ESSL NCAR

High Resolution Simulations of Snowfall over Colorado and some Climate Impacts

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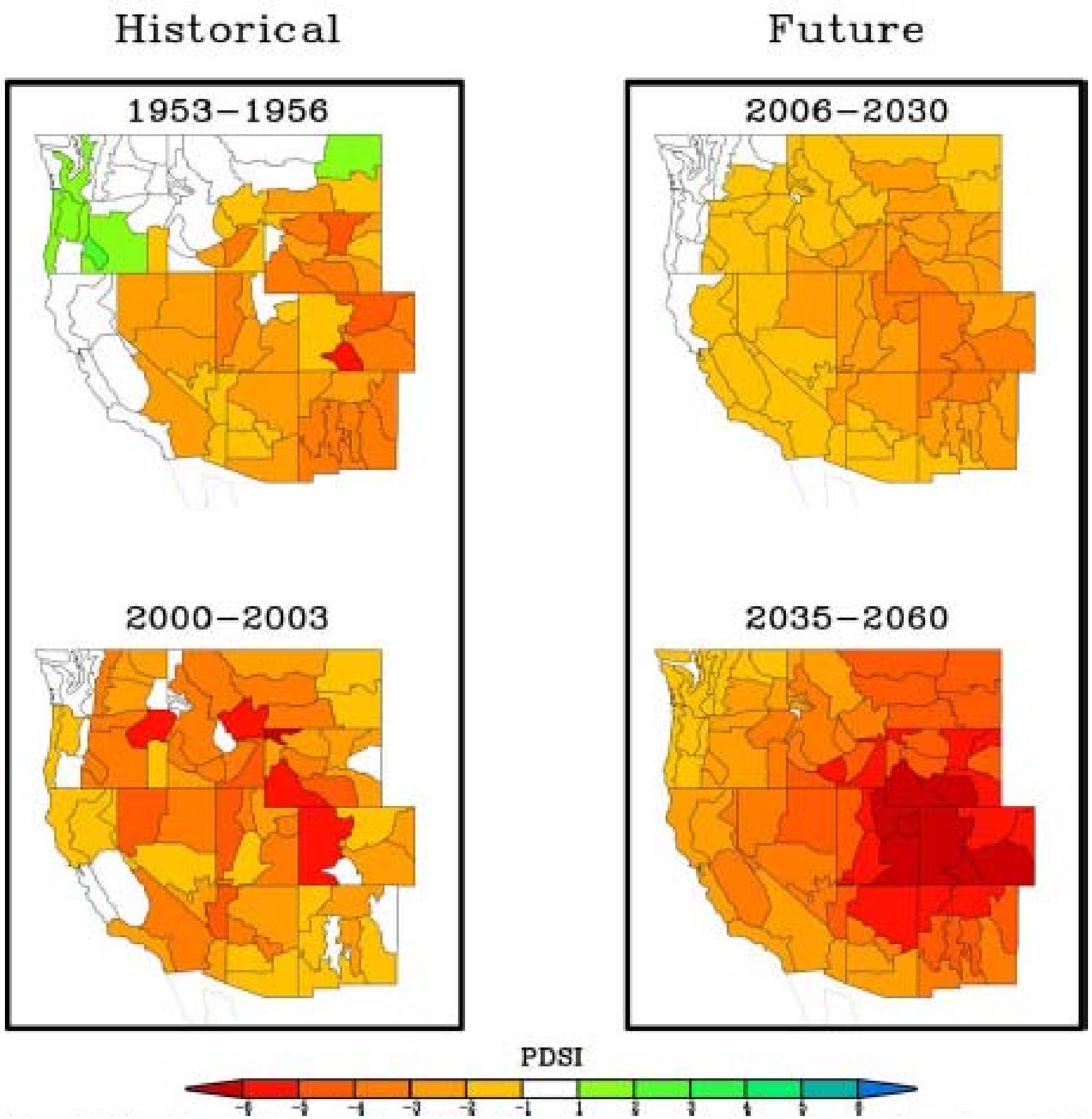
Funded by the NCAR Water System Program (NSF)

4th IPCC Model Projections of the Palmer Drought Severity Index

MOTIVATION



Hoerling (2007)

- Snowpack is the most important water source in the western US

- Climate models show warm & dry conditions in the SW US. However, these models do not resolve the complex terrain and orographic effects well

- Regional climate models show inconsistent snowpack projections

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Colorado's Headwaters

Continental-scale river basins whose headwaters reside in the Colorado region:

- Platte River
- Arkansas River
- Colorado River
- Rio Grande River

(courtesy Col. Div. Water Res.)

Key Questions: Will the predicted increase in snowfall due to a warmer, moister climate be enough to offset the enhanced melting and sublimation due to the warmer temperatures? Will this be sufficient to maintain river flow at current levels, or is it expected to decrease? How high resolution of the regional climate model do we need to answer these questions?

TIMES
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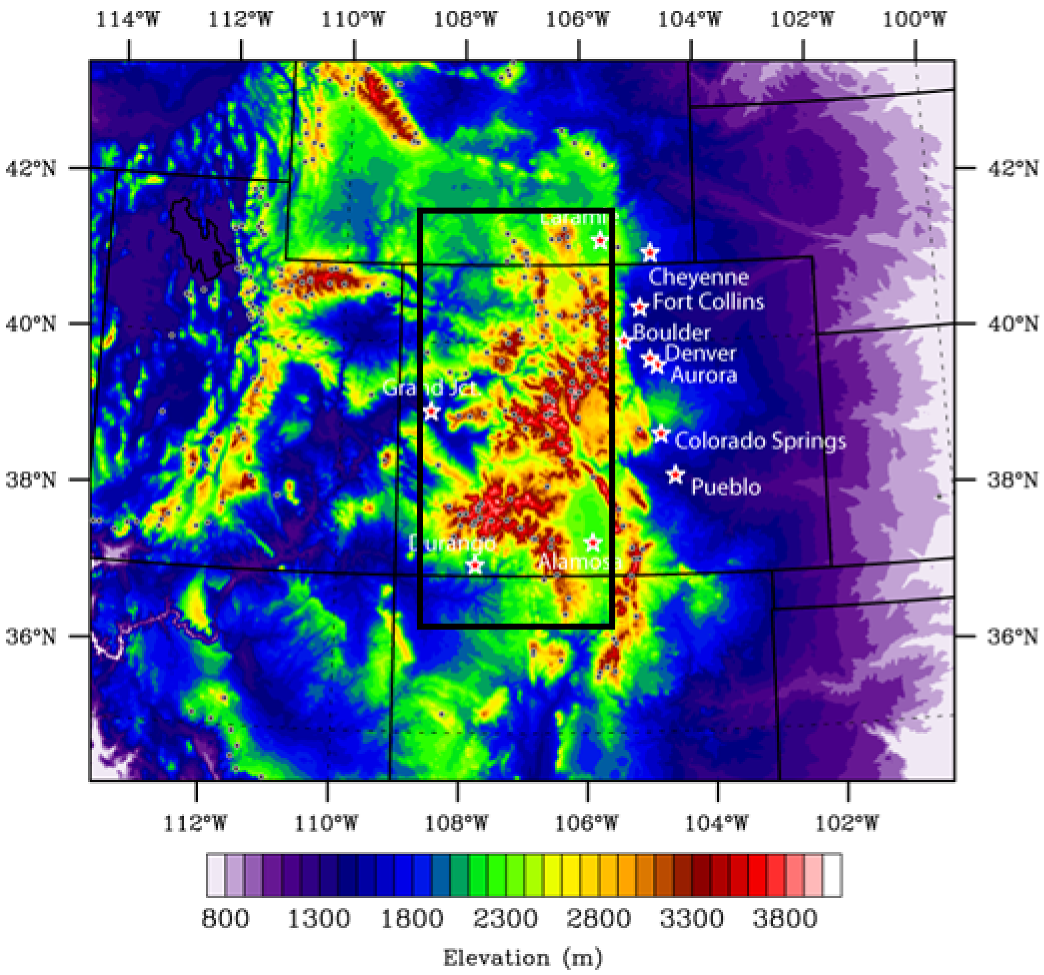
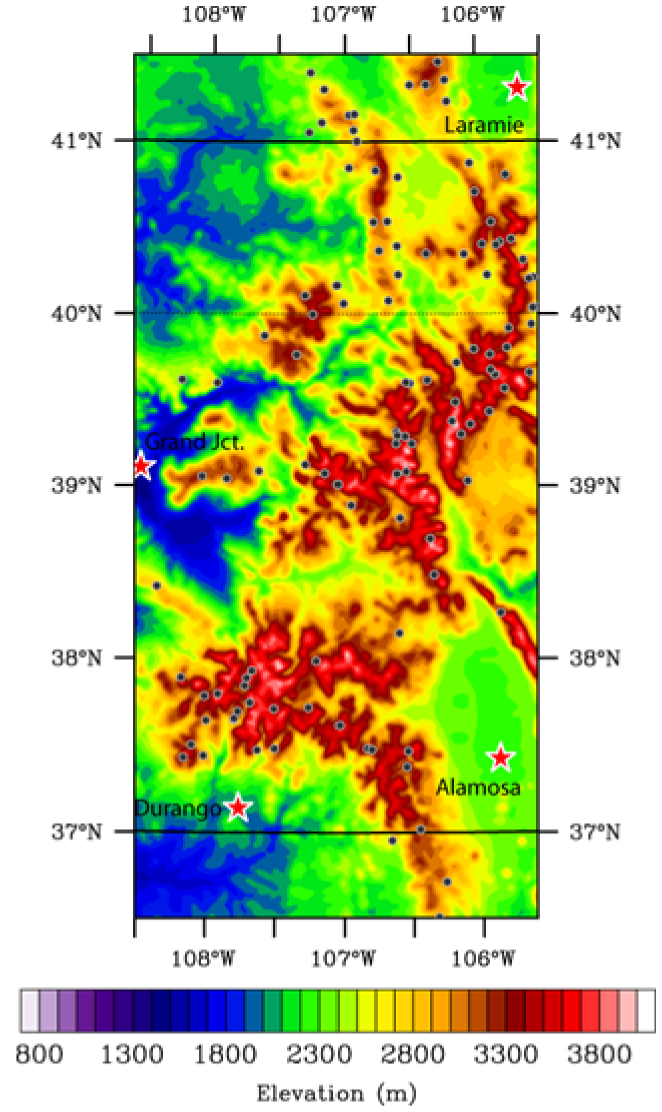
Model Domain

Full Domain



Sub-domain



Verification with SNOTEL data

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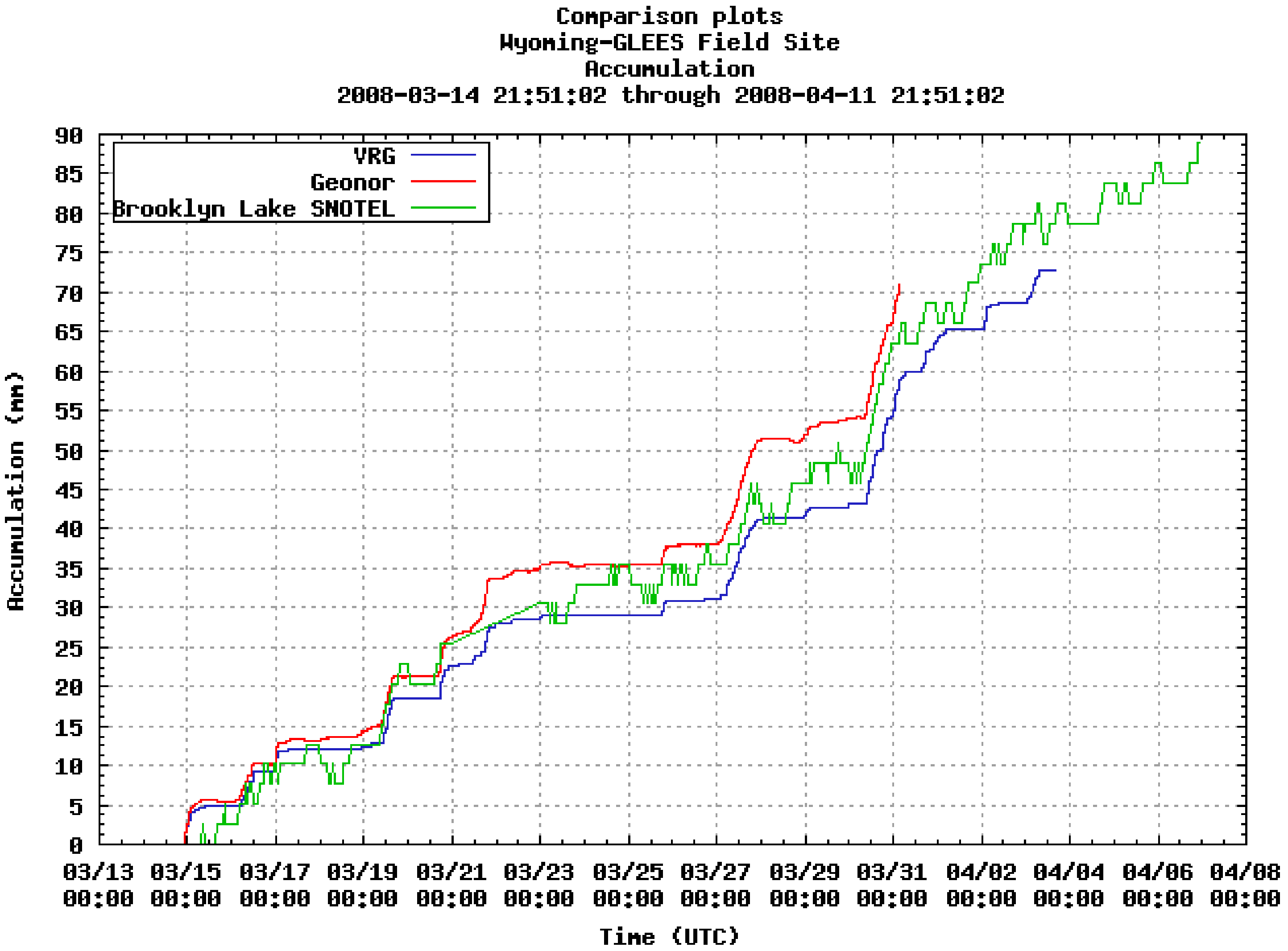
SNOTEL s
snowgaug



- Site run on batte
  recharged by so
  on tower
- Data transferrec
  day using mete
  technology
- Sensors at site:
  Snow pillow
  Snow gauge
  Snow depth (u

Methodology

- **Study of impact of varying model resolution**
  - Ten day model runs at 20, 10, 4, and 2, km resolution

- **High-res regional current and future WRF climate model simulations verified by SNOTEL data** .

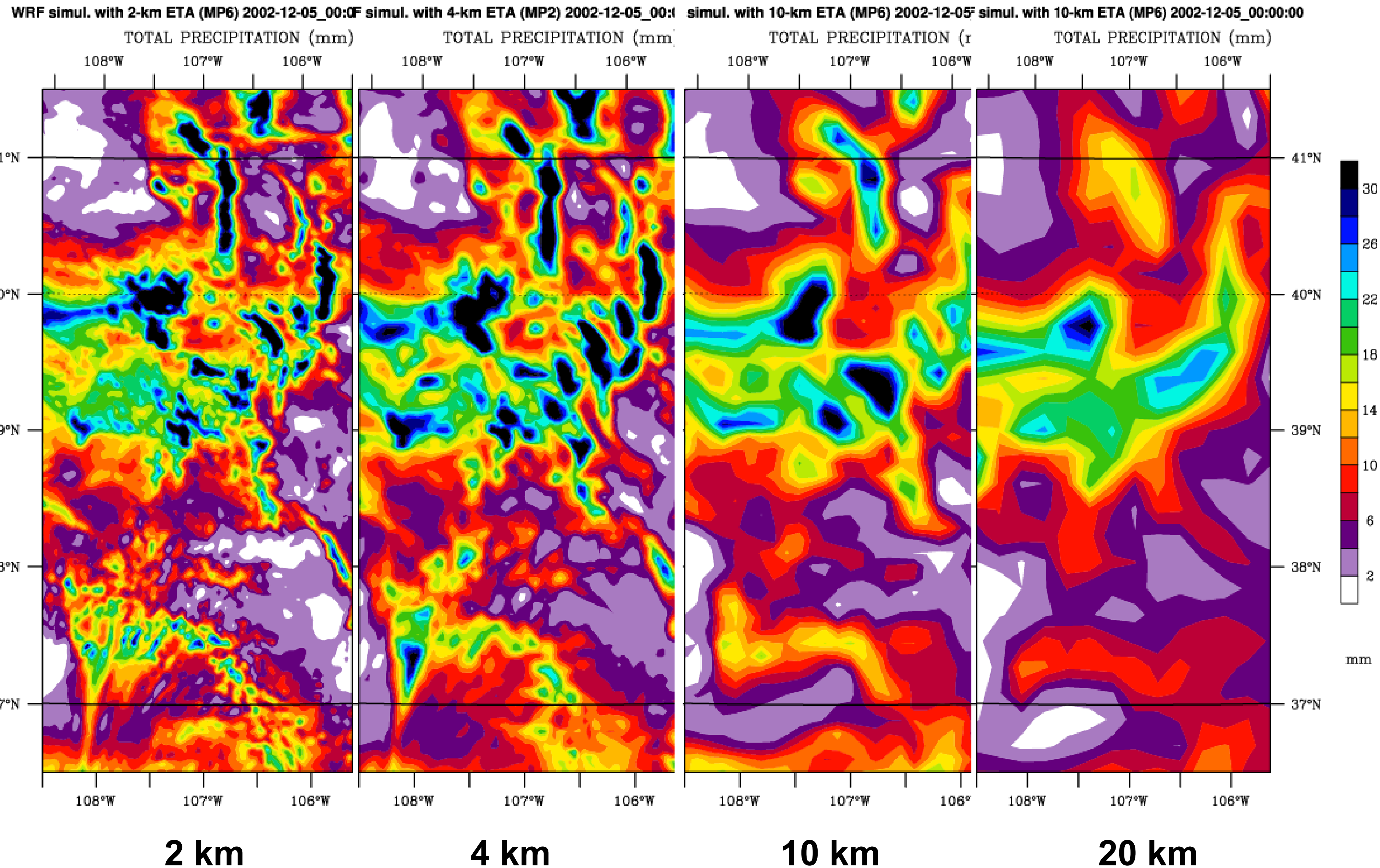
  - Six month snowfall and snowpack simulations for an average, above average, and below average winter season.
  - Multi-year cold-season snowpack simulations in a GCM-projected warmer climate.

Computer Time Award

• 500,000 GAUs on IBM Power 575 (Bluefire) as part of the Accelerated Science Discovery competition

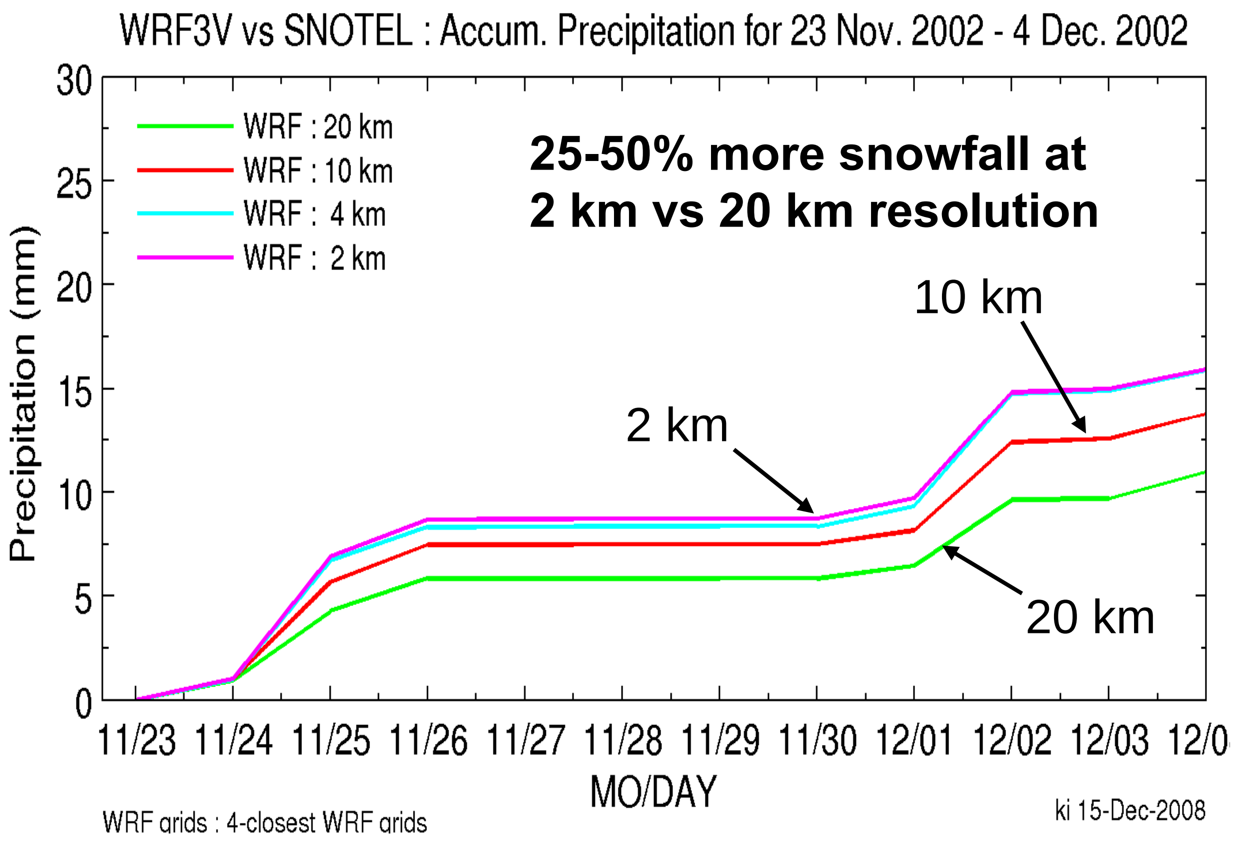
Ten Day WRFV3 Model Run with NARR

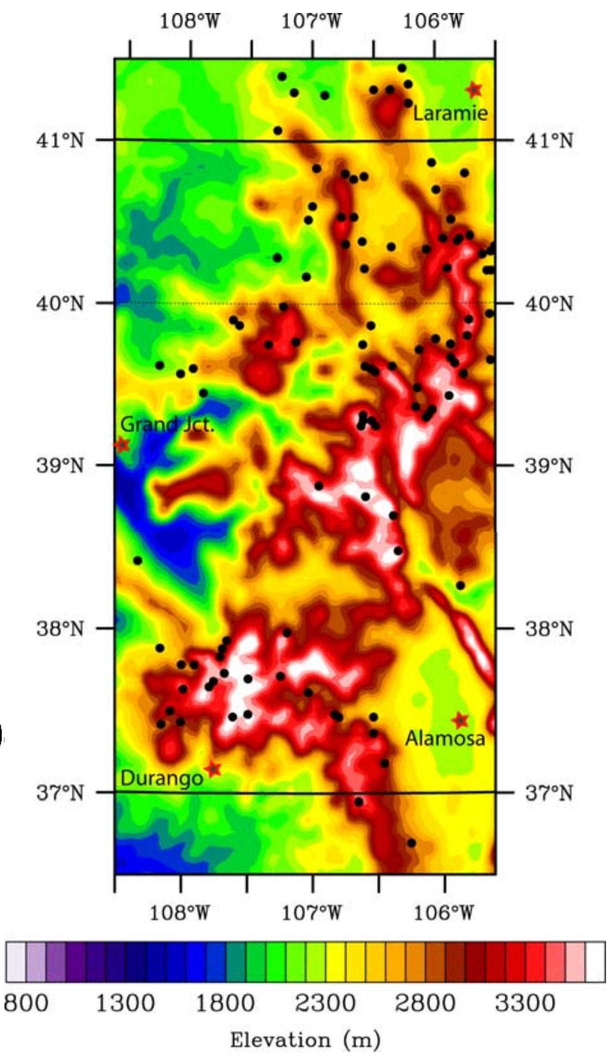
23 November 2002 – 4 December 2002



WRFV3 simulations at 20, 10, 4, and 2 km horizontal resolution

Average precipitation at high elevation SNOTEL sites





Simulations were performed with WRFV3 using NARR model data for lateral boundary conditions. Thompson microphysics scheme was used for all the simulations.

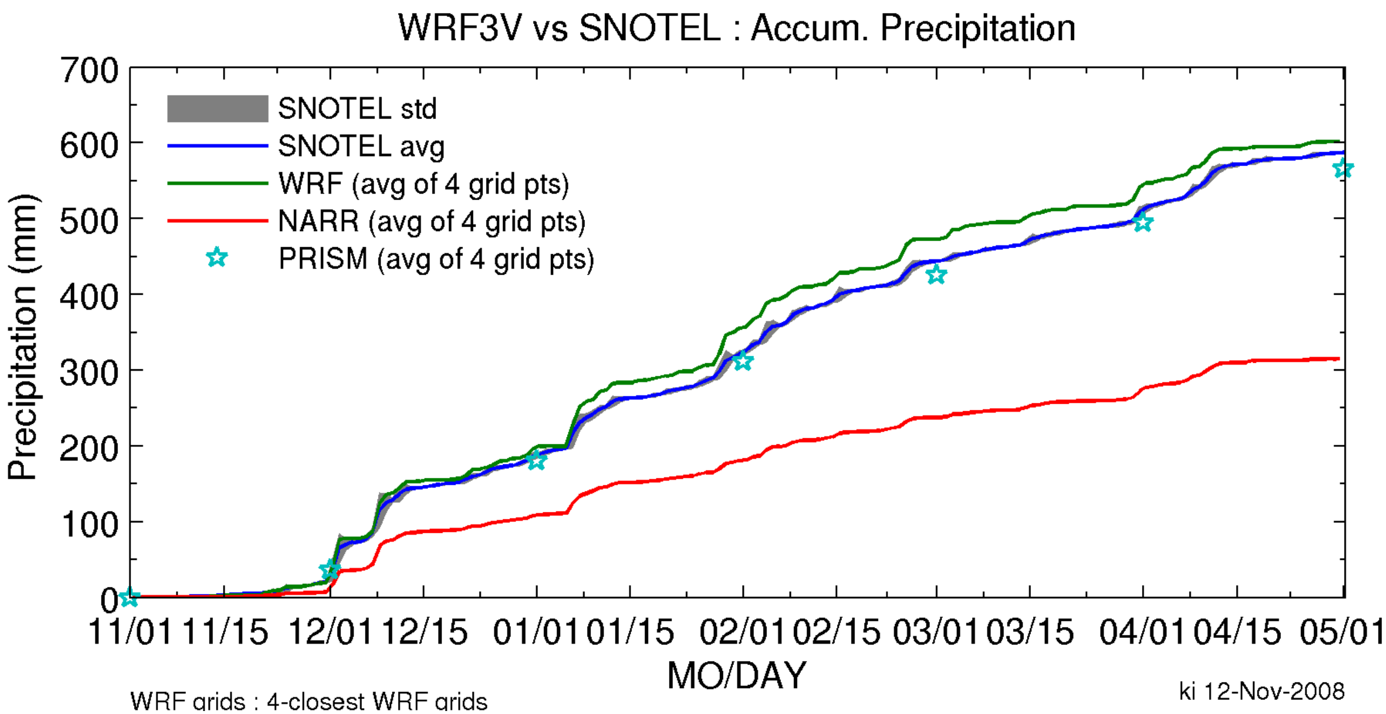
Model data points are averages of values at four grid points nearest to the individual SNOTEL sites. There were 100 operational SNOTEL sites in the subdomain (shown right) in 2002.

Full Water Year Historical Simulations

- 6 month period from Nov. 1 – May. 1
- Four years simulated:
  - 2001/2002 (dry)
  - 2003/2004 (average)
  - 2005/2006 (average)
  - 2007/2008 (wet)
- Model setup and design
  - WRF Model (version 3)
  - A single domain: 1200x1000 km^2; 2 km grid spacing; 45 levels
  - PBL scheme: MYJ
  - Noah land-surface model
  - CAM longwave & shortwave scheme
  - Thompson et al. cloud microphysics scheme
  - The 3-hourly, 32-km NARR data provide the initial and lateral boundary conditions

Full Water Year Simulation

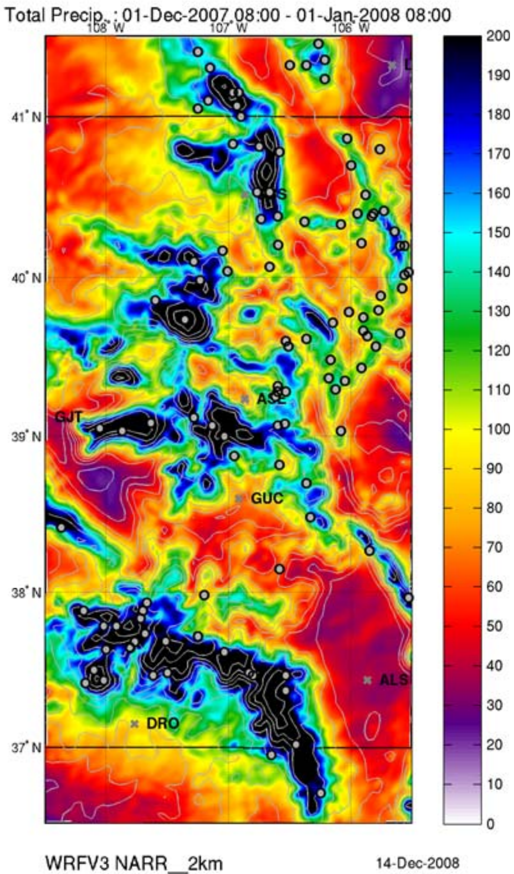
Nov. 2007-May 2008



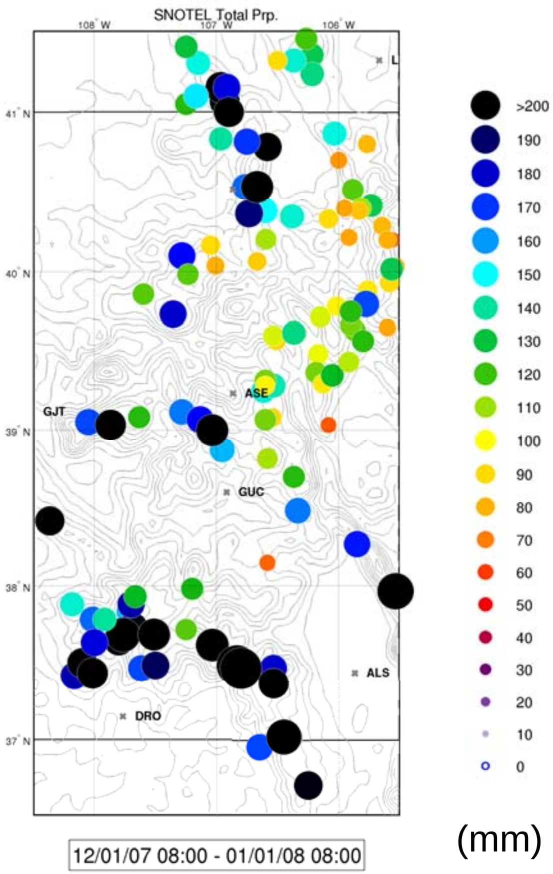
		Monthly						Sim. Period
		November	December	January	February	March	April	11/1-5/1
Difference in accumulative precipitation between WRF and OBS (WRF-SNOTEL)	Mean of 4-grid points	-1.70	7.10	23.43	-1.44	4.24	-18.32	14.76
	Inverse distance weighted mean of 4-grid points	-1.66	7.48	23.90	-1.15	4.29	-18.27	16.16
Absolute difference in accumulative precipitation between WRF and OBS (WRF-SNOTEL)	Mean of 4-grid points	6.82	27.54	30.43	21.57	16.11	21.75	88.95
	Inverse distance weighted mean of 4-grid points	6.82	27.39	30.26	21.51	16.03	21.72	87.67

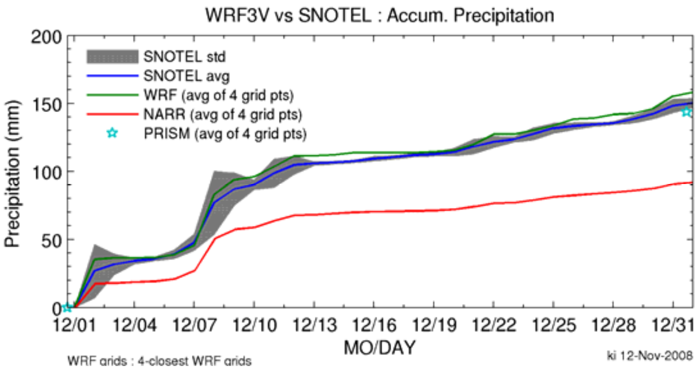
Total Precipitation: December 2008

WRF simulation



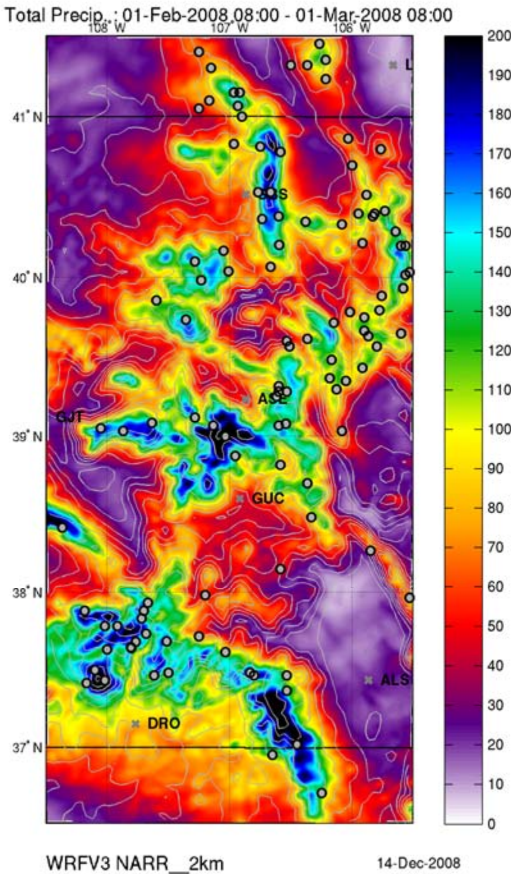
SNOTEL observations



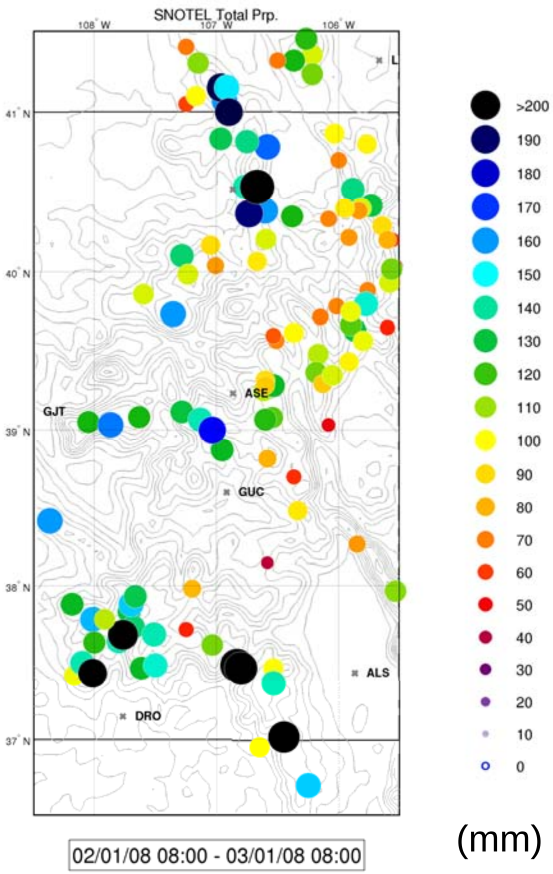


Total Precipitation: February 2008

WRF simulation



SNOTEL observations



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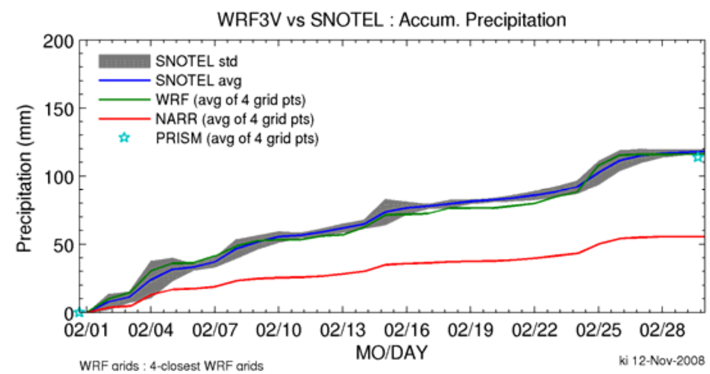
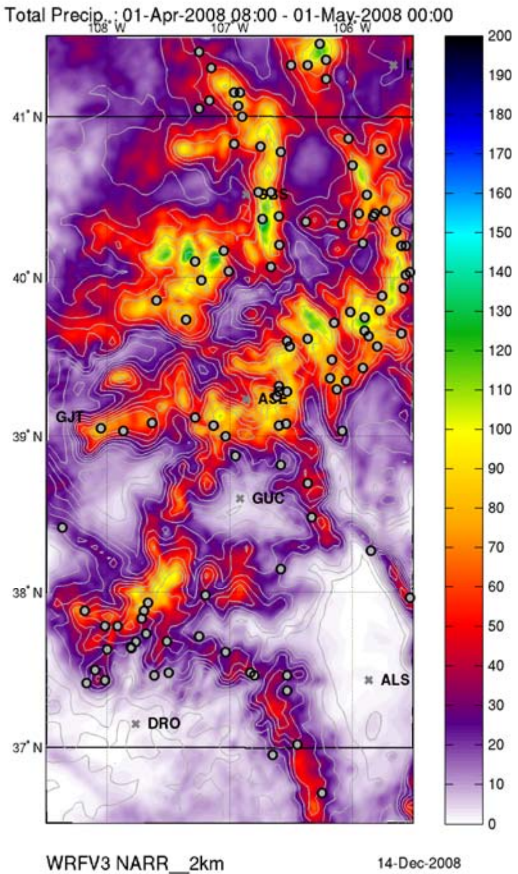
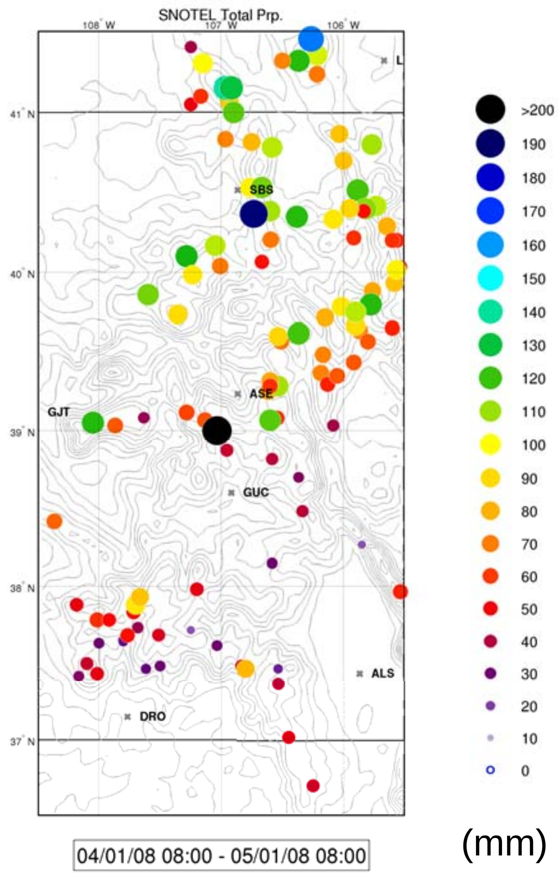


Total Precipitation: April 2008

WRF simulation



SNOTEL observations



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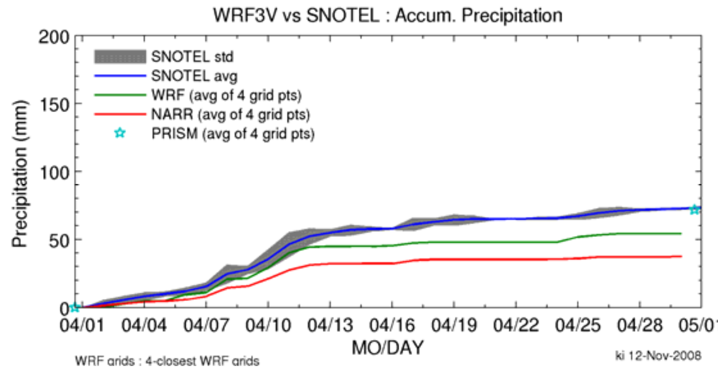
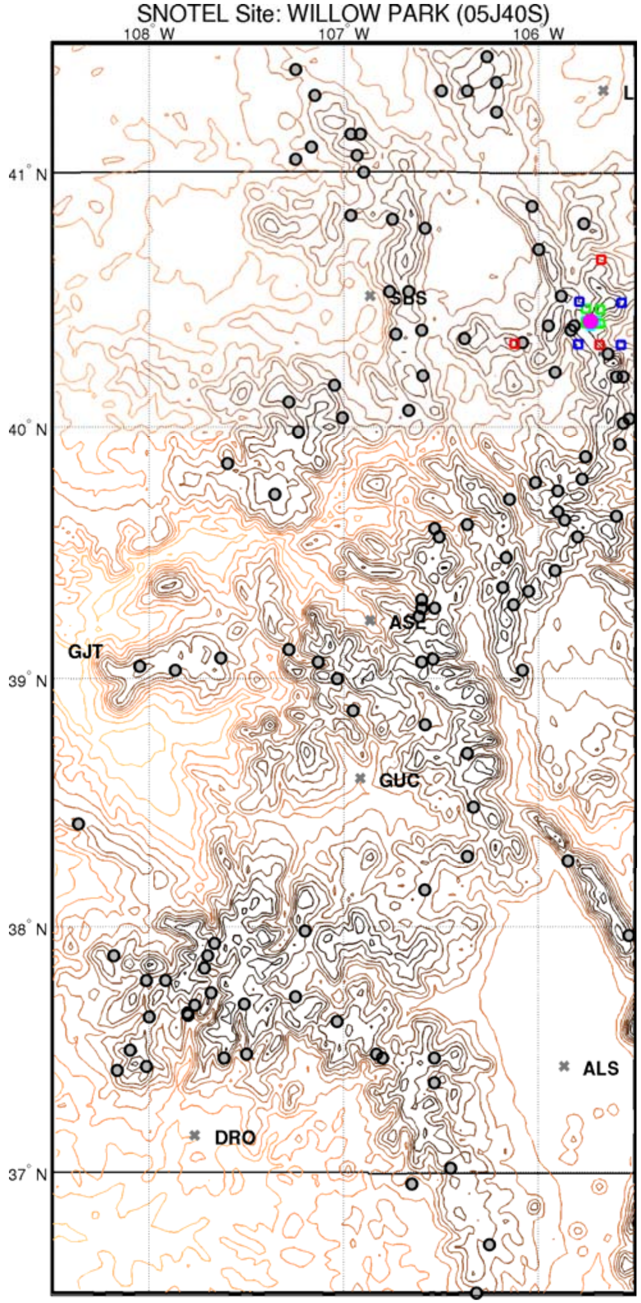
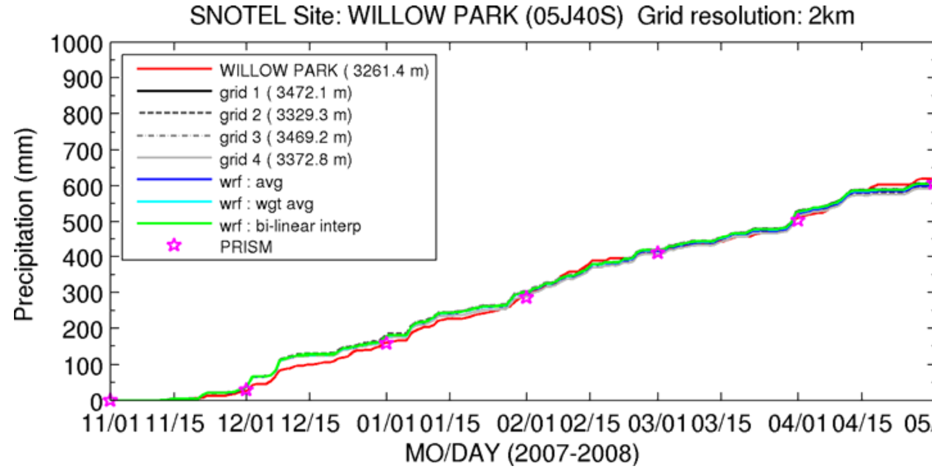
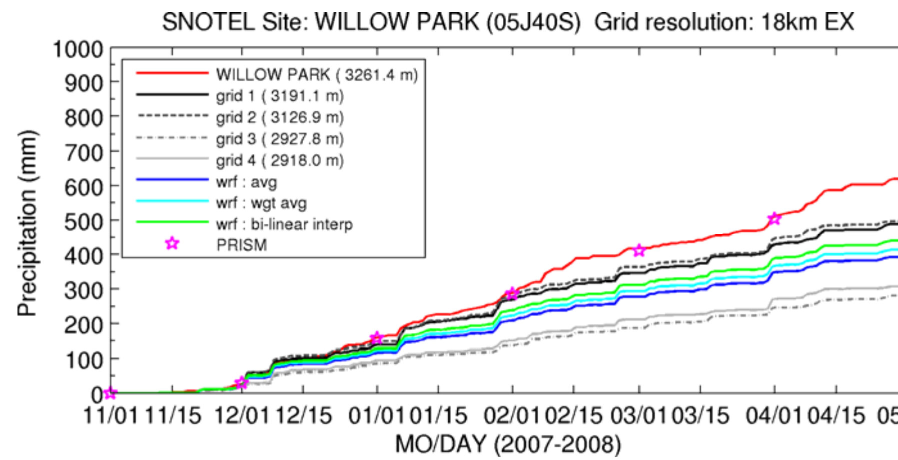


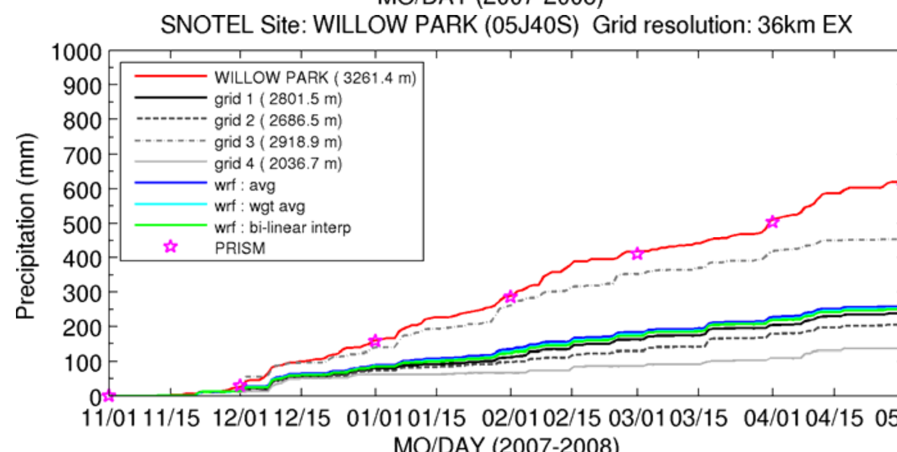




2 km

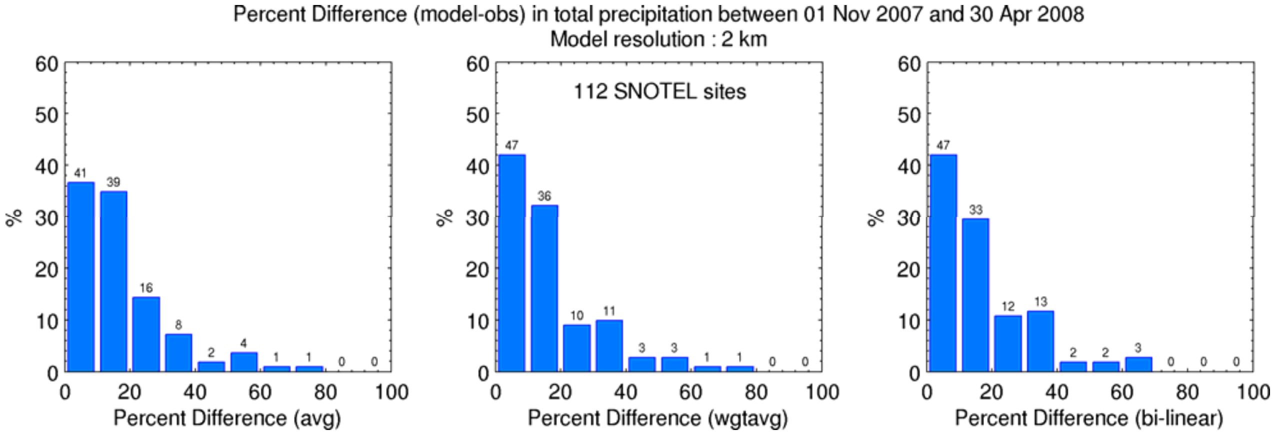


18 km

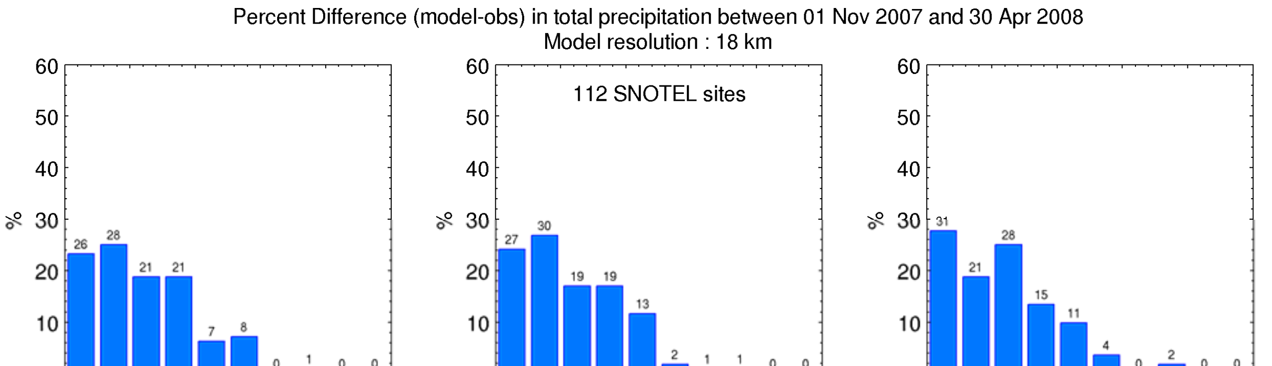


36 km

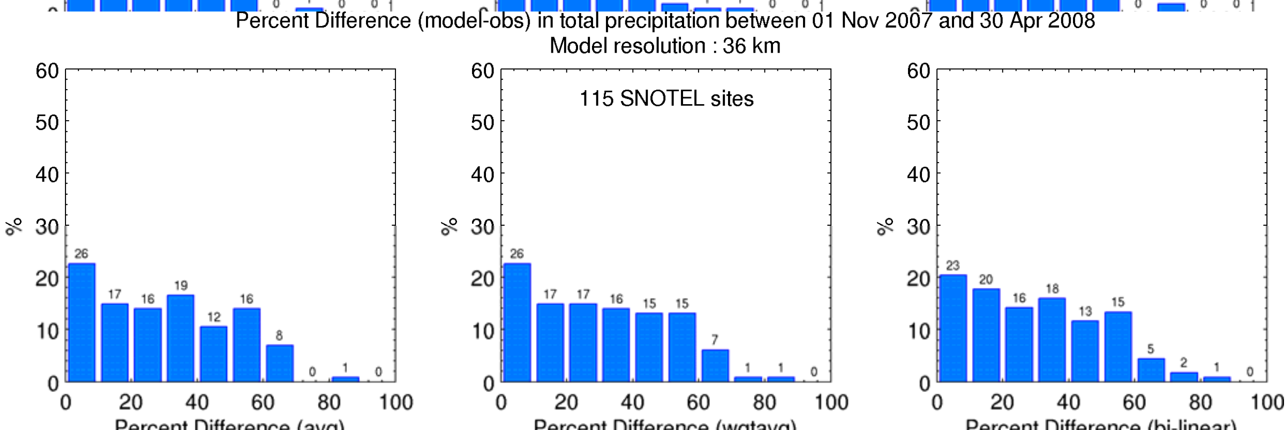
Histogram of percent differences between model and SNOTEL by grid resolution 2007/2008



2 km

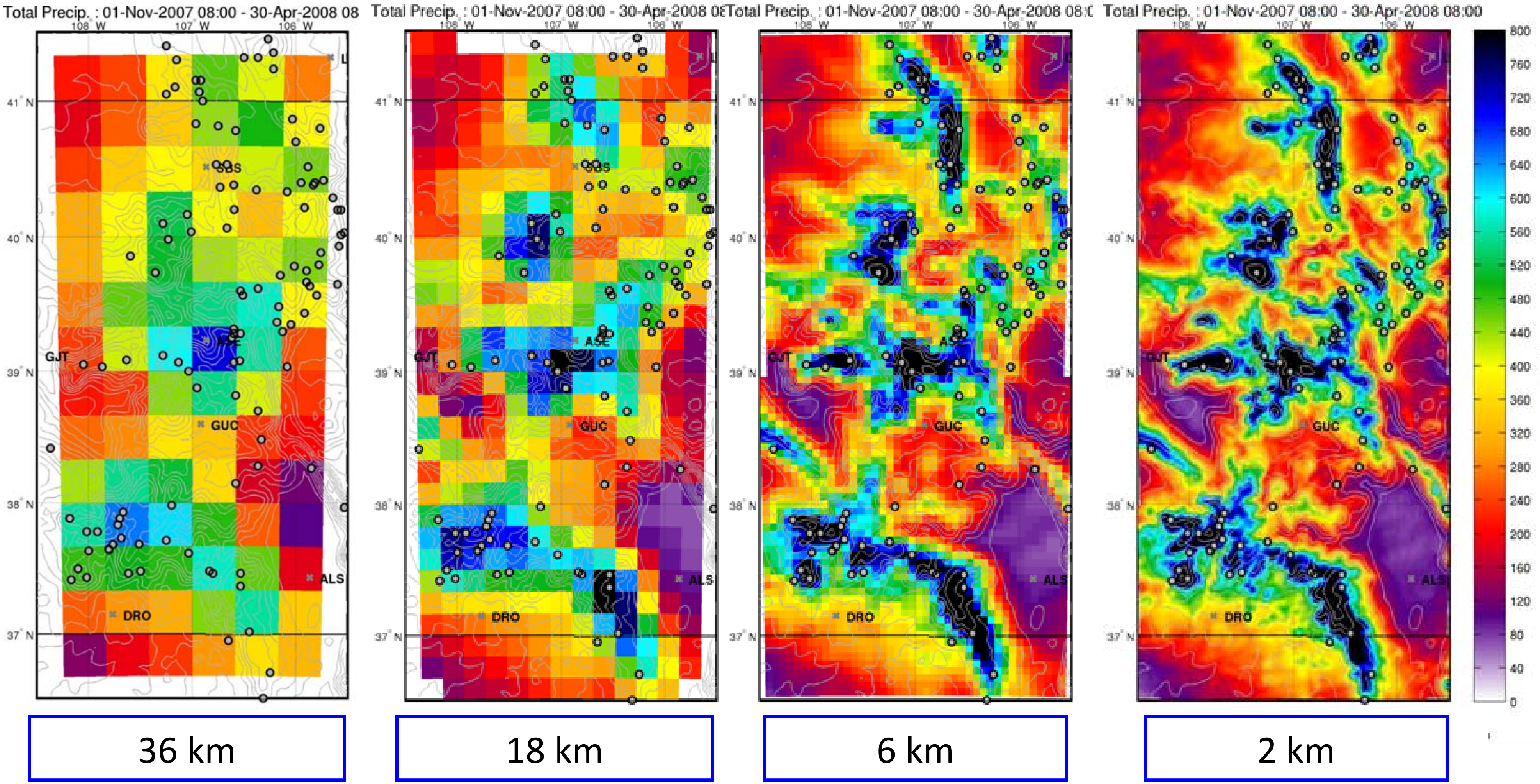


18 km

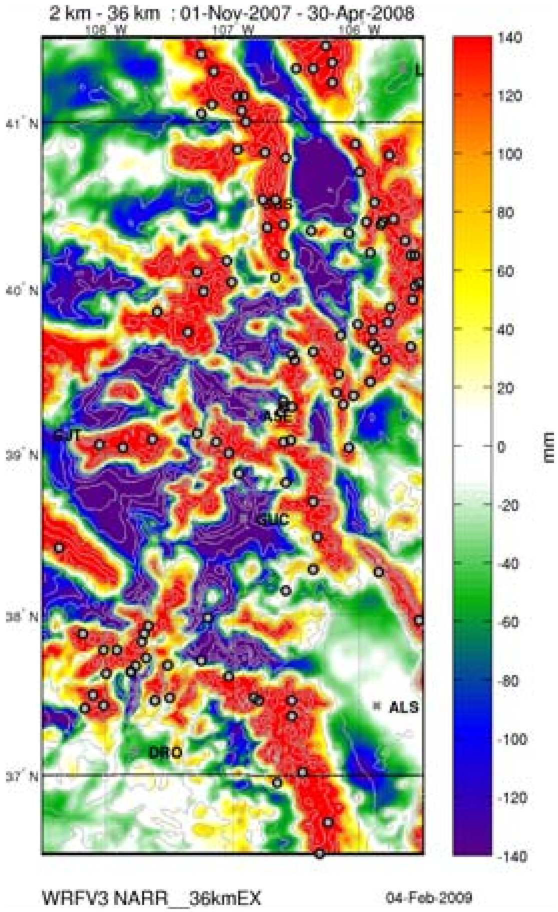


36 km

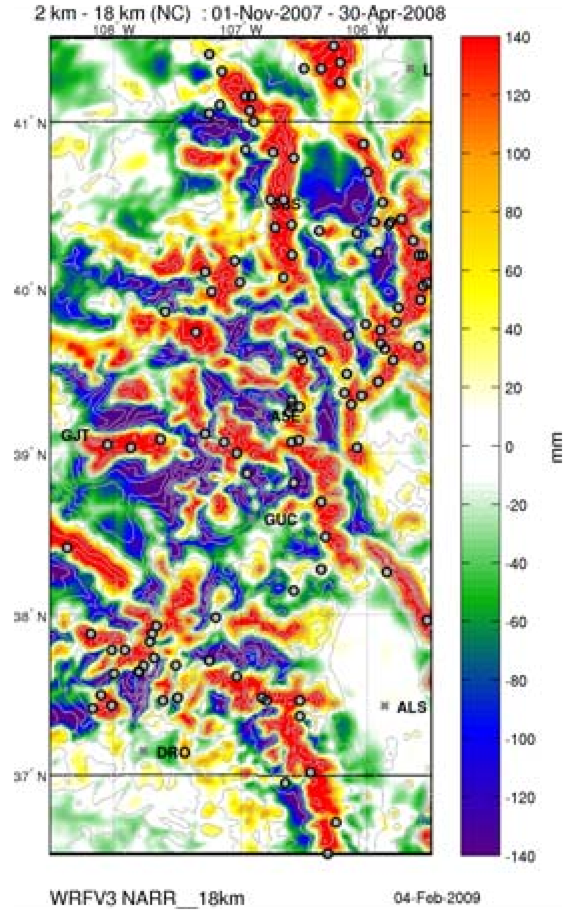
Comparisons : Total Precipitation for 1 Nov. 2007-1 May 2008



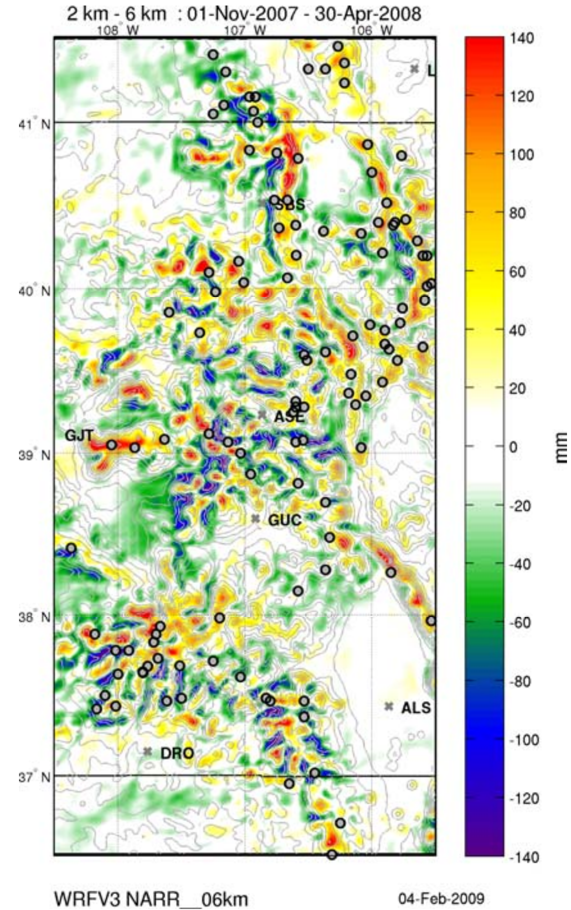
Difference in Total Precipitation for 1 Nov. 2007-1 May 2008



2 km - 36 km



2 km - 18 km



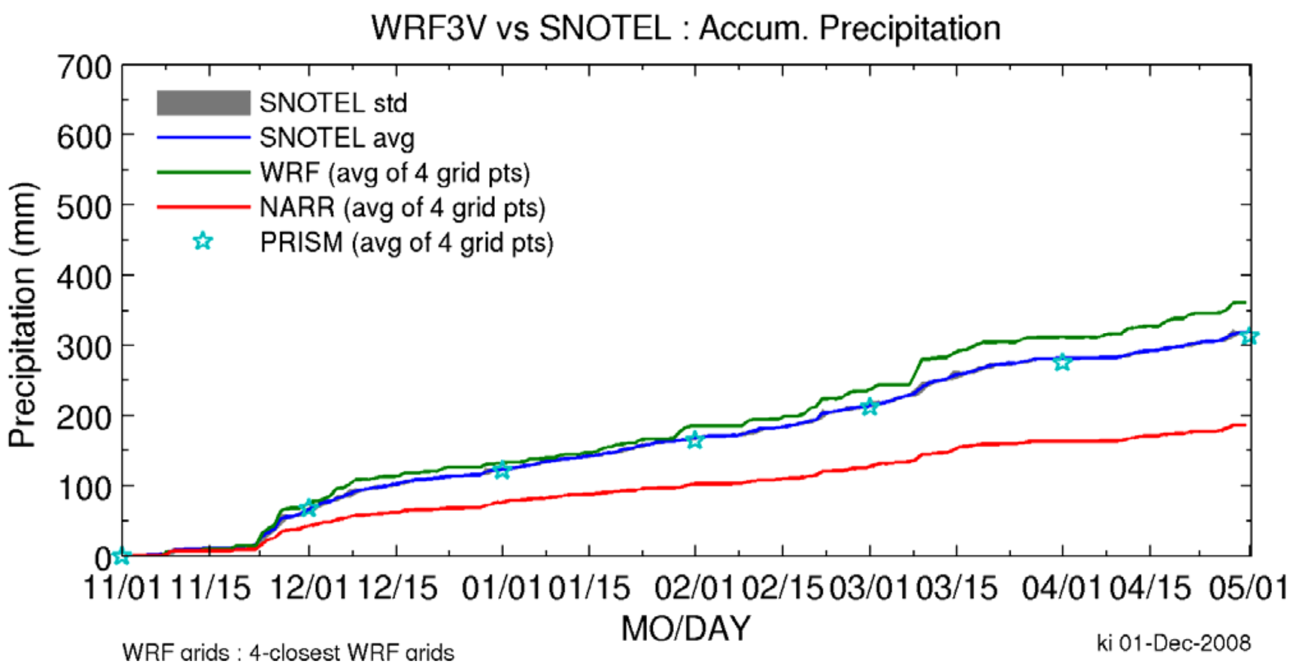
2 km - 6 km

2 km simulation has higher snowfall over the peaks, less in the valleys

(No cumulus parameterization for the simulation results with 18 and 36 km grid resolutions shown here.)

Full Water Year Simulation

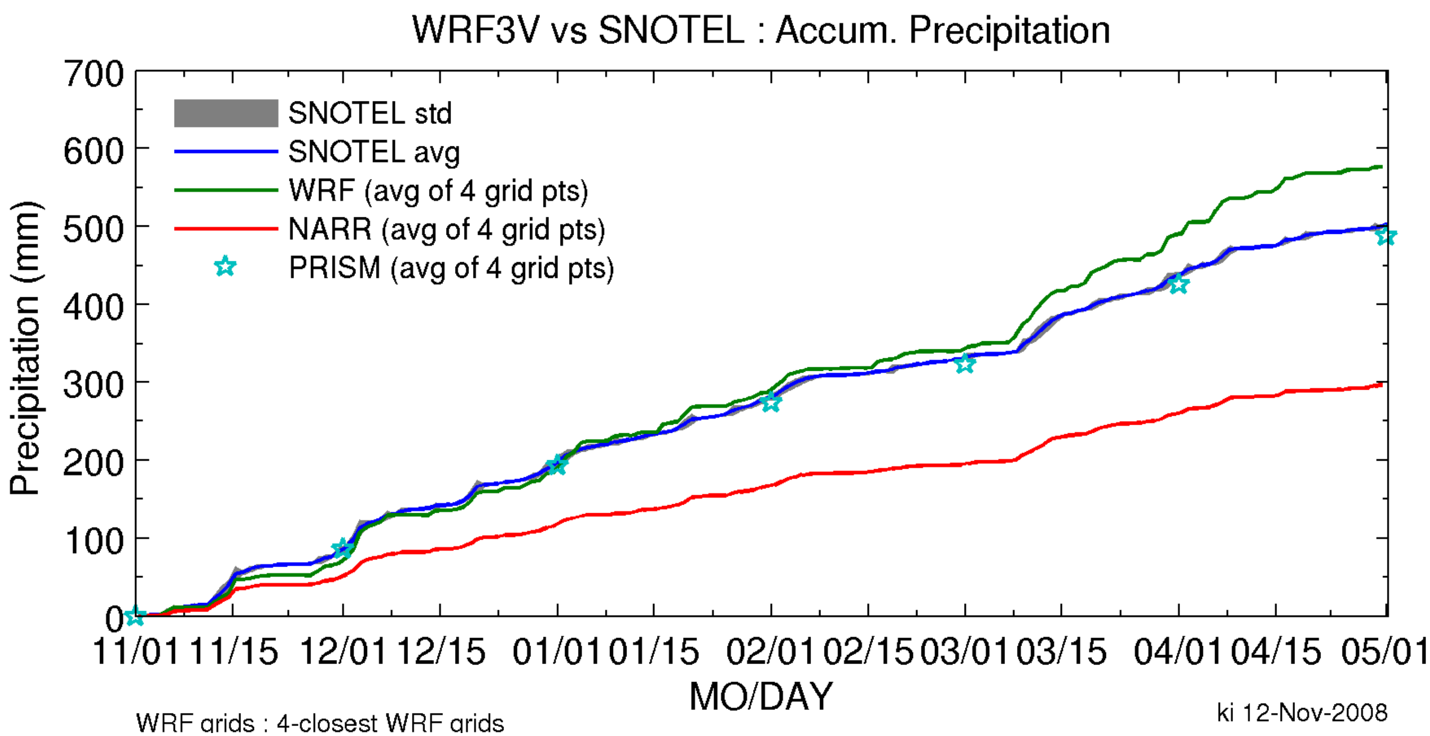
Nov. 2001-Apr. 2002



		Monthly						Sim. Period
		November	December	January	February	March	April	11/1-5/1
Difference in accumulative precipitation between WRF and OBS (WRF-SNOTEL)	Mean of 4-grid points	9.30	-0.63	7.97	5.63	7.51	12.84	42.61
	Inverse distance weighted mean of 4-grid points	9.38	-0.49	8.02	5.72	7.59	12.86	43.08
Absolute difference in accumulative precipitation between WRF and OBS (WRF-SNOTEL)	Mean of 4-grid points	15.38	11.52	15.06	12.28	16.63	17.29	58.79
	Inverse distance weighted mean of 4-grid points	15.43	11.42	14.92	12.29	16.60	17.27	58.61

Full Water Year Simulation

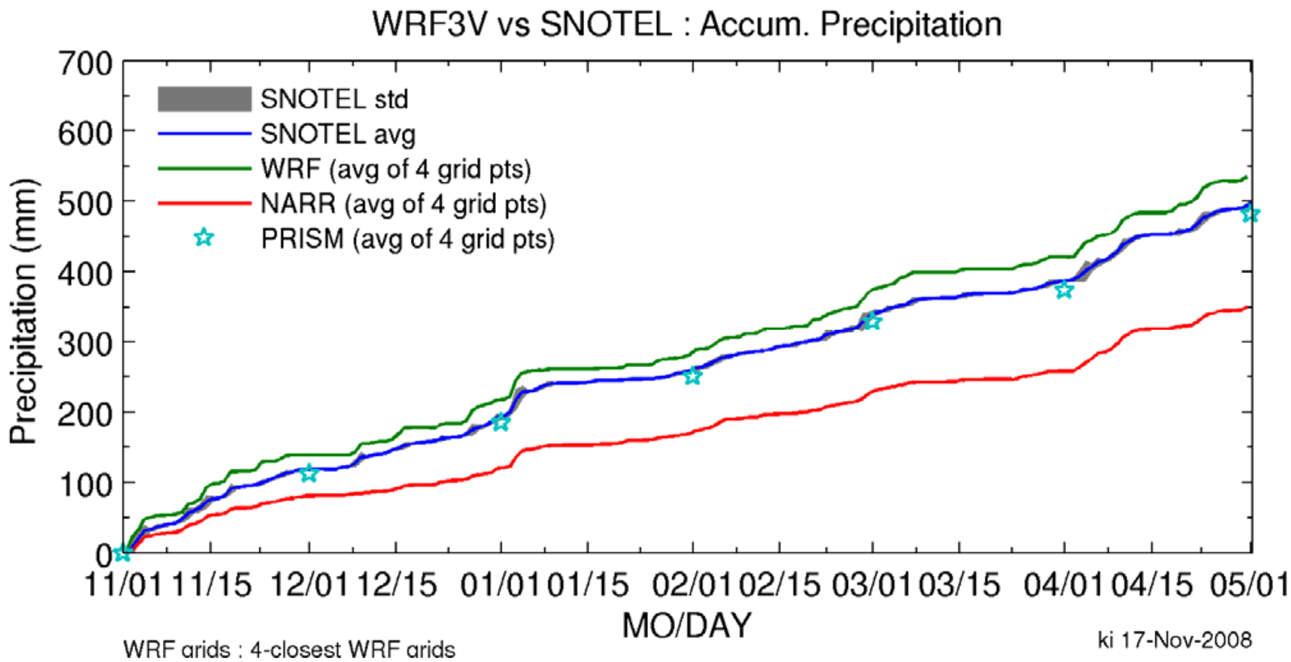
Nov. 2005-May. 2006



		Monthly						Sim. Period
		November	December	January	February	March	April	11/1-5/1
Difference in accumulative precipitation between WRF and OBS (WRF-SNOTEL)	Mean of 4-grid points	-15.79	4.83	13.13	-1.23	41.54	24.38	75.85
	Inverse distance weighted mean of 4-grid points	-15.74	5.01	13.32	-1.15	42.00	24.56	77.03
Absolute difference in accumulative precipitation between WRF and OBS (WRF-SNOTEL)	Mean of 4-grid points	19.95	19.97	18.96	11.06	43.95	25.51	99.02
	Inverse distance weighted mean of 4-grid points	19.80	20.00	18.92	10.99	44.23	25.62	98.43

Full Water Year Simulation

Nov. 2003-May. 2004



		Monthly						Sim. Period
		November	December	January	February	March	April	11/1-5/1
Difference in accumulative precipitation between WRF and OBS (WRF-SNOTEL)	Mean of 4-grid points	20.43	4.12	3.04	8.99	-1.42	9.27	40.72
	Inverse distance weighted mean of 4-grid points	20.64	4.31	3.23	9.26	-1.36	9.44	41.81
Absolute difference in accumulative precipitation between WRF and OBS (WRF-SNOTEL)	Mean of 4-grid points	36.16	15.81	17.35	16.98	12.29	22.35	76.38
	Inverse distance weighted mean of 4-grid points	35.84	15.66	17.31	16.87	12.24	22.56	76.27

Future Climate Sensitivity Run

Motivation
Prohibitively expensive to run high-resolution models at the desired resolutions for decades to generate a statistically meaningful future climate (time-slice method)

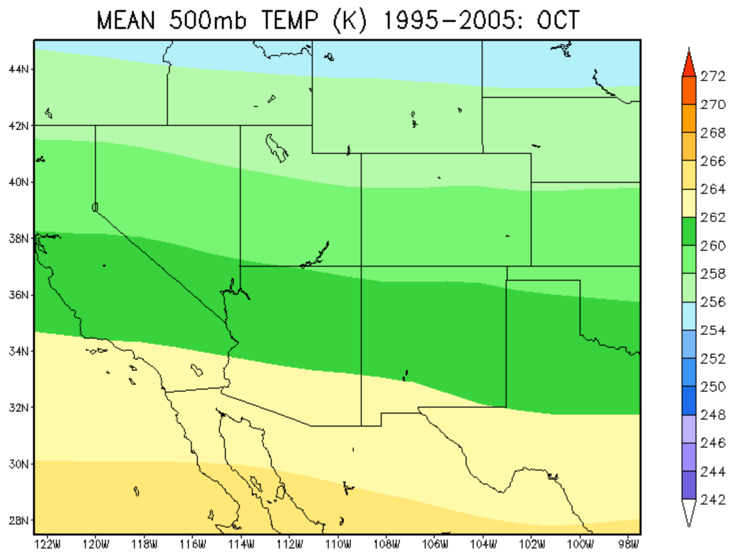
Approach:
Add a climate signal to the current-day high resolution simulations. Primary impact of the climate signal is to warm and moisten the troposphere.
Signal derived from future climate model runs.

Future Climate Sensitivity Run Setup

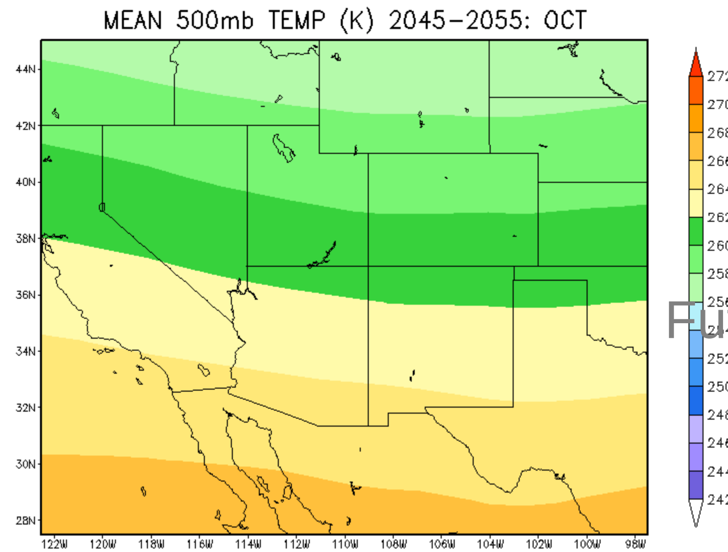
- Climate sensitivity run performed using modified boundary conditions to the NARR analysis of a current water year following the approach by Kawase et al. 2008 and Hara et al. 2008.
  - Modified initial and boundary conditions obtained by subtracting the 10 year average monthly conditions of 10 2050s CCSM3 A1B scenario runs from the average of 10 1990s CCSM3 present climate runs averaged over the month and added to the NARR initial and boundary conditions from a current water year (temperature, relative humidity, geopotential height, and wind).
- Modified initial and boundary conditions show a 1.5 C temperature increase over Colorado, and an increase of mixing ratio on the order of 10%. RH in the simulation similar to the control.
- WRF model run using the new boundary conditions for high resolution simulations of two full water years

500mb-Temperature

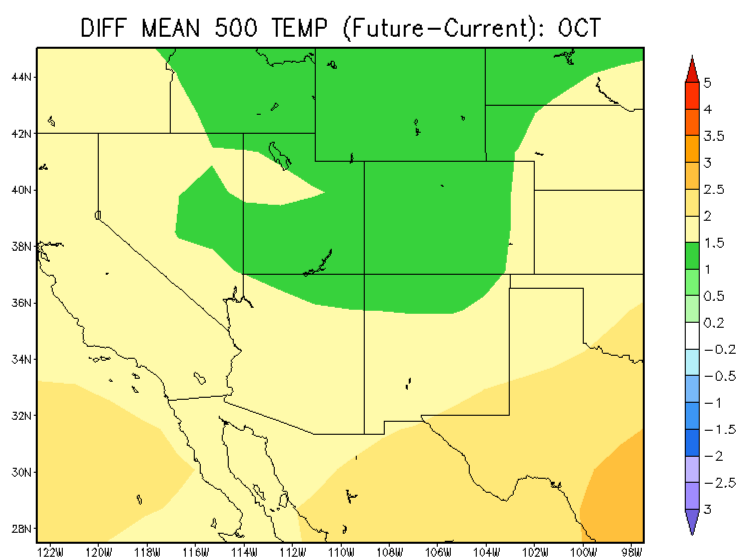
Current



Future

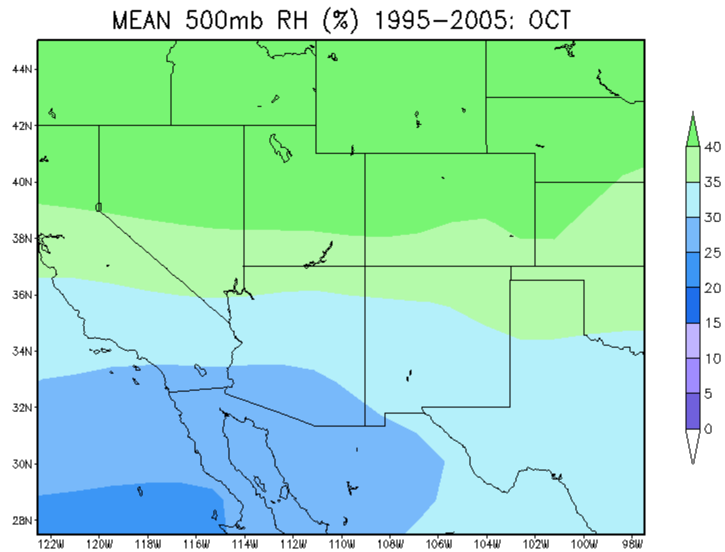


Future-Current

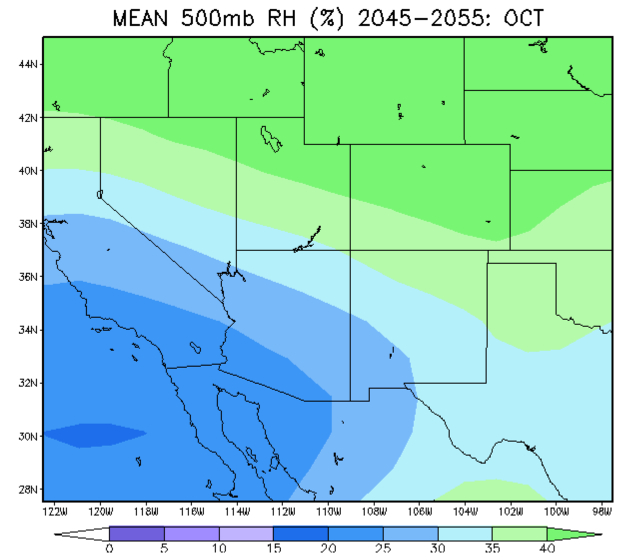


500mb-RH

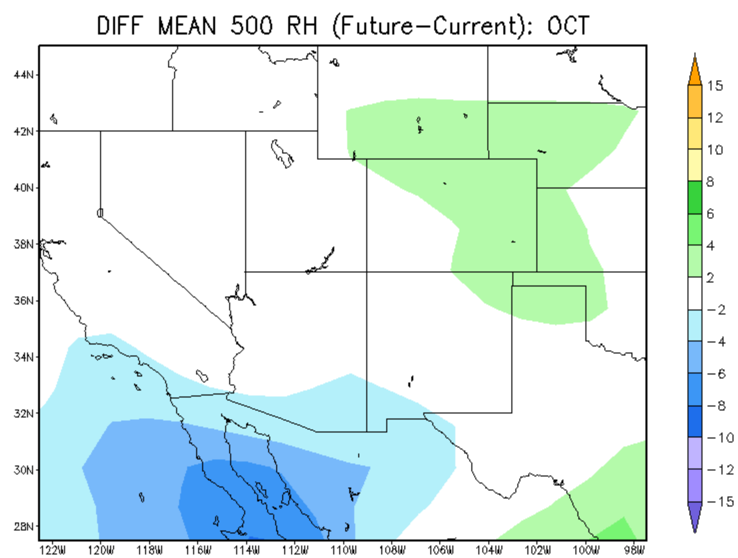
Current



Future



Future-Current

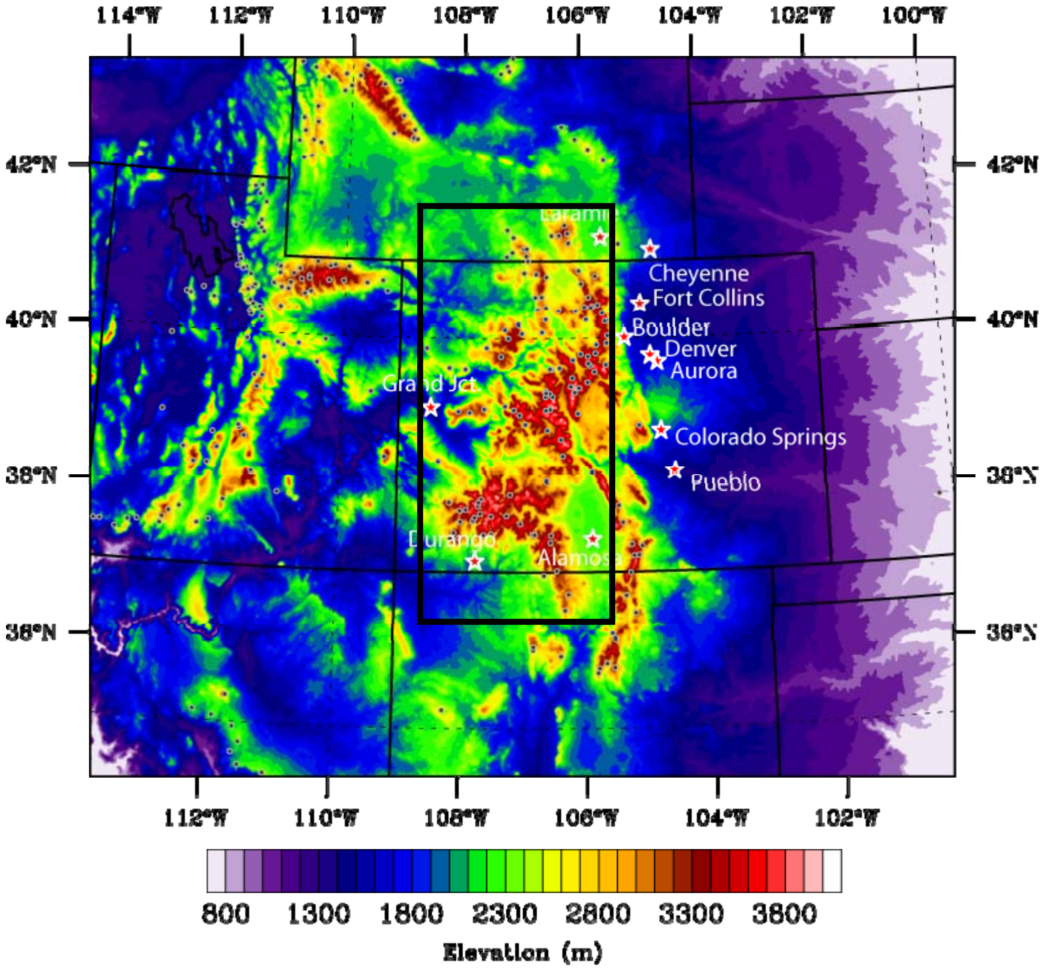


Sensitivity Run Results:
November 2007 – May 2008 (“wet” year)

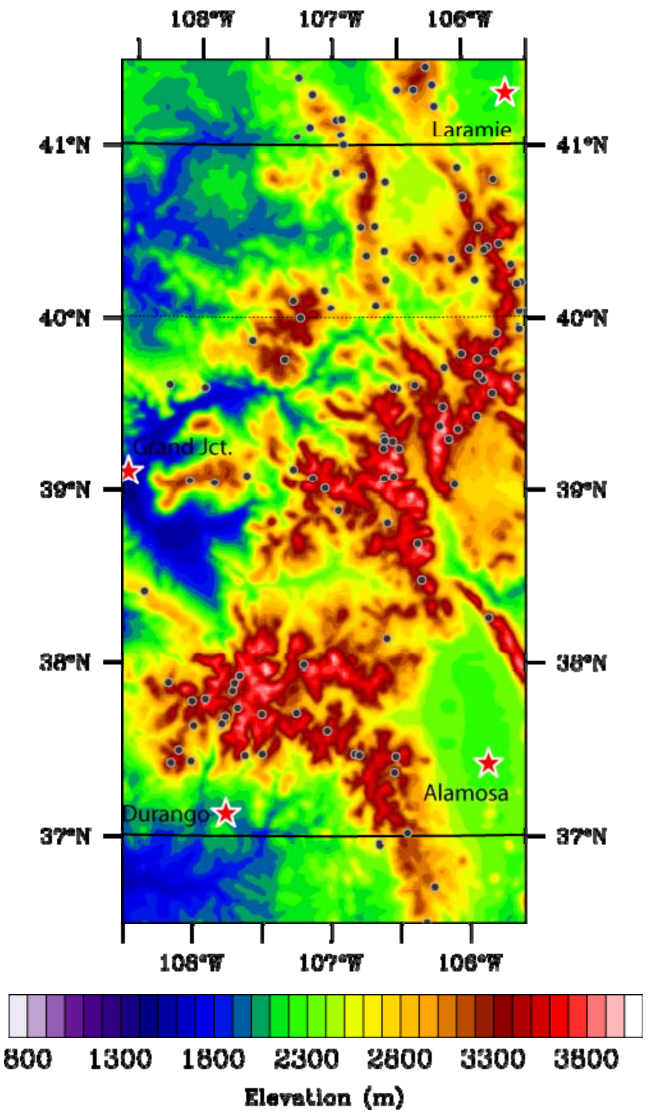
Total Precipitation

Model Domain

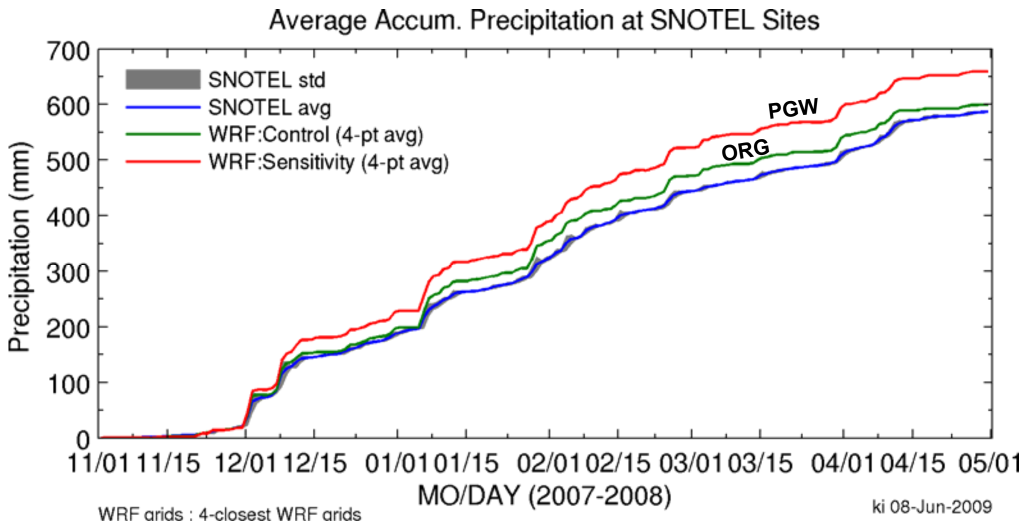
Full Domain



Sub-domain



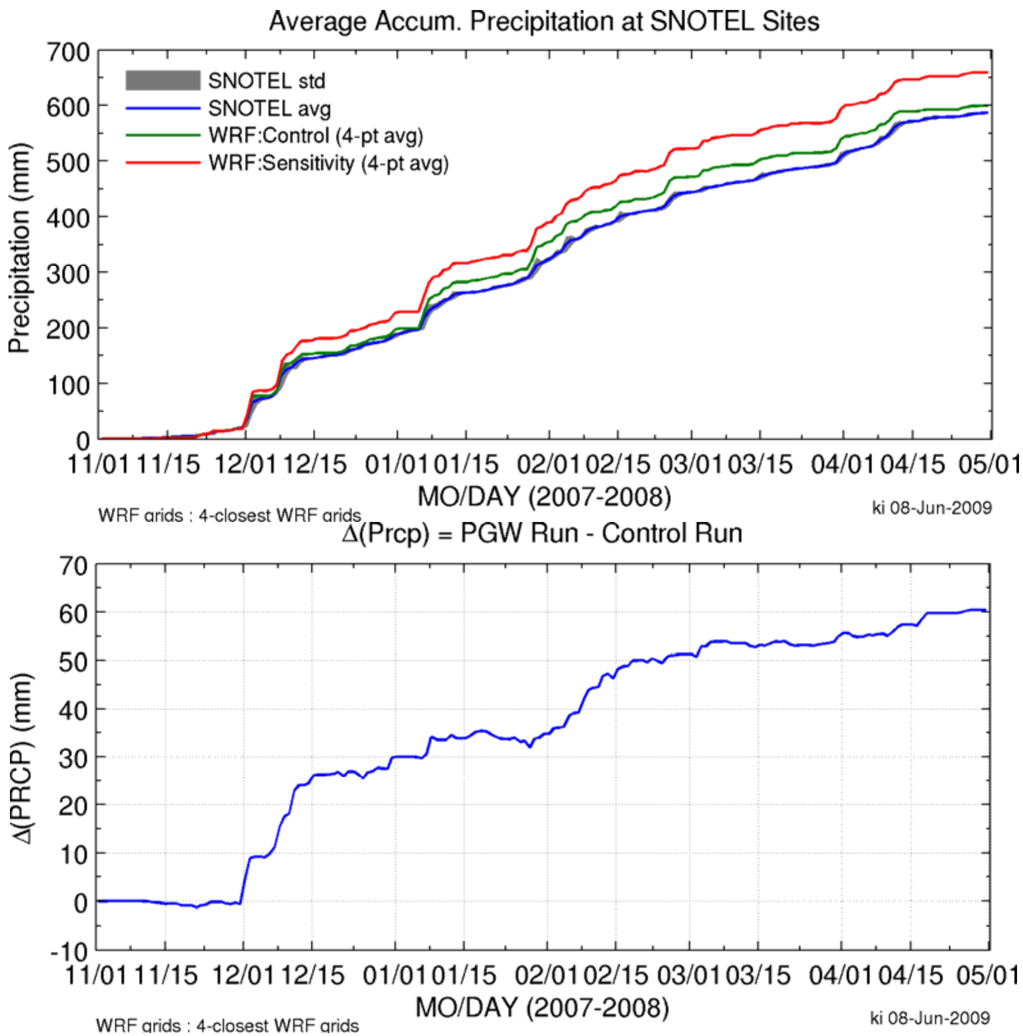
Precipitation in the CNTRL and sensitivity runs at SNOTEL Sites 1 Nov. 2007-1 May. 2008



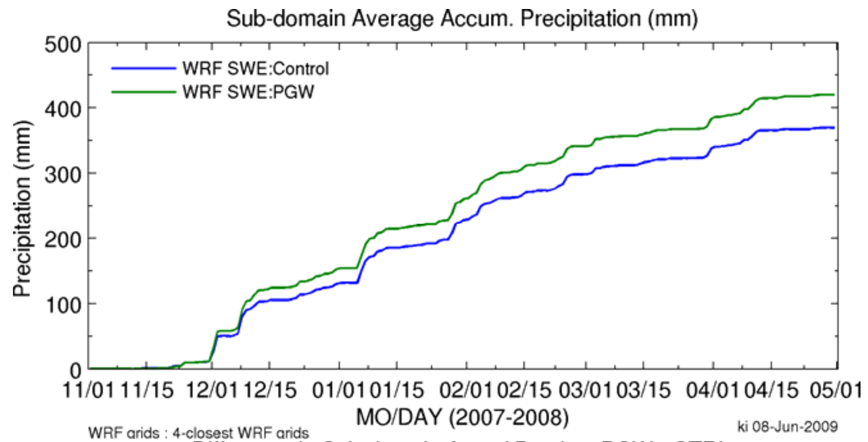
Average Total Precipitation : model values are the average of four nearest grid points from each SNOTEL site.

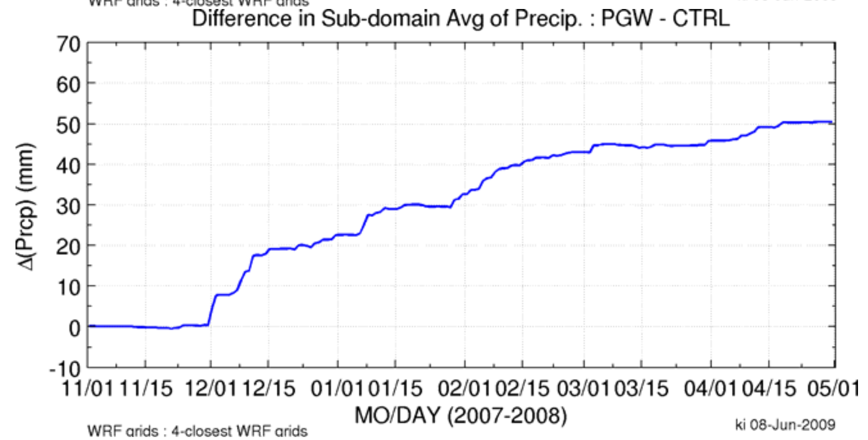
	Monthly Total (mm)						Sim. Period
	November	December	January	February	March	April	11/1-5/1
Control Run	41.2	157.5	156.7	115.5	73.9	54.0	598.8
Sensitivity Run	46.0	182.7	161.5	131.9	78.3	58.8	659.2
% difference	**+11.7%**	**+16.0%**	**+3.0%**	**+14.2%**	**+5.9%**	**+8.9%**	**+10.1%**

Average Precipitation in the CNTRL and sensitivity runs at SNOTEL Sites
1 Nov. 2007-1 May. 2008



Sub-domain Average of Precip. in the CNTRL and PGW runs 1 Nov. 2007-1 May. 2008

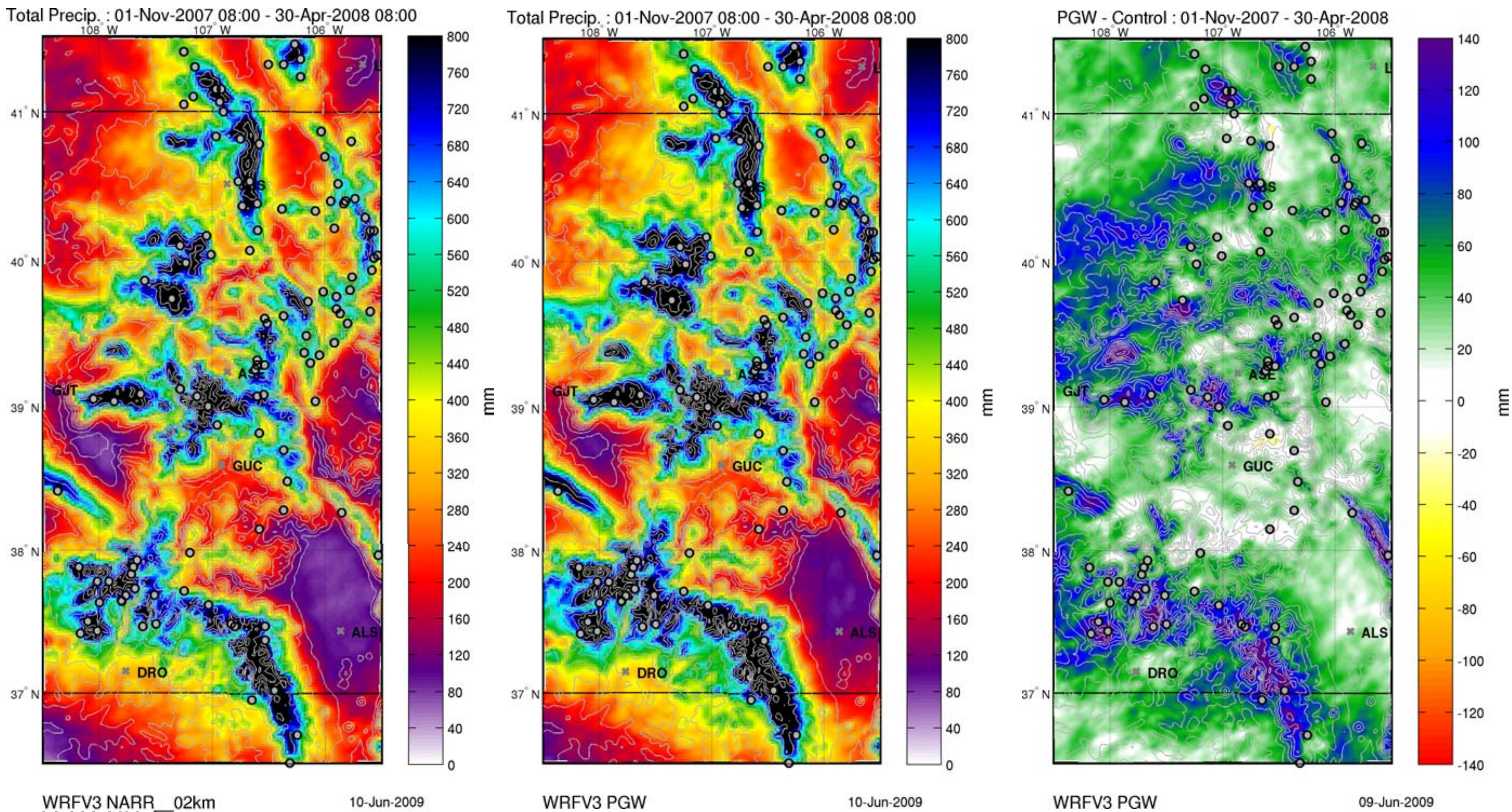




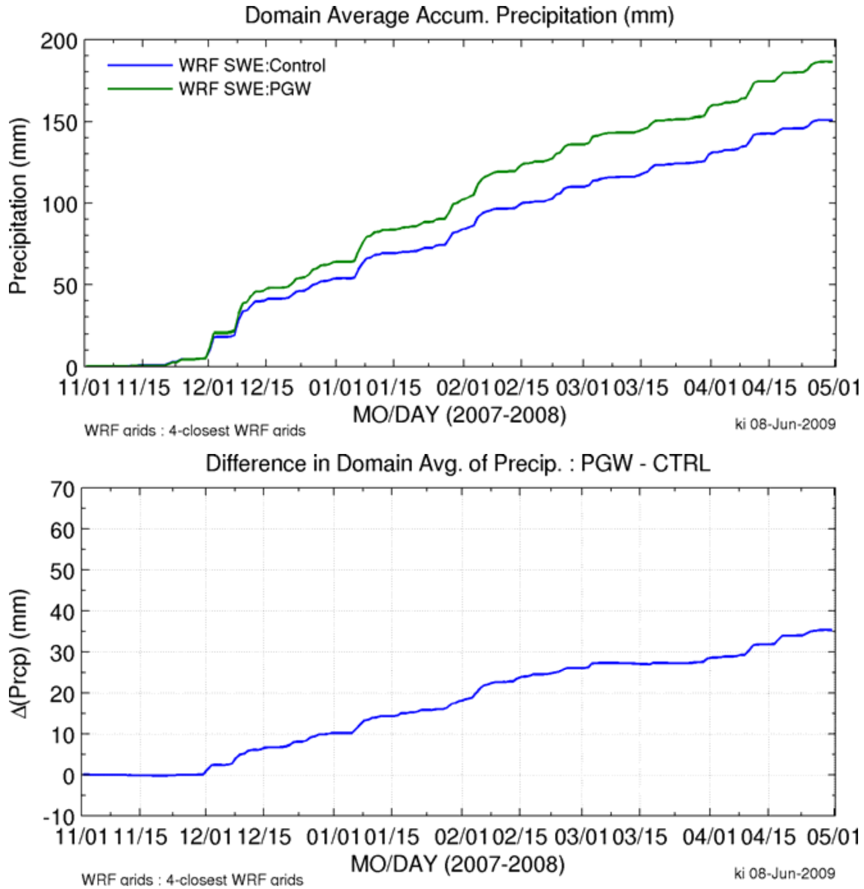
	November	December	January	February	March	April	11/1-5/1
% difference	**+1.8%**	**+18.6%**	**+10.3%**	**+15.0%**	**+13.6%**	**+7.2%**	**+13.7%**

Total Precipitation: Nov 2007 - MAY 2008

WRF Control Run | **WRF PGW Run** | **PGW Run – Control Run**



Domain Average of Precip. in the CNTRL and PGW runs 1 Nov. 2007-1 May. 2008



	November	December	January	February	March	April	11/1-5/1
% difference	**0.0%**	**+21.0%**	**+26.2%**	**+30.0%**	**+12.2%**	**+32.1%**	**+23.4%**

Summary

- Comparison of WRF high resolution simulations of annual snowfall to SNOTEL observations over the Colorado Headwaters regions show very good agreement if resolutions below 6 km are used.
  - WRF model water year accumulated snowfall at SNOTEL sites agrees are within 20% of the observations for 80% of the 112 Colorado Headwaters sites
  - Some areas of disagreement due to the WRF model creating too much snow to the lee of steep topography
  - Other disagreements under investigation
- 18 km resolution runs underestimated SNOTEL snowfall by 25-50% as a result of:
  - Terrain smoothing and associated spreading of the precipitation horizontally as a result of a broader and weaker updraft
  - Not resolving mesoscale circulation patterns such as Conditional Symmetric Instability which produce snow bands.

Colorado Headwaters Summary

- High resolution simulations (2 km horizontal) of annual snowfall suggests that current global and regional model estimates of snowfall at the ground (18 km resolution and higher) underestimate high elevation snow by 25-50%, and over estimate low elevation snow fall by a similar amount.
- A sensitivity run simulating the impact of enhanced atmospheric moisture due to global warming from an ensemble of CCSM centered on 2050 suggests that high elevation snowpack increases by ~10-25% under this scenario.
- Future simulations will focus on:
  - Verifying the hydrology of the model runs, including SWE and streamflow
  - Applying the verified high resolution model to future climate impacts using a Time Slice approach