Final Report:
High-Resolution Modeling of Precipitation, Snowpack, and Streamflow in Wyoming: Quantifying Water Supply Variations in Future Decades

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Abstract

This grant uses a community-supported weather forecast model to study precipitation, snowpack dynamics, and streamflow in and around Wyoming, a key headwaters region for the nation. The Weather Research and Forecasting (WRF) model has been run over a 30 year period (1980/10-2010/09) driven by actual weather (using a "reanalysis" product) at a sufficiently fine resolution (4 km) to capture orographic precipitation and runoff, which are very terrain-sensitive. Our simulations show that WRF, with a land surface model (the NOAH multiphysics scheme) accurately captures observed seasonal precipitation and snowpack build-up in Wyoming. The rather long simulation time is needed to validate statistical probabilities of extreme precipitation amounts at timescales ranging from hourly to annual, 1 April snowpack water loading, and streamflow at various times of the year for all streams in Wyoming at locations upstream of the first reservoir.

The proposal aims to answer two questions: firstly, *how well does WRF simulate the observed year-to-year variations in precipitation, snowpack dynamics, and streamflow in the headwaters region of Wyoming*? And secondly, *how is the distribution of these parameters expected to change in a changing climate*? As to the latter, a pseudo-global warming technique is used to perturb the retrospective reanalysis with the anticipated change according to the consensus global model guidance under IPCC's most likely scenario. This technique preserves low-frequency general circulation patterns and the characteristics of storms entering the domain. The model then is being rerun over 30 years with perturbed conditions representing anno ~2050, and any changes in the probability density functions of the above-mentioned parameters are examined. Thus we aim to quantify changes in water supply parameters in Wyoming not just in an average sense, but also in terms of probabilities of water excesses and shortages.

After three years of research, we are excited to report that *both questions largely have been answered*. Regarding the first question, we compared the 30-year retrospective simulation, called IWUS (Interior US), against SNOTEL and PRISM precipitation. While precipitation amounts validate very well (better than 10% over the mountains, at SNOTEL sites), the snowpack's water loading (snow water equivalent or SWE) tends to be underestimated by 20-30%. The seasonal cycle of SWE is captured well, including the rate of spring ablation. The cold season precipitation is captured so well that we can question the gauge-based gridded datasets: we have promoted the use of IWUS to question the accuracy of certain SNOTEL records and to guide the location of new SNOTEL sites by the NRCS other other agencies.

Regarding the second question, we ran the 30-year future climate (~2050) simulation, and found that while orographic precipitation will increase ~10-40% in winter (DJF), it will decrease slightly in summer. At high-elevation places, the snowpack in Colorado and Wyoming will build up at nearly the same rate, but reach a peak earlier and melt off 2-3 weeks earlier. The 1 April snowpack in CO/WY will be smaller compared to IWUS, but the reduction is not nearly as large as in the mountains of Idaho and western Montana.

In the original proposal, we called for WRF Hydro to be run offline to simulate streamflow in the WRF-simulated current and future climates. We ran into challenges calibrating WRF Hydro for the many watersheds in the Interior West, and did not complete this task. Admittedly, we underestimated the work involved. It is not possible to evaluate the land surface model's water fluxes, in particular evapotranspiration and soil infiltration, at least not to the same level of accuracy as precipitation or temperature, mainly because good-quality, reliable gridded data are not available. Therefore, and because groundwater release (in springs) depends on unresolved sub-soil water flow characteristics, the conversion of rainwater and snow melt to run-off and stream flow, requires calibration of WRF Hydro streamflow against observed streamflow (gauge data). This watershed-specific calibration (or "training") process optimally captures unknown sub-surface and surface parameters. We did work on such WRF-Hydro "training" for the upper Green River basin in WY, based on the 30-year retrospective run. Once completed, we argued that because the unknown sub-surface and surface parameters are largely permanent (not affected by climate change), the same watershed-specific training can be used to estimate changes in seasonal and extreme streamflow in an anno ~2050 climate. It turns out that because of our limited experience with WRF Hydro, and hydrology in general, and because of additional computational resources needed (WRF Hydro requires <1 km resolution over steep terrain), this task could not be accomplished, but the partial work completed will be used as basis for one or more new research proposals, in collaboration with a hydrologist.

Major research findings and education activities

1. Relevance to critical regional and State water problems

Water is essential to the economy and the natural resources of the arid western USA. The interannual variation of water availability is significant in this region, and remains essentially unpredictable. In a warming climate, the snowpack may melt off earlier in spring and water may become less readily available in the warm season for most years. But predictions of the climate over the next few decades are highly uncertain, especially regarding precipitation, snowpack dynamics, and streamflow. And an average change carries far less meaning in Wyoming than a change in probabilities of a dry or wet year.

Gaining a better understanding of such change matters. For instance, water treaties between Wyoming and its neighboring states involve rigid parameters such as growing season streamflow expectations based on 1 April snowpack conditions. Long-term changes in the relationship between the snowpack's water loading on 1 April and spring runoff are entirely speculative at this time, and better guidance would be most welcome, for instance to the State's Engineer's Office. A better understanding of long-term changes in typical and extreme patterns of snowpack accumulation & ablation and in seasonal water discharge in the North Platte, the Snake, and especially the Green River watersheds is of great interest to Wyoming's water obligations and water development opportunities, as well as to agricultural and forestry interests in the state, and to downstream stakeholders.

2. Objectives

The objectives of this project are twofold: firstly, we calibrate the WRF model, with atmospheric physics choices determined in our previous work, by selecting land surface parameter choices that optimally simulate a 30-year record of precipitation, snowpack dynamics, and streamflow in the headwaters region of Wyoming. And secondly, we use this calibrated WRF model to examine differences in the distribution of precipitation, snowpack SWE, and streamflow in a 2050s climate, compared to the climate of the last three decades. The term "distribution" implies that we do not only examine the mean, but also the spread and the probability of extremes. The focus is on the seasonal cycle and specific times of the year (e.g. 1 April, by which time water allocations to downstream states have to be negotiated), but we also look at daily and hourly precipitation distributions and their changes, because of the relevance to agricultural interests and hydraulic structures engineering.

3. Methods, procedures, and facilities

3.a Numeric model and validation datasets

The Weather Research and Forecasting (WRF-ARW) model version 3.7.1 is applied to the western interior U.S. (**Fig. 1**). The computational domain has 420 × 410 grid points with 51 stretched vertical levels topped at 50 hPa. The model domain has a 4 km grid spacing in the horizontal, which is fine enough to resolve deep convection and the details of the terrain. The model integration is conducted over a 30 year period from 1 October 1980 through 30 September 2010. The model was configured with the Thompson cloud microphysics scheme, the Rapid Radiative Transfer Model (RRTMG) shortwave and longwave radiation scheme, the Yonsei University (YSU) planetary boundary layer scheme, and the revised Monin-Obukhov surface layer scheme, as well as the Noah-MP land surface schemes. No cumulus scheme is used because the 4 km resolution can resolve convection explicitly. These schemes were chosen based on the sensitivity investigation of three years of 4 km WRF simulations over the studied domain (Fig. 1) for three parameters. i.e., the monthly mean diurnal minimum and maximum temperatures and monthly precipitation, including snow accumulation during the cold season. Validation datasets include all SNOTEL (Snow Telemetry) sites, providing precipitation rate and snowpack snow water equivalent (SWE), and the 4 km PRISM (Parameter-elevation Regressions on Independent Slopes Model) estimates of monthly mean values of precipitation and temperature.

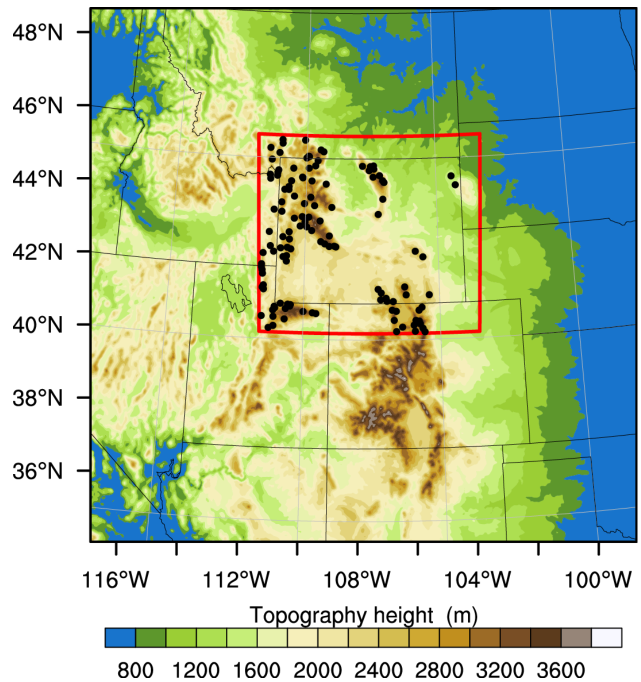

Fig. 1: Model domain of the 4-km regional climate simulation. The black dots are SNOTEL sites within Wyoming and vicinity.

3.b Current climate reanalysis data, CMIP-5 model guidance, and the PGW technique

Several "reanalysis" products (i.e., balanced 3D representations of the atmosphere and the underlying surface at a specific time in the recent past) have been developed. The Climate Forecast System Reanalysis (CFSR) is used in this work to provide initial and lateral boundary conditions. This dataset has a 0.5^{o} x 0.5^{o} spatial resolution and a 6-hourly temporal resolution.

The 2050s climate uses the same reanalysis data in the same domain at the same resolution, but the initial and boundary conditions are continuously perturbed using the pseudo-global-warming (PGW) technique.

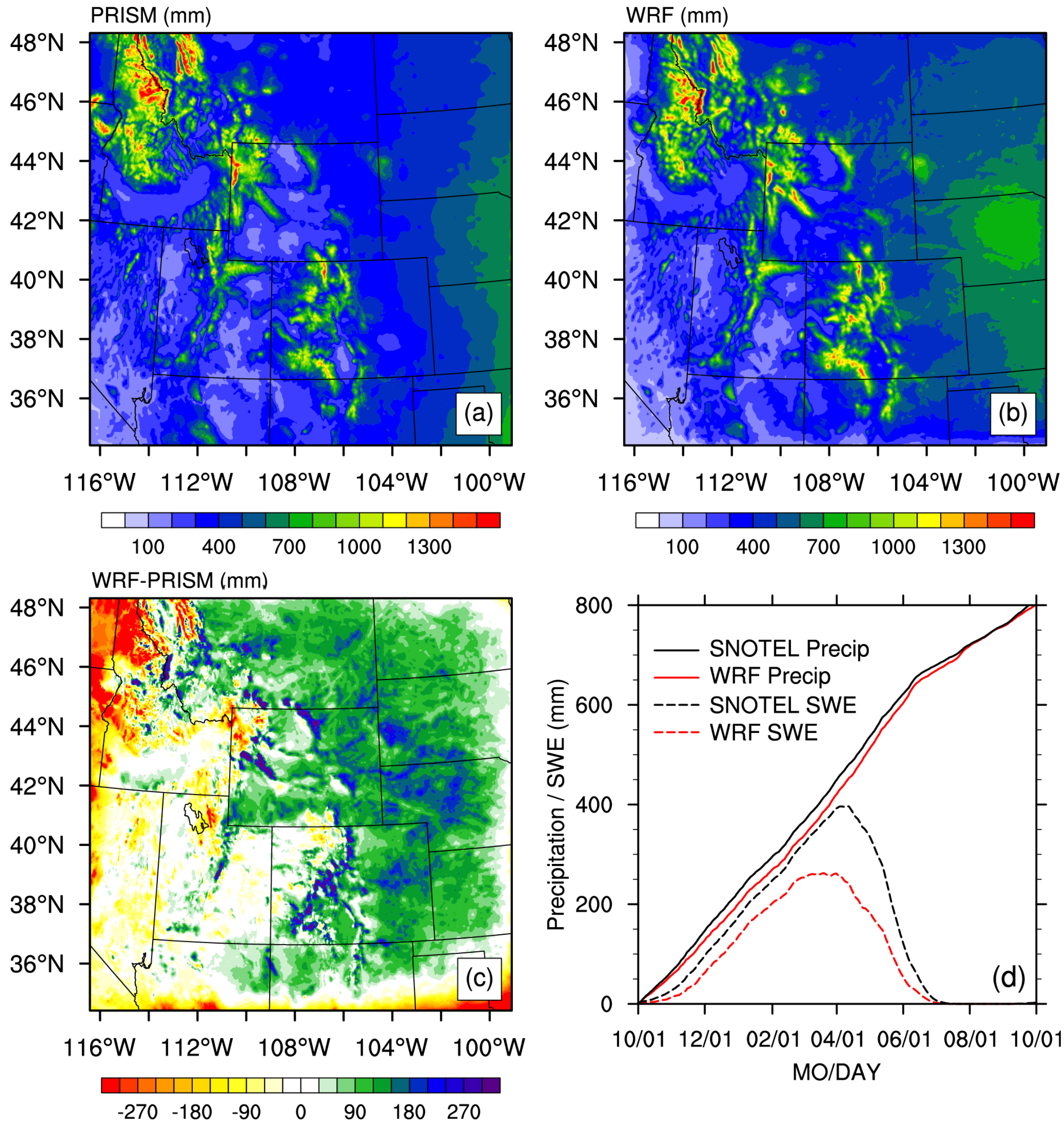

Fig. 2. Evaluation of 30 years of WRF (3.7.1) simulations. (a) PRISM annual precipitation; (b) WRF annual precipitation; (c) absolute difference between (b) and (a); (d) average seasonal precipitation accumulation and snowpack SWE at all SNOTEL sites shown in Fig. 1 as modelled (WRF) and observed (SNOTEL).

The perturbations are the monthly-mean Coupled Model Intercomparison Project 5 (CMIP-5) predicted changes in a 50-year period. The PGW technique allows unbiased climate change assessment relative to current low-frequency variability such as El Niño. The PGW technique is based on the premise that changes in intra- to inter-annual atmosphere-ocean teleconnections are inadequately understood, therefore it is best to preserve low-frequency general circulation patterns and the characteristics of storms entering the domain. We have followed NCAR's guidance as to which the ensemble of 19 CMIP-5 models has been used. All climate models have been run for several emission scenarios out to 2050 and beyond. We have used the Regional Concentration Pathway 8.5 scenario, as it is the most likely one.

3.c NCAR Wyoming Supercomputer Center (NWSC)

The proposed modeling work would not be possible without access to the facilities at the NWSC, in particular the Yellowstone system and massive data storage. Our current work has been supported by three separate NWSC allocations totaling 18.96 M core hours on Yellowstone. Large Allocation Requests under the "Wyoming allowance" can be submitted twice a year, most recently in May and November. These are no-cost high performance computing requests, reviewed by the Wyoming–NCAR Resource Advisory Panel (WRAP). This opportunity is designed specifically for federally-funded research in atmospheric, earth system and closely related sciences. The present grant from the UW Office of Water Programs (partly funded by the USGS) qualifies for a large NWSC allocation request. We received a new allocation in Aug 2016 for 6 M core hours on Yellowstone, of which 1.8M core hours remains unused at this time (1 May 2017).

4. Progress to date

4.a Retrospective simulations: the IWUS dataset

In July 2015 we completed the full 30-year simulation using an earlier version of WRF (v. 3.5.1). After some analysis we found a characteristic, seasonally dependent spatial precipitation bias pattern across the mountains, changing sign across the continental divide range. This bias remained small in the first 20 years of simulations, but became quite large in the last 10 years. WRF developer Jimy Dudhia found that it was caused by a deficient treatment of lateral boundary conditions, causing severe problems for long-term (multi-decadal) simulations particularly when a very high resolution is used. This bug was fixed in the new version 3.7.1. We completed the entire 30-year simulation with WRF v. 3.7.1 in June 2016. Results for this simulation are shown in **Fig. 2**.

Wang et al. (2017a) describe this new 30-year retrospective simulation, which we refer to as IWUS, or *Interior Western United States* simulation, to contrast it against NCAR's CONUS (CONtinental US) simulation (Liu et al. 2016, in *Climate Dynamics*). Wang et al. (2017a) describes describe WRF's architecture, calibration technique, and performance in comparison with SNOTEL (precipitation) and PRISM (precipitation and surface temperature) datasets, and also a comparison with CONUS. Results show that WRF v3.7.1 accurately captures observed seasonal precipitation, snowpack build-up, and snowpack ablation in the headwaters region around Wyoming (Fig. 2). The differences in annual precipitation between WRF and PRISM are quite small compared to the total (Fig. 2c against Fig. 2a or b). WRF seems to overpredict precipitation in the high ranges of the Wind River and Bighorn mountains. This may reflect an underestimate in the PRISM dataset (there are no SNOTEL sites above the tree line). WRF may slightly underestimate precipitation over lower ranges, such as the Wyoming range, Yellowstone NP, and the Sierra Madre. Precipitation is overestimated in the High Plains, mostly because thunderstorm activity is overestimated in summer. Please ignore the WRF underestimation along the upstream domain boundaries. In short, it is captured quite well in the Colorado-Wyoming headwater region (Fig. 2c). Overall, WRF underestimates precipitation by 7% at the SNOTEL sites shown in Fig. 1 (Fig. 2d).

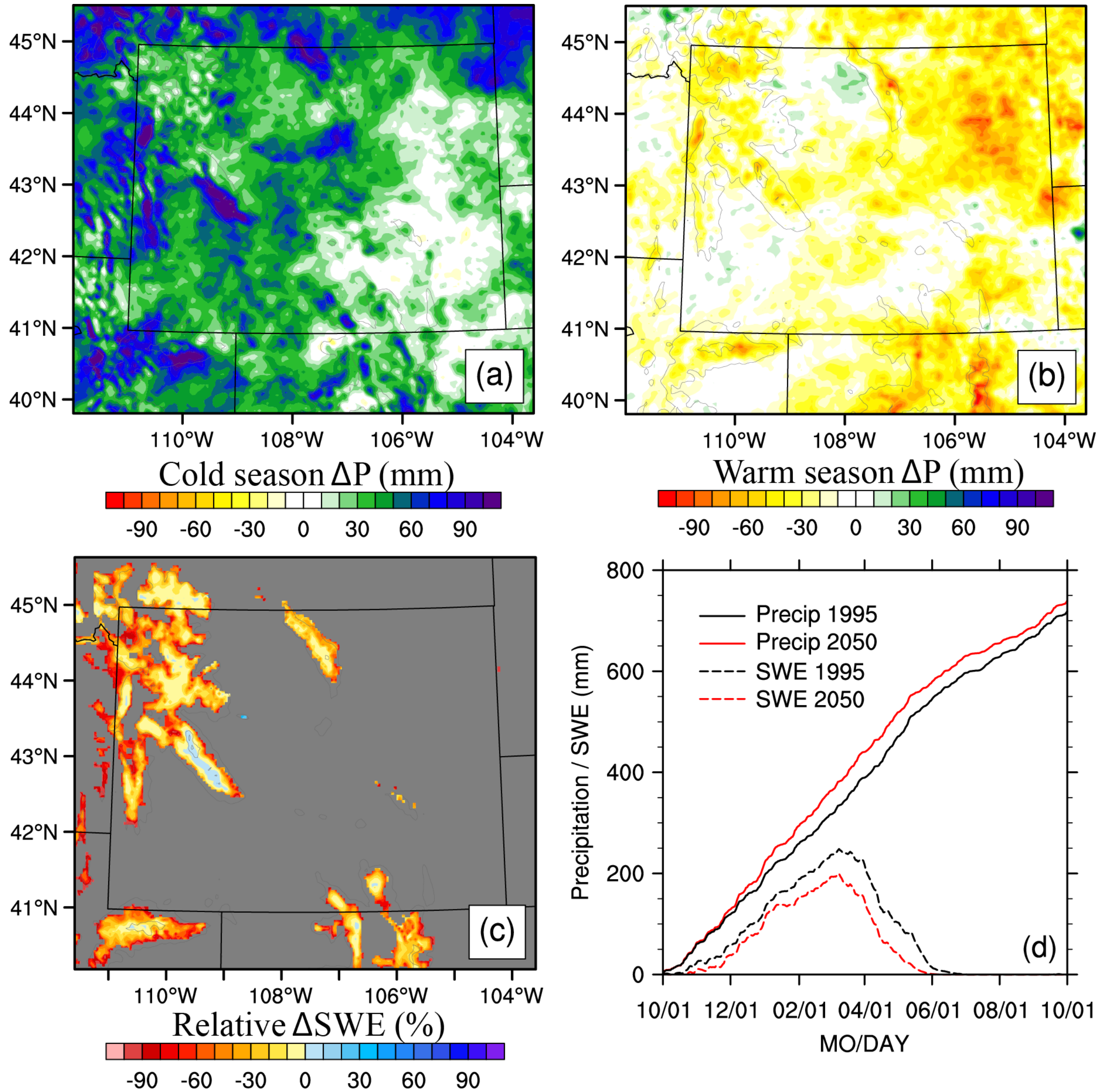

Fig. 3. Comparison of 30 years of retrospective and PGW simulations over Wyoming and vicinity. (a) The 30-yr average difference of precipitation during the cold season (future minus current); (b) same as (a), but for warm season; (c) the 30-yr average difference of SWE on 1 April (future minus current); (d) average seasonal precipitation accumulation and snowpack SWE at all SNOTEL sites shown in Fig. 1 from retrospective (black curves) and PGW (red curves) simulations. The thin grey contours in (a)-(c) show the terrain.

Snowpack dynamics at SNOTEL sites in this region are captured well (Fig. 2d), although the SWE are underestimated somewhat, by 20-30%. The seasonal distribution of SWE is captured well in particular the rate of spring ablation.

The retrospective and future simulations are archived by the USGS North Central Climate Science Center, through a framework agreement with the director (Dr. Morisette). Thus, the data are publically available at this time.

Jing et al. (2017 paper, presented orally at an AMS meeting in 2016) compares precipitation simulated by WRF with that from the datasets of SNOTEL, PRISM, and National Centers for Environmental Prediction (NCEP) National Hourly Multisensor Precipitation Analysis Stage IV dataset, using the 10-year subset of the 30-year retrospective simulation described in Wang et al. (2017). The results show WRF compares well against SNOTEL, especially for wintertime precipitation, as well as against NCEP IV and PRISM in the plains and valleys in the vicinity of NEXRAD radars. However, NCEP IV significantly underestimates orographic precipitation. PRISM is good in areas near SNOTEL sites but questionable in areas without gauges, esp. in areas above the treeline. Statistical analysis of wintertime precipitation suggests the bias and correlation between PRISM and WRF depend on gauge density and elevation.

4.b PGW simulations

We conducted the 30-year future climate simulations centered on 2050 using the PGW technique over the same domain in Fig. 1. The results indicate 10-30% more precipitation over Wyoming and vicinity in winter (DJF) (Fig. 3a), but summer precipitation decreases slightly (Fig. 3b). Less SWE is predicted on 1 Apr in future climate (Fig. 3c), and a significantly earlier date of peak SWE and earlier snowmelt at most places (Fig. 3d), except at high-elevation places (> ~3,300 m MSL), on account heavier spring snowfall there. The fraction of precipitation falling as snow decreases in future climate, especially at elevations between 6000-8000 ft MSL (not shown). We completed the WRF v3.7.1 future climate simulation in late June 2016. Since then we have been using the results to examine the effect of climate variability and projected global warming on the statistical distributions of precipitation amounts and SWE in the interior western US (Wang et al. 2017b).

4.c Publications

Jing, X., B. Geerts, Y. Wang, and C. Liu, 2017: Regional climate simulation of orographic precipitation in the Interior Western United States: comparisons with gauge and high-resolution gridded datasets. *J. Hydromet*., 18, 2541–2558. https://doi.org/10.1175/JHM-D-17-0056.1

Wang, Y., B. Geerts, and C. Liu, 2018: A 30-year convection-permitting regional climate simulation over the Interior Western United States. Part I: validation. *Int. J. Climat*., in press.

Wang, Y., B. Geerts, and C. Liu, 2018: A 30-year convection-permitting regional climate simulation over the Interior Western United States. Part II: changes in precipitation and snowpack by 2050. *Int. J. Climat.*, in preparation.

4.d Presentations

In the last 10 months, since the completion of the IWUS retrospective and future climate simulations, we have given numerous presentations to local, regional, and national stakeholder meetings.

Wang, Y., B. Geerts and C. Liu, 2015: Regional climate simulations of cold-season precipitation and snowpack over the US northern Rockies: validation and examination of factors controlling the precipitation distribution. Presented at the 2015 annual meeting of the American Meteorological Society (AMS), Phoenix AZ.

Wang, Y., B. Geerts, and C. Liu, 2016: Precipitation and snowpack dynamics over mountains in the interior Western US in a changing global climate. Presented at the AMS 17th Conference on Mountain Meteorology, Burlington VT, 27 June – 1 July 2016.

Jing, X, B. Geerts, Y. Wang and C. Liu, 2016: Regional Climate Simulation of Precipitation in the Interior Western US: Comparisons with High-Resolution Datasets and Ambient Factors Controlling Wintertime Orographic Precipitation Distribution. Presented at the AMS 17th Conference on Mountain Meteorology, Burlington VT, 27 June – 1 July 2016

Geerts, B., 2016: Assessment of gridded precipitation estimates in the Interior Western US using a Regional Climate Simulation, and changes in precipitation and snowpack in a changing climate. Fall 2016 Wyoming Water Association meeting, Casper, 28 Oct.

Geerts, B., 2016: Assessment of changes in precipitation and snowpack in a ~2050 climate in the Cheyenne water supply watershed areas. City of Cheyenne Board of Public Utilities presentation, 29 Nov.

Geerts, B., 2017: Assessment of gridded precipitation estimates in the Greater Yellowstone Area using a Regional Climate Simulation, and changes in precipitation and snowpack in a changing climate. Yellowstone River Compact Technical Committee, Thermopolis, 6 April.

Geerts, B., 2017: Assessment of gridded precipitation estimates in Wyoming using a Regional Climate Simulation, and changes in precipitation and snowpack in a changing climate. Spring 2017 Wyoming Water Forum, Cheyenne, 11 April.

Geerts, B., and Y. Wang, and X. Jing: Assessment of Gridded Precipitation Estimates in the Interior Western United States using a Regional Climate Simulation. Presented at the 2017 Western Snow Conference, 17-19 April, Boise ID. (https://westernsnowconference.org/files/2017WSC-Agenda.pdf)

Wang, Y., 2017: Precipitation and snowpack dynamics over mountains in the interior Western US in a changing global climate. Presented as a seminar at the South-Central Climate Science Center, July 2017.

5. Student and post-doc support and achievements

This project built **Dr. Yonggang Wang**'s post-doctoral expertise in regional climate modeling and fostered his collaborative ties with NCAR. Through many visits to Boulder and close collaboration, Yonggang built on the expertise developed by Dr. Roy Rasmussen's group at NCAR in their "Colorado Headwaters project", in particular the expertise of Dr. Changhai Liu. Dr. Liu's guidance in this project has been invaluable. Undoubtedly this project was essential in Yonggang's success in landing a Research Faculty position at Texas Tech University, starting in Aug 2016. Note that Yonggang's departure did not mean an end of his commitment to this project. He has continued to work on this remotely, work for which he has been compensated in part.

Xiaoqin Jing, a PhD student, is being trained as part of this project. Her dissertation, to be defended in Aug 2017, focuses on the general validation of orographic precipitation, and the ambient factors controlling wintertime orographic precipitation distribution using the 30-year retrospective simulation. She uses the IWUS retrospective model output and gauge-based gridded precipitation datasets such as PRISM. She has accepted a tenure track faculty position in the Dept. of Atmospheric Science at Nanjing Inst. of Technology, one of the most prestigious schools in Atmospheric Science in China.

Other graduate students have used or are using the IWUS dataset. **Thomas Mazzetti** (MS student, started in Jan 2017) is using IWUS as initial and boundary conditions to drive his high-resolution simulations over the Wind River Range under seeded and natural conditions. He received support from this grant from Jan 2017 – expiration. PhD student **Adam Tripp** and MS student **Coltin Grasmick** also used IWUS, as a driver dataset for their simulations and case studies in Idaho, and received some support through this grant.