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

Is this the new March?

http://www.archive.org/details/SVS-2487
Colorado Front Range
Past work: High Resolution Simulations of the Colorado Headwaters snowfall, snowpack and runoff

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
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.

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

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

- **EXP1**: Retrospective/Control simulation
  - forced with ERA-I reanalysis

- **EXP2**: Pseudo-Global Warming (PGW) simulation
  - forced with ERA-I plus climate perturbation
  - $\Delta_{RCP8.5} = \text{CMIP5}_{2071-2100} - \text{CMIP5}_{1976-2005}$
  - 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 $1360 \times 1016 \times 51$ 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
## 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.

<table>
<thead>
<tr>
<th>Category</th>
<th>Improvements</th>
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<tr>
<td>Noah-MP LSM</td>
<td>1. Rain-snow partitioning using microphysics scheme</td>
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<td>2. Vegetation-dependent snow fraction/melt curves</td>
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<td>3. Allowing snow to be present at above 0°C</td>
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<td>4. Heat advection by precipitation</td>
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<td>5. Bug fix for canopy snow unloading and snow density</td>
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<tr>
<td>Microphysics</td>
<td>Aerosol emission refinement, variable cloud droplet initiation though inclusion of cloud condensation nuclei prognostic equations (Thompson and Eidhammer 2014)</td>
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<tr>
<td>Re-analysis tests</td>
<td>NARR, CFSR, and ERA-Interim tested. ERA-Interim chosen.</td>
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<tr>
<td>Spectral nudging</td>
<td>Testing and parameter adjusting. Nudged above BL to small wave numbers (2 and 3).</td>
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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

NOAHMP adds three layers of snow: Allows for melting and refreezing

Precipitation
Condensation

on vegetation

Transpiration
Canopy Water Evaporation

Deposition/Sublimation to/from snowpack

Evaporation from Open Water

Runoff

on bare soil

Internal Soil Moisture Flux

D Z = 10 cm
D Z = 30 cm
D Z = 60 cm
D Z = 100 cm

Snowmelt

Soil Heat Flux

Internal Soil Heat Flux

Gravitational Flow
SWE underprediction from test runs

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

\( T_{\text{max}} \) bias

\( T_{\text{min}} \) bias

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
Numerical Experiments

• **EXP1:** Retrospective/Control simulation
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• **EXP2:** Pseudo-Global Warming (PGW) simulation
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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
• 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

Variables changed: U, V, T, geopot. hgt., P_{sfc} and Q_v

No change in storm tracks. Same transient spectra as current climate.
Comparison of monthly precipitation between WRF and PRISM for 2008
PRISM observations averaged over 2001-2008

a) DJF  b) MAM  c) JJA  d) SON

Precipitation (mm/day)

Precipitation bias (mm/day)

Observational data set from Andy Newman

Courtesy of Andreas Prein
PRISM observations averaged over 2001-2008

2 m temperature (°C)

-20 -17 -14 -11 -8 -5 2 7 10 13 16 19 22 25 28 31 34

dJF MAM JJ A SON

2 m temperature bias (°C)

-2.7 -2.1 -1.5 -0.9 -0.3 0.3 0.9 1.5 2.1 2.7

e) DJF f) MAM g) JJ A h) SON

Observational data from Andy Newman

Courtesy of Andreas Prein
Model Evaluation at SNOTEL Sites

SNOTEL site at Brooklyn Lake, WY

Snow gauge

Snow pillow

1: Pacific Northwest
2: Sierra Nevada
3: Blue Mts
4: Idaho/w. MT
5: NW WY – S. MT
6: Utah
7: Colorado
SNOTEL vs WRF at SNOTEL sites: 13-year climatology

1: Pacific Northwest (105)
2: Sierra Nevada (31)
3: Blue Mnts (28)
4: ID, W. MT (110)
5: NW WY, S. MT (102)
6: UT (95)
7: CO (130)
All SNOTEL sites (816)

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)

DJF

MAM

JJA

SON

PGW - CTRL (°C)
PGW Results at SNOTEL Sites

SNOTEL site at Brooklyn Lake, WY

Snow gauge

Snow pillow

Elevation (m)
WRF CTRL vs PGW at SNOTEL sites: 11-year climatology

1: Pacific Northwest (110)
2: Sierra Nevada (31)
3: Blue Mnts (28)
4: ID, W. MT (113)
5: NW WY, S. MT (105)
6: UT (107)
7: CO (140)

All SNOTEL sites (730)

PRCP: 6% – 15%
SWE: -46% – -20%
Summary

• Precipitation projected to increase over all western mountain ranges by ~16%, at a 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 previous studies).

• Offset of melting also earlier.
Snow cover in 2001-2002 over North America from MODIS

April 2002

Is this the new March? Yes, with even less snow in the Pacific Northwest.

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Thank you.

Questions?