronics Engineers (IEEE) Power & Energy Magazine*, ***12***(5), 66 – 75.
- **Yates**, D., K. Miller, R. Wilby, and L. Kaatz, 2015, Decision-centric adaptation appraisal for water management across Colorado's Continental Divide, *Climate Risk Management*, accepted.

David Gochis: WRF-Hydro, NWS National Water Model, North American Monsoon, and Winter Snowpack

- Research background
  - Coupling of hydrology and climate models
  - Development of computationally efficient quasi-dynamical downscaling tool
  - Development of hydrologic measurement techniques
  - Investigations of uncertainty in climate change.
- Current research
  - Developing the NWS National Water Model
  - Leading the development of the WRF-Hydro framework
  - Investigating the distribution of snowpack in complex terrain and impact on streamflow
  - Understanding the impacts of climate change on regional water resources
- Recent publications

- **Gochis, D.J.**, R. Schumacher, K. Friedrich, N. Doesken, M. Kelsch, J. Sun, K. Ikeda, D. Lindsey, A. Wood, B. Dolan, S. Matrosov, K. Mahoney, S. Rutledge, R. Johnson, P. Kucera, P. Kennedy, D. Sempere-Torres, M. Steiner, R. Roberts, J. Wilson., W. Yu, V. Chandrasekar, R. Rasmussen, A. Anderson, B. Brown, 2014: The Great Colorado Flood of September 2013, In Press. *Bull. Amer. Meteorol. Soc.*

Julie Vano: Connecting climate science and water resource applications

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- Research background
  - Hydrologic modeling and hydrologic sensitivities to temperature and precipitation change
  - Climate change impacts on water systems
  - Science policy
- Current research
  - Understanding the impacts of climate change on water resources
  - Developing techniques and tools to better connect and improve the utility of climate science in water resource applications
  - Developing guidance for users of climate change information
- Recent publications
  - Vano, JA, JB Kim, DE Rupp, and PW Mote, 2015: Selecting climate change scenarios using impact-relevant sensitivities, Geophysical Research Letters, in press, doi: 10.1002/2015GL063208
  - Vano, JA, B Nijssen, and DP Lettenmaier, 2015: Seasonal hydrologic responses to climate change in the Pacific Northwest, *Water Resources Research*, 51(4), 1959-1976, doi:10.1002/2014WR015909
  - Vano, JA, B Udall, DR Cayan, JT Overpeck, LD Brekke, T Das, HC Hartmann, HG Hidalgo, M Hoerling, GJ McCabe, K Morino, RS Webb, K Werner, and DP Lettenmaier, 2014: Understanding Uncertainties in Future Colorado River Streamflow, *Bulletin of the American Meteorological Society*, 95, 59-78, doi: 10.1175/BAMS-D-12-00228.1

Andy Wood: Hydrologic modeling applications: streamflow forecasting, climate change, drought

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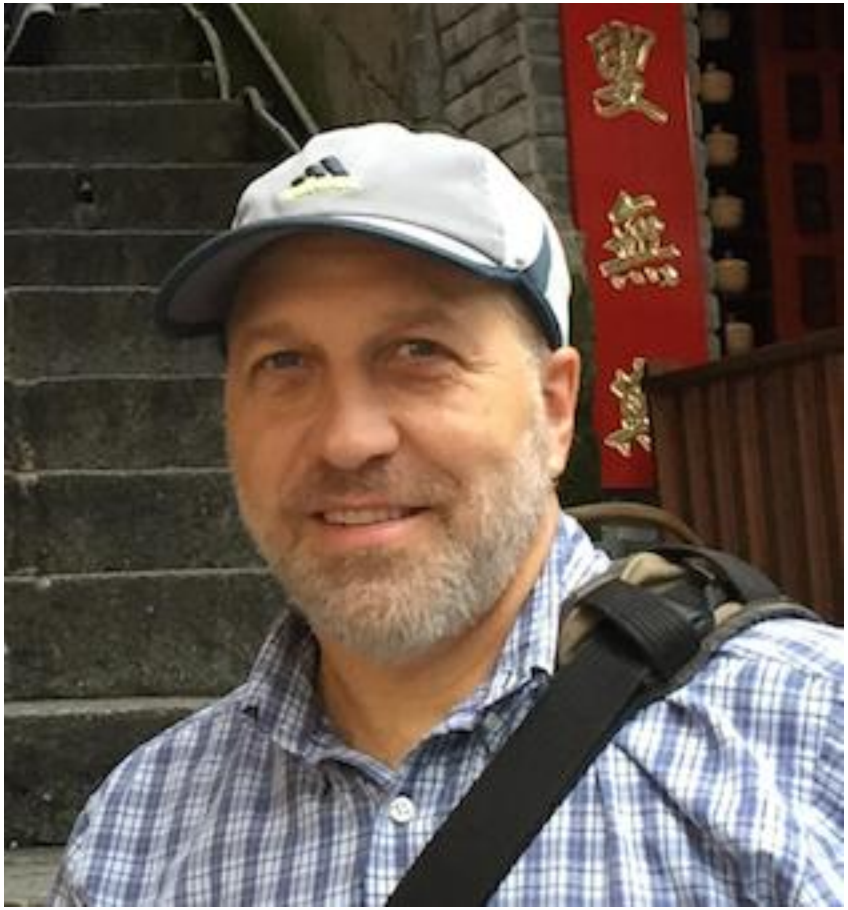

- Research background
  - Development & application of **statistical downscaling** methods for climate change impact assessment
  - Application of modern LSMs for **drought monitoring and prediction**
  - Development of approaches for **real-time streamflow prediction** from short to seasonal scales
- Current research
  - Developing methods to improve **streamflow forecasts** through application of modern models, data, and techniques for uncertainty quantification
  - Understanding the **impacts of climate change** on regional water resources
  - Improving **drought prediction** though subseasonal climate forecasting
- Recent publications
  - Wood, AW, T Hopson, A Newman, L. Brekke, J. Arnold, M Clark, 2016, **Quantifying streamflow forecast skill elasticity to initial condition and climate prediction skill.** *J. Hydromet*. **17**, 651–668. doi: http://dx.doi.org/10.1175/JHM-D-14-0213.1 .
  - Emerton, R, EM Stephens, F Pappenberger, TC Pagano, AH Weerts, AW Wood, P Salamon, JD Brown, N Hjerdt, C Donnelly and HL Cloke, 2015. **Continental and Global Scale Flood Forecasting Systems,** *WIREs Water* 3:391–418. doi: 10.1002/wat2.1137

Ethan Gutmann: Climate Downscaling, Hydrologic Processes, and Alpine Snowpack

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- Research background
  - Coupling of hydrology and climate models
  - Development of computationally efficient quasi-dynamical downscaling tool
  - Development of hydrologic measurement techniques
  - Investigations of uncertainty in climate change.
- Current research
  - Developing the Intermediate Complexity Atmospheric Research model (ICAR)
  - Investigating the distribution of alpine snowpack
  - Understanding the impacts of climate change on regional water resources
- Recent publications
  - Gutmann, E.,et al. (2014), An intercomparison of statistical downscaling methods used for water resource assessments in the United States, *Water Resources Research*, *50*(9), 7167–7186, doi:10.1002/2014WR015559.
  - Gutmann, E., et al. (2016), The Intermediate Complexity Atmospheric Research Model (ICAR), *J. Hydrometeor*, *17*(3), 957–973, doi:10.1175/JHM-D-15-0155.1.
  - Clark et al. (2016), Characterizing uncertainty of the hydrologic impacts of climate change. *Current Climate Change Reports*, 1-10, doi: 10.1007/s40641-016-0034-x

Andrew Newman: Observations and Uncertainty, Land-Surface and Mesoscale Modeling

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- Research background
  - Convective permitting simulations of North American Monsoon Precipitation Events
  - Land-surface sub-grid scale representativeness
  - Hydrometeorlogical dataset generation
  - Frozen phase cloud microphysics
- Current research
  - Developing hydrometeorlogical datasets
  - Investigating land-surface and hydrological model benchmarking, agility, and parameter estimation
  - Analyzing and diagnoising errors in atmospheric model output
- Recent publications
  - **Newman, A. J.**, and co-authors, 2015: An observationally based gridded ensemble of precipitation and temperature data for the contiguous USA., *J. Hydrometeorology*, doi:10.1175/JHM-D-15-0026.1.
  - **Newman, A. J.**, and co-authors, 2015: 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 Science*, 19, 209-223, doi:10.5194/hess-19-209-2015.
  - **Newman, A. J.**, M. P. Clark, A. Winstral, D. Marks, and M. Seyfried, 2014: The use of similarity concepts to represent sub-grid variability in hydrologic and land-surfacemodels: Case study in a snowmelt dominated watershed, J. Hydrometeorology, 15, 1717-1738.

Naoki Mizukami: Large scale Hydrologic modeling: water resource applications, climate impacts

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- Research background
  - Large-scale snow distribution.
  - Snow model parameter estimations
  - Evaluation of effects of meteorological forcing on Hydrologic simulations.
- Current research
  - Evaluating methodological impact on continental scale hydrologic simulations.
  - Developing methods to estimate spatially continuous hydrologic model parameters over contiguous United States.
  - Improving continental scale river routing model.
- Recent publications
  - Mizukami, N., M. Clark, E. Gutmann, P. Mendoza, A.J. Newman, B. Nijssen, B. Livneh, L.E. Hay, J.R. Arnold, and L.D. Brekke, 2016: Implications of the methodological choices for hydrologic portrayals of climate change over the contiguous United States: Statistically downscaled forcing data and hydrologic models. *Journal of Hydrometeorology*, **17**, 73-98, DOI: 10.1175/JHM-D-14-0187.1.
  - 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**, 474-488, DOI:10.1175/JHM-D-13-036.1.

Keith Musselman: observation and numerical prediction of cold region hydrological processes

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- Research background
  - Energy balance snow modeling in discontinuous forests
  - Evaluation of forest – snow interactions
  - Development of methods for spatial prediction of shortwave canopy transmittance using airborne lidar
- Current research
  - Evaluating and improving hydrological model simulations of cold region processes
  - Understanding the impacts of climate change on snow water resources
  - Development of fine-scale hydrometeorological models for simulation of forest disturbance impacts
  - Regional and large-scale snowmelt modeling
- Recent publications
  - *Musselman, KN, Pomeroy, JW, Essery, RLH, and Leroux, N (2015), Impact of windflow calculations on simulations of alpine snow accumulation, redistribution and ablation. Hydrol. Process., 29, 3983–3999. doi: 10.1002/hyp.10595.*
  - Musselman, K.N., J.W. Pomeroy, T.E. Link (2015), Variability in shortwave irradiance caused by forest gaps: Measurements, modelling, and implications for snow energetics. Agricultural and Forest Meteorology, 207, 69-82.
  - Musselman, K.N., S.A. Margulis, and N.P. Molotch (2013), Solar direct beam transmittance of conifer canopies from airborne LiDAR. Remote Sensing of Environment. 136 403-415.

Nans Addor: Hydrological modeling under present and future climate

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- Research background
  - Quantitative assessment of the robustness and uncertainty sources in hydrological projections.
  - Characterization and adjustment of biases in regional climate model simulations in presence of observational uncertainty, natural climate variability and synoptic biases.
- Current research
  - Developing methods to explicitly relate catchment attributes and dominant processes to the structure of hydrological models.
  - Developing methods to systematically explore the balance between complexity and realism in conceptual to process-based hydrological models.
  - Developing process-based diagnostics for climate and hydrological models for a realistic sampling and simulation of future hydro-climatic conditions.
- Recent publications

  - Addor et al., 2016: Propagation of biases in climate models from the synoptic to the regional scale: Implications for bias adjustment. *JGR Atmos.*, doi:10.1002/2015JD024040.
  - Addor et al., 2015: The influence of natural variability and interpolation errors on bias characterization in RCM simulations, *JGR Atmos.*, doi:10.1002/2014JD022824.
  - Addor et al., 2014: Robust changes and sources of uncertainty in the projected hydrological regimes of Swiss catchments. *WRR*, doi:10.1002/2014WR015549.

Pablo Mendoza: Hydrologic modeling applications: climate change impacts, streamflow forecasting

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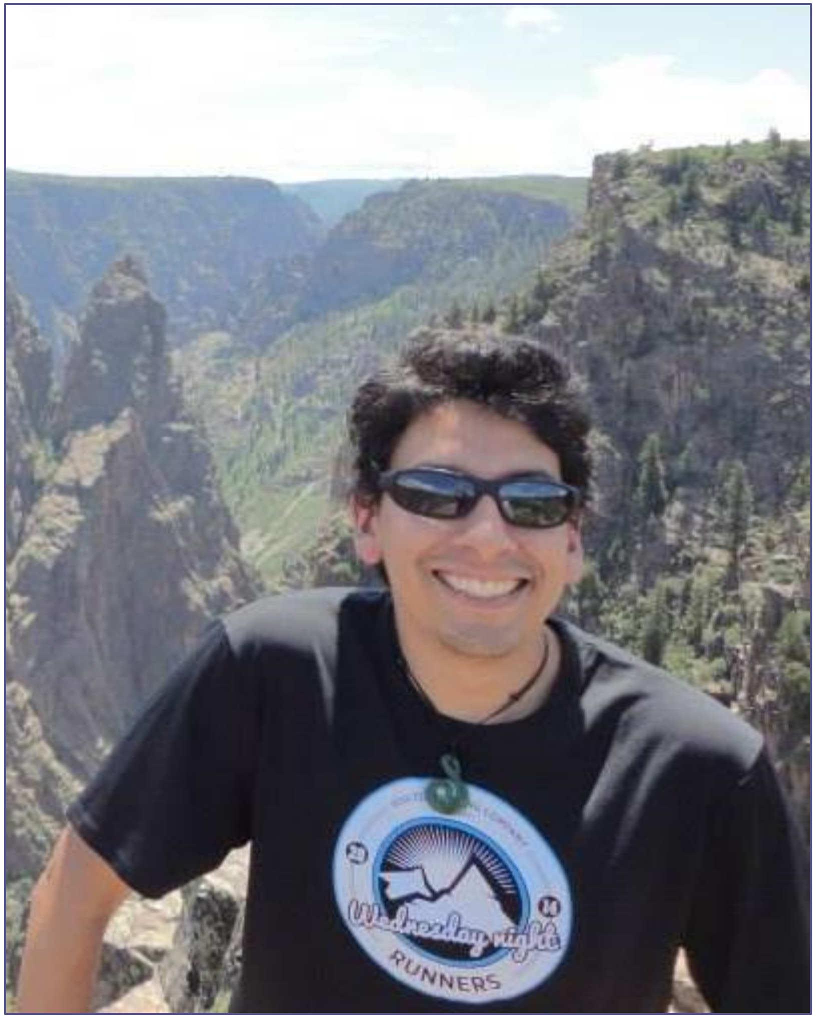

- Research background
  - Real-time flood forecasting.
  - Advanced data analysis techniques with applications on water resources.
  - Effects of hydrologic modeling decisions on the assessment of climate change impacts.
- Current research
  - Assessment of predictability from large-scale climate processes and initial hydrologic conditions on seasonal streamflow forecasts.
  - Inter-comparison of seasonal streamflow forecasting techniques.
  - Evaluation of methodological impacts on projected hydrologic changes at the basin scale.
- Recent publications
  - **Mendoza et al.** (2016) How do hydrologic modeling decisions affect the portrayal of climate change impacts? Hydrol. Process., 30: 1071–1095. doi: 10.1002/hyp.10684.
  - **Mendoza et al.** (2015), Statistical post-processing of High-Resolution Regional Climate Model Output, Mon. Wea. Rev., 143, 1533–1553, doi:10.1175/MWR-D-14-00159.1.
  - **Mendoza et al.**(2015), Are we unnecessarily constraining the agility of complex process-based models? Water Resources Research, 51, doi: 10.1002/2014WR015820 [Editor's highlighted article].

Snow cover over North America from MODIS

January 2002

http://www.archive.org/details/SVS-2487

Snow cover over North America from MODIS

March 2002

http://www.archive.org/details/SVS-2487

Snow cover in 2001-2002 over North America from MODIS

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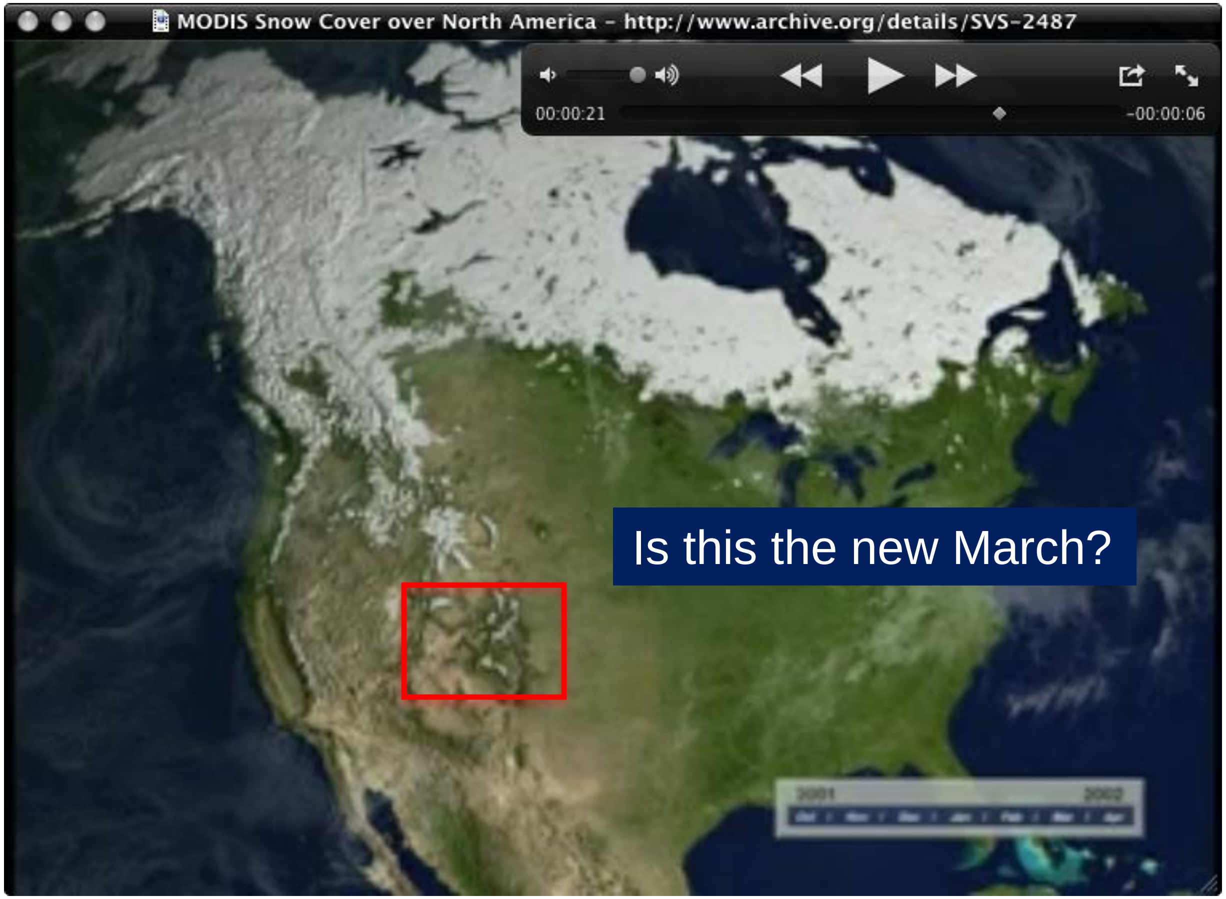
April 2002



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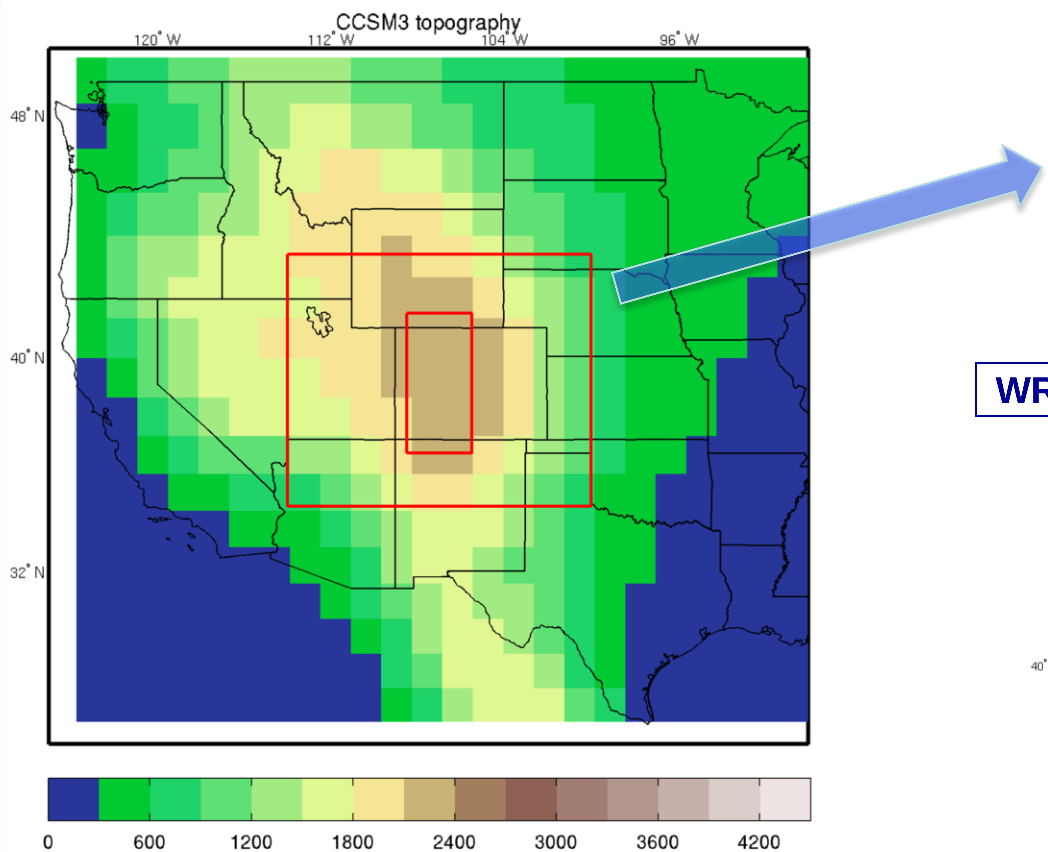
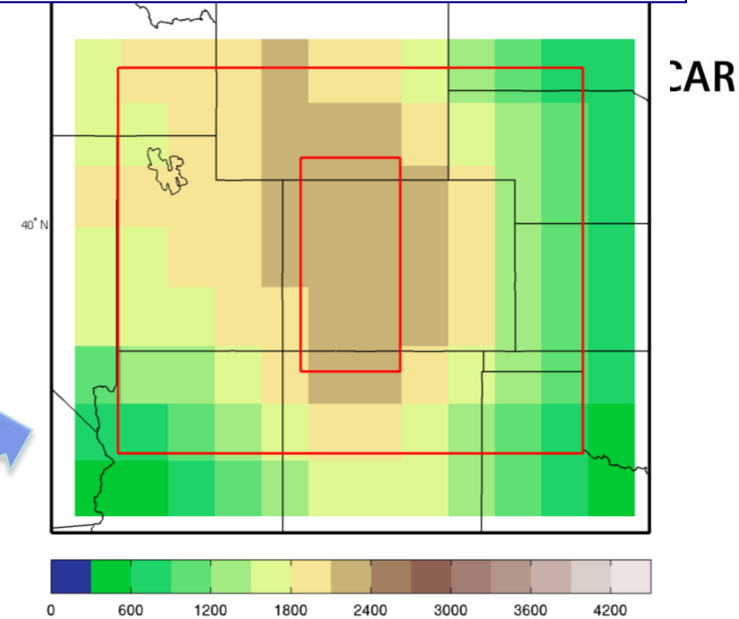
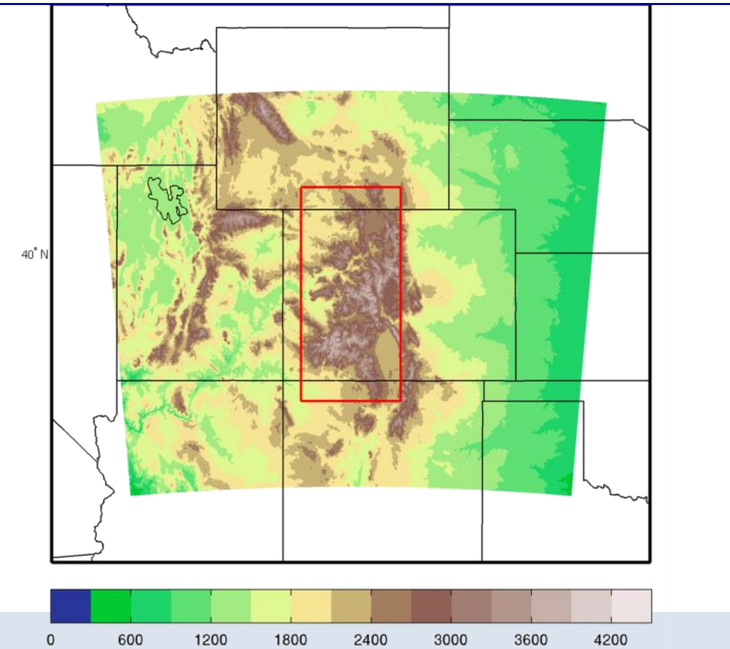
CCSM Elevation



CCSM3 MODEL TOPOGRAPHY



WRF MODEL TOPOGRAPHY at 2 KM RES.



CCSM and the 2-km WRF Elevation Profile in the CO Headwaters Domain

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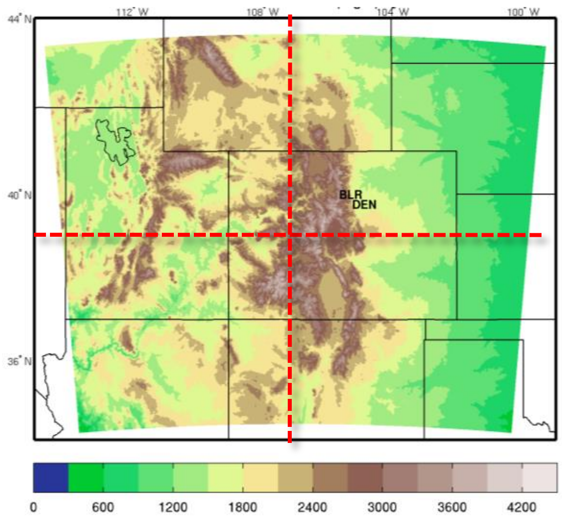

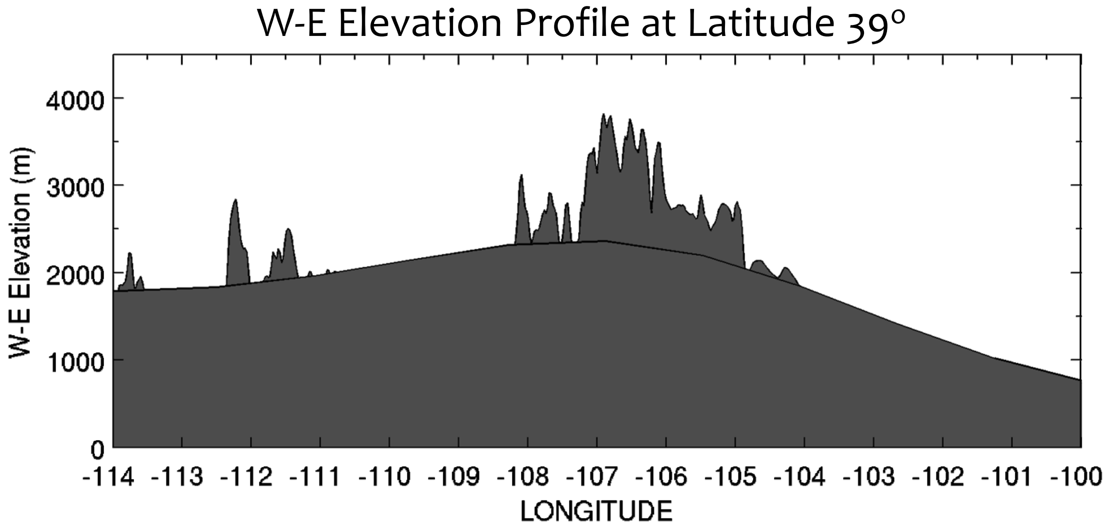

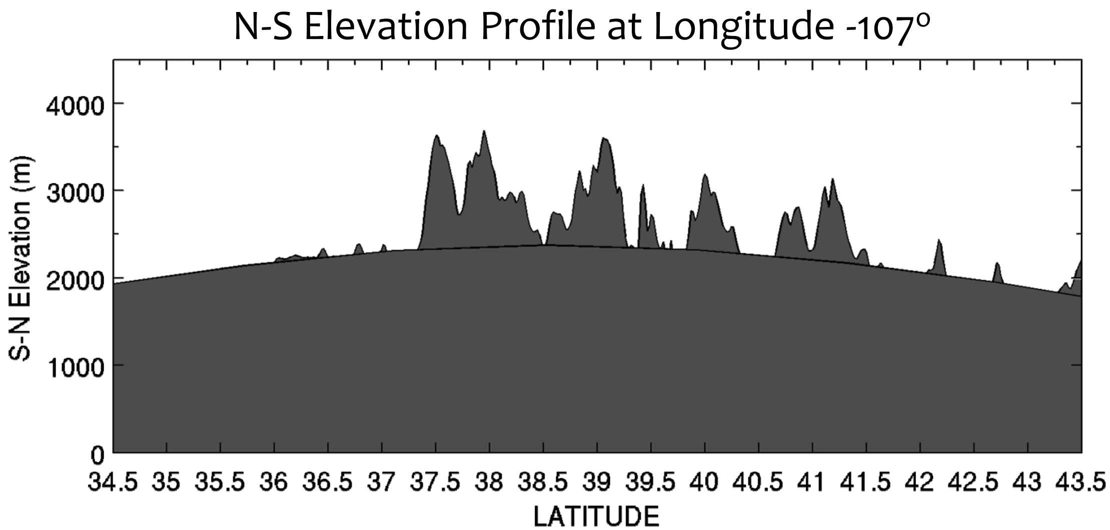

Past work: High Resolution Simulations of the Colorado Headwaters snowfall, snowpack and runoff

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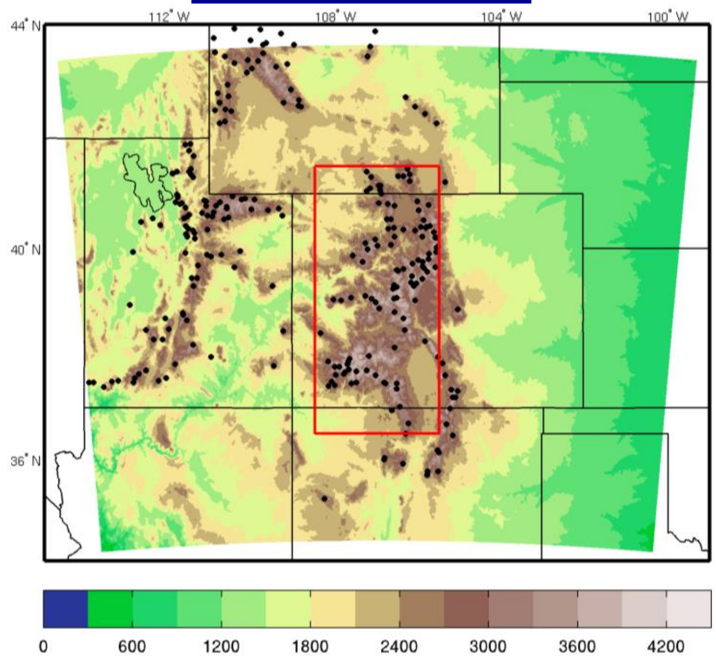
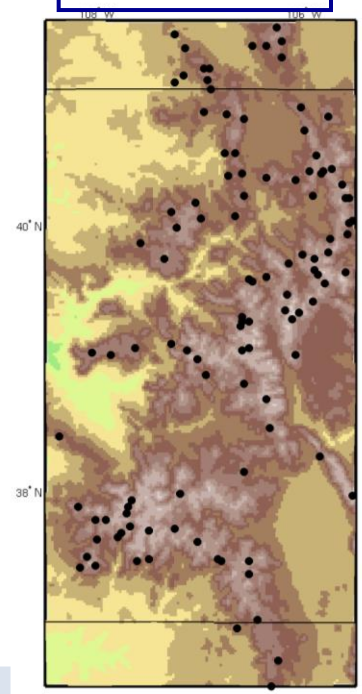
1. Performed past climate simulations using high resolution WRF model
   - Grid spacing: 4 km.
   - Continuous eight years: 2000 – 2008
2. Verified results of WRF integrations using NRCS SNOTEL data and showed that grid spacing of at least 6 km needed to faithfully reproduce the spatial pattern and amount of precipitation (Rasmussen et al. 2011, J. Climate).
3. Investigate enhancement of water cycle by adding CCSM 10 year mean temperature and moisture perturbation from 50 year future A1B simulations from AR4 runs to NARR boundary conditions

Full Domain



Headwaters domain



● SNOTEL sites

WRF model able to reproduce the amount and spatial distribution of snowfall and snowpack over a winter season over the Colorado Headwaters at spatial resolutions less than 6 km

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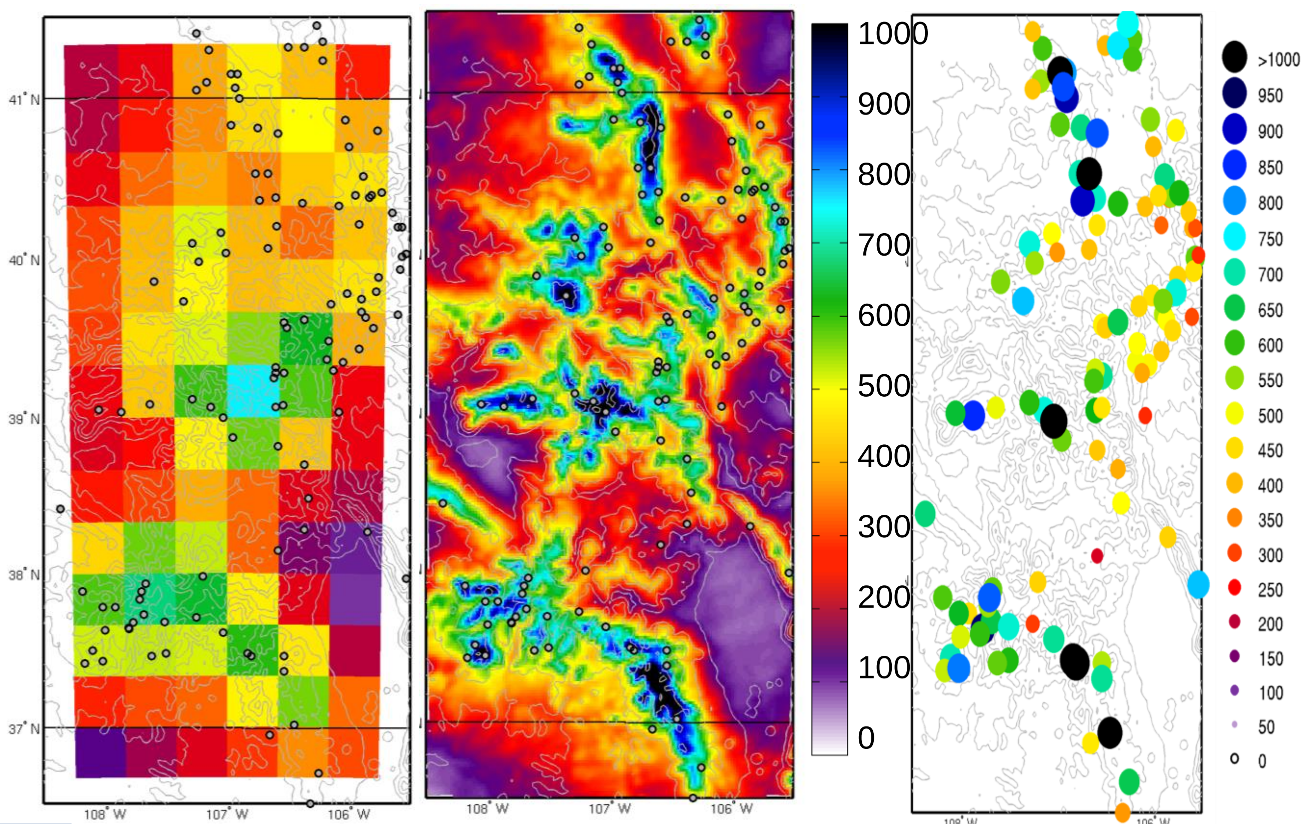
36 km | 2 km | SNOTEL Obs.



6-mo. Total Precipitation (mm) Comparison
1 Nov. 2007-1 May 2008

SNOTEL Precip gauge

Ikeda et al, 2010, Rasmussen et al. 2011

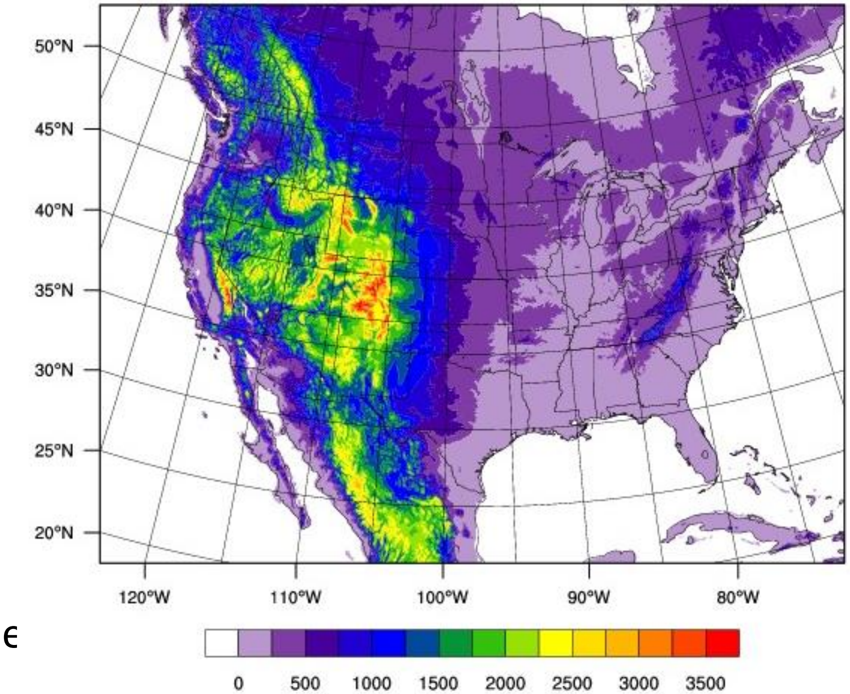
Science Objectives of the CONUS Project

- To evaluate WRF's ability to capture orographic precipitation/ snowpack in western US, convective precipitation in eastern US and hurricanes in the gulf of Mexico.
- To assess future changes of snowfall/snowpack and associated hydrological cycles.
- To examine precipitation changes under the CMIP5 projected global warming, including extremes and warm-season precipitation.

Weather Research and Forecast Regional Climate Model Setup over CONUS

- V3.4.1 WRF model with a 4-km-spacing domain of ***1360*x*1016*x*51*** points
- Physics parameterizations:
  1. Thompson aerosol-aware microphysics
  2. Noah-MP LSM
  3. YSU PBL
  4. RRTMG radiation
- Use of spectral nudging to re-analysis of climate simulation above PBL
- Other features: MODIS green fraction; terrain slope impact on radiation; in-land water temperature treatment
- CMIP5 (19) model ensemble mean climate from RCP8.5 runs
  - Taking the mean of many models helps eliminates natural variability due to climate modes not part of GHG forcing

WRF Model Domain



Efforts to improve WRF high-resolution climate simulations

1. Computing requirements
   - Obtained 42M core hours on NCAR Yellowstone supercomputer
2. Significant model deficiencies found in test runs led to an intensive effort to improve the model over the CONUS domain.

	Improvements
Noah-MP LSM	1. Rain-snow partitioning using microphysics scheme 2. Vegetation-dependent snow fraction/melt curves 3. Allowing snow to be present at above 0^oC 4. Heat advection by precipitation 5. Bug fix for canopy snow unloading and snow density
Microphysics	Aerosol emission refinement, variable cloud droplet initiation though inclusion of cloud condensation nuclei prognostic equations (Thompson and Eidhammer 2014)
Re-analysis tests	NARR, CFSR, and ERA-Interim tested. ERA-Interim chosen.
Spectral nudging	testing and parameter adjusting

CONtinental US (CONUS) High Resolution Climate Change Experiments (4 km grid spacing)

- **EXP1**: Retrospective/Control simulation
  - forced with ERA-I reanalysis
  - 13-year integration: *Oct. 1 2000 – Oct. 1 2013*

- **EXP2**: Pseudo-Global Warming (PGW) simulation
  - forced with ERA-I plus climate perturbation
  - $\Delta_{RCP8.5} = CMIP5_{2071\text{-}2100} - CMIP5_{1976\text{-}2005}$
  - 13-year integration

Pseudo Global Warming Approach Used

Schär et al (1996), Sato et al. (2007), Hara et al. (2008), Kawase et al. (2009)

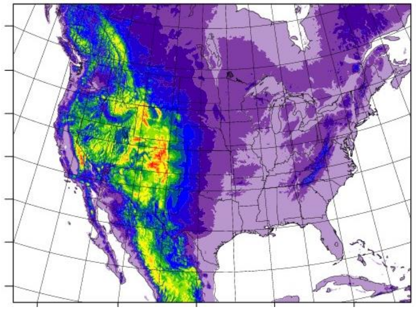
- Compute 30-year CMIP5 19 model ensemble monthly mean
  - Historical period : *1976-2005*   Future period (RCP8.5): *2071-2100*
- Compute perturbation – difference between two climates
- Add perturbation to the 6-hrly ERA-I data

Monthly mean of **historical** condition **CMIP5 1976-2005**

Monthly mean of **future** condition **CMIP5 2071-2100**

WRF Inputs for Future Climate Simulation

Monthly perturbation of CMIP5 ensemble mean + 6 hourly ERA-I data



WRF MODEL

- Variables changed: **U, V**, **T**, **geopot. hgt.**, $\mathbf{P_{sfc}}$ and $\mathbf{Q_v}$
- No change in storm tracks. Same transient spectra as current climate.

CONtinental US (CONUS) High Resolution Climate Change Experiments (4 km grid spacing)

- **EXP1**: Retrospective/Control simulation
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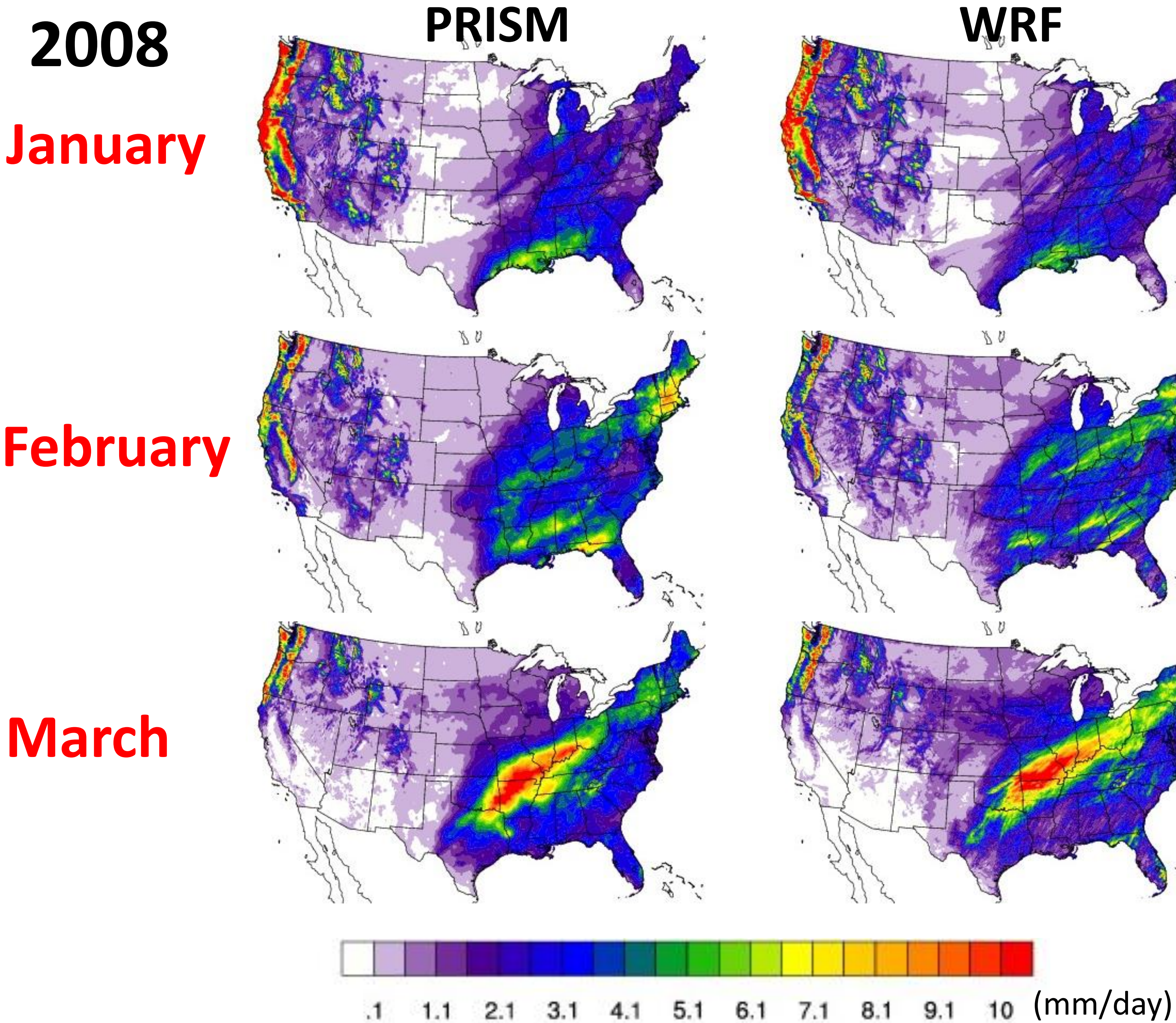
  - 13-year integration: *Oct. 1 2000 – Oct. 1 2013*

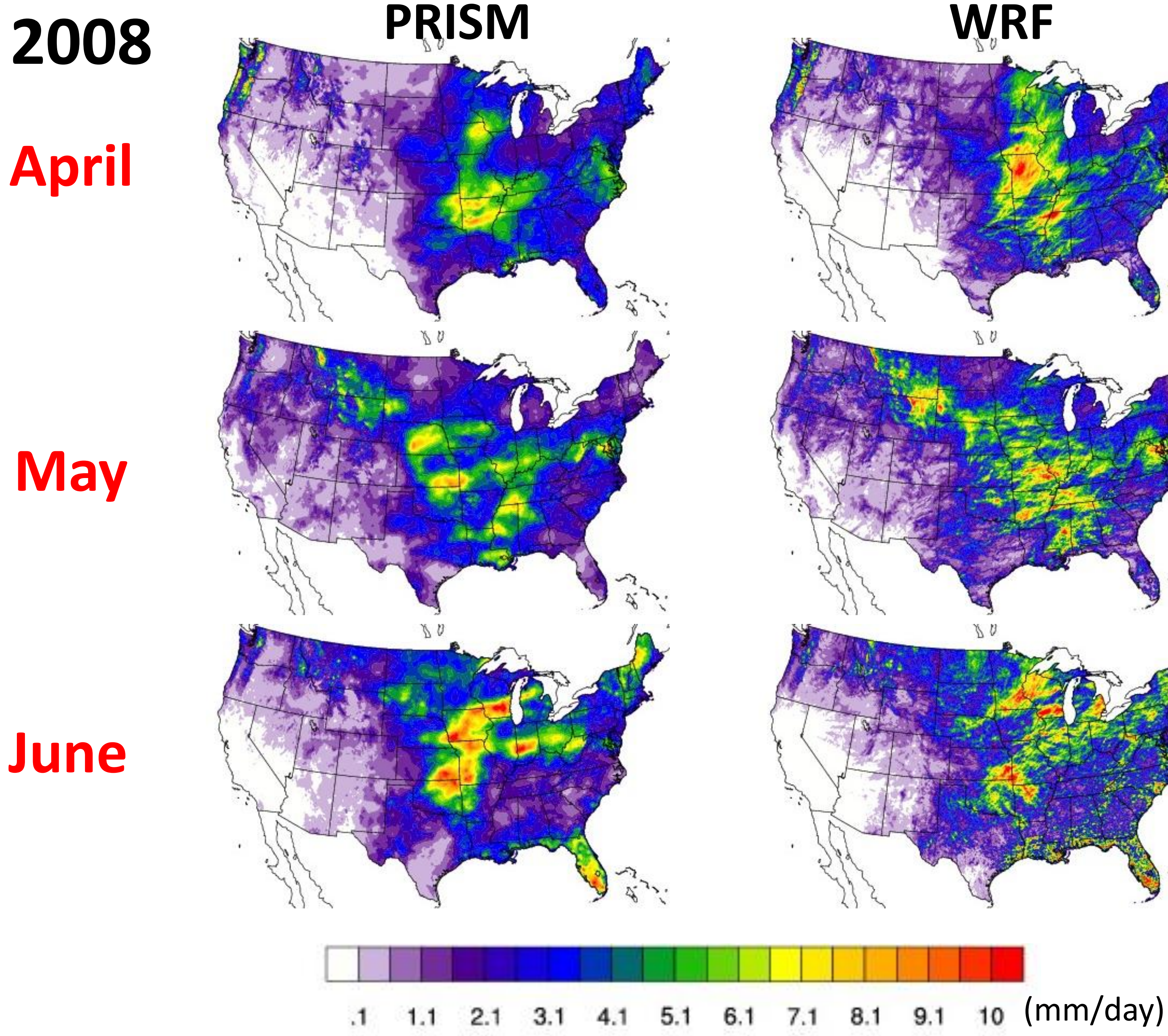
Completed April 2016!

- **EXP2**: Pseudo-Global Warming (PGW) simulation
  - forced with ERA-I plus climate perturbation
  - $\Delta_{RCP8.5} = CMIP5_{2071\text{-}2100} - CMIP5_{1976\text{-}2005}$
  - 13-year integration

Comparison of monthly precipitation

between WRF and PRISM for 2008


2008
PRISM
WRF
January
February
March
.1
1.1
2.1
3.1
4.1
5.1
6.1
7.1
8.1
9.1
10
(mm/day)


2008
PRISM
WRF
April
May
June
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2.1
3.1
4.1
5.1
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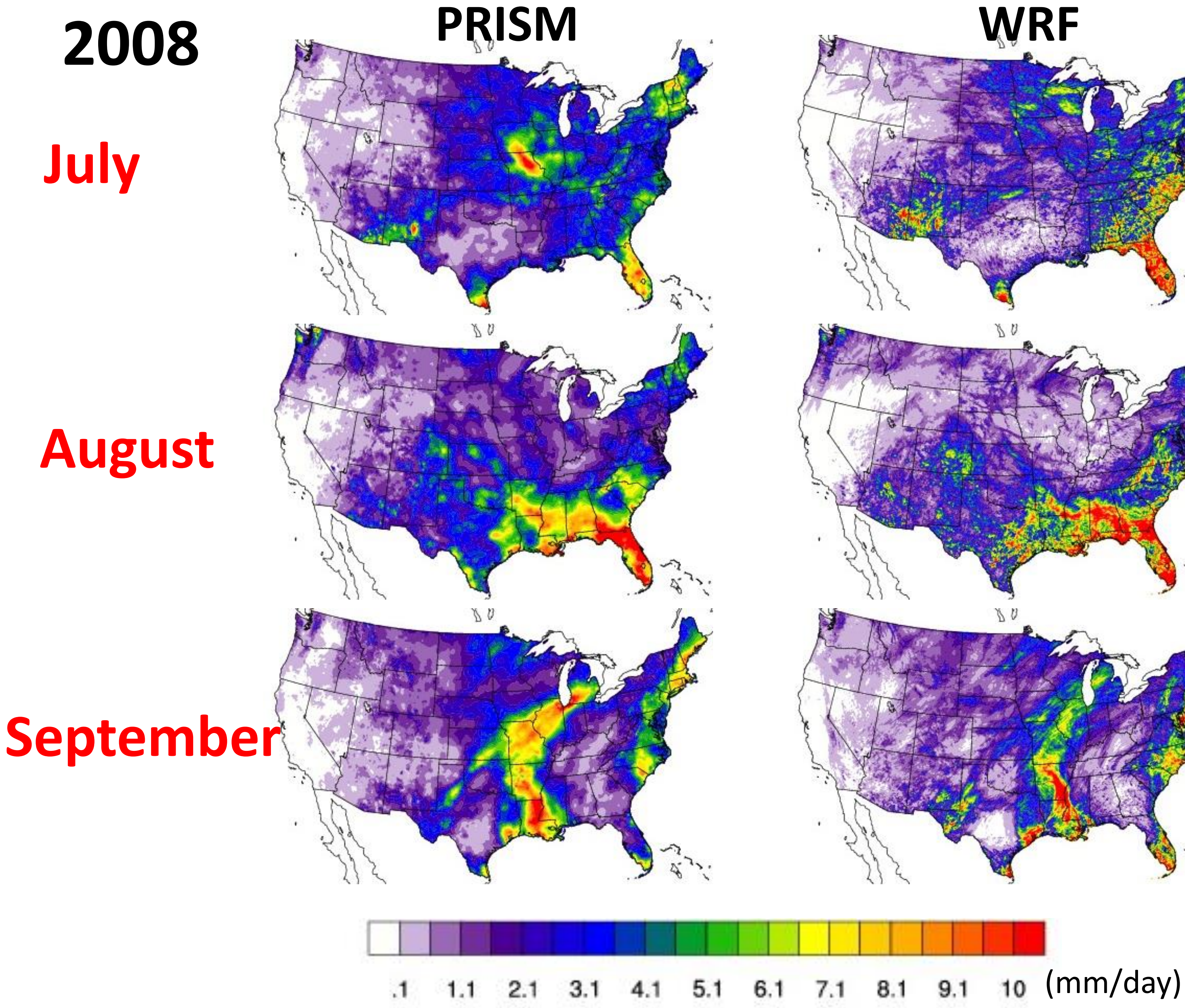
7.1
8.1
9.1
10
(mm/day)



2008
PRISM
WRF
July
August
September
.1
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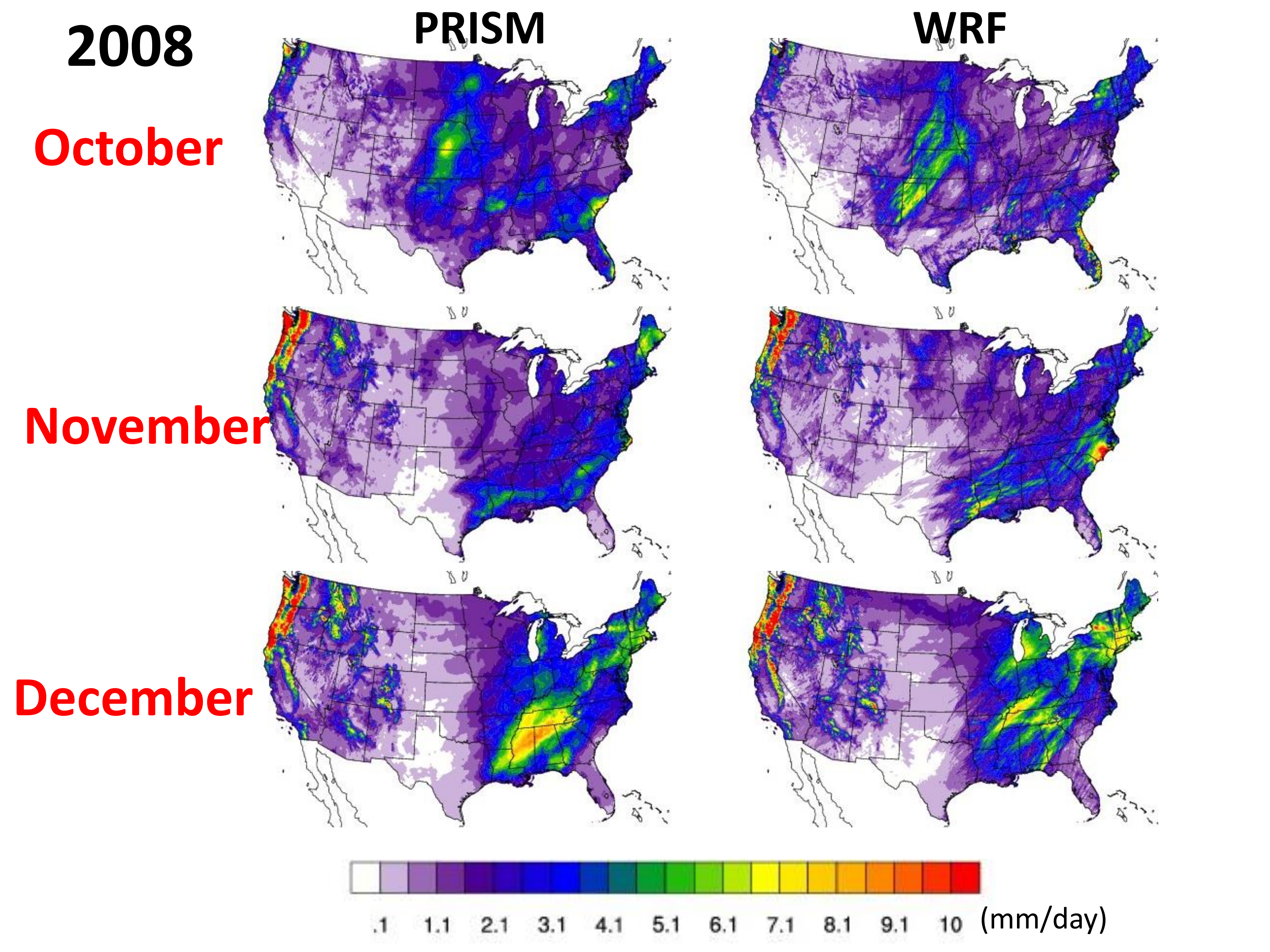
10
(mm/day)


2008
PRISM
WRF
October
November
December
.1
1.1
2.1
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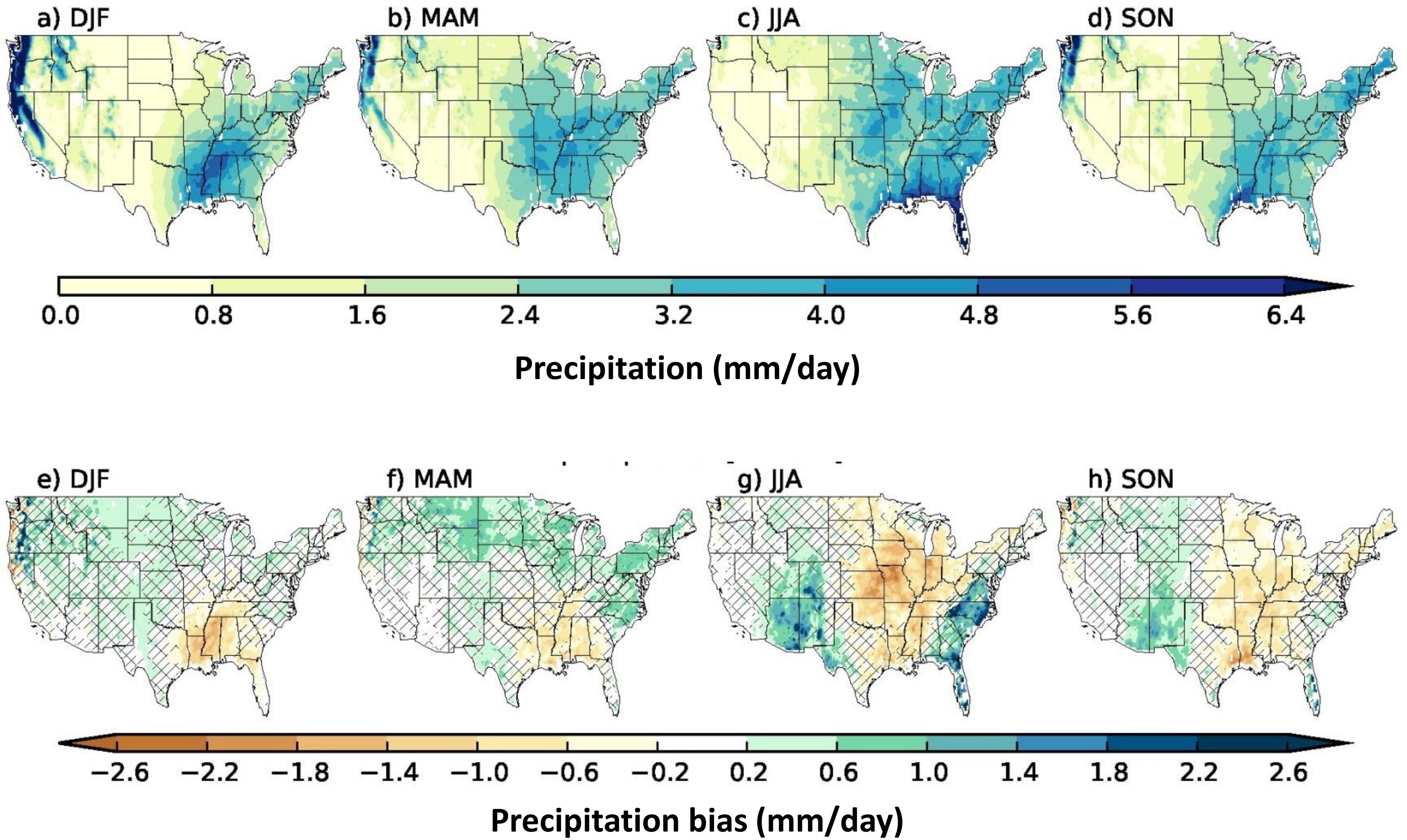
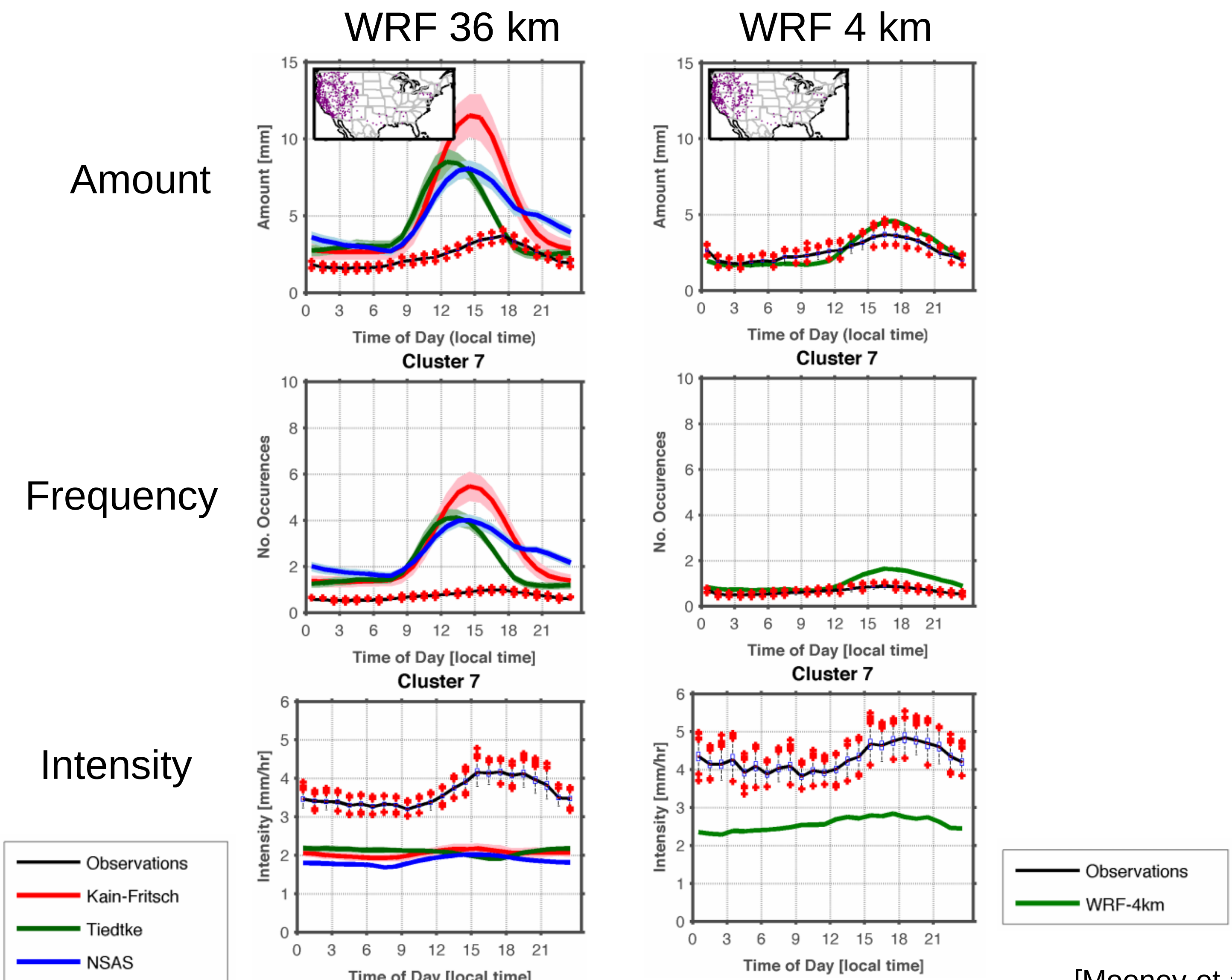
6.1
7.1
8.1
9.1
10
(mm/day)

PRISM observations averaged over 2001-2008



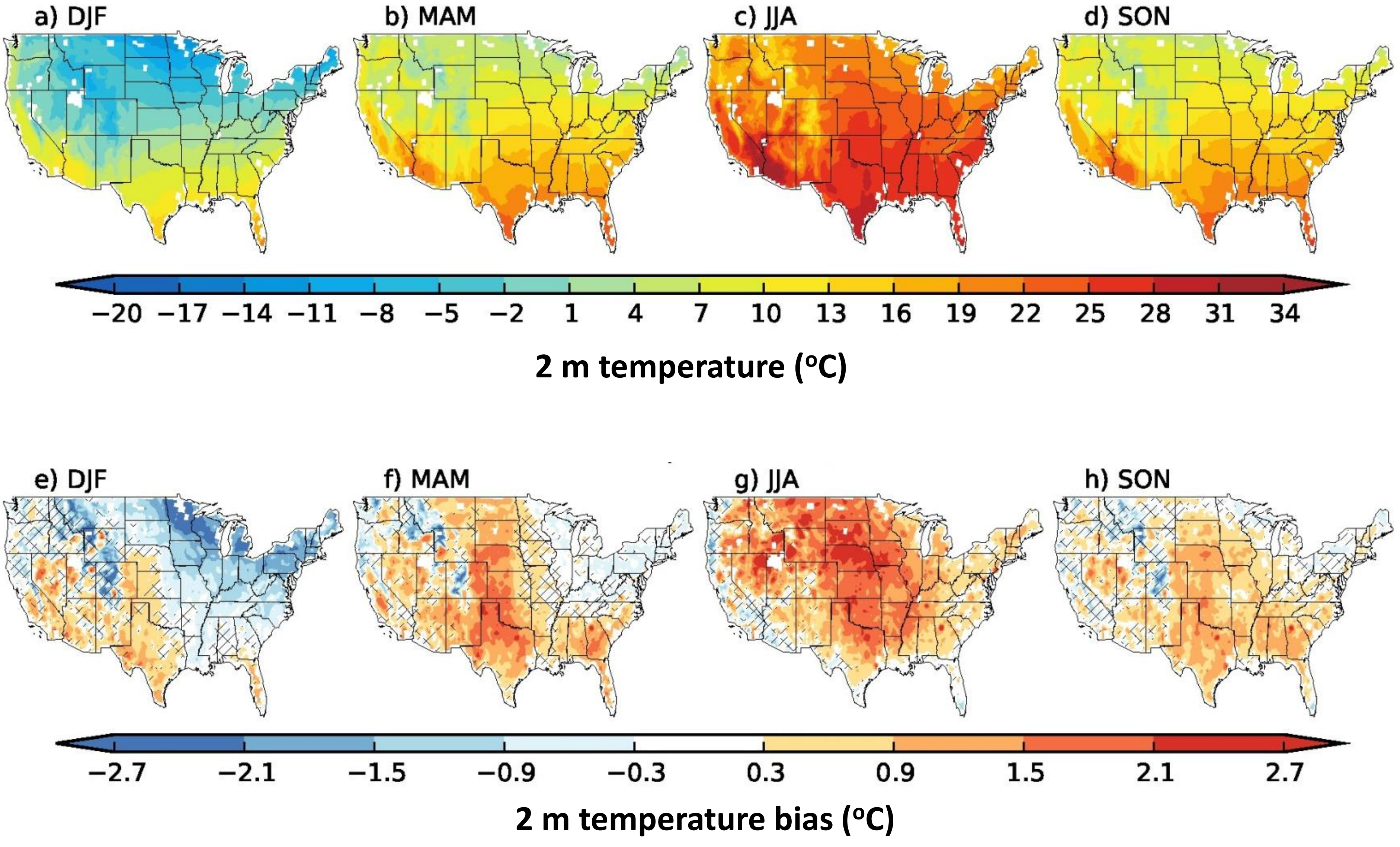
Courtesy of Andreas Prein

Summertime rainfall diurnal cycle in Western U.S.



[Mooney et al. 2016]

PRISM observations averaged over 2001-2008



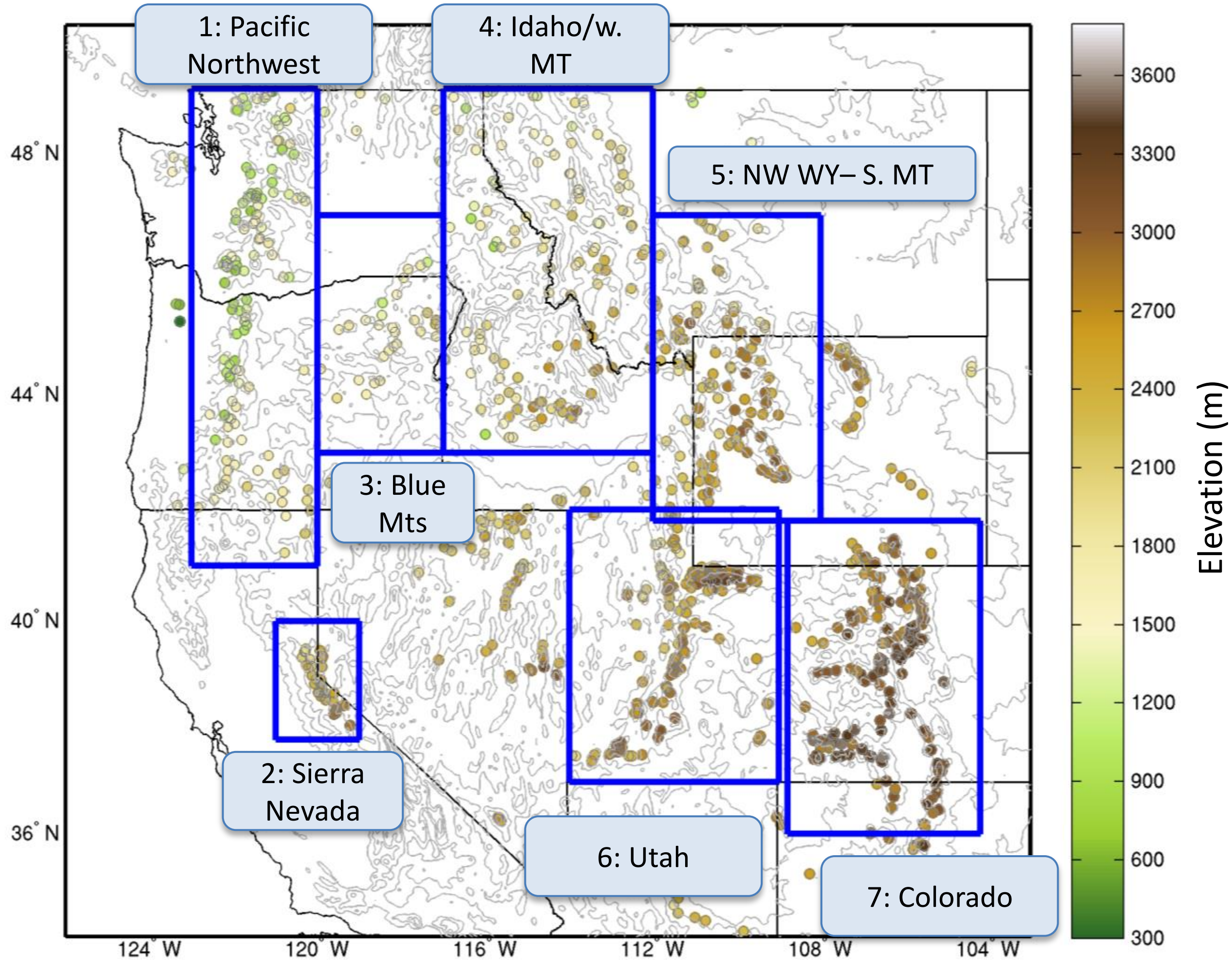
Courtesy of Andreas Prein

Model Evaluation at SNOTEL Sites

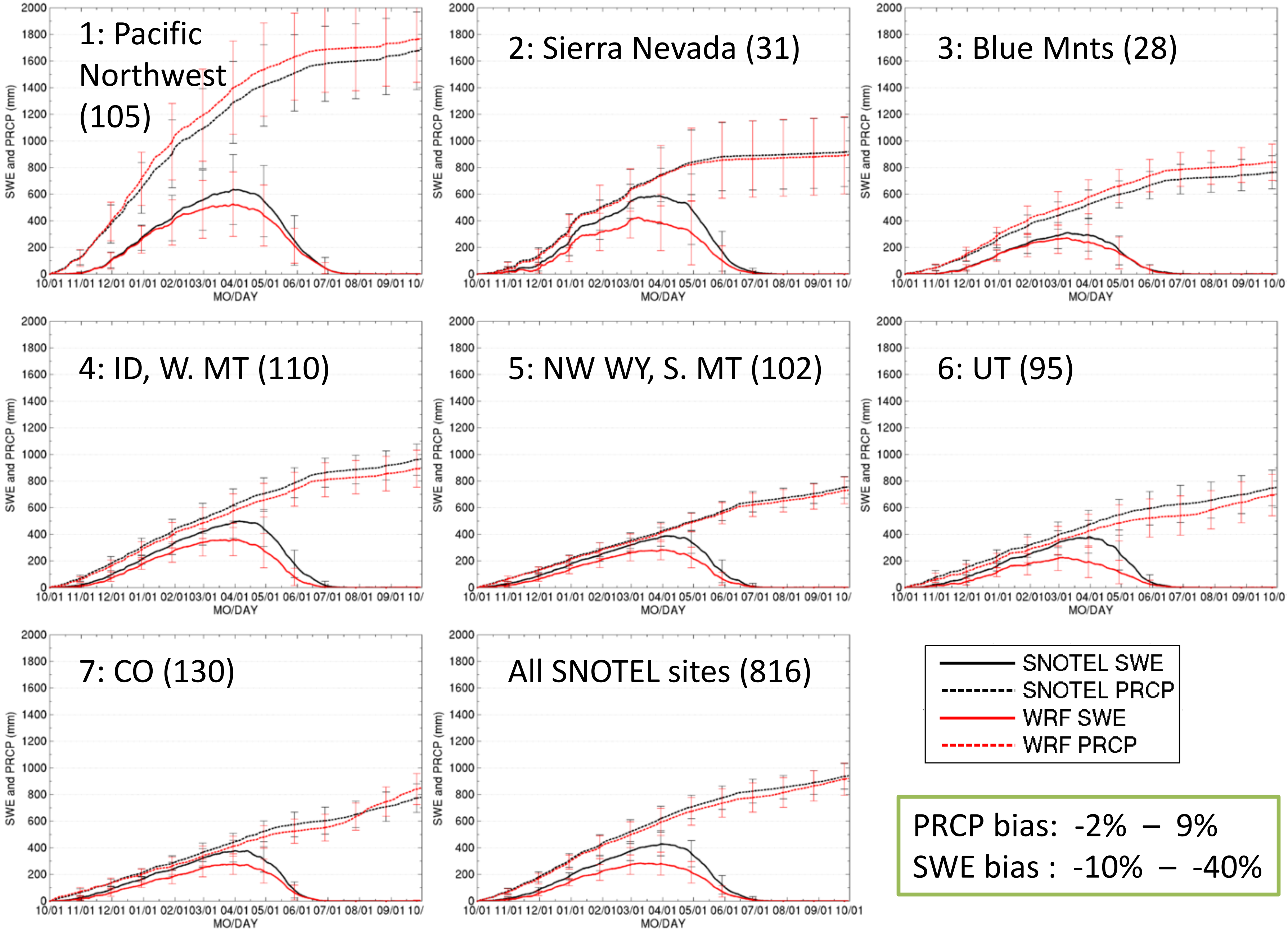
SNOTEL site at Brooklyn Lake, WY

Snow gauge

Snow pillow



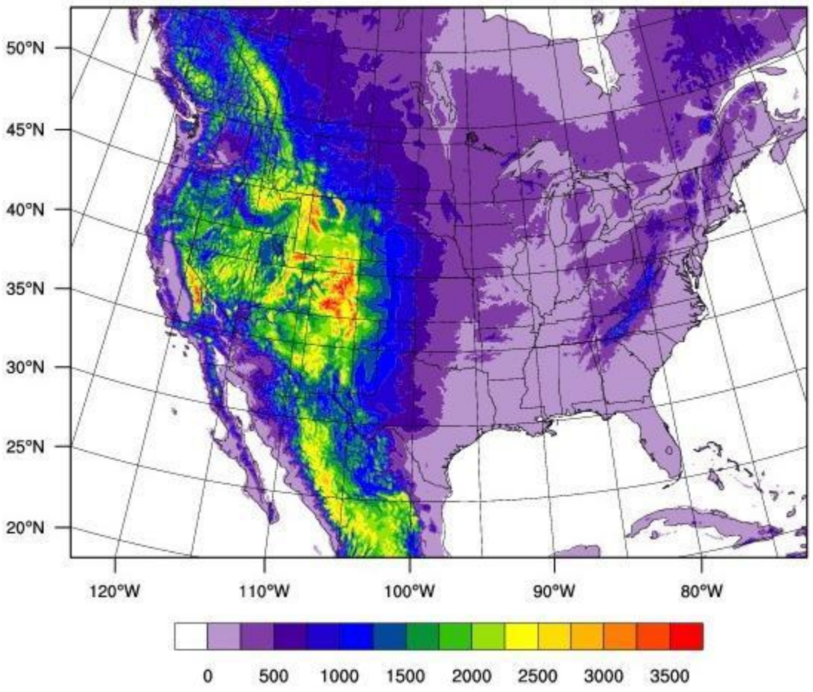
SNOTEL vs WRF at SNOTEL sites: 13-year climatology



PRCP bias: -2% – 9%

SWE bias : -10% – -40%

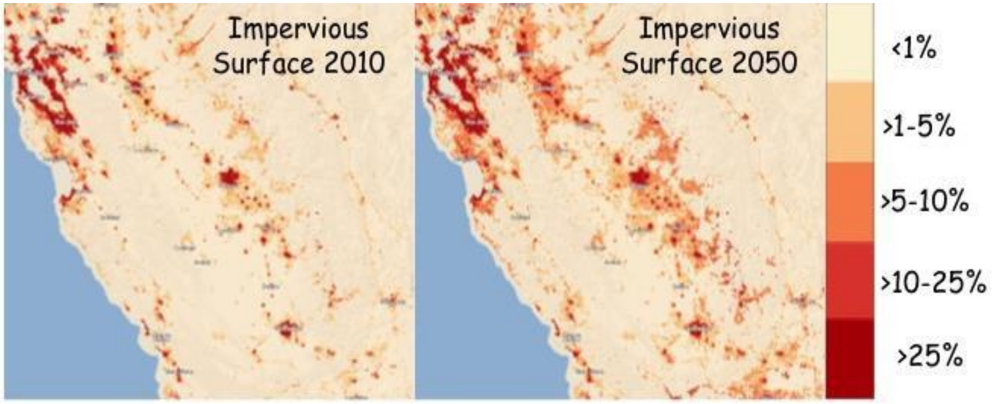
1-km WRF downscaling experiments



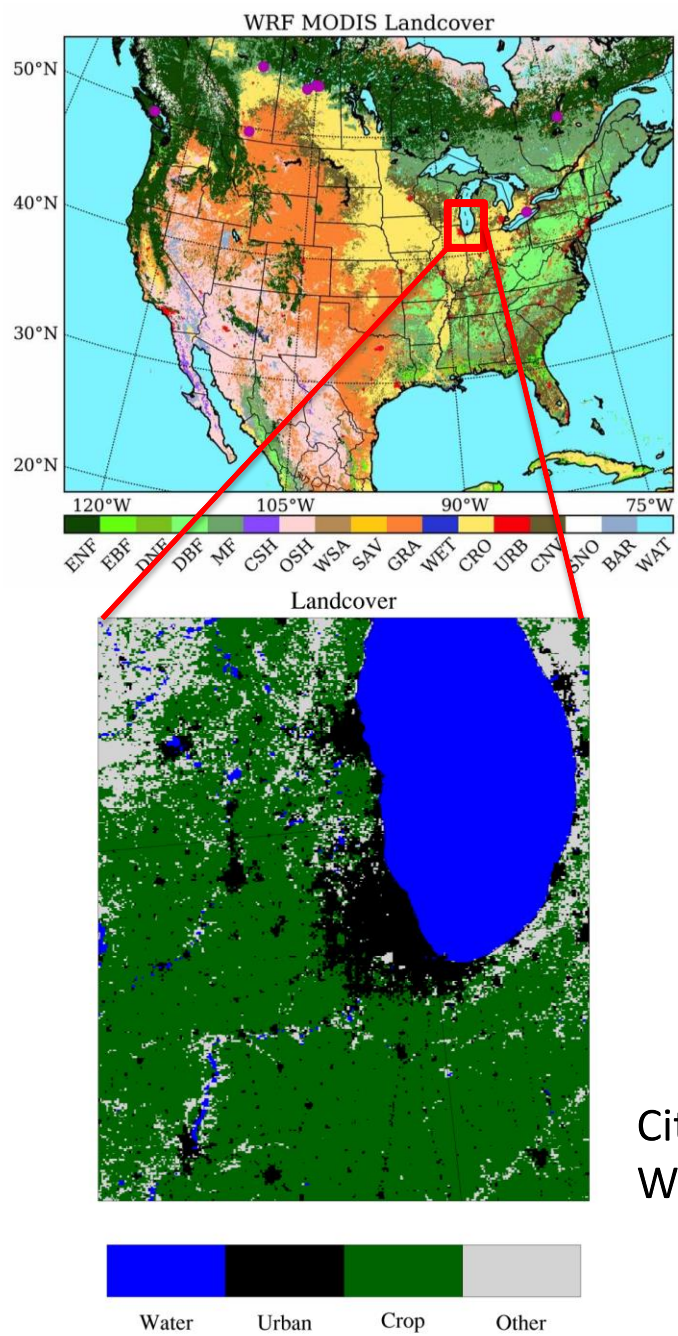
Use 4-km WRF CONUS to conduct 1-km downscaling with WRF-urban-crop modeling system for selected regions in US

- Investigate impacts of local and regional land-use change (urbanization and agriculture) on regional climate and extreme events

Urbanization in the Central Valley of California: current and projected scenario-A2 to 2050.
Source: USEPA (2010).



Example: 1km WRF downscaling for the Chicago area



Through more accurate representation of cities and cropland in 1-km WRF-urban-crop, we are interested in answering science questions:

- Would the 2006 Chicago heat wave be intensified under future climate change and land-use change
- What are integrated effects of LULC change on regional climate variability?
- What are effects of agriculture expansion and urbanization on the water and energy demands in the future?

Cities and croplands in the WRF 1-km domain

Numerical Experiments to Be Performed

- **EXP3**: CMIP5-based historical period simulation
  - Based on a **revised** bias-correction method
  - Forced with weather noise from one CESM run plus bias-corrected CMIP5 ensemble mean climate
  - 10-year integration: *2000 - 2009*
- **EXP4**: CMIP5-based future period simulation
  - Under RCP8.5 scenario
  - 10-year integration: *2090 – 2099*

Summary

- The 13 year WRF CONUS simulation at 4 km shows improved estimation of precipitation, snowfall, and snowpack as compared to 36 km simulations over the same region.

- The initial simulations for current climate and Pseudo Global Warming future climate are complete and available on GitHub from NCAR.

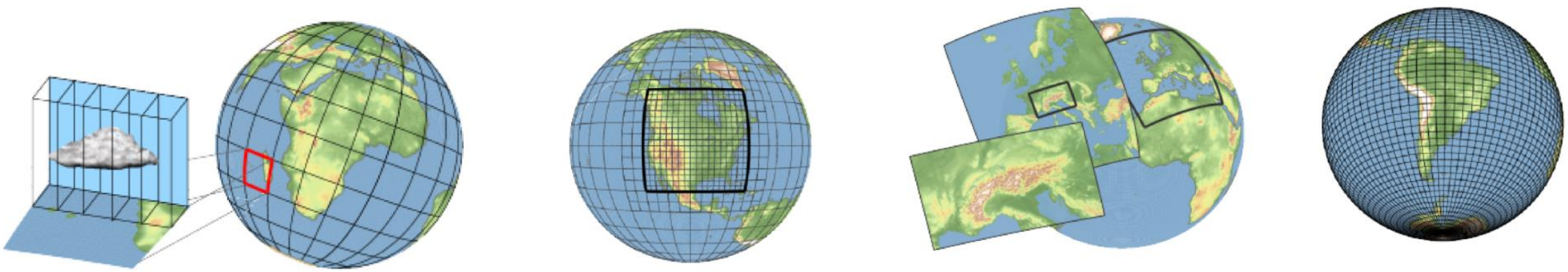
- These simulations can be used to drive even finer atmospheric and hydrological models over the CONUS region to investigate various impacts such as land cover/land use, forest fire, bark beetle, urbanization, on floods, droughts, heat waves, etc.

GEWEX

Convection-Permitting Climate Modeling Conference

September 6-8, 2016

Boulder, CO, USA



GEWEX NCAR

Scope

Adressing scientific and technical challenges related to convection-permitting climate modeling (horizontal grid spacing ≤4 km). The 3-day meeting's aim is to foster collaborations and synergies to work on this challenging topic as a community. There will be oral and poster sessions, several invited talks on key challenges, and multiple opportunities for discussions and networking.

Key Topics

- Scientific analysis of convection-permitting climate simulations
- Model setup in convection-permitting climate simulations
- Observational datasets and advanced evaluation techniques
- Using convection-permitting climate simulations in impact research
- Big-Data and future high-performance computing

Submit your Abstract now June 15, 2016

https://ral.ucar.edu/events/2016/cpcm

Thank you.

Questions?