Climate Change and Mountain Hydrology in GEWEX

Roy Rasmussen, National Center for Atmospheric Research

GEWEX Conference Talk: Extremes and Water on the Edge 2018

Mountain Hydrology Challenges

NCAR

1. Observations

- In-situ snowfall measurements: How accurate?
- Remote sensing snowfall measurements: Are we there yet?
    - Blowing snow and snow evolution
    - Dust and black carbon on snow
- Snowpack
    - SNOTEL: Is it good enough and are they at the right locations?
    - Remote sensing (satellite, Airborne Snow Observatory, drones, embedded radars): Next steps?

2. Modeling

- Convective Permitting Modeling of snowfall and snowpack
- Simulation of snowfall and snowpack at 10 meter resolution (Ecosystems and hydrology)
- Simulation of blowing snow
- Glacier formation and melt (Mass Balance)
- Accounting for snow size distribution and crystal type when correcting in-situ snow measurements.
- Estimating most likely climate change impacts at convective permitting scales:
- Flooding due to rain on snow and potentially new atmospheric conditions (black swans)

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A GEWEX Regional Hydroclimate Project for the Rocky Mountains

integrate ongoing research activities in Canada and the USA

- **Understanding the impacts of climate variability and change on water availability across the river basins of the Rocky Mountains**

- **Research needs:**

- ***<u>Observational synthesis</u>*:**
  - *Coordinated multi-scale field and remote sensing campaigns to quantify cross-scale controls on regional hydroclimatic processes*
  - *Understanding of key processes and compilation of data to test model hypotheses*

- ***<u>Modeling synthesis</u>*:**
  - *Controlled comparison of different modeling approaches*
  - *Improved model physics parameterization development for integrated water cycle projections*

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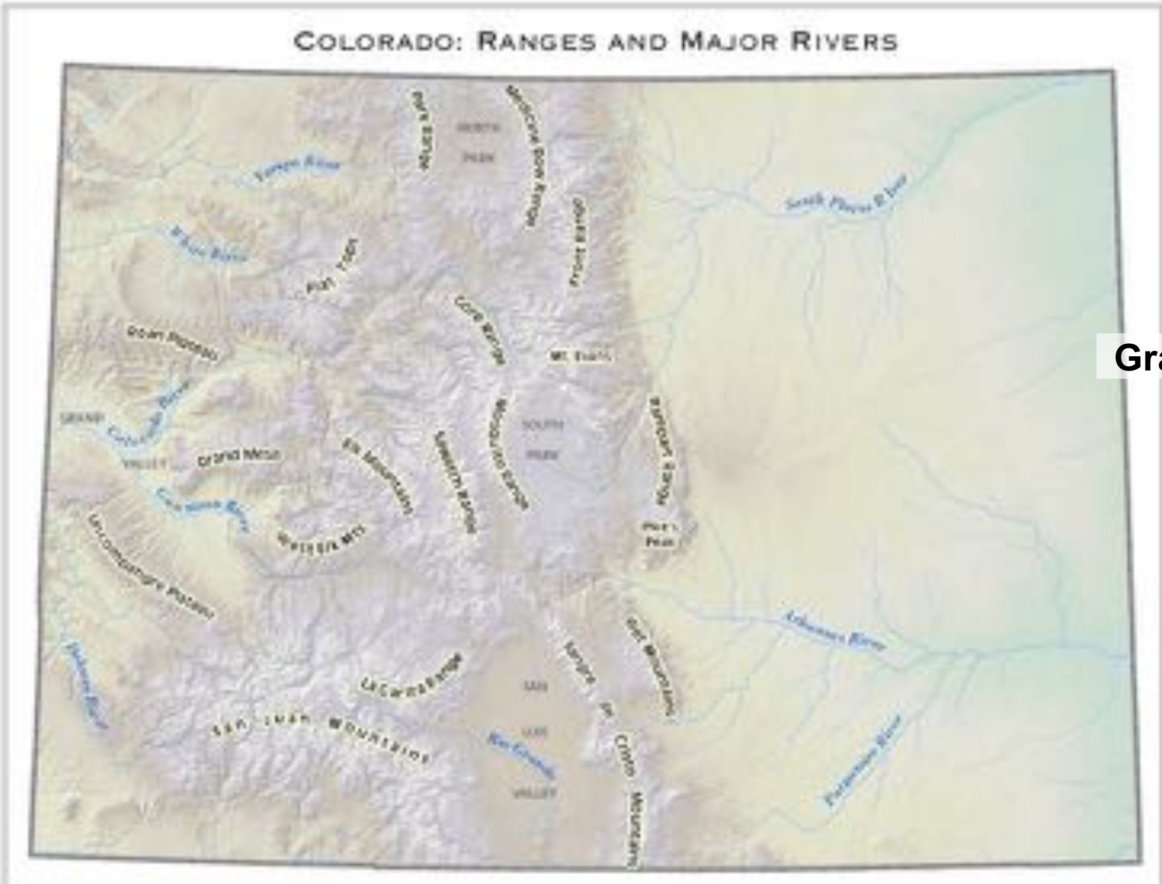
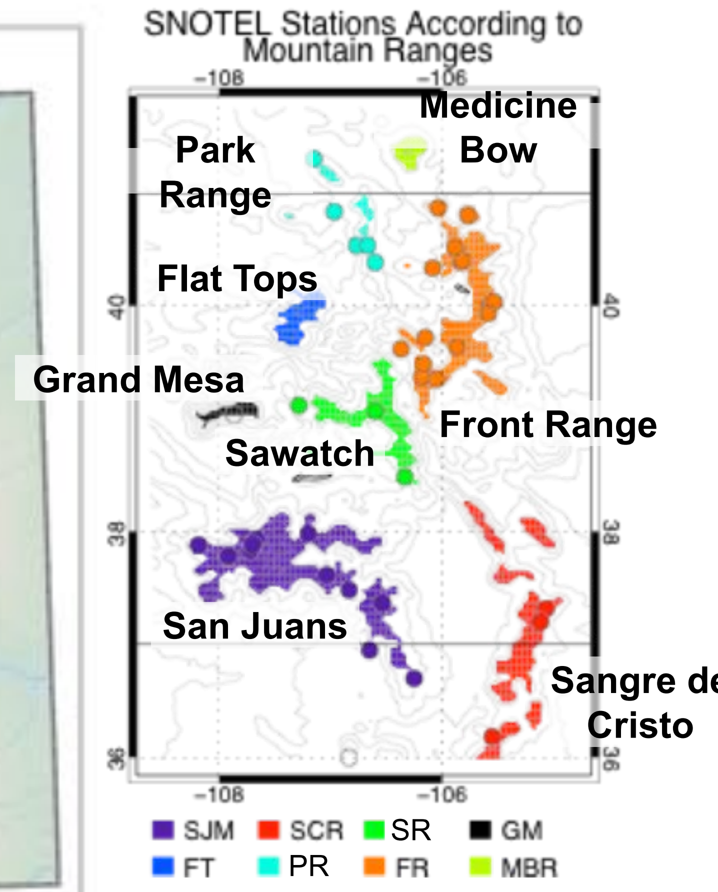
GEWEX

How fine does our model grid spacing need to be in order to capture snowfall and snowpack adequate for climate change studies?

Colorado Mountain Ranges





Headwaters Streams

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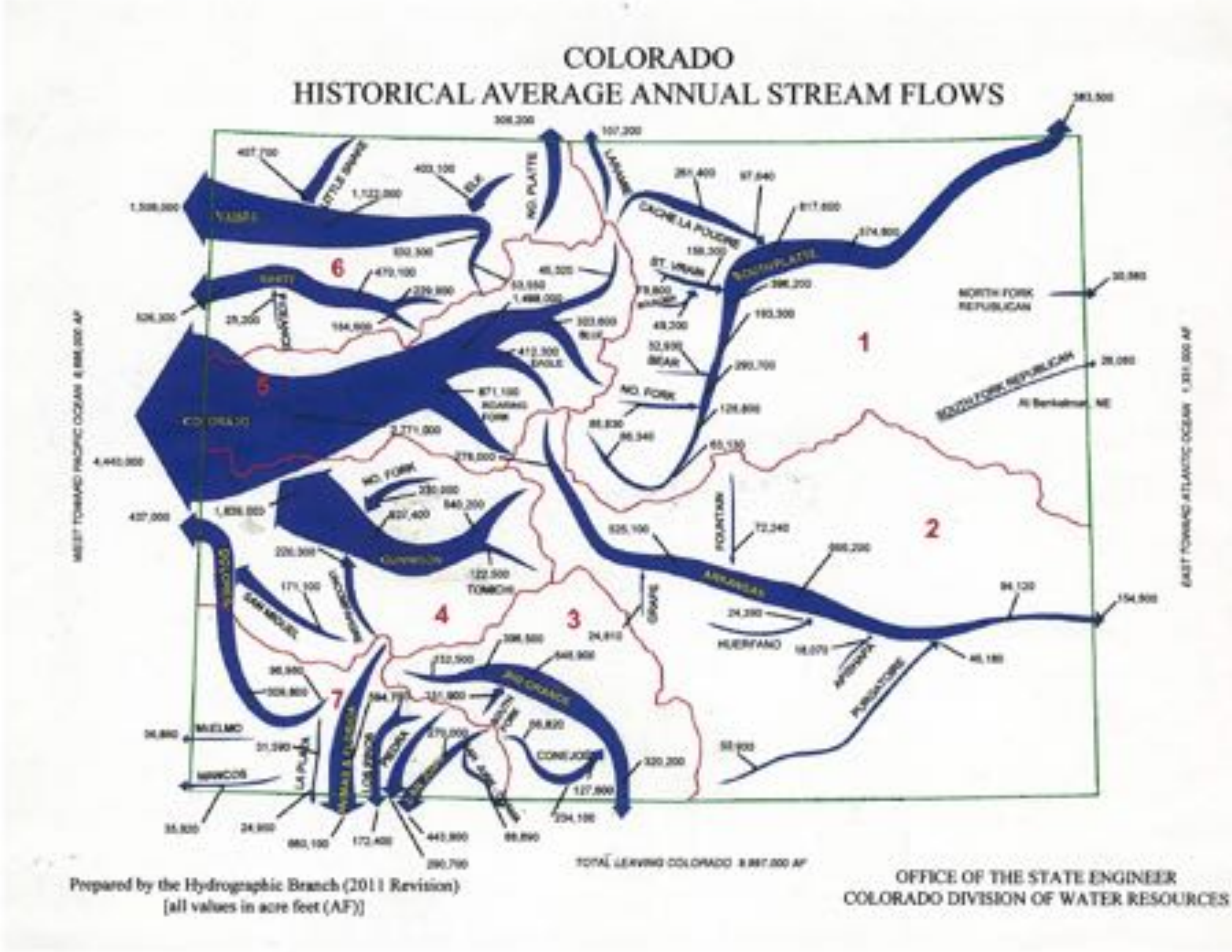
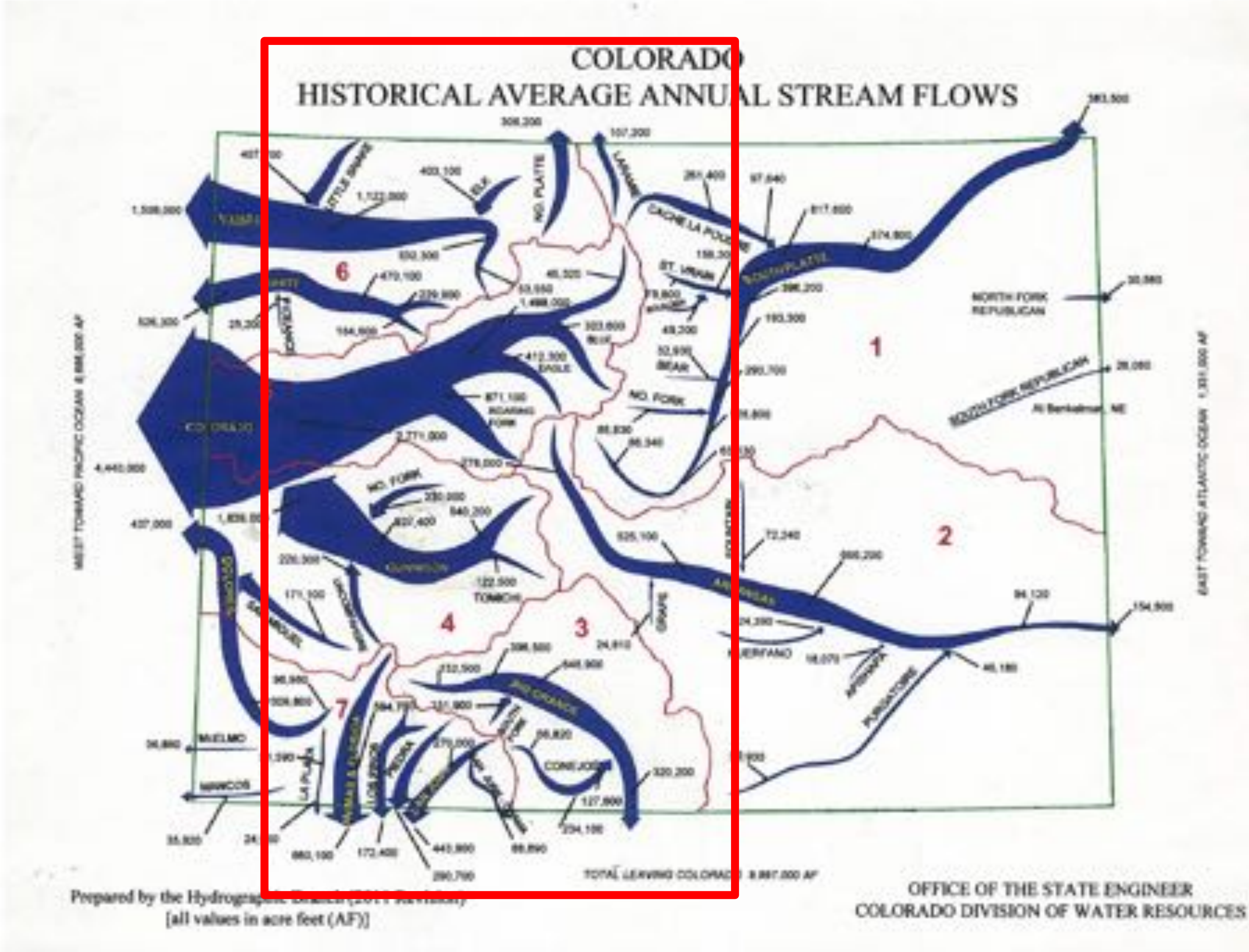
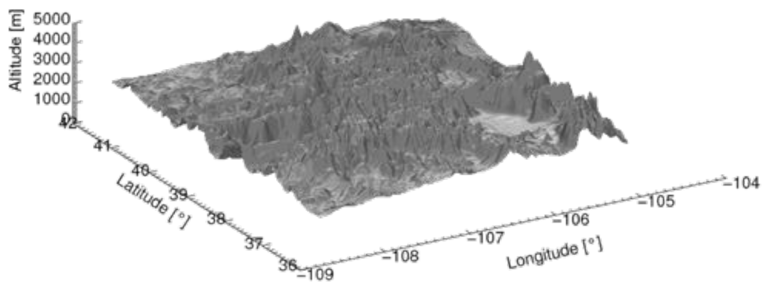


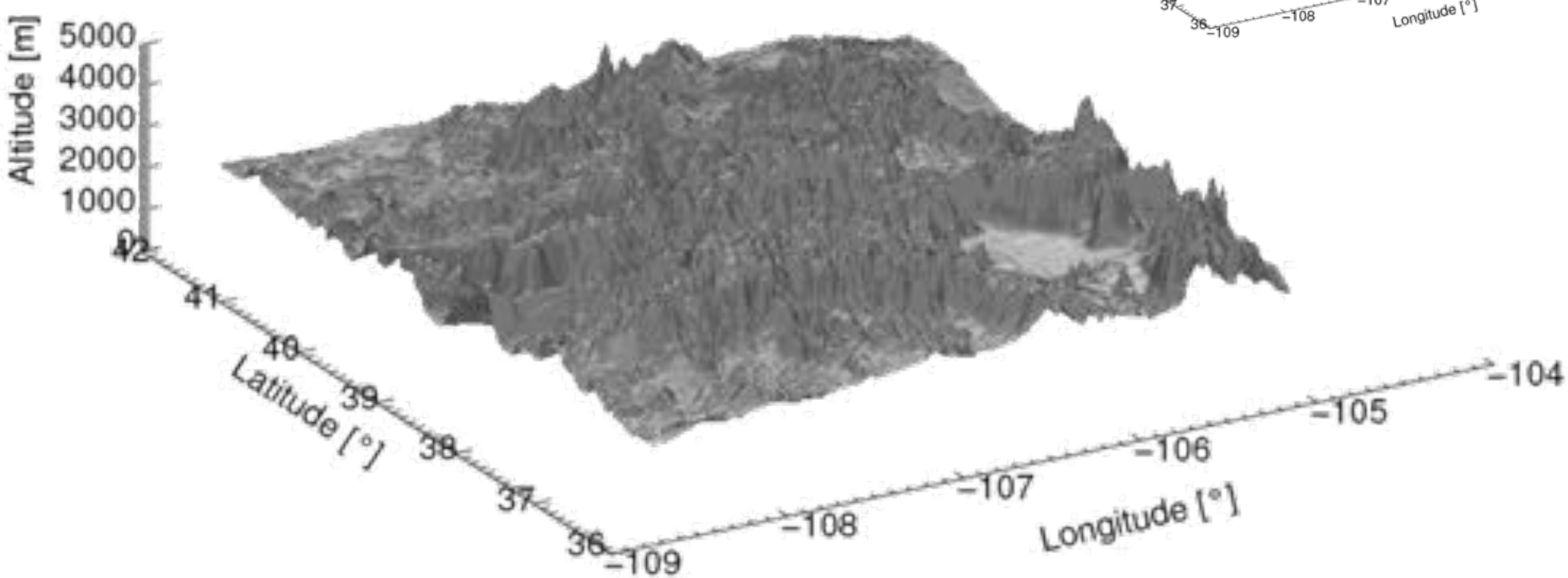
Headwaters Streams



Value of high-res. regional model

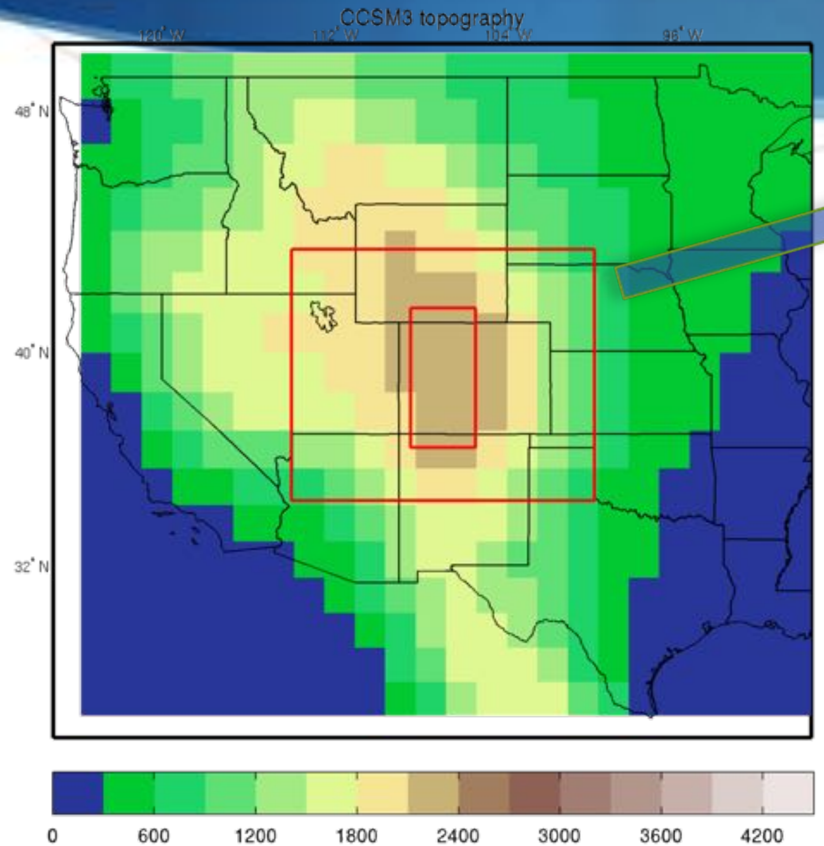
Resolution : 2.4 km



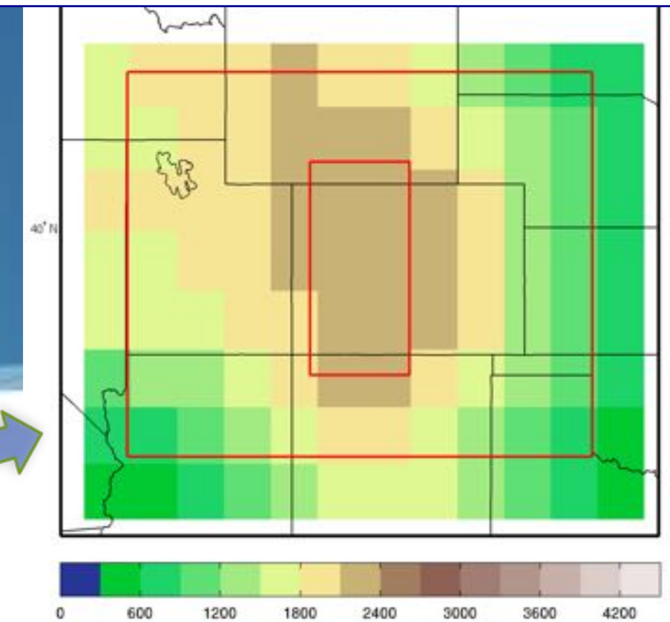


Courtesy Andy Prein

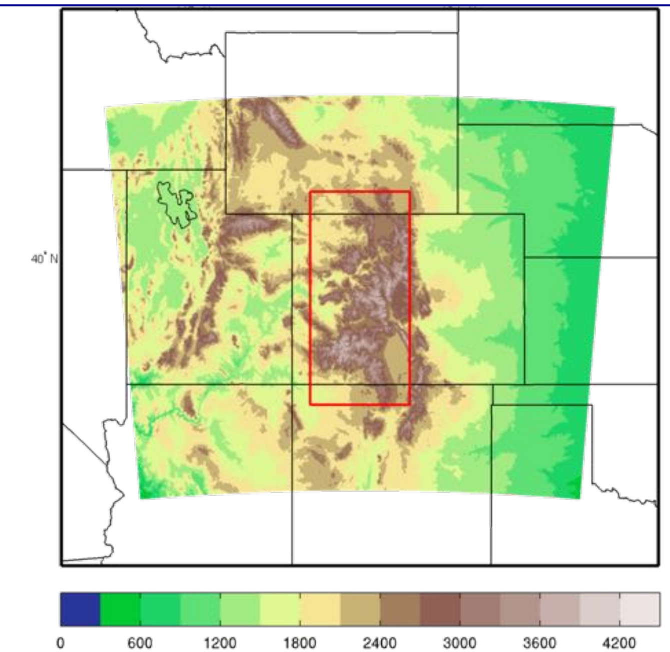
NCAR Climate Model (CCSM3) Elevation



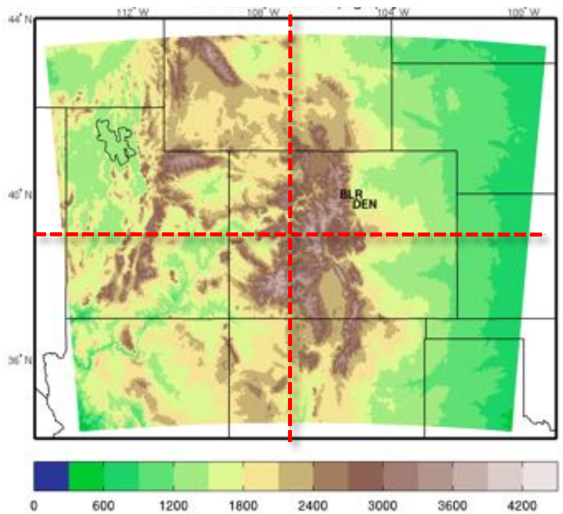
CCSM3 MODEL TOPOGRAPHY



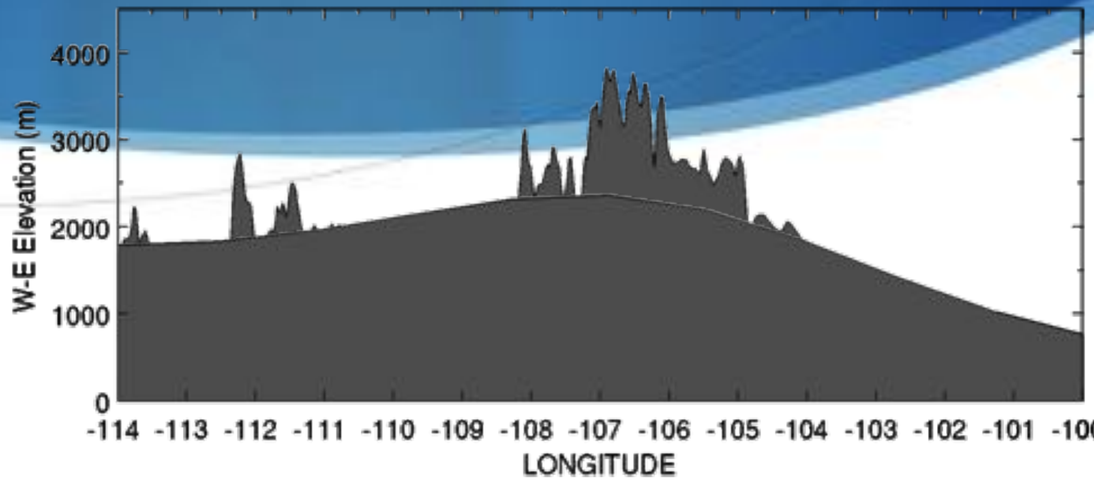
WRF MODEL TOPOGRAPHY at 2 KM RES.



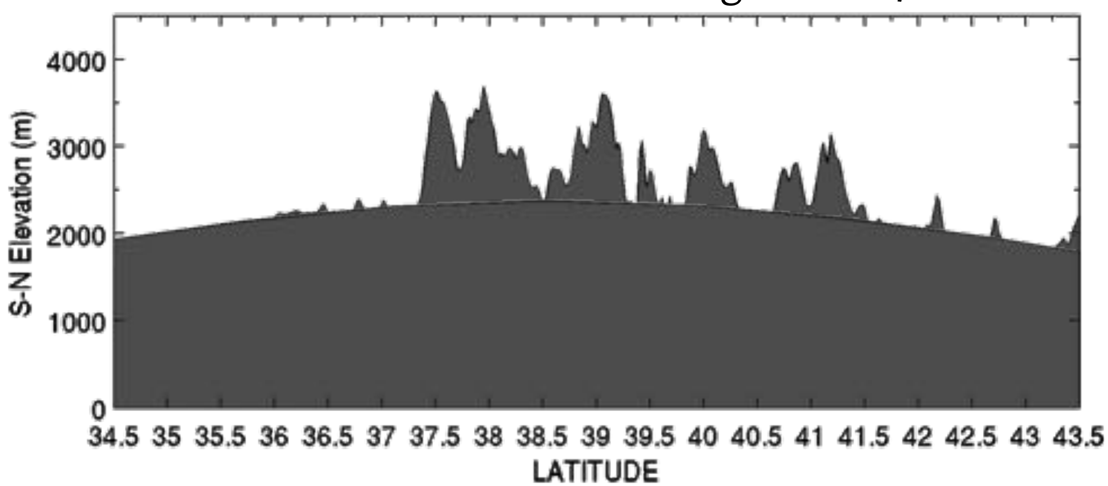
CCSM and the 2-km WRF Elevation Profile in the CO Headwaters Domain



W-E Elevation Profile at Latitude 39°



N-S Elevation Profile at Longitude -107°



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

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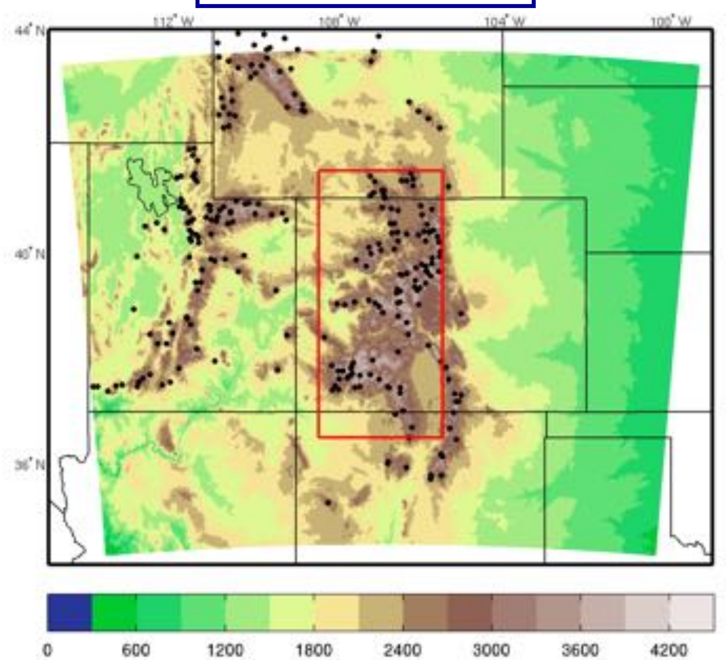
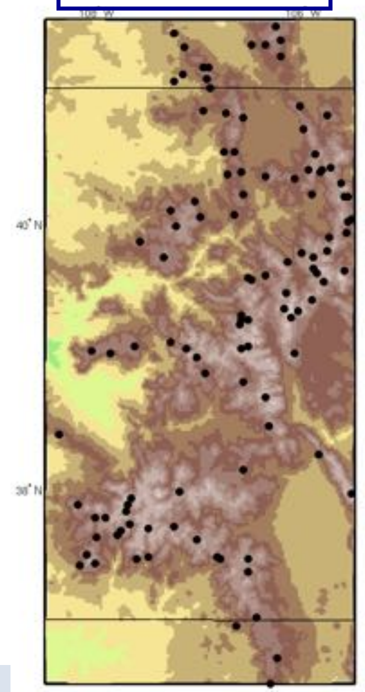
1. Perform past climate simulations using high resolution WRF model
   - Grid spacing: 4 km.
   - Continuous eight years: 2000 – 2008

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).

Full Domain



Headwaters domain



● SNOTEL sites

Weather Research and Forecasting (WRF) Model Setup and Design

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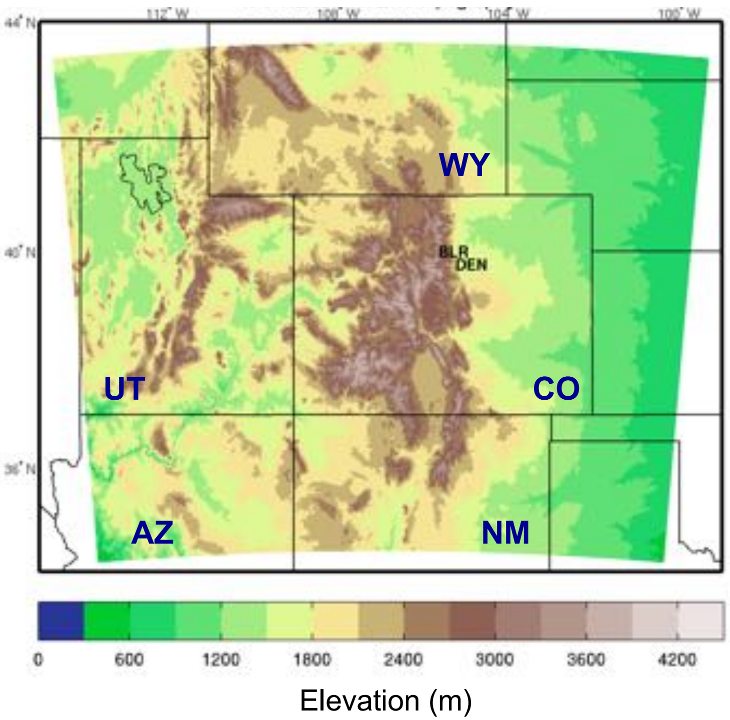
Model Setup

- NCAR WRF Model (version 3.1)
- A single domain: 1200x1000 km^2; 45 levels, 4 km grid resolutions
- PBL scheme: MYJ
- Noah land-surface model
- CAM longwave & shortwave scheme
- Thompson et al. (2008) cloud microphysics scheme

Model Domain



Initial and Lateral Boundary Conditions

- The 3-hourly, 32-km North American Regional Reanalysis (NARR) data
- Dynamical downscaling from 32km NARR. No statistical downscaling.

NCAR Water System Team

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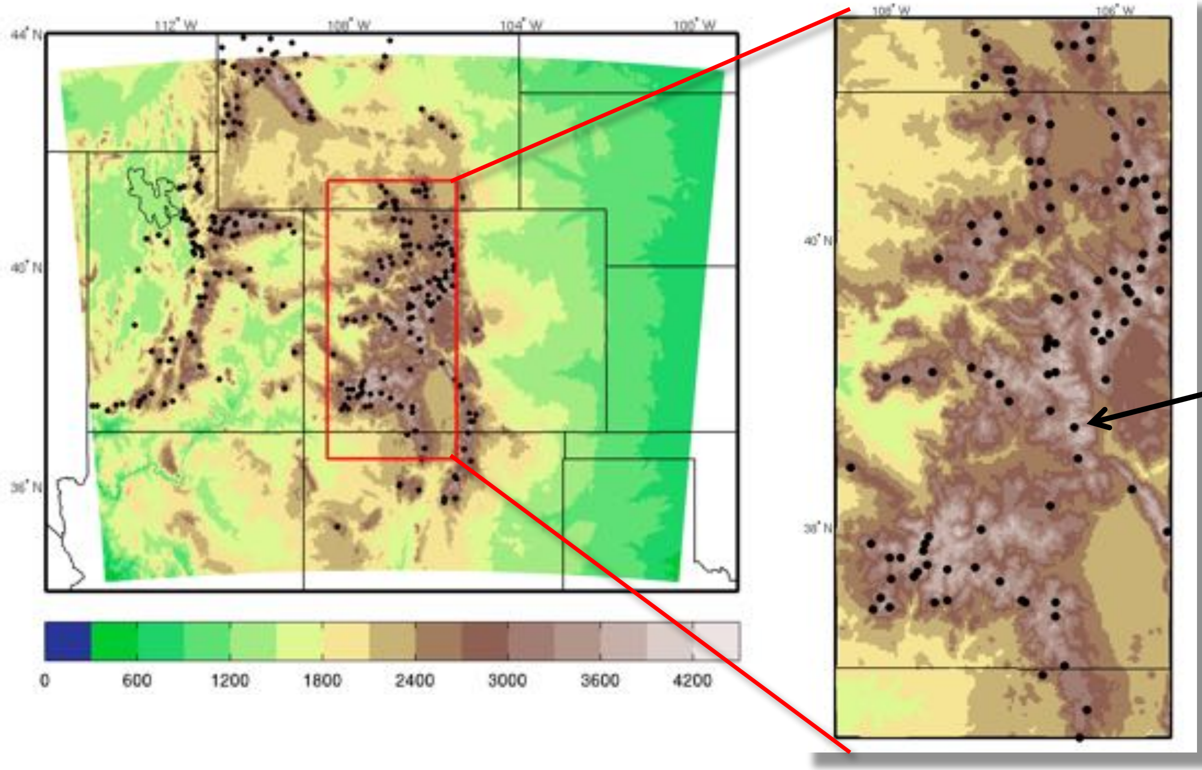
Project Lead	Roy Rasmussen	RAL/HAP
Experiment Designing and WRF Modeling	Changhai Liu	RAL/HAP
	Jimy Dudhia	MMM
	Liang Chen, Sopan Kurkute	University of Saskachewan
Data Analysis and Management	Kyoko Ikeda, Changhai Liu, Andreas Prein, Andrew Newman, Aiguo Dai	RAL/HAP MMM
Microphysics	Greg Thompson	RAL/HAP
LSM modeling	Fei Chen, Mike Barlage	RAL/HAP
Hydrology modeling	David Gochis	RAL/HAP
Snow Physics	Martyn Clark	RAL/HAP
Dynamical Downscaling	Ethan Gutmann	RAL/HAP
Social Impacts	Dave Yates	RAL/HAP

Model Verification with SNOTEL data

Full model domain

Headwaters Domain



SNOTEL

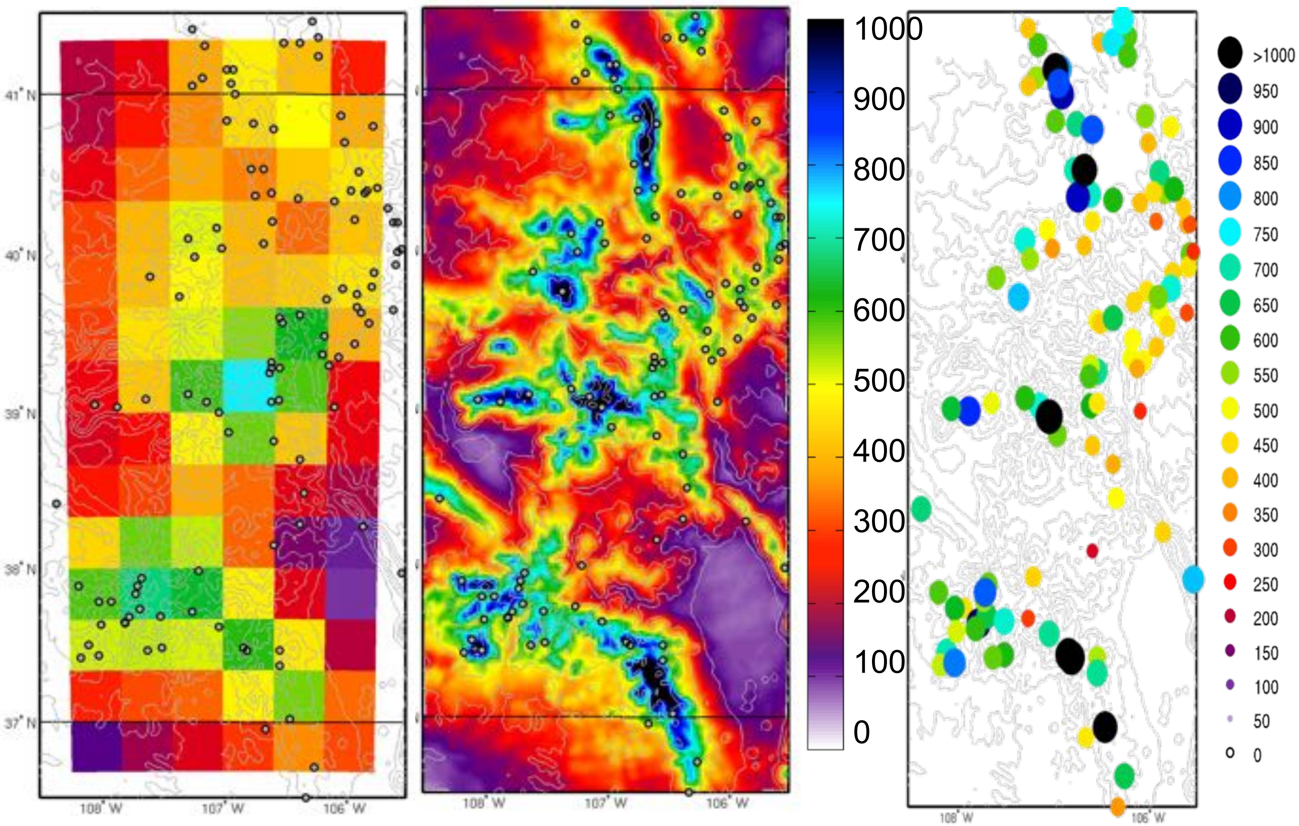
- Verifications performed using 93-112 Snowpack Telemetry (SNOTEL) sites over the Headwaters domain.
  - SNOTEL typically located at elevations between 2600 and 3600 m
- Global Historical Climatology Network (GHCN) data at lower elevations for rainfall

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

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

Mean difference in monthly precipitation between WRF and SNOTEL from 8-year climatology data

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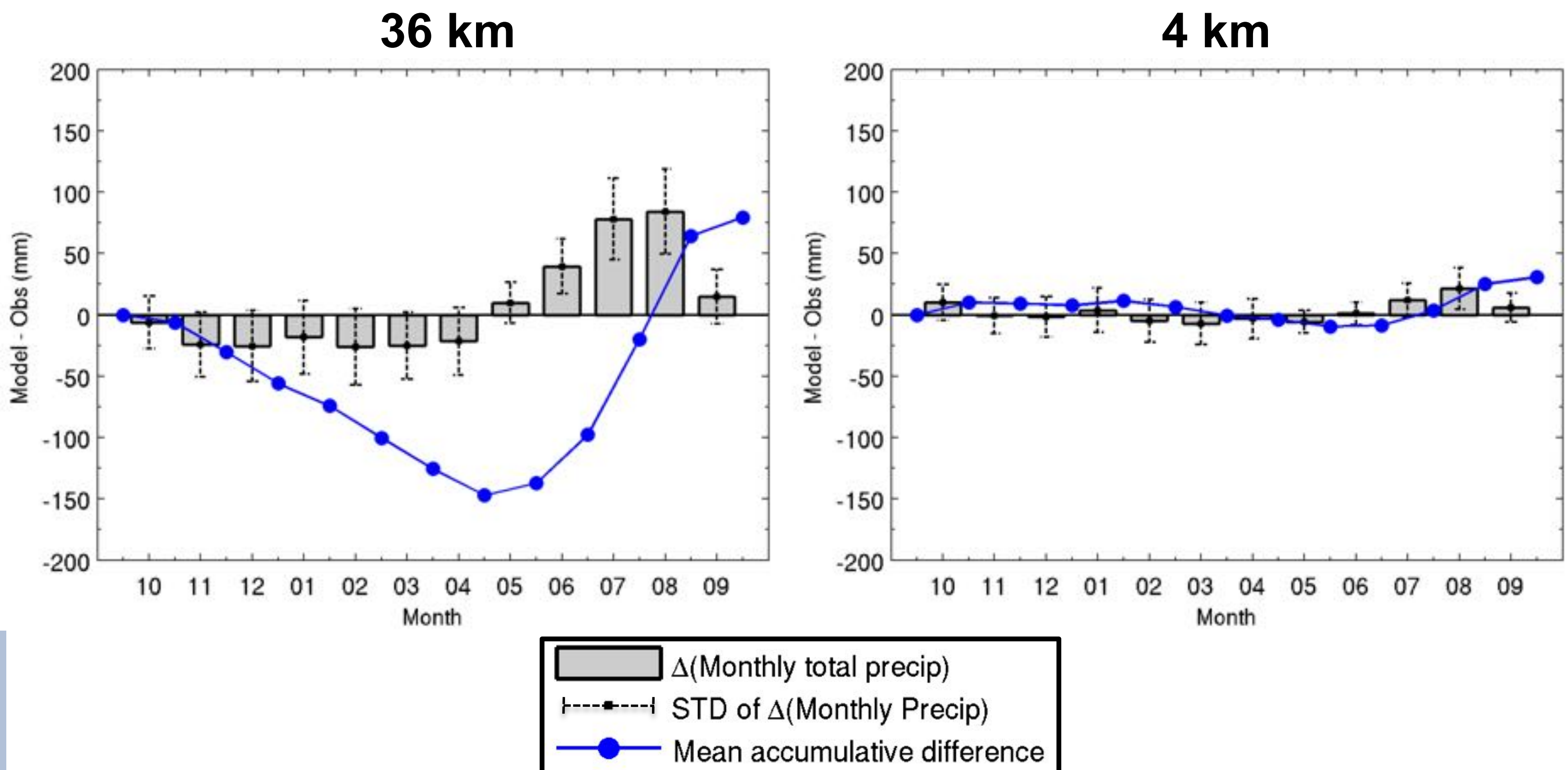
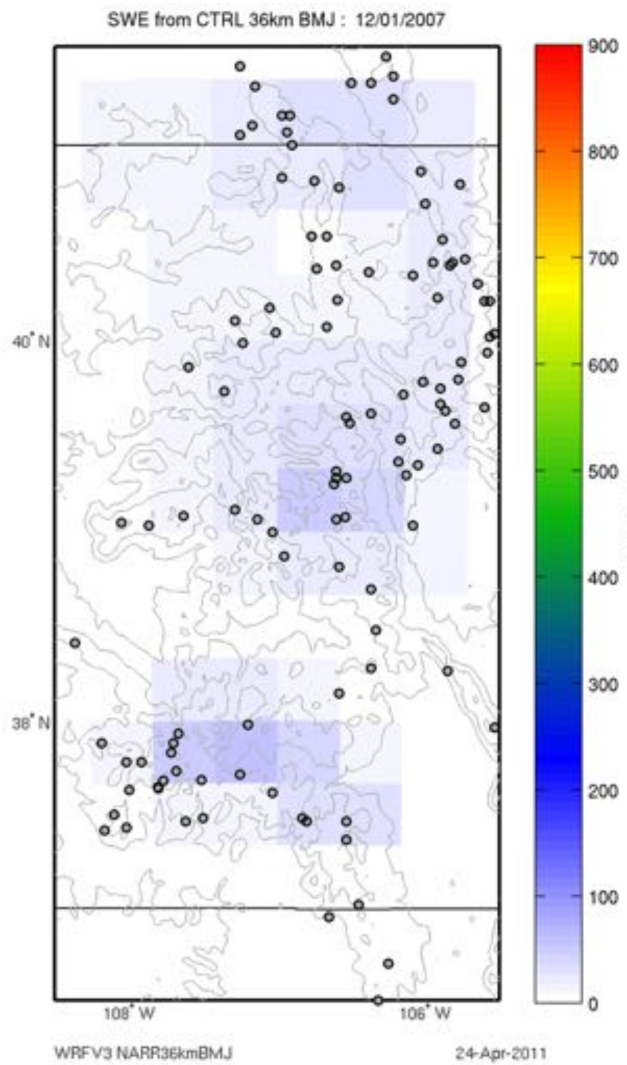


WRF model simulation of Snowpack (Snow Water Equivalent) for two different model resolutions

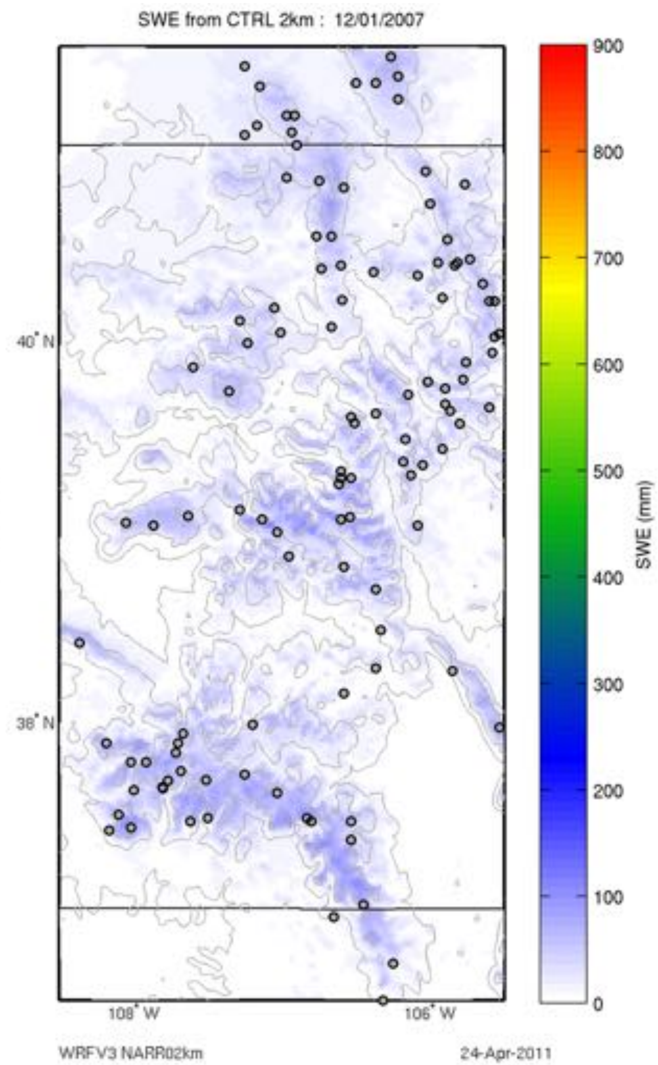
1 Dec. 2007- 1 July 2008

36 km resolution WRF simulation over water year shows complete loss of snowpack by April 30 and the smearing of snowpack across topographic gradients while 2 km simulation shows snowpack to last through the end of July and also produces the correct spatial pattern as compare to the 111 SNOTEL sites (black dots)

36 km



2 km



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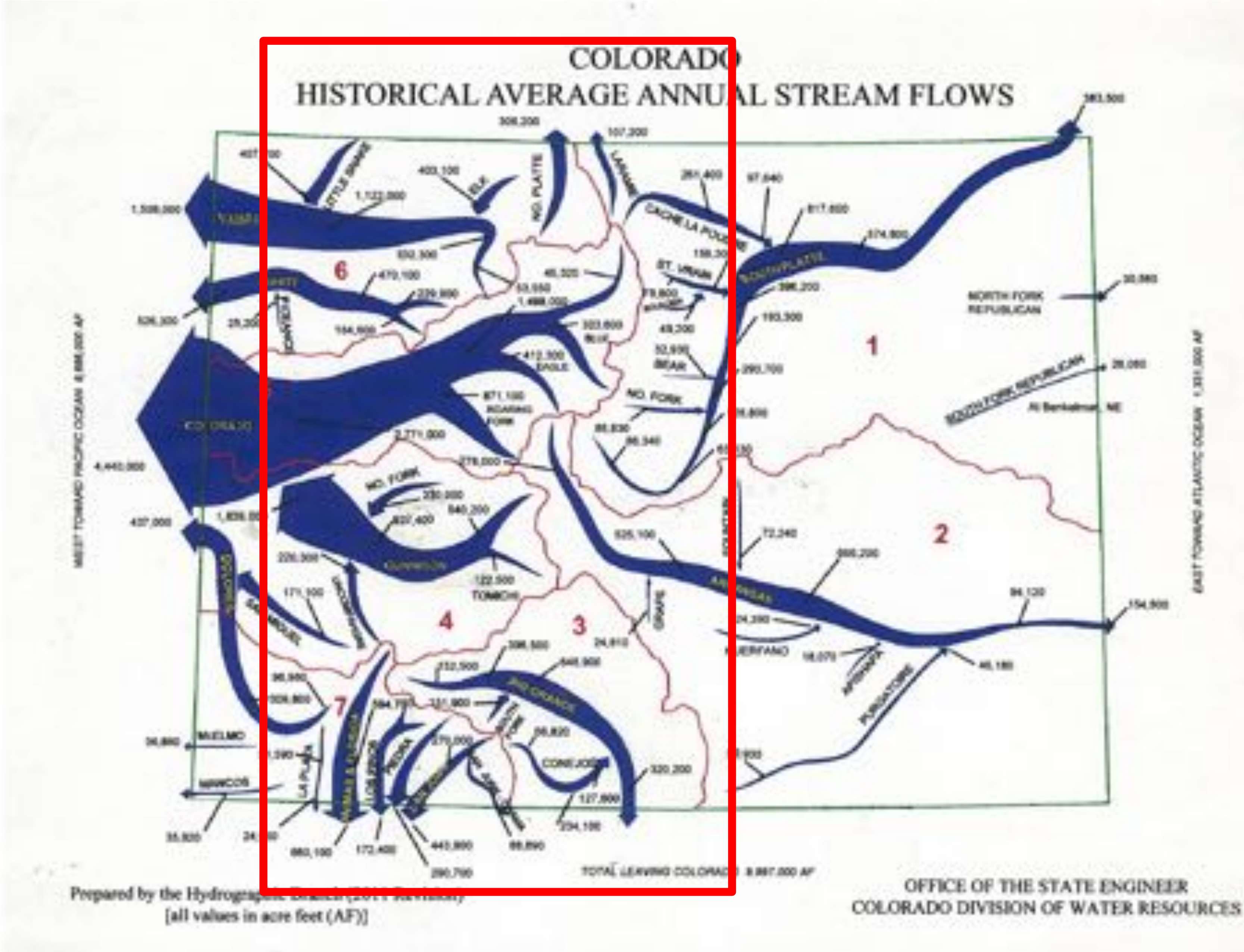
Headwaters Streams



Model resolution impact on vertical velocity

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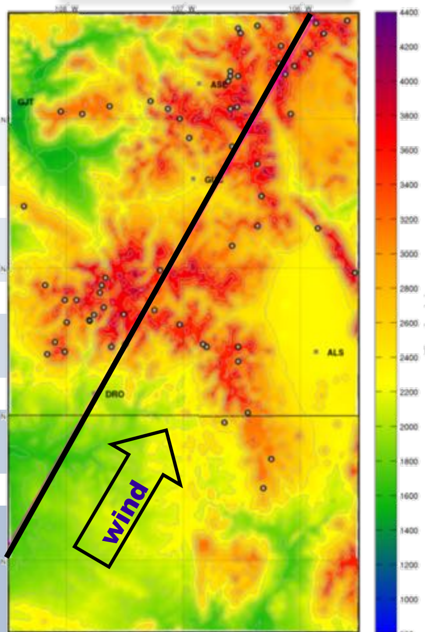
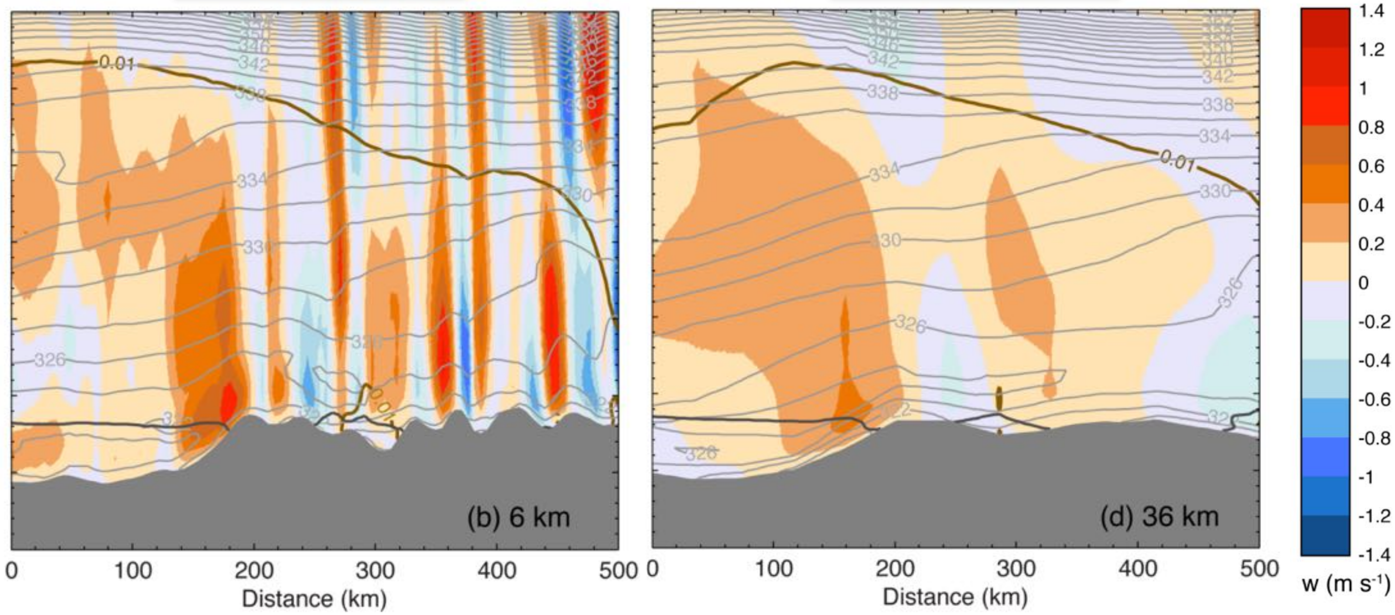
1 December 2007 0000 UTC

Elevation



6 km **36 km**



Vertical Velocity at various grid resolutions : 1 Dec. 2007 05 UTC

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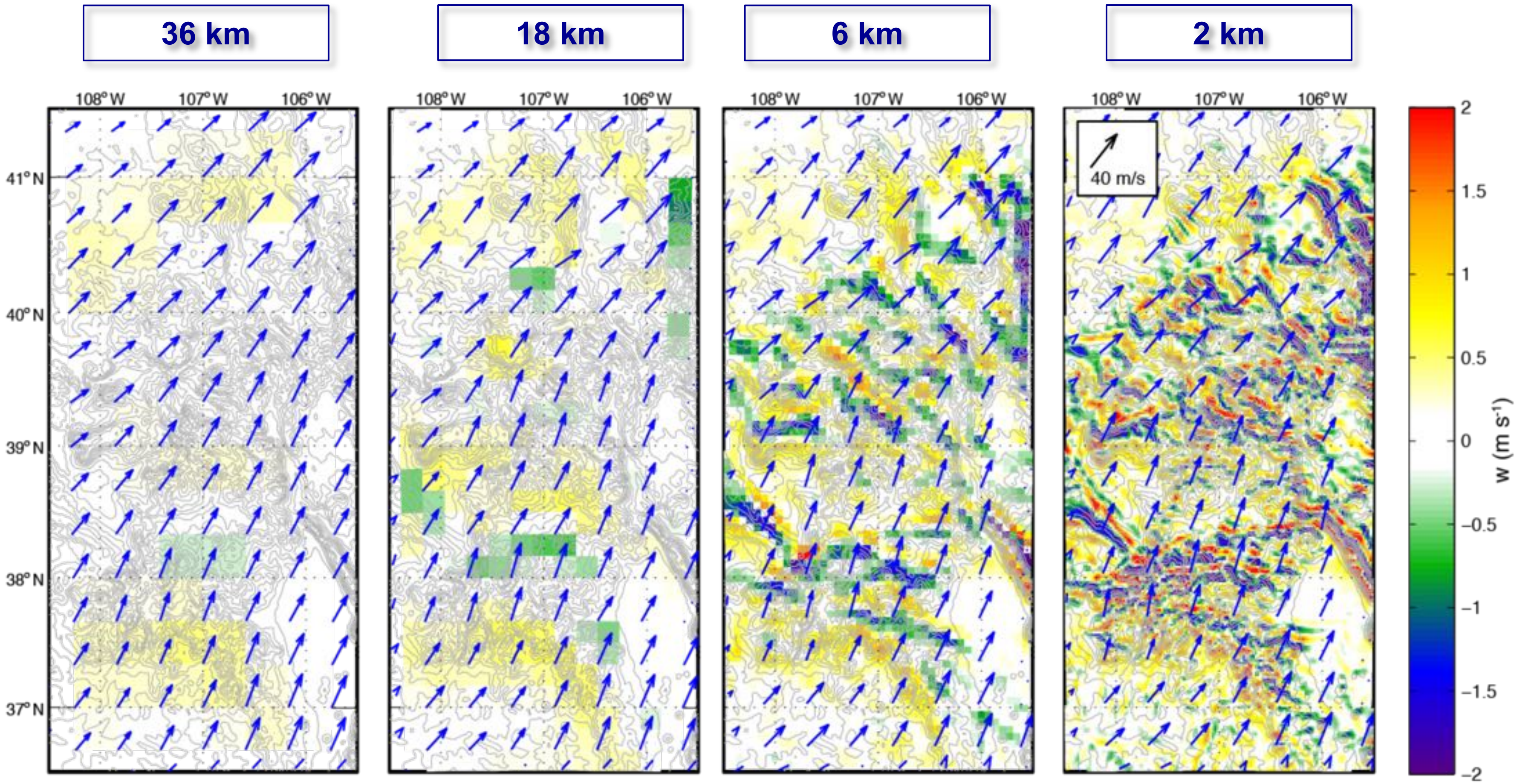

- At 2-km res., vertical motions associated with the individual mountain peaks are well solved.
- At coarser resolutions (18 and 36 km), vertical motions are not well resolved and max. w is less than half of that of the 2-km w.

1. How high a resolution of the regional climate model do we need to properly simulate climate impact on snowfall over a complex terrain?
   - Comparison of WRF simulations of seasonal precipitation to SNOTEL observations over the Colorado Headwaters regions showed very good agreement if resolutions **at or below 6 km** are used.
   - 36 km resolution runs underestimated SNOTEL snowfall by **~25%** due to terrain smoothing and associated spreading of the precipitation horizontally as a result of a **broader and weaker updraft**.

2. How does model resolution change simulation results?
   - **Model resolution is important** for adequately representing **surface temperature distribution and seasonal cycle of snowpack**.

     High resolution models put snow at colder mountain peaks. Elevations of mountain peaks are lower in low resolution models, and thus temperature is higher and precipitation phase may not be correctly represented. Impacts seasonal cycle of snowpack.

CONUS 4 km simulation

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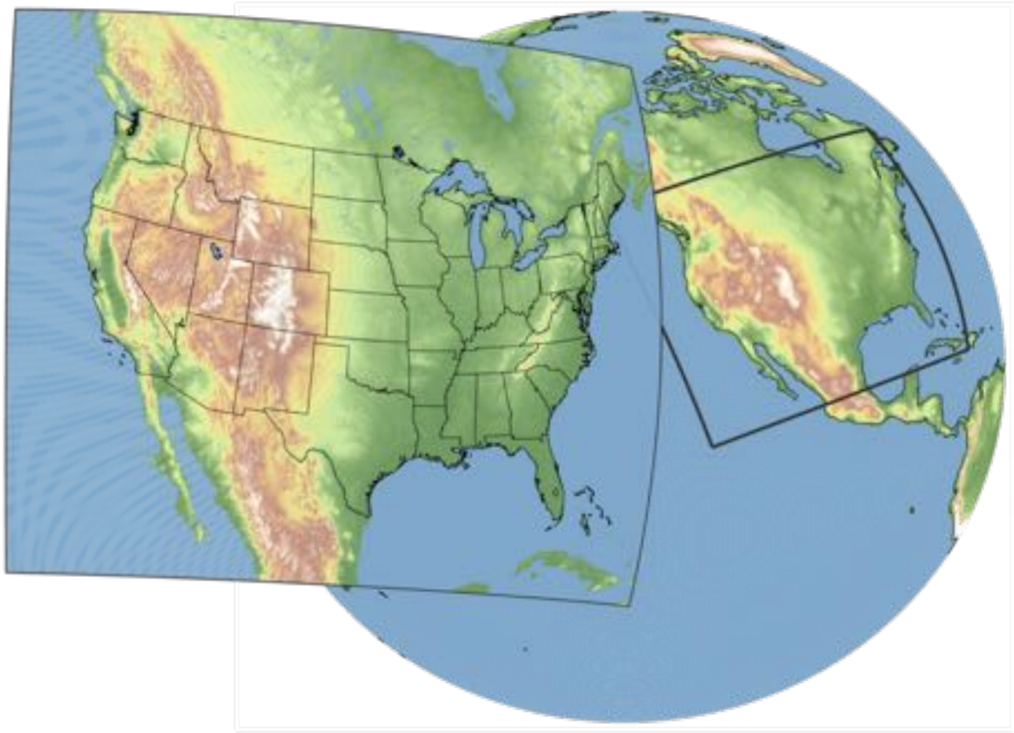
WRF 4 km | 1359 x 1015 grid cells
13 years (2001-13)
ERA-Interim

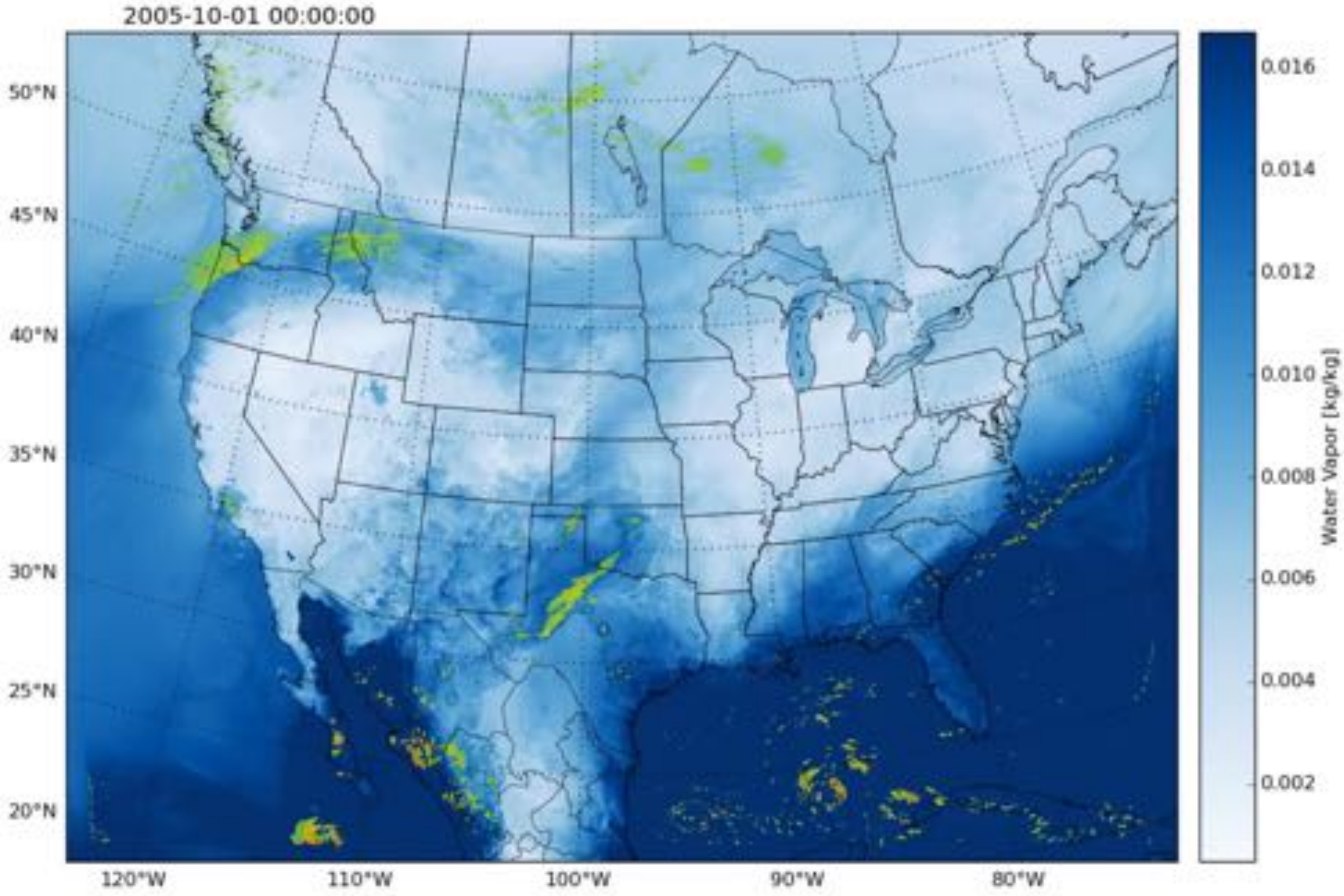


Liu et al. 2016, Clim. Dyn.

Physics

- Microphysics
  Thompson aerosol-aware
  [Thompson and Eidhammer 2014]
- Radiation RRTMG [Iacono et al. 2008]
- Land-surface model NOAH-MP
- Boundary layer YSU [Hong et al. 2006]

Spectral Nudging
U, V, T, and ZG above the PBL

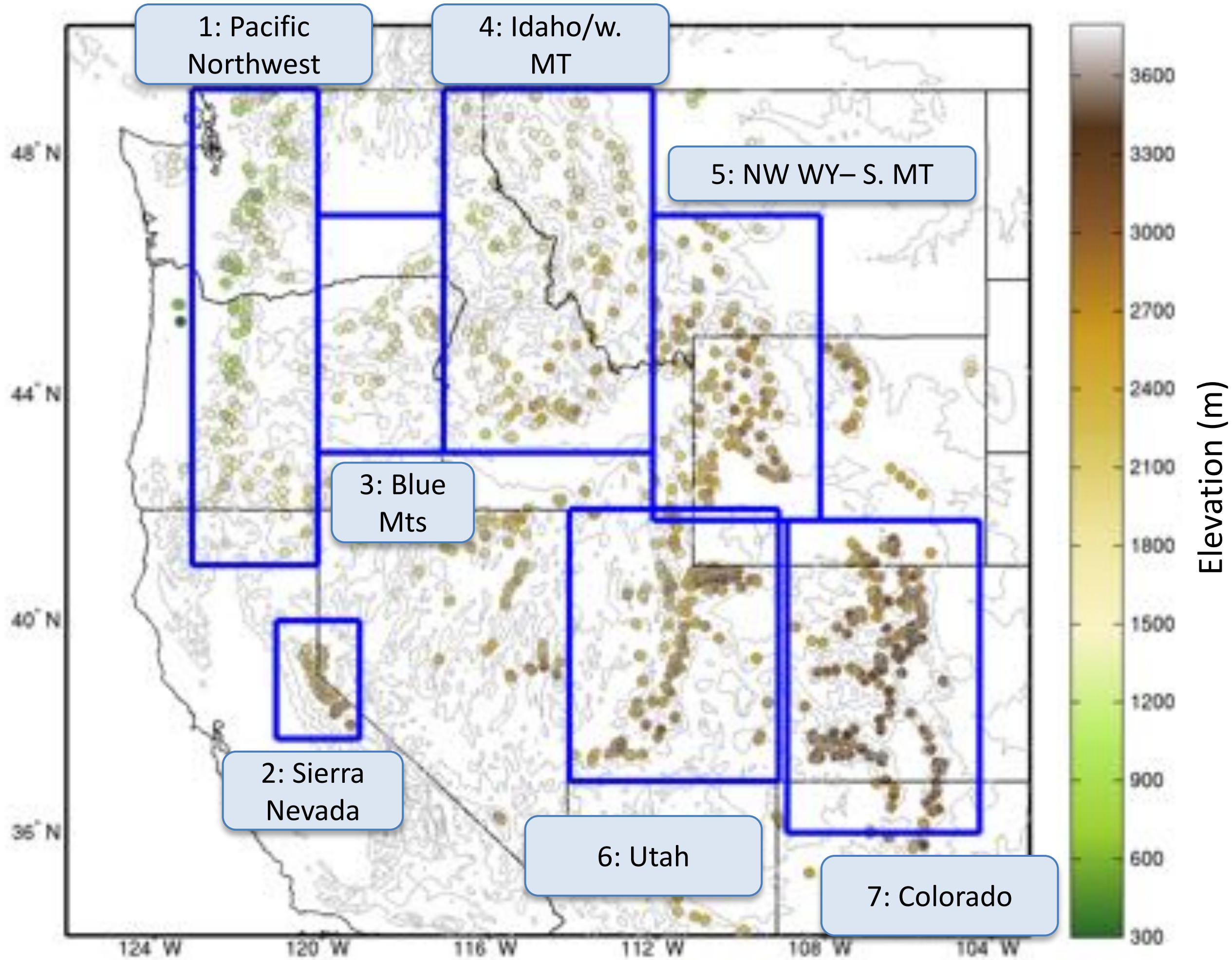

2005-10-01 00:00:00
50°N
45°N
40°N
35°N
30°N
25°N
20°N
120°W
110°W
100°W
90°W
80°W
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
Water Vapor [kg/kg]

Model Evaluation at Western SNOTEL Sites

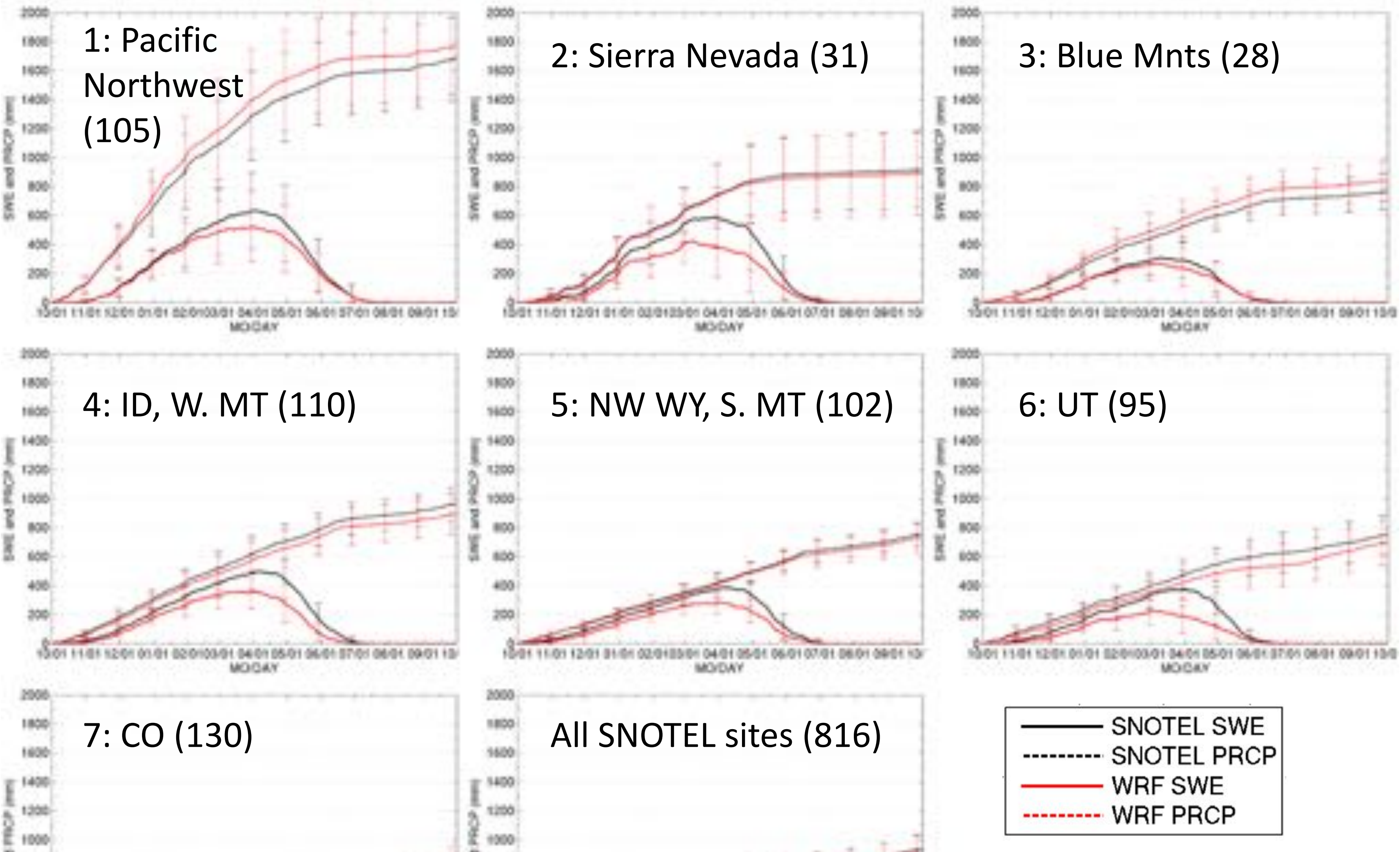
SNOTEL site at Brooklyn Lake, WY

Snow gauge

Snow pillow



SNOTEL vs WRF at Western SNOTEL sites: 13-year climatology



PRCP bias: -2% – 9%
SWE bias : -10% – -40%

Summertime rainfall diurnal cycle in Western U.S.

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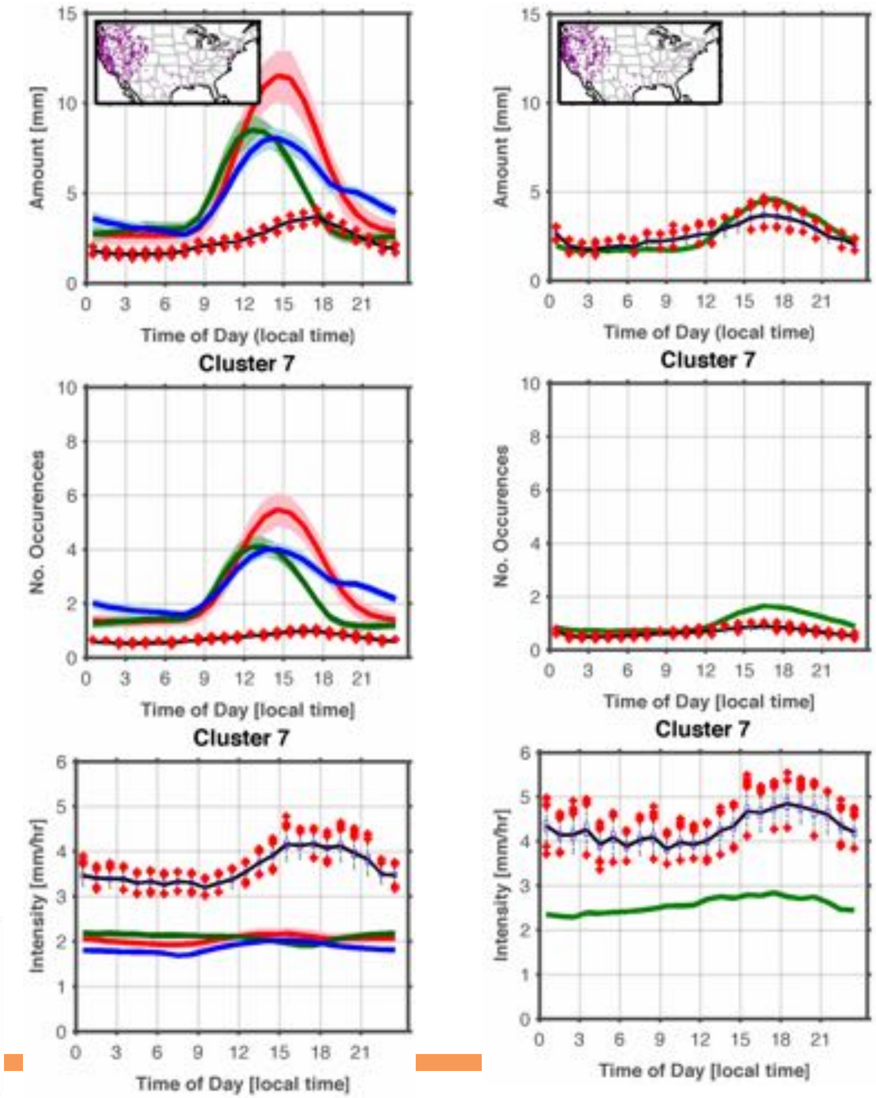
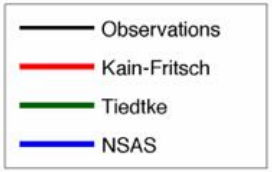
WRF 36 km | WRF 4 km

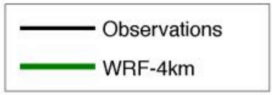
Amount

Frequency

Intensity







Non-MCS precipitation well simulated at 4 km (convective permitting) but poorly handled in **regional models (36 km)**!

[Mooney et al. 2016]

WRF Future Climate Simulation

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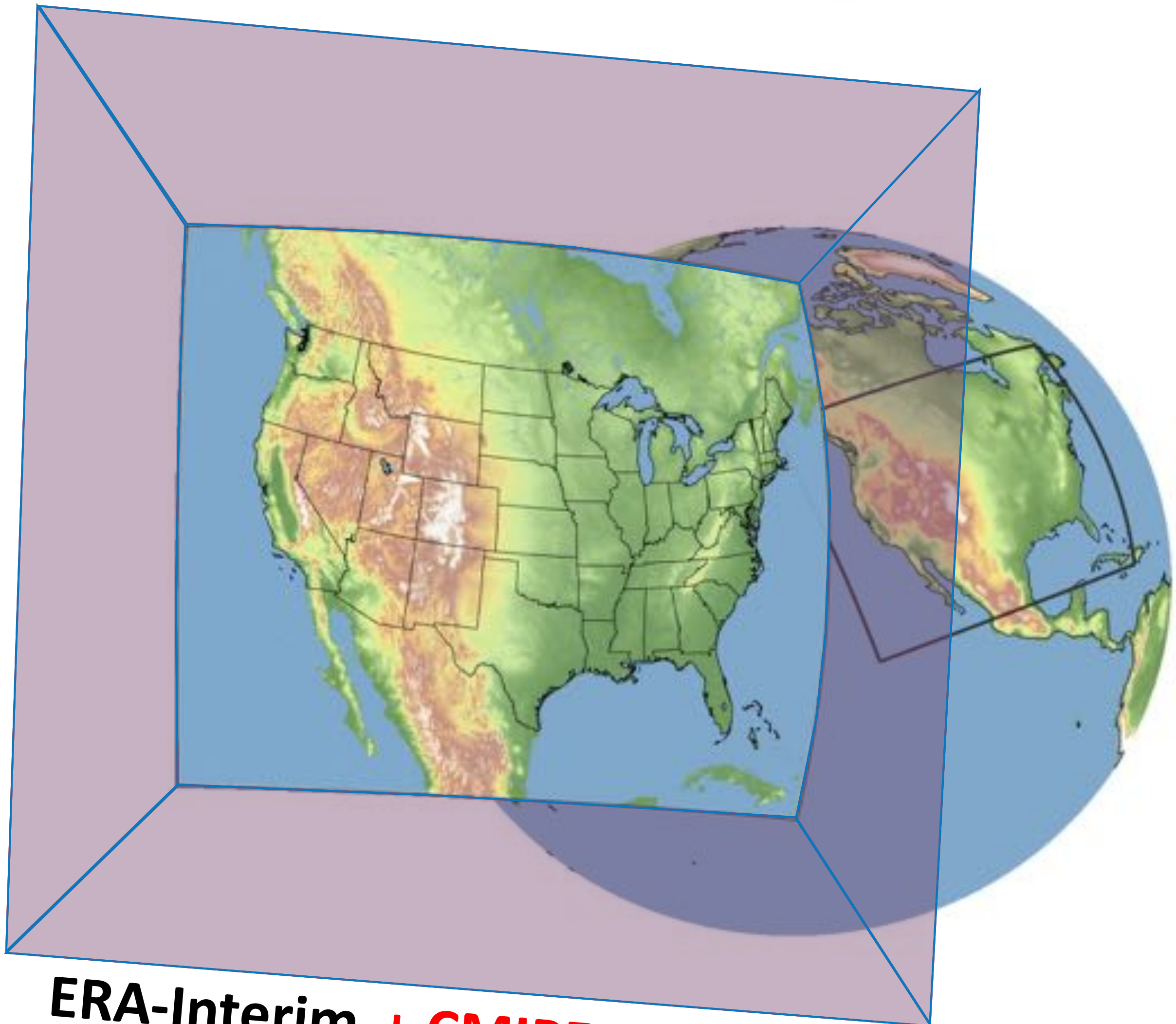
Pseudo Global Warming (PGW) [Schär et al. 1996, Rasmussen et al. 2011]

- Monthly averaged climate change perturbations from **19 CMIP5 GCMs**
- Delta 2071 to 2100 – 1976 to 2005 → RCP8.5

- Thermodynamic response of climate change
- No changes in weather patterns / moisture convergence
- No issues with internal variability



Access to the CONUS simulations

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The data has been archived and available via a portal with the DOI information given below:

DOI https://rda.ucar.edu/datasets/ds612.0/

Info on the DOI is at:

https://ezid.cdlib.org/id/doi:10.5065/D6V40SXP

or send me an e-mail (rasmus@ucar.edu)

Water for Food Baskets GEWEX Grand Challenge plans to use past 50 years CPM simulations of water cycle with and without human influences over key food basins of the world (Jan Polcher talk) and townhall on Friday at 2:30.

Abstract Submission

https://ral.ucar.edu/events/2018/cpcm

Key Topics

- Convection-permitting modeling and the water cycle
- Modeling of tropical phenomena
- Analysis of convection-permitting climate & weather simulations
- Model setup in convection-permitting simulations
- Observational datasets and advanced evaluation techniques
- Convection-permitting modeling across scales (S2S)

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Abstracts due by May 31st

Mountain Hydrology Challenges

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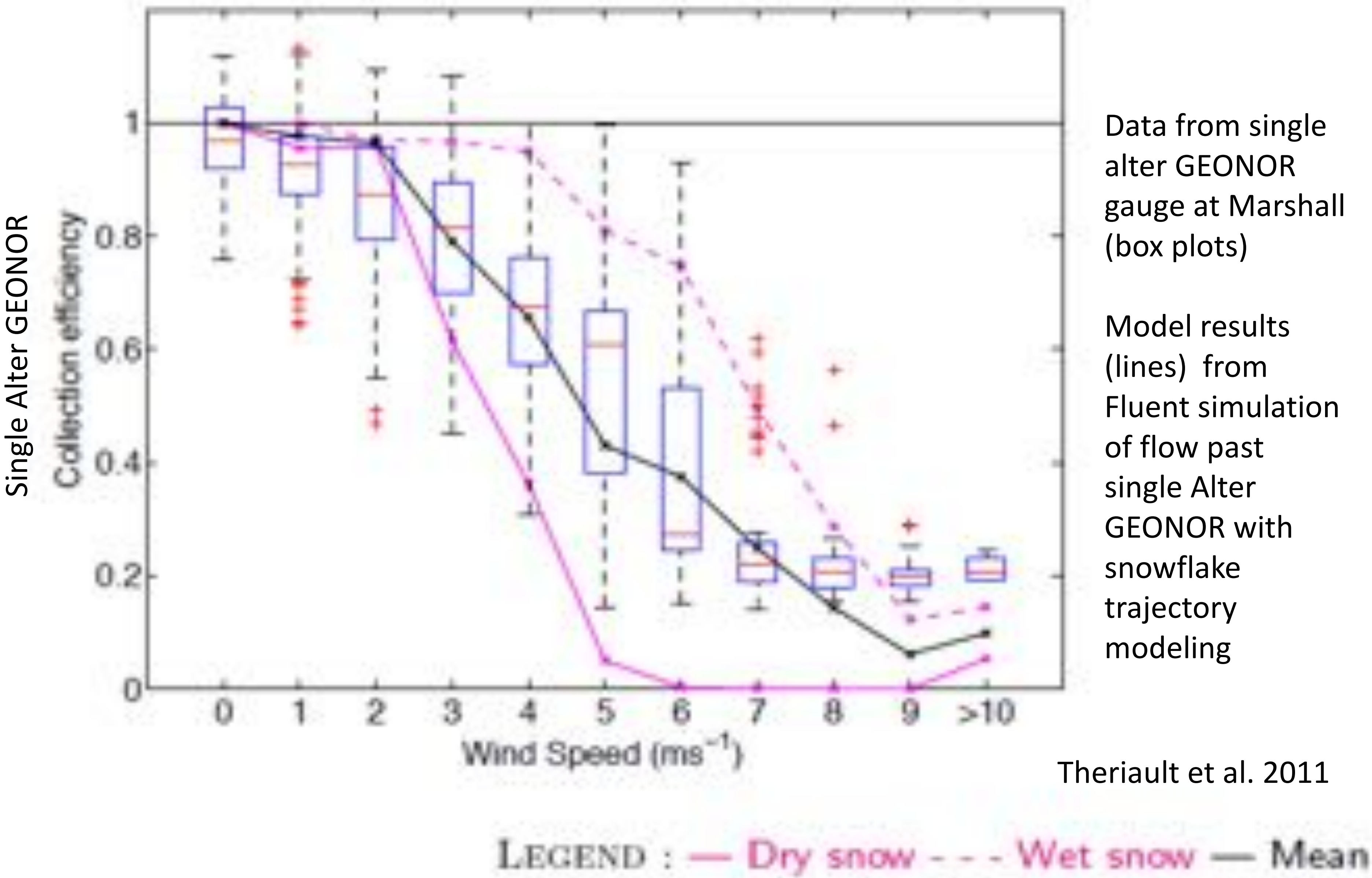
Observations

- In-situ snowfall measurements: How accurate?

  Still large uncertainty. Unknown snow type and size distribution main issue.

Due to updraft, snowgauges significantly undercatch



Data from single alter GEONOR gauge at Marshall (box plots)

Model results (lines) from Fluent simulation of flow past single Alter GEONOR with snowflake trajectory modeling

Theriault et al. 2011

Mountain Hydrology Challenges

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Modeling

- Convective Permitting Modeling of snowfall and snowpack

Need grid spacings less than 6 km to adequately capture mountain snowfall and snowpack and convection (for most of the U.S.).

Thank You!

rasmus@ucar.edu

Convective Permitting Modeling Orographic Publications

NCAR

MODEL VERIFICATION , SENSITIVITY STUDIES and DOWNSCALING

Ikeda, K., R. Rasmussen, C. Liu, D. Gochis, D. Yates, F. Chen, M. Tewari, M. Barlage, J. Dudhia, W. Yu, K. Miller, K. Arsenault, V. Grubišić, G. Thompson, E. Gutmann, 2010: Simulation of seasonal snowfall over Colorado. *Atmos. Res.* **97,** 462-477.

Barlage, M., F. Chen, M. Tewari, K. Ikeda, D. Gochis, J. Dudhia, R. Rasmussen, B. Livneh, M. Ek, and K. Mitchell 2010: Noah land surface model modifications to improve snowpack prediction in the Colorado Rocky Mountains. *J. Geophys. Res.*, **115**, D22101, doi:10.1029/2009JD013470.

Liu, C., K. Ikeda, G. Thompson, R. Rasmussen, and J. Dudhia, 2011: High-resolution simulations of wintertime precipitation in the Colorado Headwaters region: sensitivity to physics parameterizations. *Mon. Wea. Rev.,* doi:10.1175/MWR-D-11-00009.1

Gutmann, E., R. Rasmussen, C. Liu, D.J. Gochis, M. Clark, 2012: A Comparison of Statistical and Dynamical Downscaling of Winter Precipitation over Complex Terrain. J. of Climate, **25,** 262-281.

FUTURE CLIMATE COLD SEASON PRECIPITATION STUDY

Rasmussen, R., K. Ikeda, C. Liu, D. Gochis, D. Yates, F. Chen, M. Tewari, M. Barlage, J. Dudhia, W. Yu, K. Miller, K. Arsenault, V. Grubišić, G. Thompson, E. Gutmann, 2011: High-Resolution Coupled Climate Runoff Simulations of Seasonal Snowfall over Colorado: A Process Study of Current and Warmer Climate. *J. Climate,* **24,** 3015-3048.

CONUS simulations

Liu, Changhai, Kyoko Ikeda, Roy Rasmussen, Michael Barlage, A. J. Newman, A. F. Prein, F. Chen, L. Chen, Martyn Clark, Aiguo Dai, Jimy Dudhia, Trude Eidhammer, David Gochis, Ethan Gutmann, Sopan Kurkute, Yanping Li, Gregory Thompson, David Yates, 2016: Continental-scale convection-permitting modeling of the current and future climate of North America, *Climate Dynamics*, DOI 10.1007/s00382-016-3327-9.