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Convective Permitting Climate Simulations of Snowfall and Snowpack over the Western United States Including Potential Climate Change Scenarios

Presented by Roy Rasmussen

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Snow cover over North America from MODIS

January 2002

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

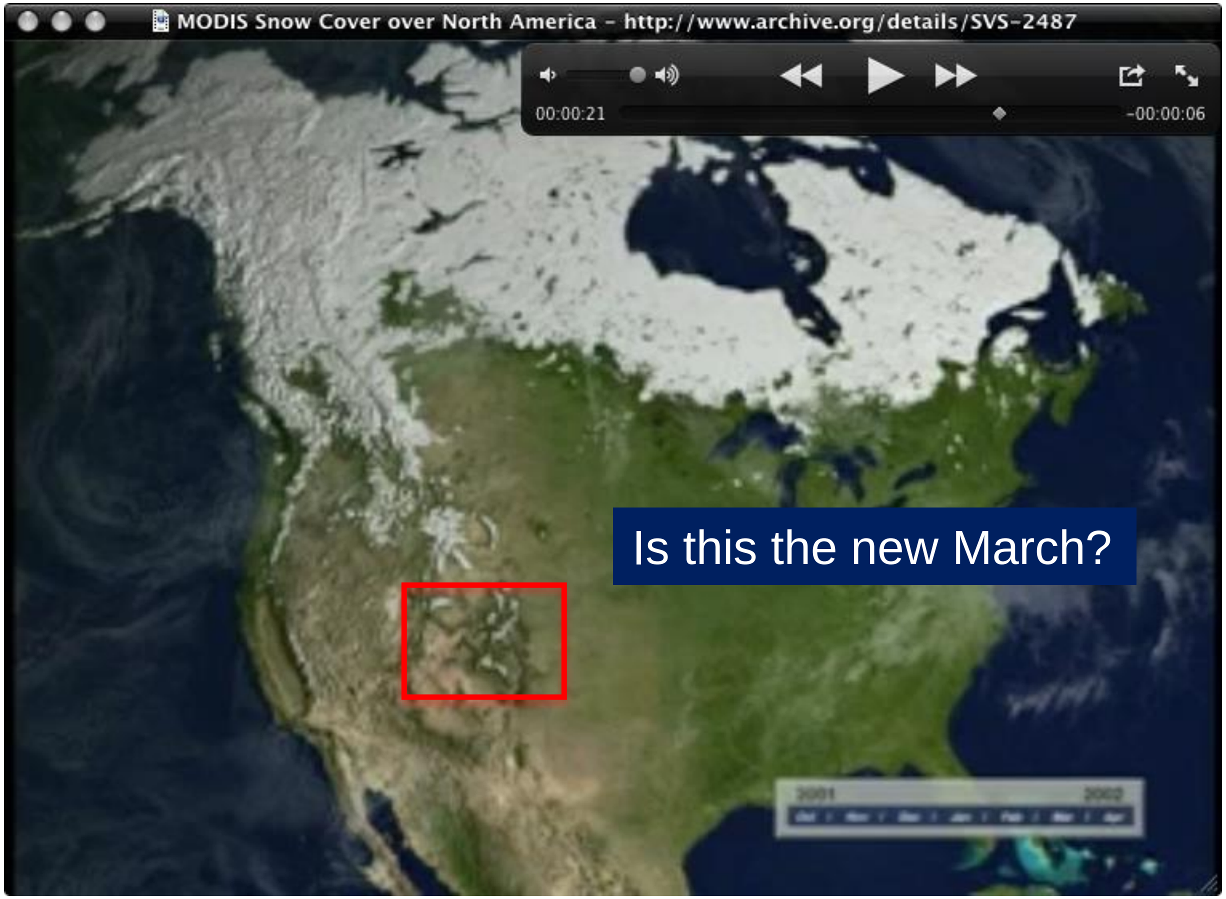
Snow cover over North America from MODIS

March 2002

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

Snow cover in 2001-2002 over North America from MODIS

April 2002



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Colorado Front Range

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

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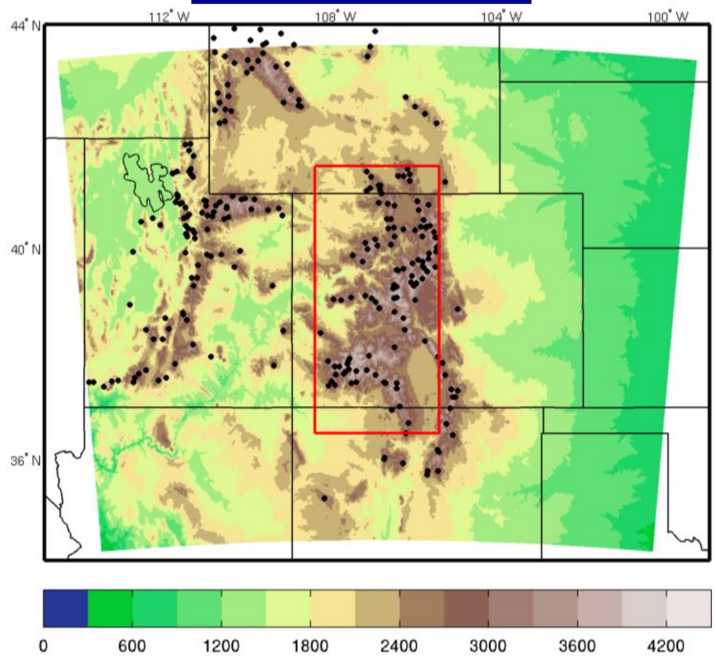
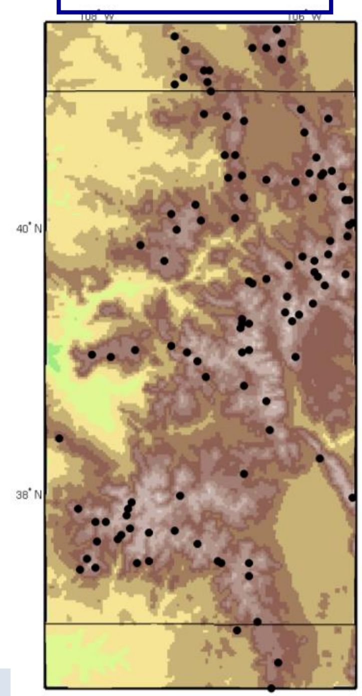
1. Performed past climate simulations using high resolution WRF model
   - Grid spacing: 4 km.
   - Continuous eight years: 2000 – 2008
2. Verified results of WRF integrations using NRCS SNOTEL data and showed that grid spacing of at least 6 km needed to faithfully reproduce the spatial pattern and amount 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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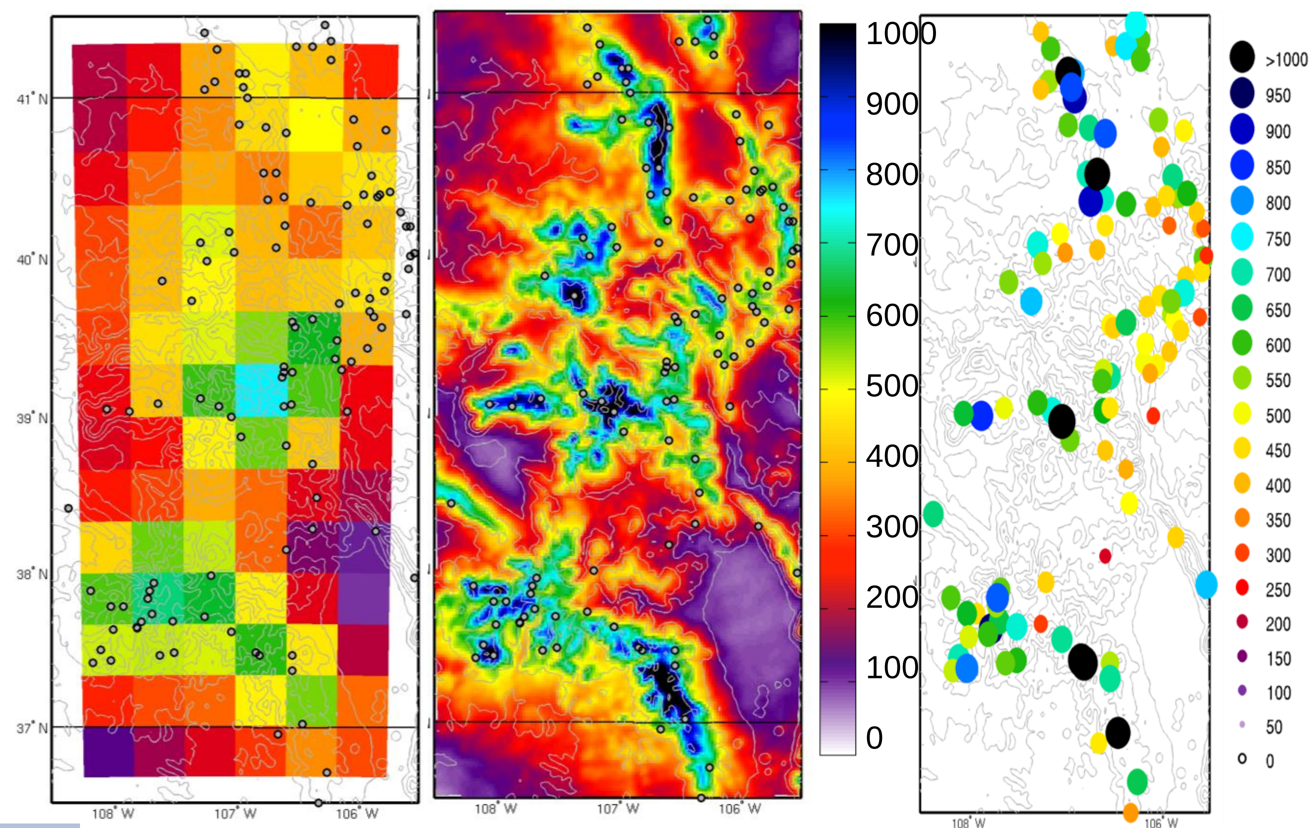
36 km | 2 km | SNOTEL Obs.



SNOTEL Precip gauge

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

Ikeda et al, 2010, Rasmussen et al. 2011

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

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.

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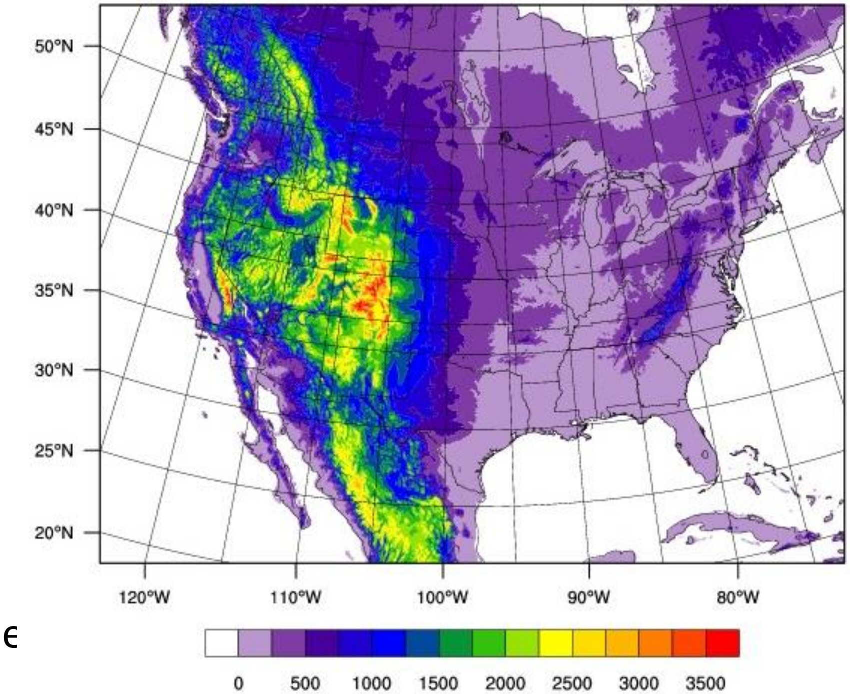
Weather Research and Forecast Regional Climate Model Setup over CONUS

- 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

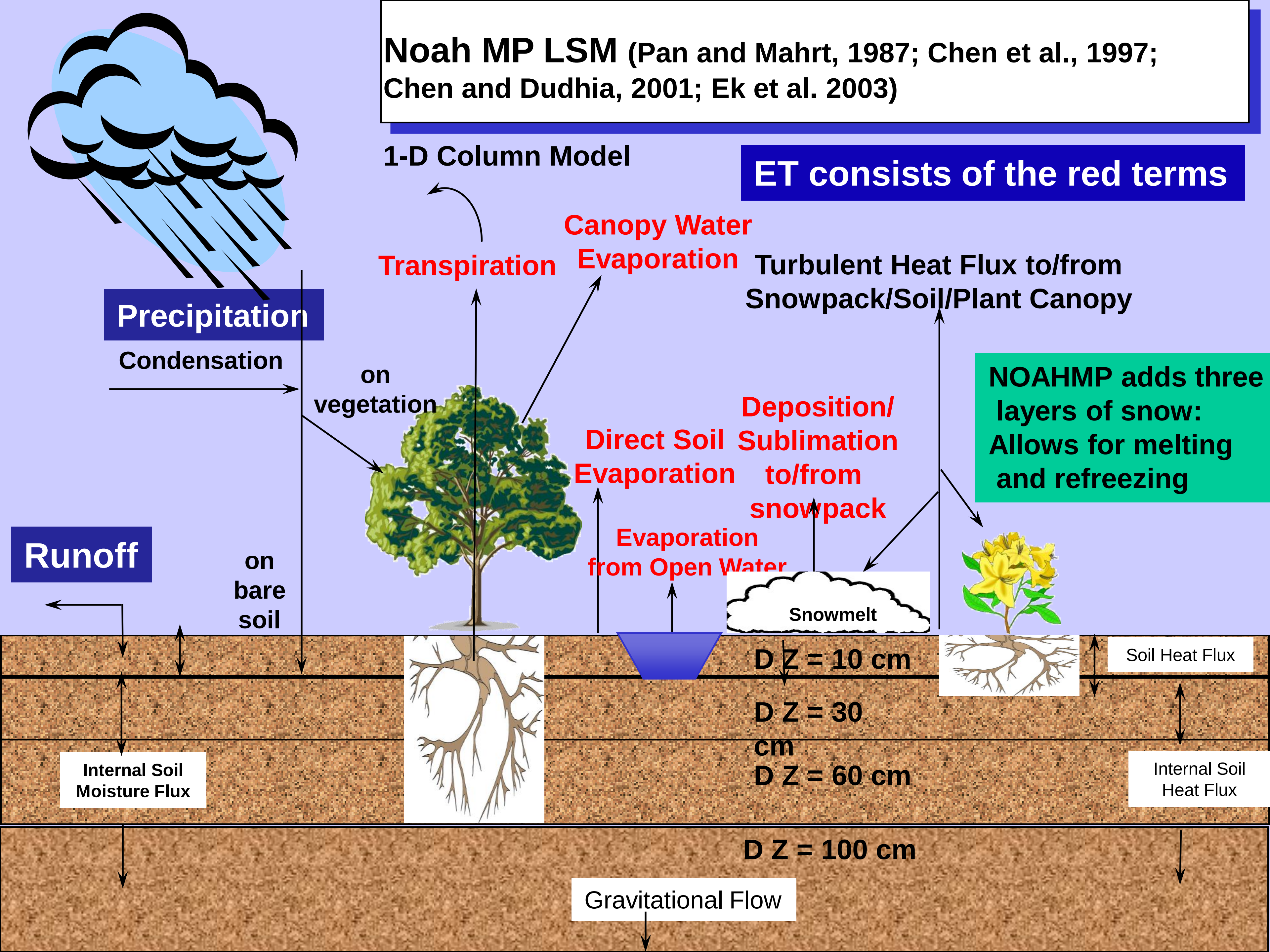
WRF Model Domain



Efforts to improve WRF high-resolution climate simulations

1. Computing requirements
   - Obtained 32M 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.

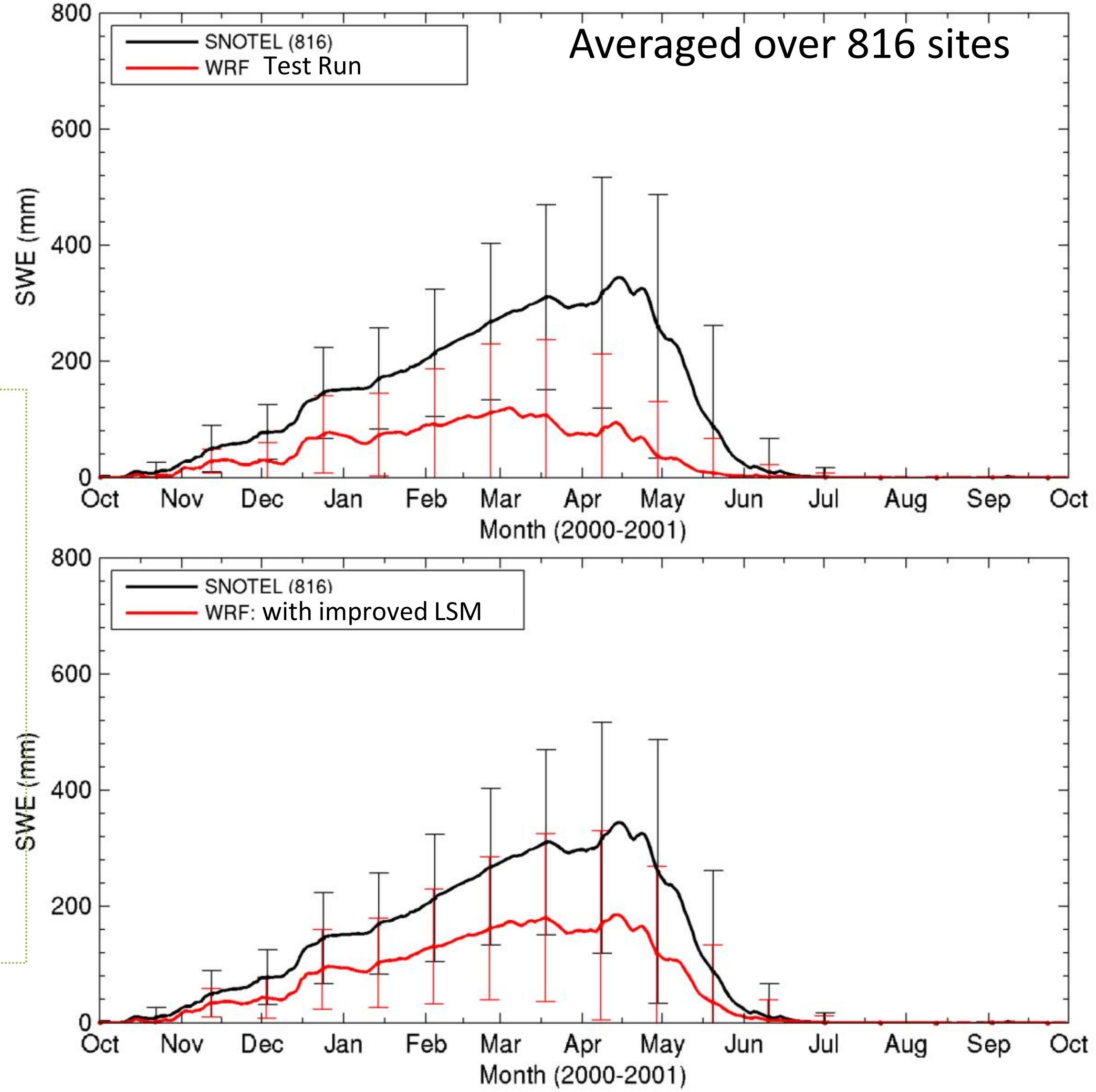
	Improvements
Noah-MP LSM	1. Rain-snow partitioning using microphysics scheme 2. Vegetation-dependent snow fraction/melt curves 3. Allowing snow to be present at above 0°C 4. Heat advection by precipitation 5. Bug fix for canopy snow unloading and snow density
Microphysics	Aerosol emission refinement, 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. Nudged above BL to small wave numbers (2 and 3).



Noah MP LSM (Pan and Mahrt, 1987; Chen et al., 1997; Chen and Dudhia, 2001; Ek et al. 2003)
1-D Column Model
ET consists of the red terms
Canopy Water Evaporation
Transpiration
Turbulent Heat Flux to/from Snowpack/Soil/Plant Canopy
Precipitation
Condensation
on vegetation
NOAHMP adds three layers of snow: Allows for melting and refreezing
Deposition/ Sublimation to/from snowpack
Direct Soil Evaporation
Evaporation from Open Water
Runoff
on bare soil
Snowmelt
D Z = 10 cm
Soil Heat Flux
D Z = 30 cm
D Z = 60 cm
Internal Soil Moisture Flux
Internal Soil Heat Flux
D Z = 100 cm
Gravitational Flow

SWE underprediction from test runs

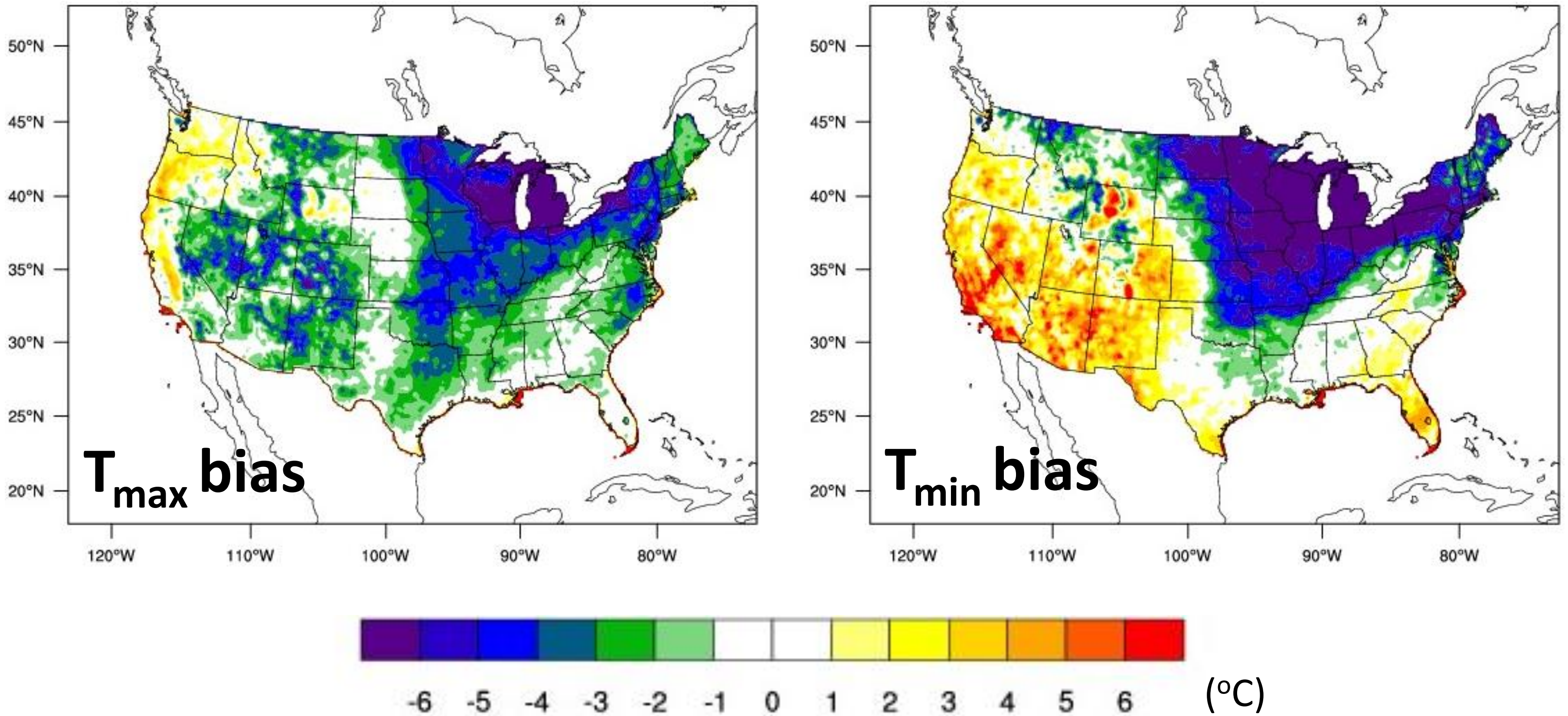
Snow Water Equivalent (SWE) at SNOTEL sites : 2000-2001



Additions:

- capability for snow being present at above 0°C (doesn't immediately melt, 3 layers to allow for re-freezing of melted snow in the layer).
- microphysics-based rain-snow partitioning

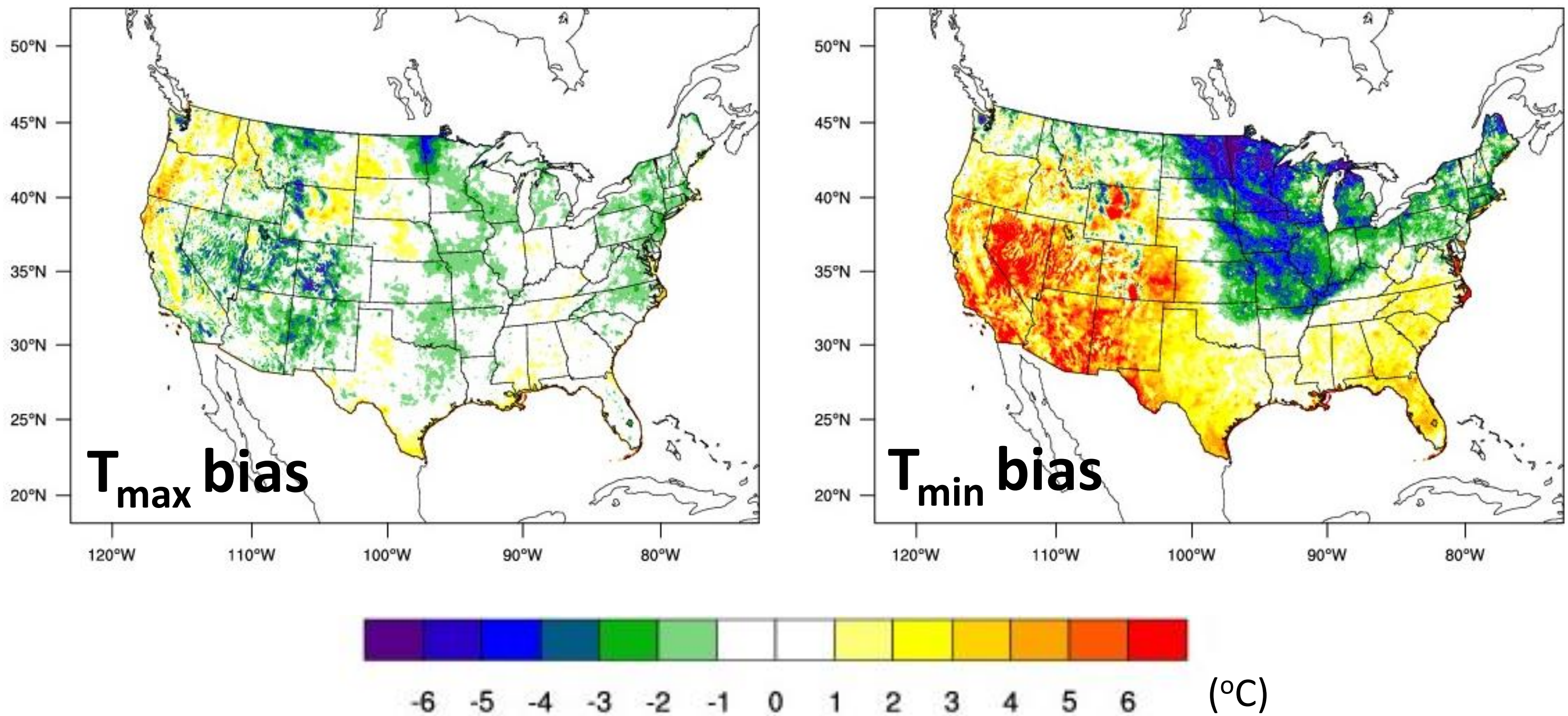
Winter cold biases from test runs compared to PRISM observations



December 2000

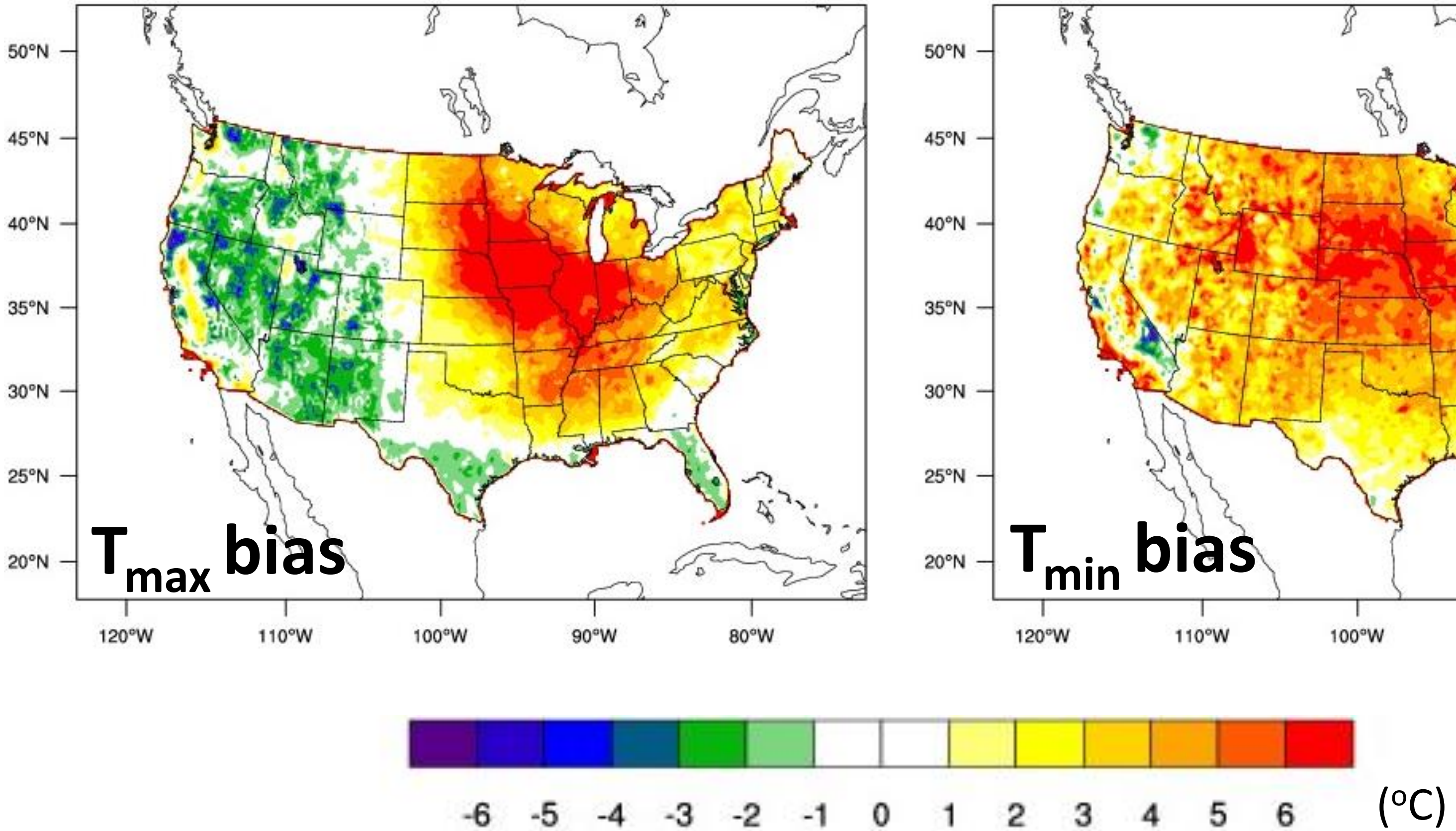
Temperature biases reduced after LSM improvement:

vegetation-dependent snow fraction/melt curves



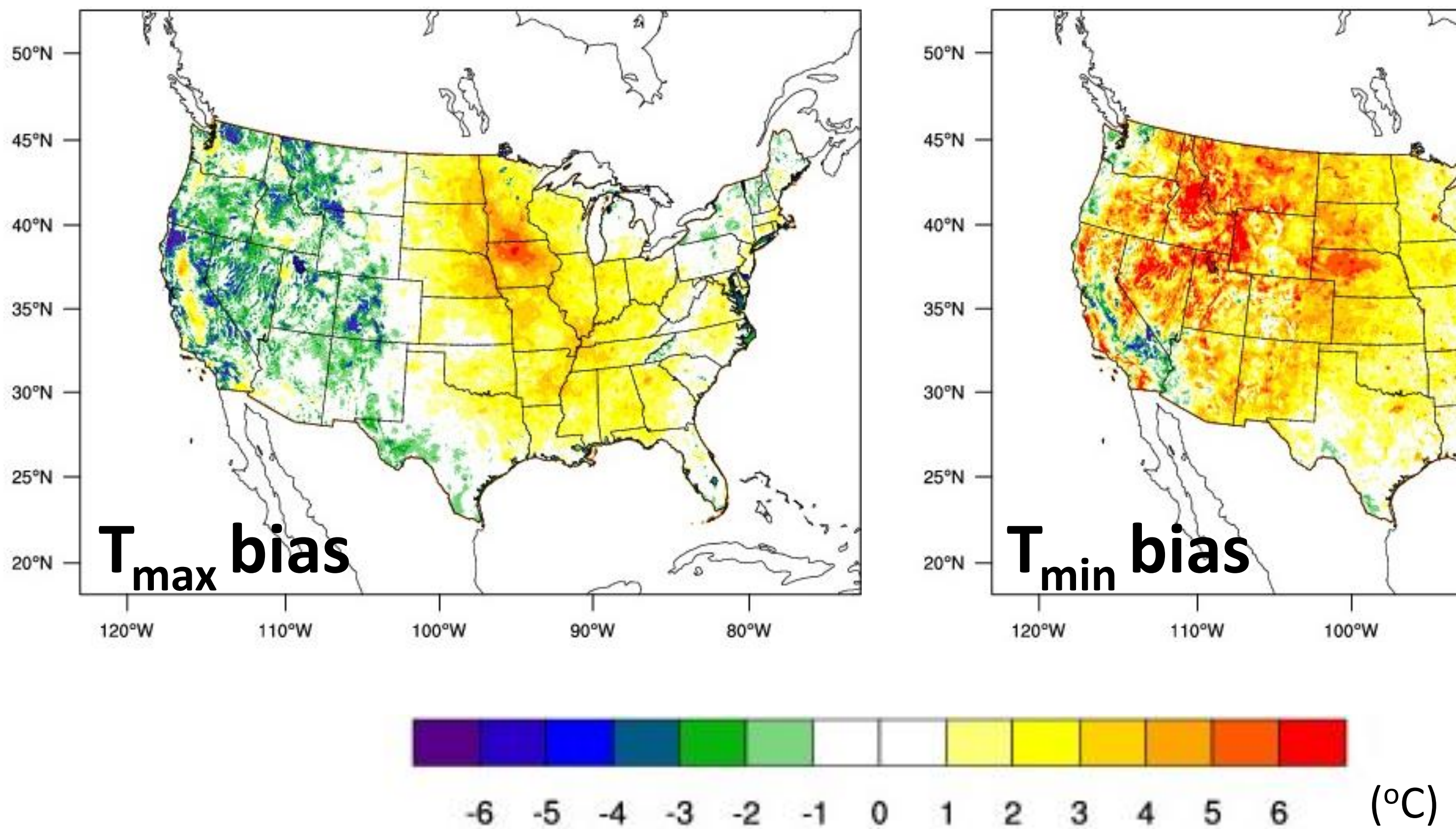
December 2000

Summer warm biases from test runs



August 2001

Warm bias over central U.S. significantly reduced with spectral nudging plus default option changes in LSM



August 2001

Numerical Experiments

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  - 13-year integration

Pseudo Global Warming Approach Used

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

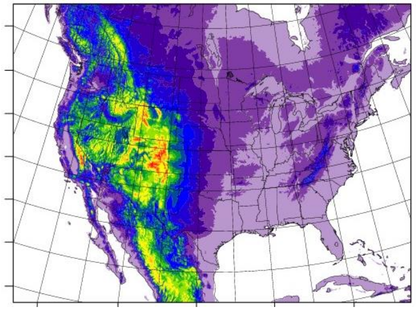
- Compute 30-year CMIP5 19 model ensemble monthly mean
  - Historical period : *1976-2005*   Future period (RCP8.5): *2071-2100*
- Compute perturbation – difference between two climates
- Add perturbation to the 6-hrly ERA-I data

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

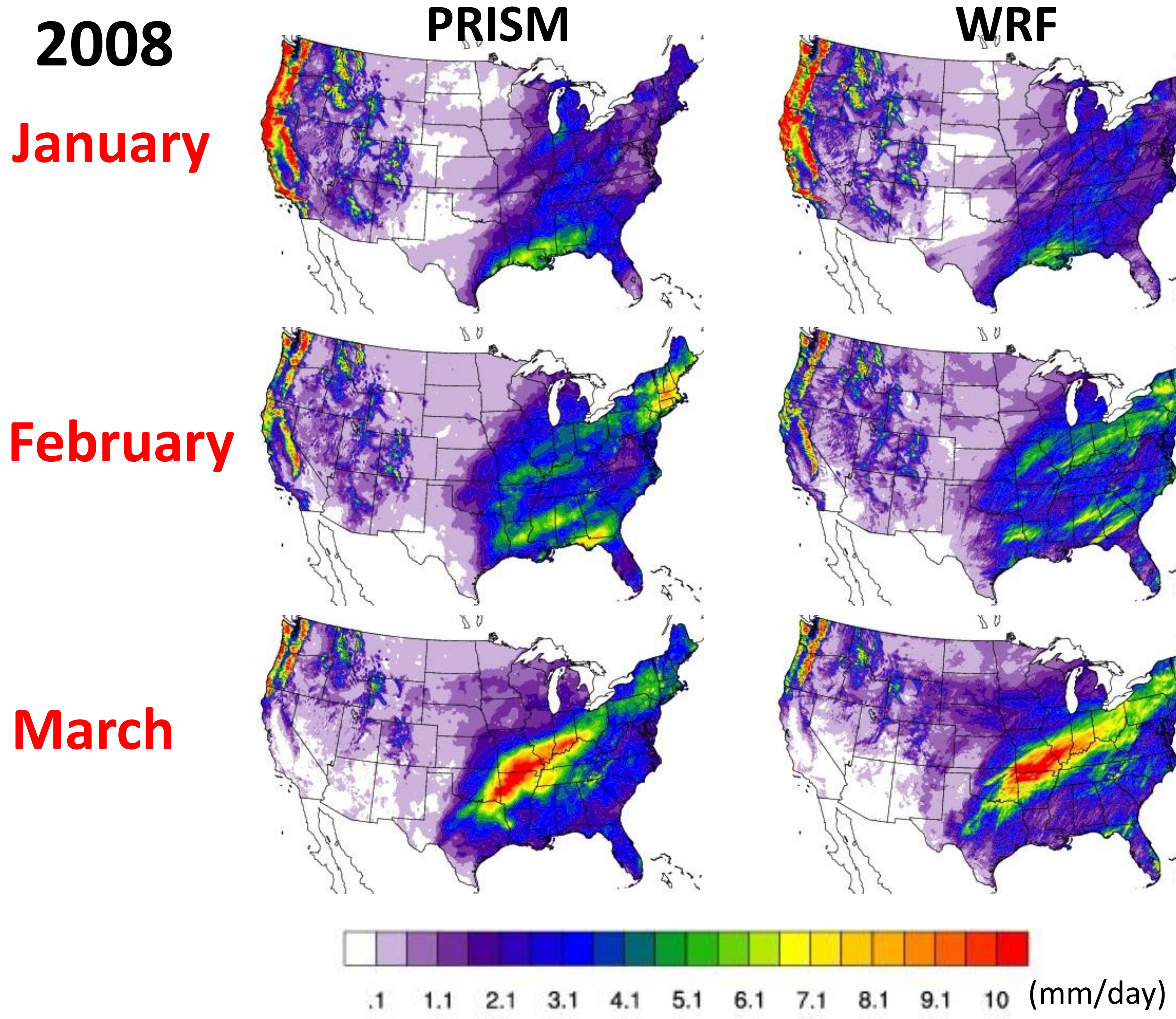


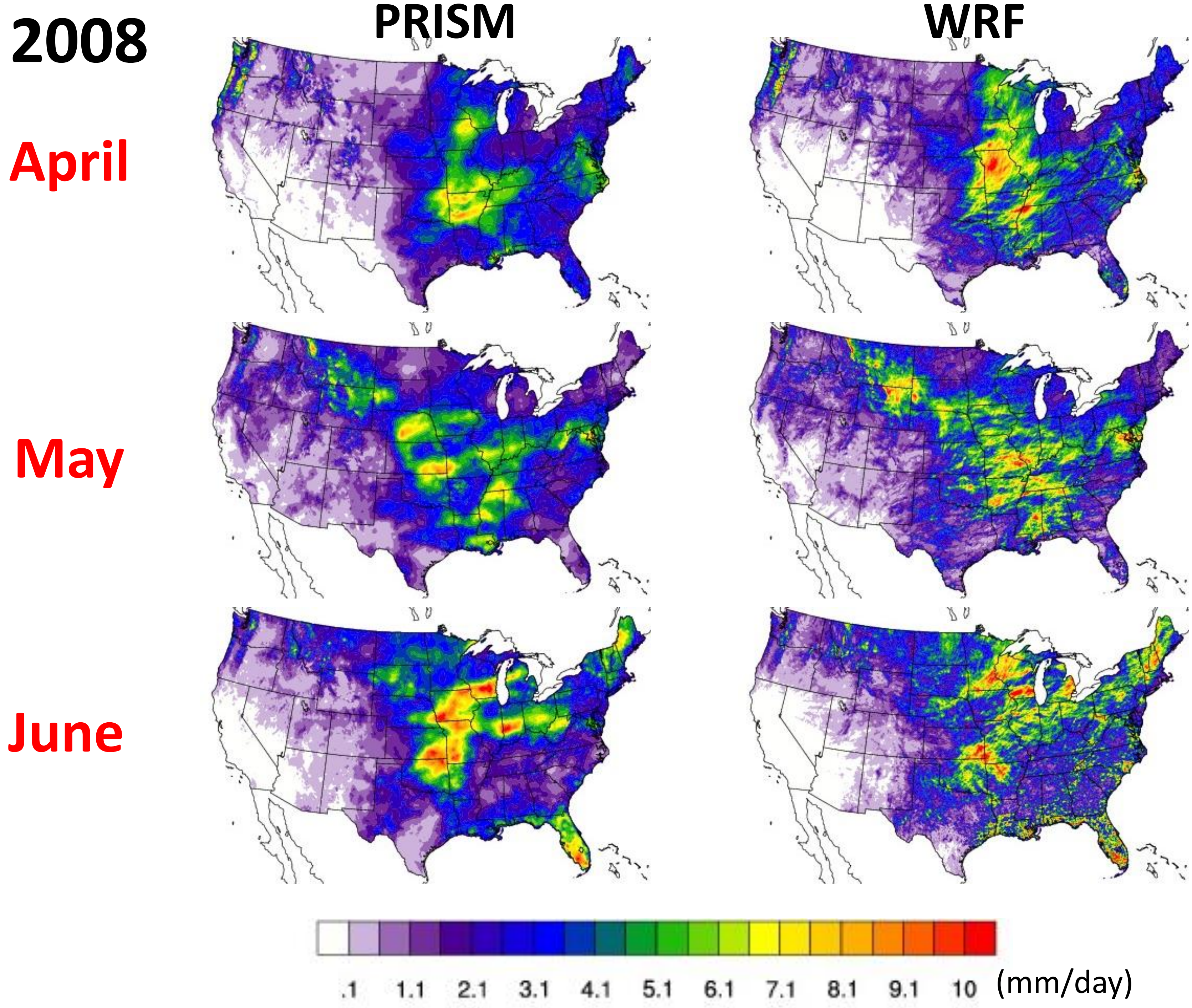
WRF MODEL

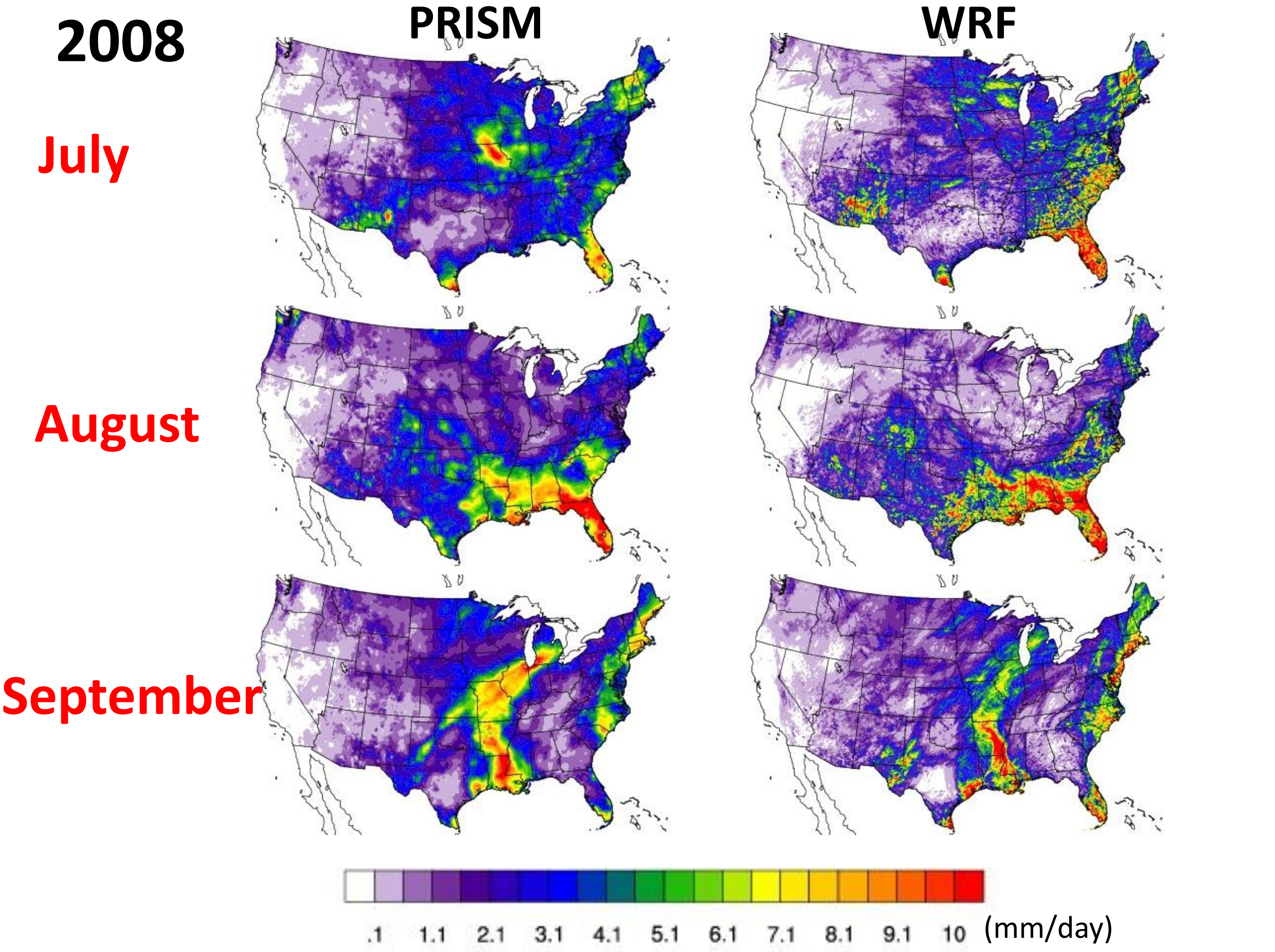
- Variables changed: **U, V**, **T**, **geopot. hgt**., $\mathbf{P_{sfc}}$ and $\mathbf{Q_v}$
- No change in storm tracks. Same transient spectra as current climate.

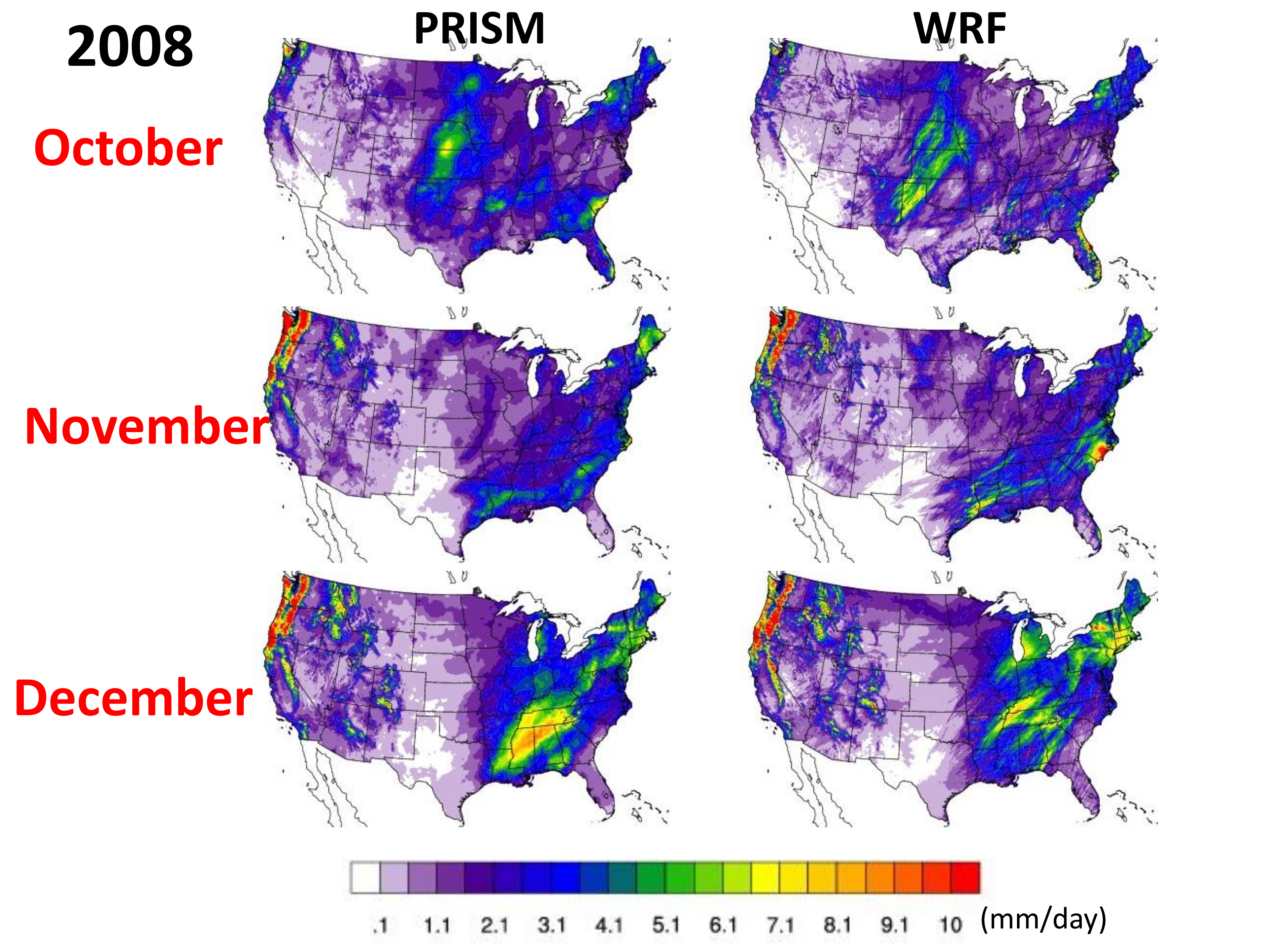
Comparison of monthly precipitation

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
.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
July
August
September
.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
October
November
December
.1
1.1
2.1
3.1
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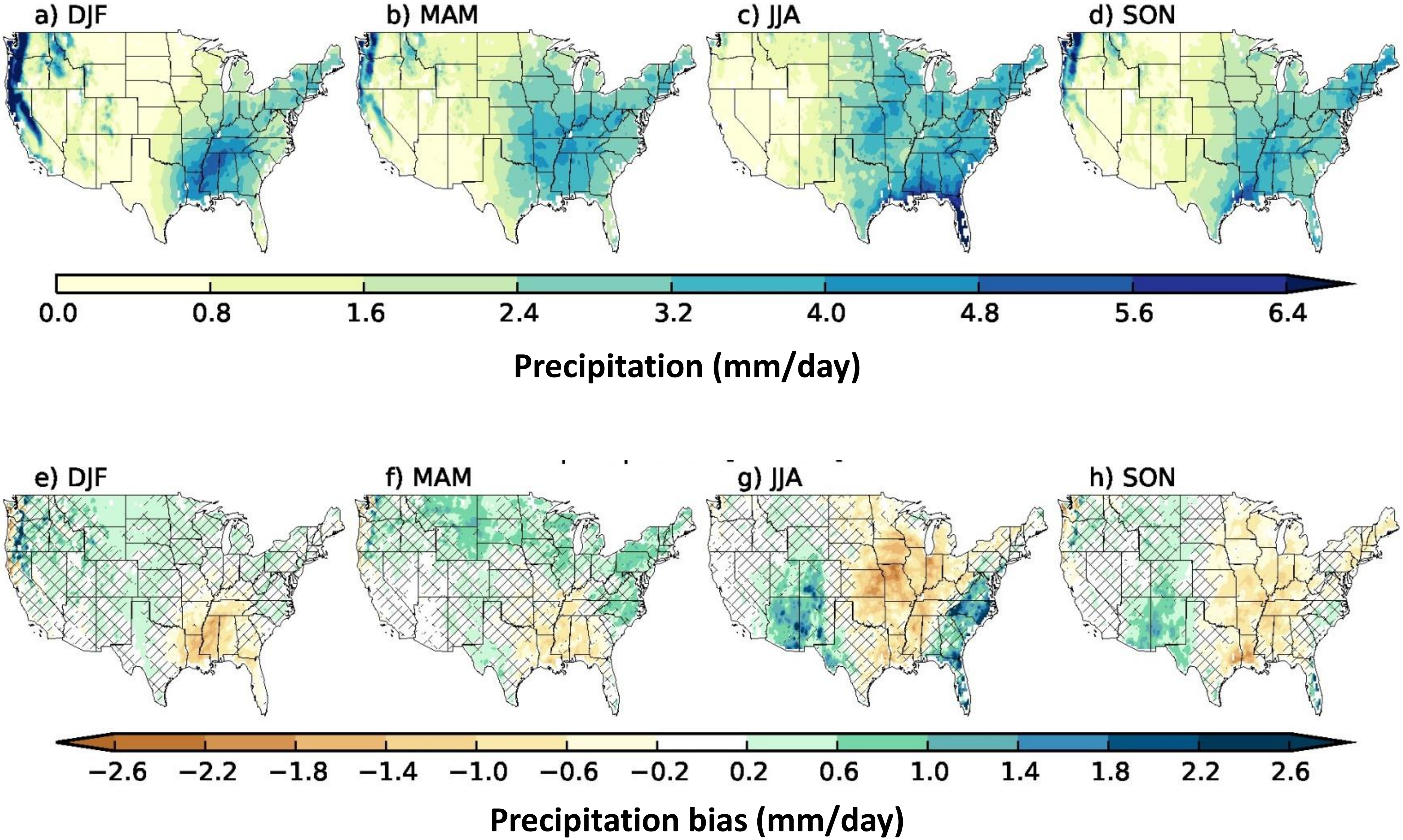
8.1
9.1
10
(mm/day)

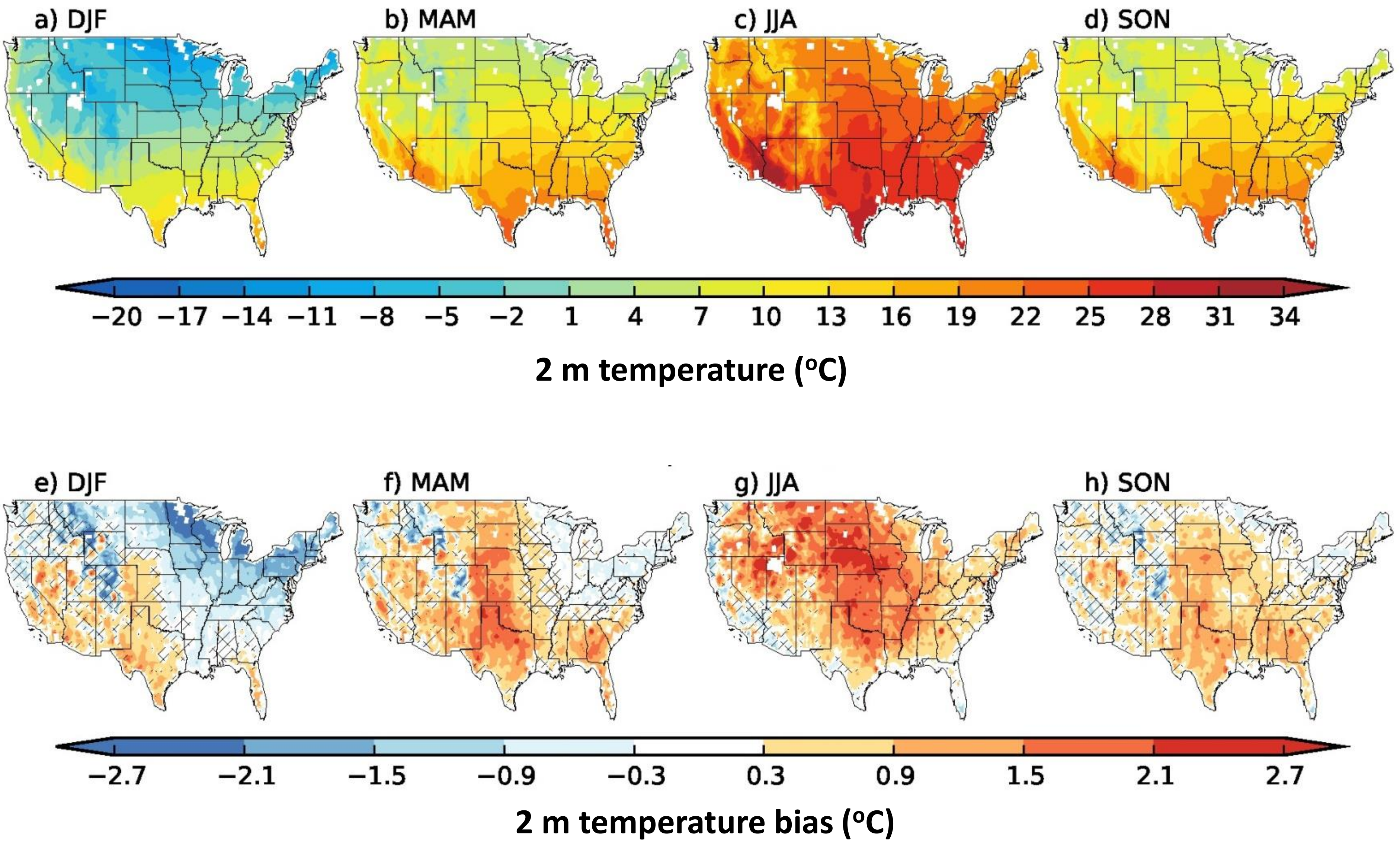
PRISM observations averaged over 2001-2008



Observational data set from Andy Newman

Courtesy of Andreas Prein

PRISM observations averaged over 2001-2008



Observational data from Andy Newman

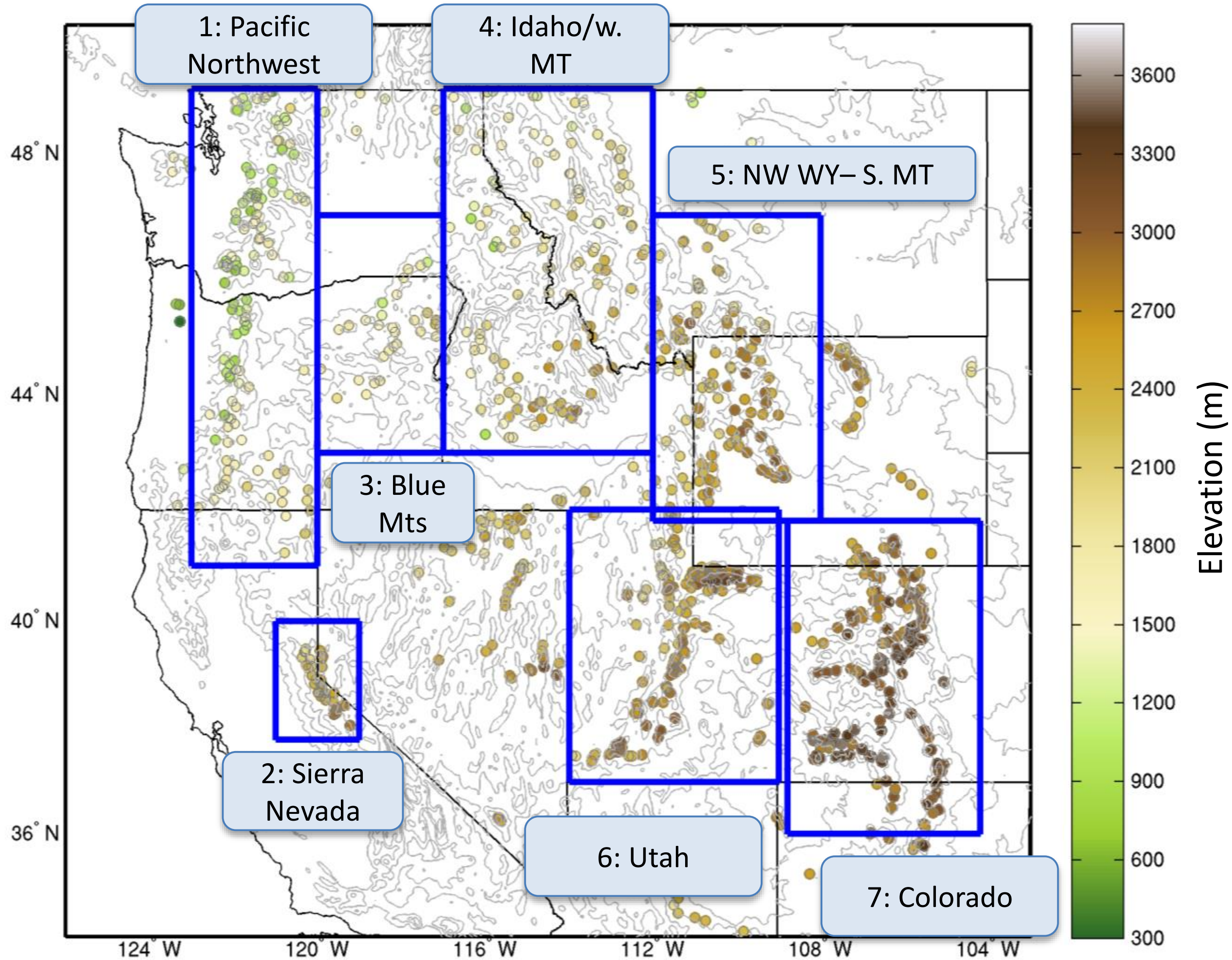
Courtesy of Andreas Prein

Model Evaluation at SNOTEL Sites

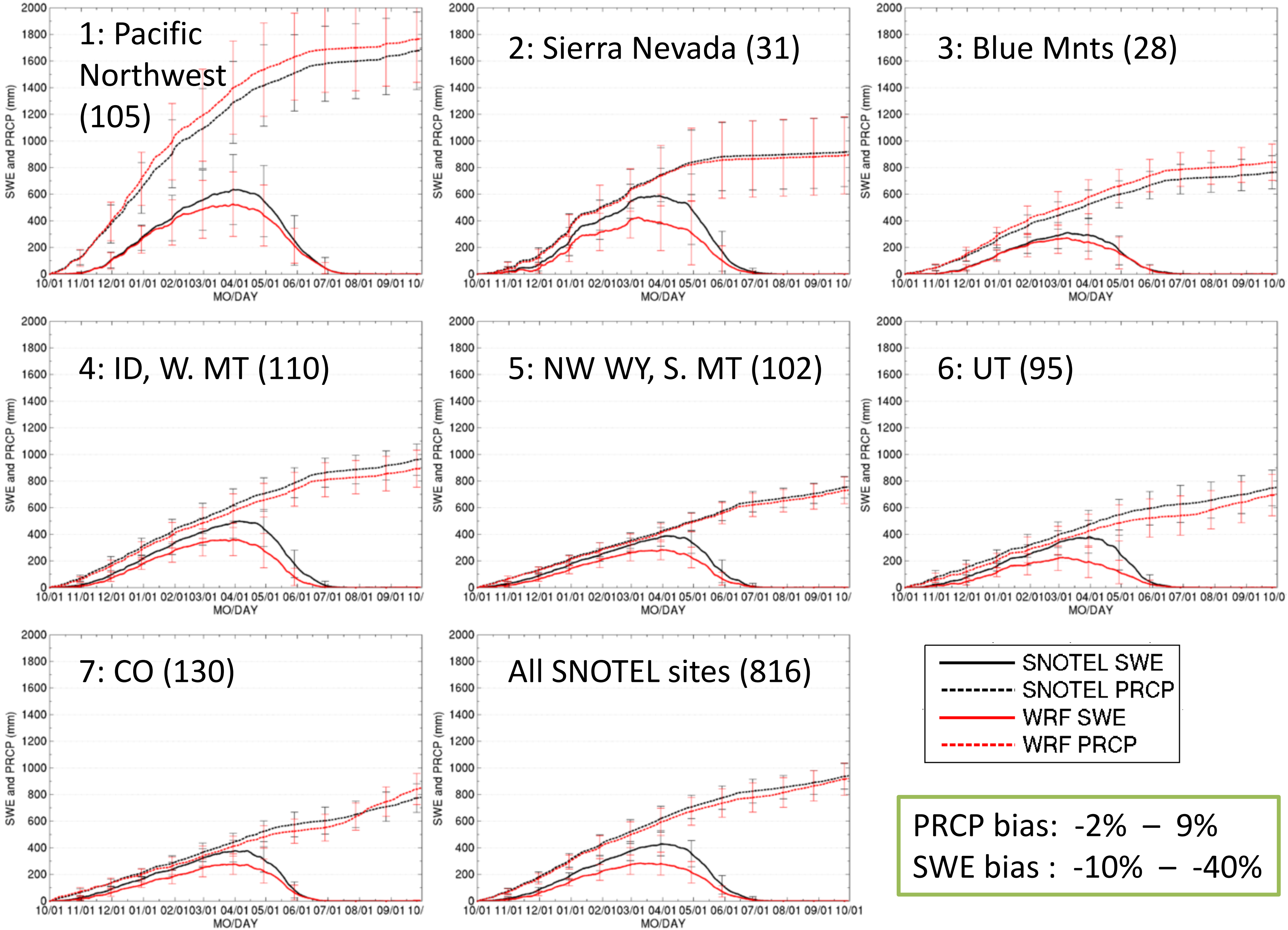
SNOTEL site at
Brooklyn Lake, WY

Snow gauge

Snow pillow



SNOTEL vs WRF at SNOTEL sites: 13-year climatology



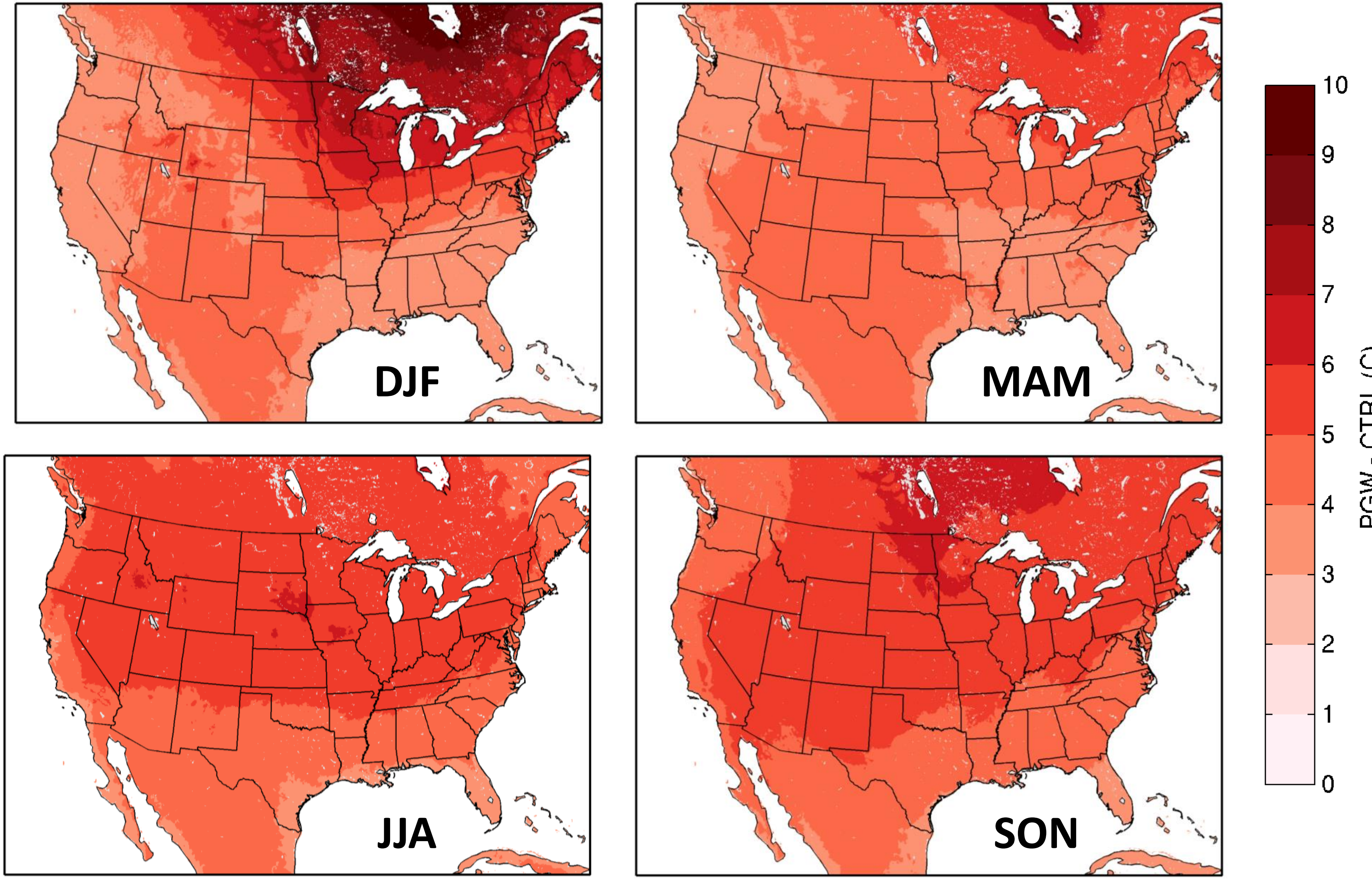
PRCP bias: -2% – 9%

SWE bias : -10% – -40%

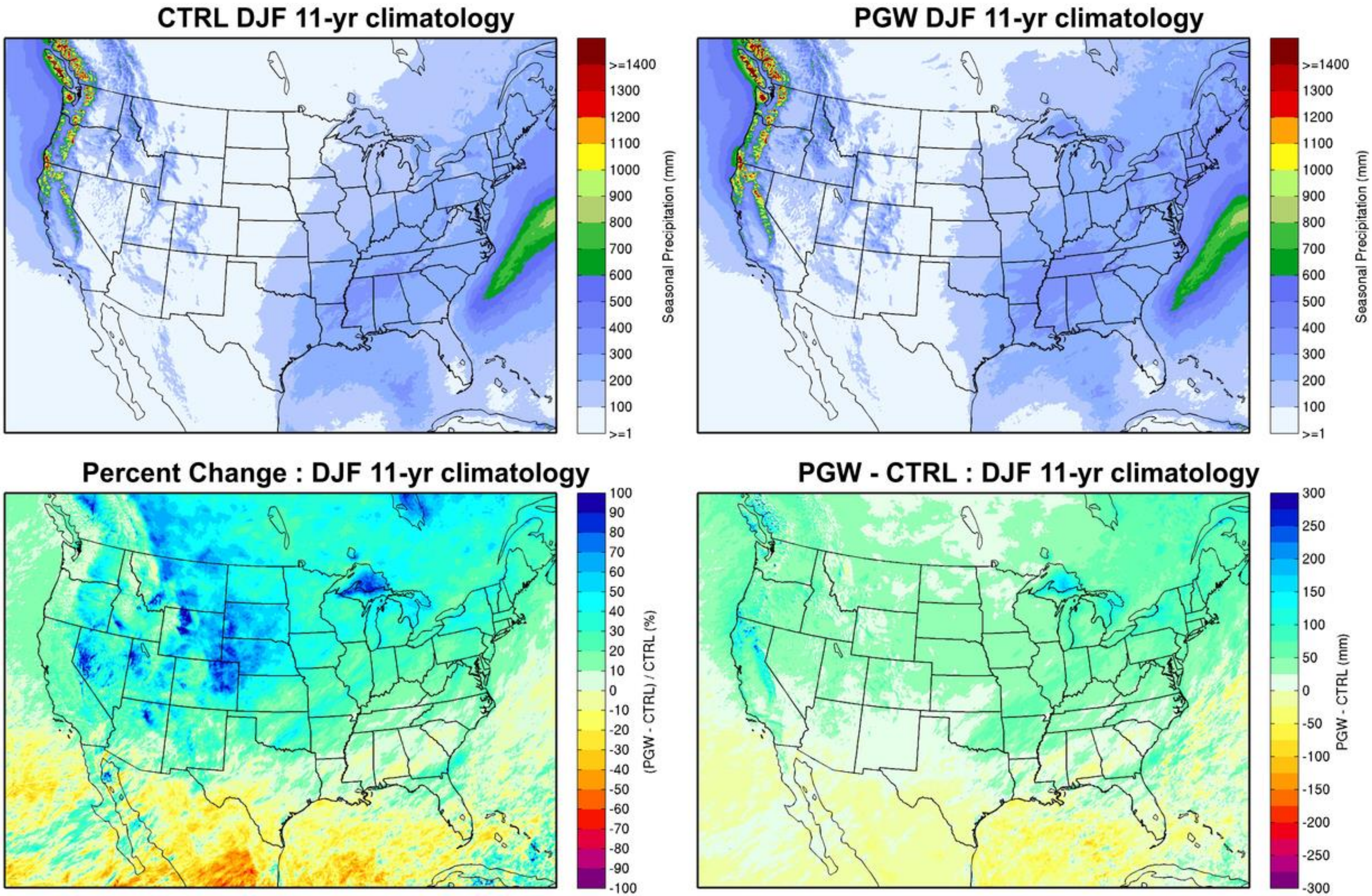
Preliminary results from PGW simulation

- Seasonal/annual surface temperature changes
- Seasonal/annual precipitation/rainfall changes
- Snowfall and Snowpack changes over western mountains

11-year Climatology of Surface Temperature Change (PGW – CTRL)



Seasonal Precipitation : DJF

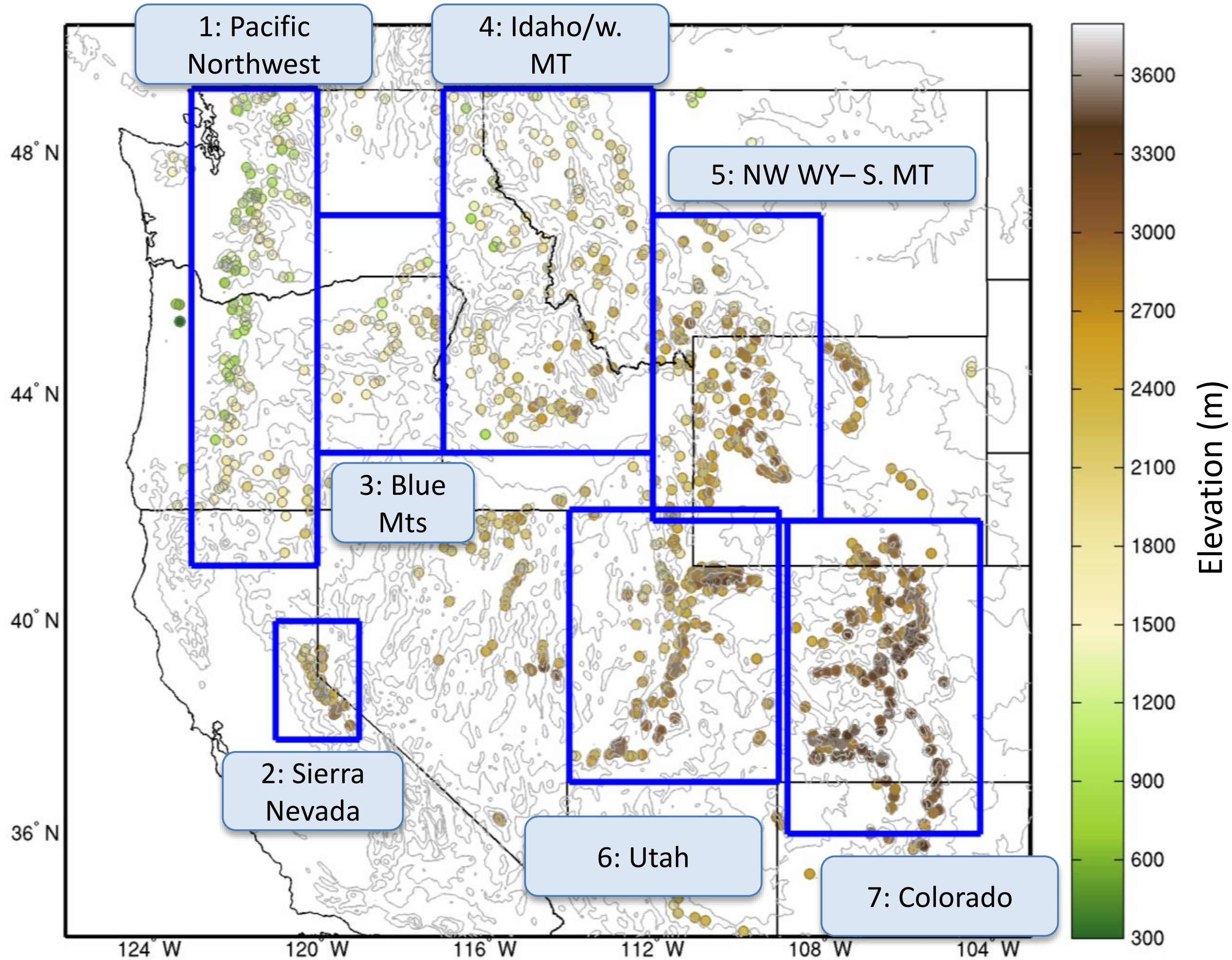


PGW Results at SNOTEL Sites

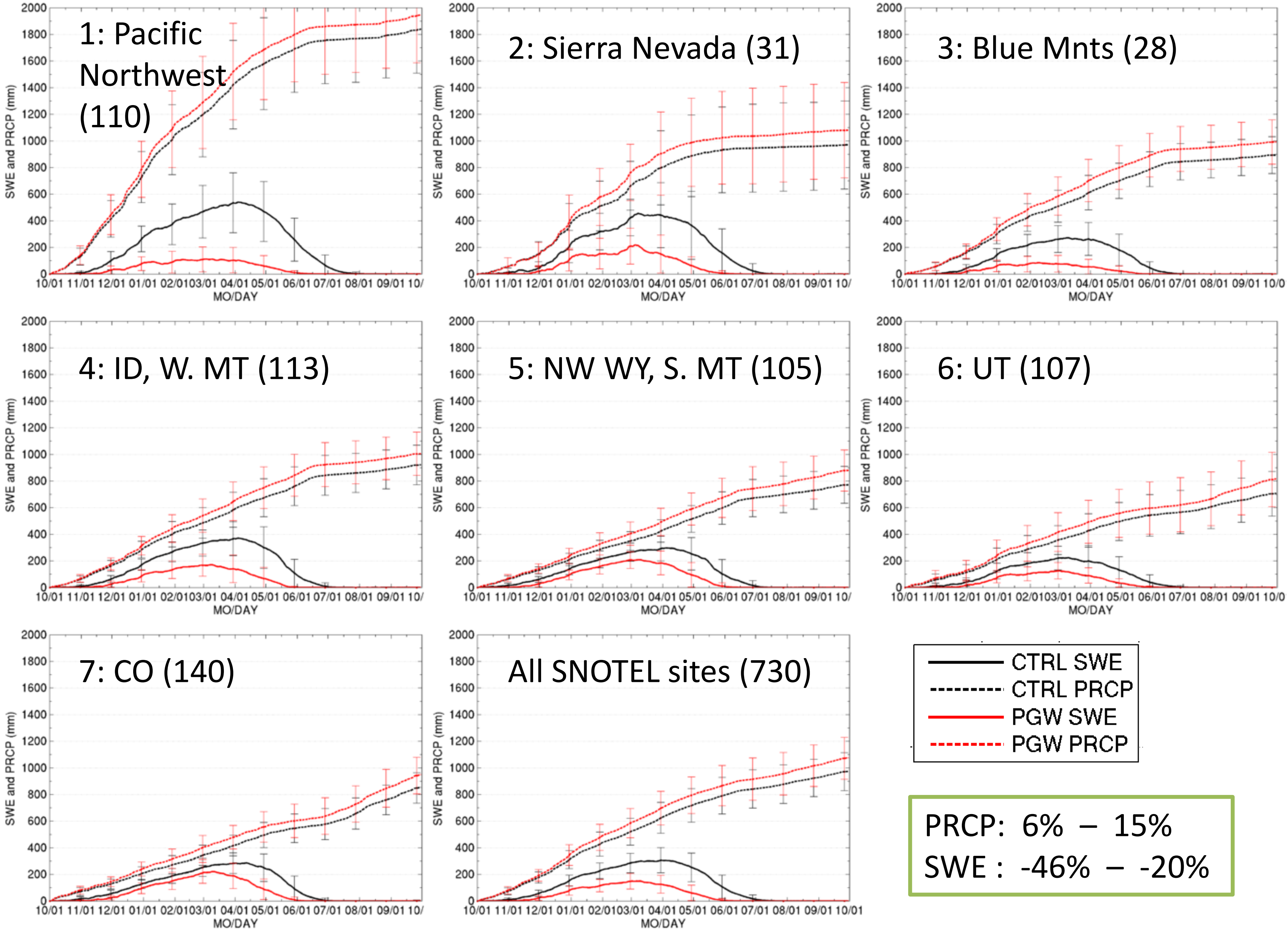
SNOTEL site at Brooklyn Lake, WY

Snow gauge

Snow pillow



WRF CTRL vs PGW at SNOTEL sites : 11-year climatology



PRCP: 6% – 15%

SWE : -46% – -20%

Summary

- Precipitation projected to increase over all western mountain ranges by ~16%, at rate of ~4%/C, below the Clausius-Clapyron rate of 7%/°C.
- The Pacific Northwest is projected to have 75% less snowpack than current climate (highest SWE in current climate). Much of this is due to the change of snowfall to rain as total precipitation increases. Consistent with observed trends.
- Despite being further south, the Sierra Nevada Range in California does not have as significant an impact of climate change due to its high elevation and therefore colder temperatures.
- High elevation continental sites such as Colorado have the smallest future climate impact due to the colder environment. During central part of winter actually get more snow. Snow albedo feedback important during the melt season.
- Northern part of the inter-mountain west and Canada projected to have more snow in mid-winter due to moister conditions and temperatures less than 0 C. The shoulder seasons are predicted to have less snow.
- Onset of snowmelt 2-4 weeks earlier in all the Ranges (consistent with prevous studies).
- Offset of melting also earlier.

Snow cover in 2001-2002 over North America from MODIS

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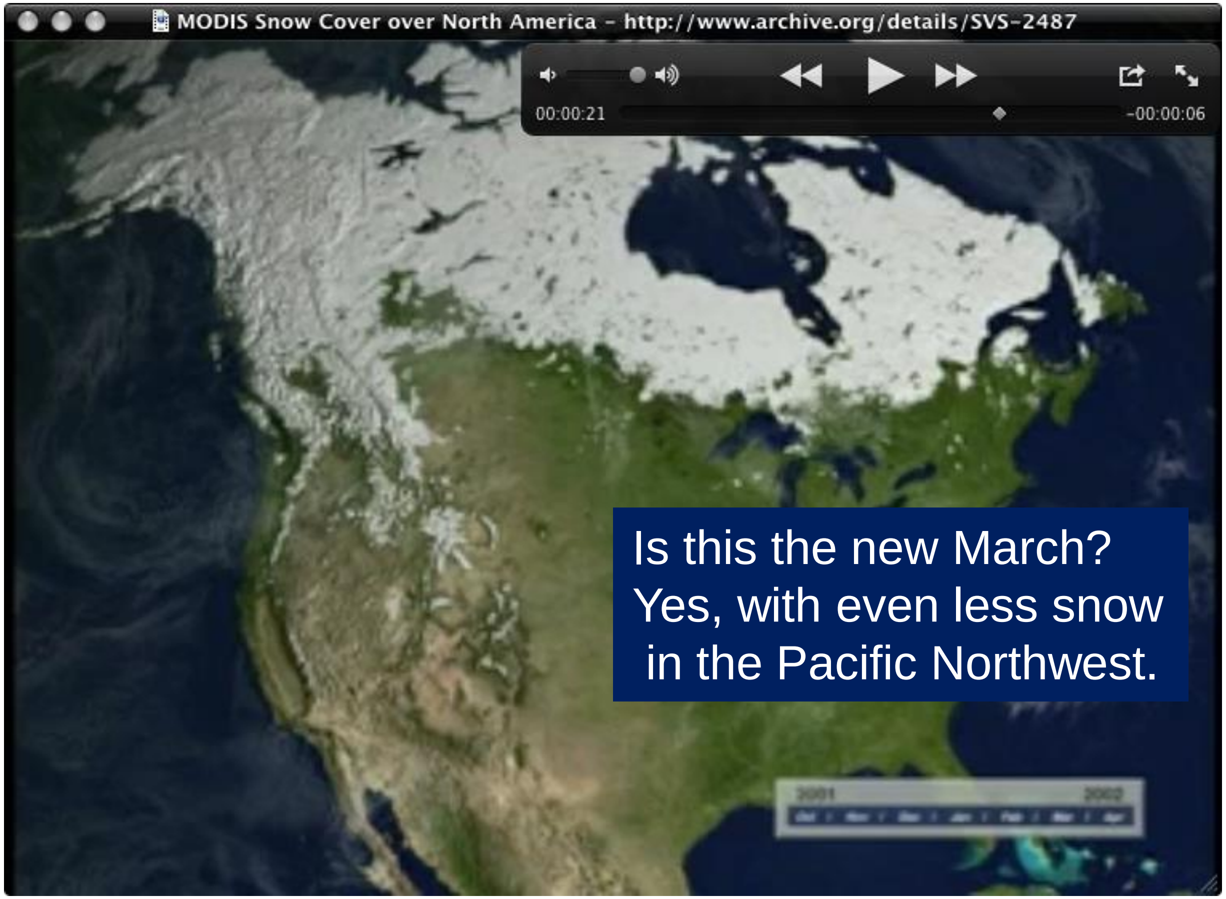
April 2002



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Thank you.
Questions?