Science Area 1: Standard Award: Model-Data Fusion to Examine Multiscale Dynamical Controls on Snow Cover and Critical Zone Moisture Inputs

Final Technical Report
DE-SC0019222

ABSTRACT

In many mountain watersheds of the world, seasonal snowpacks play an important role as natural reservoirs of water. Seasonal snowpacks accumulate water during cold, wet winter months that subsequently melts. Downstream communities depend on water from melting seasonal snowpacks to support agricultural, industrial, and municipal water needs. Rapidly melting snowpacks can also present a flooding hazard, particularly if snowpacks melt at rates faster than anticipated and where adequate reservoir capacity is unavailable to buffer river flows associated with melt. The spatial and temporal dynamics of snow accumulation and melt also play an important role in supporting upland ecosystems in mountain landscapes. Snowmelt provides soil moisture that enable terrestrial ecosystem productivity and exert control on soil microorganisms that play important roles in global carbon cycles. Climate warming is gradually decreasing the amount of precipitation in mountain watersheds arriving as snow, presenting potentially profound disruptions to mountain ecosystems, as well as downstream delivery of water. The overarching goal of this project was to understand how interactions between the near-surface atmosphere and surface topography control the input, accumulation, retention, and release of water from mountain snowpacks. Over a 5-year period, this project pursued an approach combining high-resolution regional climate modeling, satellite and airborne remote sensing data, and ground-based observations to develop and analyze benchmark datasets to address overarching science questions and hypotheses. Key products include a continuous, long-term, high spatiotemporal resolution (1 km/1 hr) dataset characterizing key climate variables in the Upper Colorado River Basin. The dataset included historical estimates of precipitation, temperature, humidity, solar and longwave radiation, and wind speeds. Additionally, the project developed a 20+ year long, 30 m spatial, daily temporal multi-sensor dataset characterizing snow presence/absence in the East/Taylor River watersheds in the Central Rocky Mountains of Colorado. The project supported training of 1 postdoctoral scholar, 1 Ph.D. student, and 1 M.S. student.

1. COVER PAGE DATA ELEMENTS

a. Federal Agency and Organization Element to Which Report is Submitted
Department of Energy

b. Federal Grant or Other Identifying Number Assigned by Agency
DE-SC0019222

c. Project Title
Science Area 1: Standard Award: Model-Data Fusion to Examine Multiscale Dynamical Controls on Snow Cover and Critical Zone Moisture Inputs

d. PD/PI Name, Title and Contact Information
Alejandro N. Flores, Associate Professor, lejoflores@boisestate.edu, (208) 426-2903

e. Name of Submitting Official, Title, and Contact Information
A

f. Submission Date
05/22/2023

g. DUNS Number
072995848

h. Recipient Organization (Name and Address)
Boise State University, 1910 University Dr., Boise, ID 83725

i. Project/Grant Period (Start Date, End Date)
09/15/2018, 09/14/2022

j. Reporting Period End Date
09/14/2022

k. Report Term or Frequency
Final

l. Signature of Submitting Official
Alejandro N. Flores

2. ACCOMPLISHMENTS

a. What are the major goals and objectives of this project?

The overarching goal of this project is to advance the ability to predict the timing, spatial distribution, and rate of delivery of water to the CZ in complex watersheds exhibiting multiple‑scale variation in hydrometeorological forcings, topography, and vegetation cover. In complex terrain, the redistribution of moisture exerts a first‑order control on key ecosystem functions including the mineralization and immobilization of soil carbon. The role of moisture redistribution in ecosystem function is more complex in seasonally snow‑dominated watersheds because snowpacks are ephemeral reservoirs of water that vary in space and time, and in response to climate and weather forcings at multiple spatiotemporal scales.

The goals of this project are as follows:

Goal 1: Develop a high spatiotemporal resolution (<1 km in space, hourly in time) reconstruction of historical climate in the broader study region using a coupled land‑atmosphere model, forced by high quality reanalysis data, and verify that dataset using extant field, remote sensing, and reanalysis products,

Goal 2: Synthesize datasets capturing the spatiotemporal evolution of snow covered area at 30‑m spatial resolution and daily temporal resolutions by fusing extant multispectral remote sensing data, and

Goal 3: Leverage both of the above to provide constraints on the spatiotemporal distribution of delivery of water to the CZ.

b. What was accomplished under these goals?

b.1 Major Activities

Goal 1: Develop a high spatiotemporal resolution reconstruction of historical climate

- [1.1] Developed and carried out a historical regional climate simulation over the Upper Colorado River Basin using the Weather Research and Forecasting (WRF) model, forced by Climate Forecast System analysis data. The domain was centered over the East River/Taylor River watersheds in the Central Rocky Mountains of Colorado. The simulation output was associated with a spatial resolution of 1 km and a temporal resolution of 1 hr. The simulation spanned Water Years 1987 to 2022, comprising a spatiotemporally complete dataset of 34 Water Years.
- [1.2] Developed and applied a Bayesian Inference approach to benchmark simulated precipitation from the above simulation by combining SNOTEL observations in the East and Taylor River watersheds, Airborne Snow Observatory (ASO) retrievals of snow depth (SD) and snow water equivalent (SWE), and discharge observations from the East River watershed.

Goal 2: Predict 30‑m resolution, daily snow covered area by fusing extant remote sensing data

- [2.1] Designed a computational workflow to apply an data fusion algorithm to combine two remote sensing datasets characterizing snow covered area – MODIS data associated with a spatial resolution of 500 m and temporal revisit interval of 1 day, and Landsat data associated with a spatial resolution of 30 m and temporal revisit interval of 16 days.
- [2.2] Used the above computational workflow to create a 20+ year dataset predicting the spatial distribution of snow covered area in the East River watershed for the period from ~2002-2020 at a spatiotemporal resolution of 30 m and 1 day.

- [2.3] Examined the developed snow covered area dataset to test hypothesized relationships between snow cover persistence and watershed physiographic attributes like elevation, slope, aspect, and vegetation cover.

Goal 3: Leverage developed datasets to understand controls on delivery of water to the CZ

- [3.1] Designed and carried out a suite of numerical experiments designed to assess the sensitivity of predictions of precipitation, SD, and SWE to the choice of cloud microphysics scheme in the WRF model.
- [3.2] Analyzed the above dataset to understand how the choice of microphysics scheme influences spatial patterns of precipitation, SD, and SWE, and the associated implications for how uncertainties in near-surface atmospheric process representation influences predictions of the input, accumulation, retention, and release of water from mountain snowpacks.

b.2 Specific Objectives

Goal 1: Develop a high spatiotemporal resolution reconstruction of historical climate

- The specific objectives motivating this project goal were to develop a high spatiotemporal resolution, serially complete dataset characterizing climate conditions for the last ~30 years in the Upper Colorado River Basin. Previously existing datasets: (1) were associated with significantly coarser spatial resolutions, temporal resolutions, or both, (2) spanned periods of time insufficiently long for trend detection, and/or (3) exhibited spatial and/or temporal gaps. The dataset was developed by using a regional climate model to downscale coarse scale climate conditions from water years 1987-2020. This approach explicitly accounts for interactions between the land surface topography and the atmosphere in terms of influences on vertical motions of air, orographic effects on temperature, pressure and humidity, as well as land-atmosphere energy exchange. In addition to providing a benchmark dataset to test hypotheses about associations between topography, precipitation, and other hydrologic variables, the dataset contains the surface hydrometeorological variables that would be needed to force other models of land surface and groundwater hydrology, terrestrial and aquatic ecosystem functioning, and other environmental systems processes.

Goal 2: Predict 30‑m resolution, daily snow covered area by fusing extant remote sensing data

- The objective underlying this goal was to leverage existing remote sensing datasets to derive a value-added dataset, with higher spatiotemporal resolution than either product independently, in order to examine and test hypotheses about physiographic controls on the spatiotemporal extent of snow cover. In particular, we were interested in understanding how terrain attributes like elevation, slope, aspect, and vegetation cover exert controls on the persistence of snow cover in mountain watersheds. To accomplish this, we had to design a suite of numerical experiments designed to test the feasibility of applying an existing MODIS/Landsat data fusion algorithm, the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM), for developing high spatiotemporal resolution estimates of snow covered area.

Goal 3: Leverage developed datasets to understand controls on delivery of water to the CZ

- The specific objective underlying this project goal was to use the datasets developed in support of Goals 1 and 2, along with other targeted numerical experiments with the WRF model to understand how regional topographic characteristics interact with coarse-scale atmospheric conditions to control how water is input, accumulates, is retained, and is released from mountain watersheds. An additional objective underlying this goal is to understand how uncertainties and assumptions made in coupled land-atmosphere models potentially influence predictions of the retention and release of water from mountain landscapes to identify potential pathways for improving model predictability.

b.3 Significant Results

Goal 1: Develop a high spatiotemporal resolution reconstruction of historical climate

- Significant project results associated with activities supporting this goal, include the following findings:
    - Streamflow and, more accurately, runoff volume represents an important, if underutilized, source of observational constraint on predicted precipitation. Using a simple water balance model driven only by observational data together with a Bayesian inference method, this project evaluated a long-term (34 year), high spatiotemporal resolution (1 km/1 hr), WRF-derived simulation of precipitation in the East River watershed. This approach allowed a more independent comparison of the developed precipitation products with other, broadly available, precipitation products, like the Parameter-elevation Regressions on Independent Slopes Model (PRISM) products.
    - This comparison between WRF-derived precipitation, a number of gridded precipitation products, and the discharge-derived estimate of mean annual precipitation provided additional context for apparent difference between WRF-derived precipitation and those gridded products. Further comparison with ASO data revealed that, while WRF precipitation estimates were systematically higher than PRISM and other gridded products in the western and northern margins of the East River Watershed, this was broadly consistent with ASO observations of SD and estimates of SWE.
    - Gridded precipitation products, like PRISM, are broadly used in climate and hydrological science and applications in the US. The models and algorithms underlying these products depend on data from surface observational networks that continuously change (i.e., through the addition and decommissioning of sites). As such, direct comparison of predicted precipitation derived from the WRF model (like those developed in this project) and products like PRISM requires care because introduction or deletion of new observational sites can introduce shifts in precipitation in the vicinity of new or decommissioned sites.

Goal 2: Predict 30‑m resolution, daily snow covered area by fusing extant remote sensing data

- Key findings arising from activities in support of this research goal include the following:
    - Estimates of snow covered area at spatiotemporal resolutions of 30 m and 1 day derived from the STARFM data fusion algorithm, performed significantly better than random when compared to withheld actual Landsat observations of snow covered area on the same day.
    - Cloud contamination of coarse scale MODIS imagery required as input to the STARFM algorithm limits the spatiotemporal extent over which data fusion can be performed, particularly at high elevations more commonly cloud covered in winter months.
    - Accuracy in predictions does not systematically vary by elevation, slope, aspect, or land cover. However, north-facing aspects seem to be associated with lower data availability. Since north-facing aspects tend to be associated with higher snow cover in the Northern

Hemisphere, this potentially indicates that some cloud-free pixels in MODIS data are incorrectly classified as cloud covered.

Goal 3: Leverage developed datasets to understand controls on delivery of water to the CZ

- Significant findings of this component of the research include the following:
    - The choice of cloud microphysics schemes in coupled land-atmosphere models has important ramifications for the predicted spatiotemporal distribution of precipitation – particularly precipitation as snow – in mountain landscapes. They correspondingly exert influence on the accumulation and retention of water in seasonal snowpacks and, subsequently, downstream hydrologic response.
    - Novel remote sensing datasets like those provided by the Airborne Snow Observatory (ASO) provide important observational constraint on snow depth and water storage in mountain watersheds, thereby providing important information that can be used to assess the predictions associated with different cloud microphysics schemes.
    - Co-located atmospheric and hydrological/critical zone field observatories, like the ARM SAIL campaign and Watershed Function Scientific Focus Area, provide important opportunities and associated data to evaluate existing and develop new microphysics schemes.

b.4 Other Achievements

Nothing to Report.

c. What opportunities for training and professional development has the project provided?

Describe opportunities for training and professional development provided to anyone who worked on the project or anyone who was involved in the activities supported by the project. “Training” activities are those in which individuals with advanced professional skills and experience assist others in attaining greater proficiency. Training activities may include, for example, courses or one-on-one work with a mentor. “Professional development” activities result in increased knowledge or skill in one’s area of expertise and may include workshops, conferences, seminars, study groups, and individual study. Include participation in conferences, workshops, and seminars not listed under major activities.

If the project was not intended to provide training and professional development opportunities or there is nothing significant to report during this reporting period, state “Nothing to Report.”

d. How have the results been disseminated to communities of interest?

Nothing to Report.

e. What do you plan to do during the next reporting period to accomplish the goals and objectives?

Nothing to Report.

3. PRODUCTS: Optional

a. Publications, conference papers, and presentations

i. Journal publications

Rudisill, W., Flores, A., and Carroll, R.: Evaluating Three Decades of Precipitation in the Upper Colorado River Basin from a High-Resolution Regional Climate Model, Geosci. Model Dev. Discuss. [preprint], https://doi.org/10.5194/gmd-2023-69, in review, 2023.

Rudisill, W.J., Flores, A.N., Marshall, H.-P., Siirila-Woodburn, E., Feldman, D.R., Rhoades, A.M., Zu, Z., and Morales, A.: Cold-Season Precipitation Sensitivity to Microphysical Parameterizations: Hydrologic Evaluations Leveraging Snow Lidar Datasets, J. Hydrometeor., in review.

ii. Books or other non-periodical, one-time publications

Rudisill, William J., "From River Channel to Cloud Tops: Evaluation and Applications of Regional Climate Models in Mountain Watersheds" (2022). Boise State University Theses and Dissertations. 1992. https://doi.org/10.18122/td.1992.boisestate

Vincent, Allison N., "Using Remote Sensing Data Fusion Modeling to Track Seasonal Snow Cover in a Mountain Watershed" (2021). Boise State University Theses and Dissertations. 1810. http://doi.org/10.18122/td.1810.boisestate

iii. Other publications, conference papers and presentations

Flores, A.N., Rudisill, W., Carroll, R., Feldman, D., Marshall, H.-P., Morales, A., McNamara, J.P., Rhoades, A., Vincent, A.N., Siirilla-Woodburn, E., Xu, Z.: From Snowflake to Snowpack: How do Cloud Microphysical Representations Influence Hydrologic Response? 103rd Annual Meeting of the American Meteorological Society. Jan. 8-12, 2023. Denver, CO.

Siirilla-Woodburn, E.R., Dennedy-Frank, P.J., Thiros., N.E., Rudisill, W.J., Xu, Z., Rhoades, A., Feldman, D., Gardner, W.P., Flores, A.N., Carroll, R.W.H., Newcomer, M.E., Williams, K.H., and Brodie, E.: Determining the role of low-to-no snow years on mountainous water budgets with bedrock through atmosphere models and observations. American Geophysical Union Fall Meeting, Dec. 12-16, 2022. Chicago, IL.

Flores, A.N., Rudisill, W., Carroll, R., Feldman, D., Marshall, H.-P., Morales, A., McNamara, J.P., Rhoades, A., Vincent, A.N., Siirilla-Woodburn, E., Xu, Z.: From Snowflake to Snowpack: Examining the Consequences of Cloud Microphysical Representations for Hydrologic Uncertainty (Invited). American Geophysical Union Fall Meeting, Dec. 12-16, 2022. Chicago, IL.

Feldman, D., Aiken, A.C., Beutler, C.A., Boos, W.R., Carroll, R.W.H., Chandrasekar, V., Collis, S.M., Creamean, J., deBoer, G., Deems, J., DeMott, P.J., Fan, J., Flores, A.N., Gochis, D., Hodshire, A.L., Levin, E.J.T., Leung, L.R., Newman, A., Raleigh, M.S., Rhoades, A., Rudisill, W.J., Siirilla-Woodburn, E.R., Skiles, M., Smith, J.N., Varble, A., Williams, K.H., Xu, Z. Surveying the First Year of SAIL Data and Formulating Hypotheses for its Second Year. American Geophysical Union Fall Meeting, Dec. 12-16, 2022. Chicago, IL.

Flores., A.N., Vincent, A.N., McNamara, J.P., Carroll, R.W.H., Marshall, H.-P.:Imposing Snow and Discharge Constraints on a Regional High-Resolution Precipitation Data Using Bayesian Inference. American Geophysical Union Fall Meeting, Dec. 12-16, 2022. Chicago, IL.

Rudisill, W.J., and Flores, A.N.: Applying Hydrologic and Snow Data Inference Methods to Evaluate Dynamically Downscaled Precipitation Fields. American Geophysical Union Fall Meeting, Dec. 13-17, 2021. New Orleans, LA.

Feldman, D., Xu, Z., Siirilla-Woodburn, E.R., Rhoades, A., Rudisill, W.J., and Flores, A.N.: Using SAIL Campaign Measurements and Integrated Process Modeling to Better Understand the Headwater Hydrology of the Upper Colorado River Basin. American Geophysical Union Fall Meeting, Dec. 13-17, 2021. New Orleans, LA.

Vincent, A.N., Flores, A.N., Glenn, N.F., Marshall, H.-P., Nash, C.: Applying Multisensor Data Fusion via the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM) for Improved Monitoring of Seasonal Snowpack. American Geophysical Union Fall Meeting, Dec. 9-13, 2019. San Francisco, CA.

Rudisill, W.J., Nash, C., Flores, A.N., Feldman, D., Carroll, R.W.H.: A Comparison of Dynamically Downscaled and Interpolated Daily Meteorological Datasets in the East River, CO. American Geophysical Union Fall Meeting, Dec. 9-13, 2019. San Francisco, CA.

b. Website(s) or other Internet site(s)

None to Report.

c. Technologies or techniques

None to Report.

d. Inventions, patent applications, and/or licenses

None to Report.

e. Other products

Rudisill W ; Vincent A ; Nash C ; Flores A (2022): Dynamically Downscaled (WRF) 1km, Hourly Meteorological Conditions 1987-2020. East/Taylor Watersheds. Science Area 1: Standard Award: Model-Data Fusion to Examine Multiscale Dynamical Controls on Snow Cover and Critical Zone Moisture Inputs, ESS-DIVE repository. Dataset. doi:10.15485/1845448 accessed via https://data.ess-dive.lbl.gov/datasets/doi:10.15485/1845448 on 2023-05-15

>750 views; > 50 downloads as of 05/16/2023.

Rudisill, W. (2023). WRF-Mphys-ERiv, HydroShare, http://www.hydroshare.org/resource/8b3a213f2a26474cb2d473cbb4b0ca19

4. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS: Optional

a. What individuals have worked on the project?

1. Participant: Alejandro Flores		
Project Role: PI/PD	**Person Months Worked:** 2	**Funding Support (if other than this award):**
Contribution to the Project: ● Overall management of project scope, budget, and timelines ● Coordination of research activities within project ● Design of numerical experiments for coupled land‑atmosphere modeling activities, remote sensing data fusion activities, synthesis activities ● Coordination with other research teams within the Watershed Function SFA East River Study Area, as well as other ESS investigator teams working in the East River Watershed ● Reporting to DOE ● Leading design and contributing to preparation of manuscripts for submission to peer-reviewed journals ● Communicating science outcomes to broad audiences		
International Collaboration: No		
International Travel: No		

2. Participant: William Rudisill		
Project Role: Graduate Student	**Person Months Worked:** 24	**Funding Support (if other than this award):**
Contribution to the Project: ● Managed WRF long‑term simulations over East River Watershed ● Analyzed WRF simulation output and investigation of trends in simulated climate and delivery of water to the Critical Zone ● Designed and carried out WRF microphysics experiments ● Lead preparation of manuscripts for submission to peer-reviewed journals		
International Collaboration: No		
International Travel: No		

3. Participant: Caroline Nash		
Project Role: Postdoctoral	**Person Months Worked:** 12	**Funding Support (if other**

scholar		**than this award):**
Contribution to the Project: ● Assisted in managing and executing WRF long-term simulations over the East River Study Site ● Assisted in developing and conducting numerical experiments to test STARFM output against verification data ● Assisted in design of data management systems ● Preparation of manuscripts for submission to peer-reviewed journals		
International Collaboration: No		
International Travel: No		

4. Participant: Allison Vincent		
Project Role: Graduate Student	**Person Months Worked:** 6	**Funding Support (if other than this award):** Allison's academic year funding for 2 years was provided via a Graduate Assistantship from the Boise State Department of Geosciences
Contribution to the Project: ● Developed workflows to process Landsat and MODIS remote sensing data for snow covered area estimation ● Prepared data for input to and oversaw execution of STARFM data fusion algorithm runs ● Acquired and processed independent data to verify STARFM output, including ASO data ● Developed and conducted numerical experiments to test STARFM output against verification data ● Assisted in preparing manuscripts for submission to peer-reviewed journals		
International Collaboration: No		
International Travel: No		

5. Participant: Matt Masarik		
Project Role: Staff Scientist	**Person Months Worked:** 1.5	**Funding Support (if other than this award):**

Contribution to the Project: ● Assisted in developing computational software to execute long-term WRF simulations on Boise State and Idaho National Lab (INL) High Performance Computing (HPC) assets ● Assisted in the design of long-term WRF numerical experiments and simulation
International Collaboration: No
International Travel: No

6. Participant: Jack Herzoff		
Project Role: Undergraduate Student	**Person Months Worked:** 2	**Funding Support (if other than this award):**
Contribution to the Project: ● Supported A. Vincent in developing computational software to automate processing of Landsat data in Google Earth Engine ● Explored machine learning methods for classifying true-positive and false-positive cloud contaminated MODIS pixels		
International Collaboration: No		
International Travel: No		

7. Participant: Kathryn Murenbeeld		
Project Role: Graduate Student	**Person Months Worked:** 5.5	**Funding Support (if other than this award):**
Contribution to the Project: ● Assisted in data management activities on Boise State and INL HPC resources ● Supported execution of long-term WRF simulation		
International Collaboration: No		
International Travel: No		

8. Participant: Rosemary Carroll		
Project Role: Co PD/PI	**Person Months Worked:** 3	**Funding Support (if other than this award):**
Contribution to the Project:		

● Assisted in the interpretation of WRF and STARFM outputs based on cumulative field and modeling experience. ● Provided feedback on numerical experiment design of WRF simulations and STARFM runs ● Assisted in preparing manuscripts for submission to peer-reviewed journals
International Collaboration: No
International Travel: No

9. Participant: Dan Feldman		
Project Role: Co PD/PI	**Person Months Worked:** 1	**Funding Support (if other than this award):**
Contribution to the Project: ● Provided input and consultation on coupled land‐atmosphere model runs, particulary design and execution of microphysics experiment runs ● Assisted in identifying other scientific applications of land‐atmosphere model output data ● Assisted in preparation of manuscripts for submission to peer-reviewed journals		
International Collaboration: No		
International Travel: No		

b. Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?
Nothing to Report.

c. What other organizations have been involved as partners?

1. Partner Organization: Idaho National Lab, Idaho Falls, ID
Partner's Contribution to Project: ● Idaho National Lab's High Performance Computing office provided in-kind project support through the use of the (now decommissioned) Falcon supercomputing system. Project personnel were able to use Falcon for WRF runs and temporary data storage through an Idaho University Allocation.

d. Have other collaborators or contacts been involved?
None to Report.

5. IMPACT:

a. What was the impact on the development of the principal discipline(s) of the project?

The project provided additional context and quantification of how well regional climate models can simulate climate at high spatiotemporal resolution in topographically complex watersheds. It provided a long-term, high spatiotemporal resolution, serially complete dataset characterizing surface hydrometeorology over the Upper Colorado River Basin and the East and Taylor River Watersheds. It made these data broadly available to the scientific community by making them available through the ESS-DIVE data portal. It further illustrated to the hydrologic science community that choices of microphysics parameterizations used when configuring coupled-land atmosphere models exert significant influence on the amount and spatial organization of precipitation and, ultimately, snow depth and snow water equivalent. As such, this project identified an important line of interdisciplinary inquiry between land surface hydrologists and atmospheric scientists around improving representation of cloud microphysical processes in land-atmosphere models.

This project further illustrated the utility of an existing data fusion algorithm, STARFM – which was originally developed to fuse MODIS and Landsat data for surface vegetation applications, is also useful for estimating snow covered area. In doing so, this project showed that it is possible to use multiple remote sensing products with complementary spatiotemporal resolution characteristics to estimate the historical spatiotemporal dynamics of snow covered area. In the process of carrying out this demonstration, we developed a 20+ year estimate of snow covered area over the East River Watershed at 30 m spatial and daily temporal resolution.

b. What was the impact on other disciplines?

As mentioned above, this project provided an important illustration of the consequences of cloud microphysical parameterizations in coupled land-atmosphere models on land surface (and ultimately critical zone) hydrology. In doing so, this project elevates the importance of cloud microphysics parameterizations in models like WRF on the water cycle, particularly in seasonally snow-covered mountain watersheds.

c. What was the impact on the development of human resources?

This project provided training opportunities for three early career scientists who are all now making significant impacts in the areas of water resources. One trainee completed a MS Hydrologic Sciences degree while working on project activities and is now employed by a state water management agency in managing geographic information system related to water resources. Another trainee completed a PhD in Geophysics, engaged in an Office of Science Graduate Science Research (SCGSR) project at Lawrence Berkeley National Lab and is now a Postdoctoral scholar working at LBNL with SCGSR advisors. One postdoctoral trainee supported by the project is now a science principal in a company focused on water-related climate resilience solutions like beaver dam analogs.

d. What was the impact on teaching and educational experiences?

None to Report.

e. What was the impact on physical, institutional, and information resources that form infrastructure?

Nothing to Report.

f. What was the impact on technology transfer?
Nothing to Report.

g. What was the impact on society beyond science and technology?
Nothing to Report.

h. What percentage of the award's budget was spent in foreign country(ies)?
Nothing to Report.

6. CHANGES/PROBLEMS:

a. Changes in approach and reasons for change

None to Report.

b. Actual or anticipated problems or delays and actions or plans to resolve them

The onset of the COVID-19 pandemic towards the beginning of the award disrupted initially planned field activities in the East River watershed. These activities were ultimately de-scoped from the project. Since these activities constituted a minor portion of the overall work effort, however, this change in scope did not significantly impact research activities, outputs, or findings.

c. Changes that have a significant impact on expenditures

None to Report.

d. Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

None to Report.

e. Change of primary performance site location from that originally proposed

None to Report.

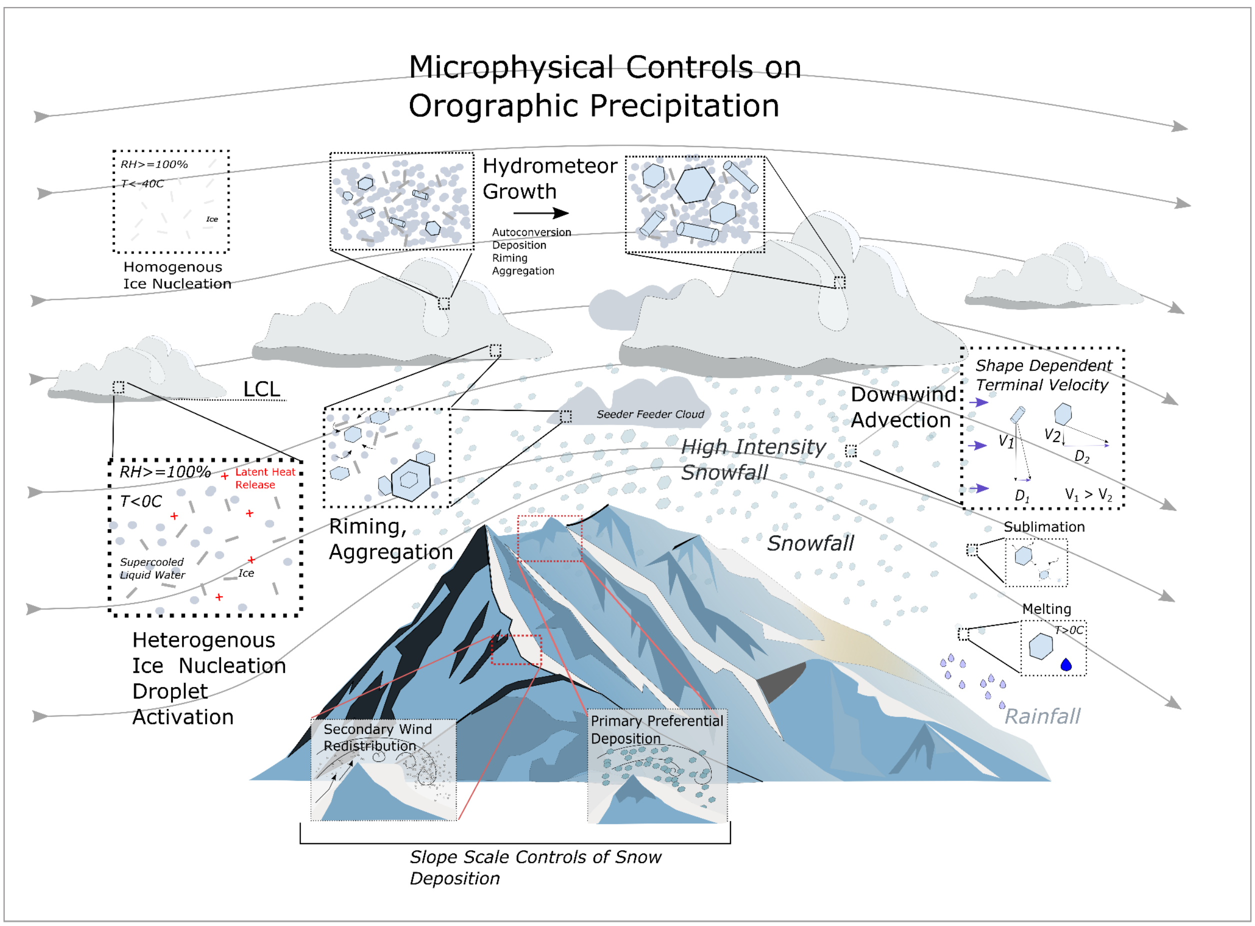
7. SPECIAL REPORTING REQUIREMENTS:

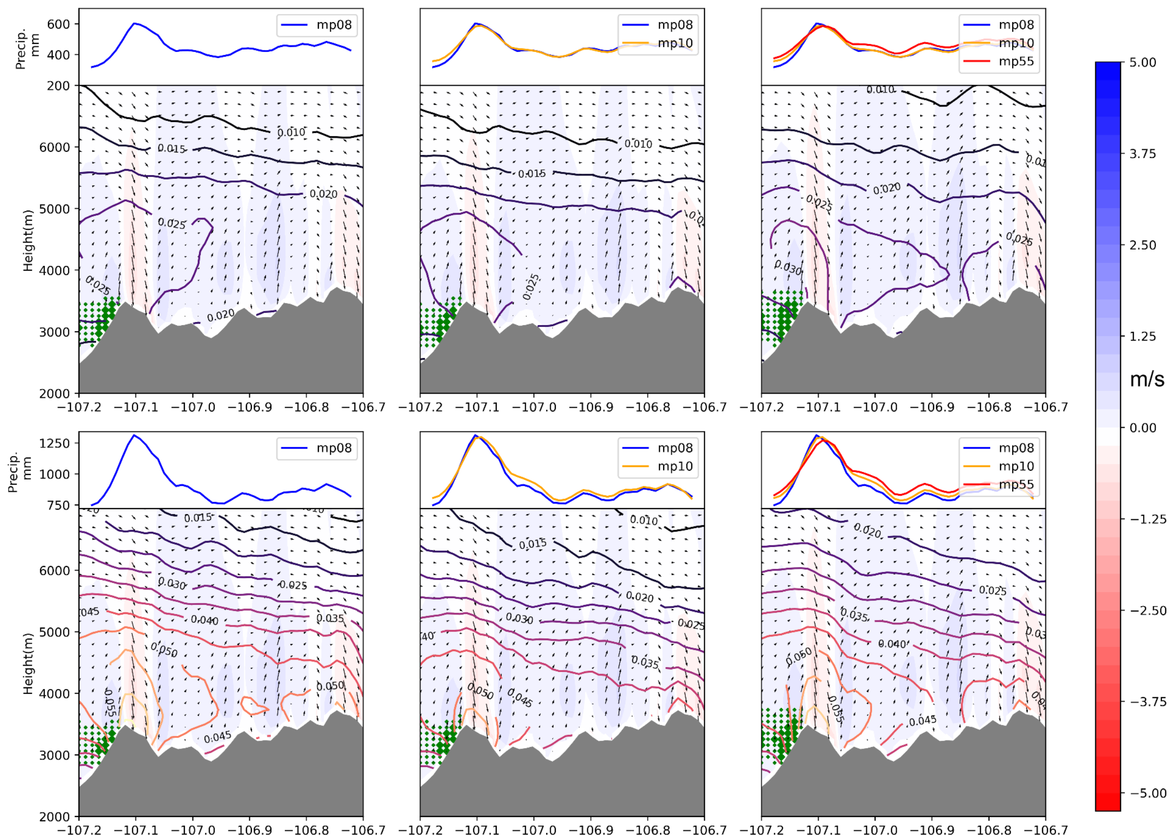
None to Report.

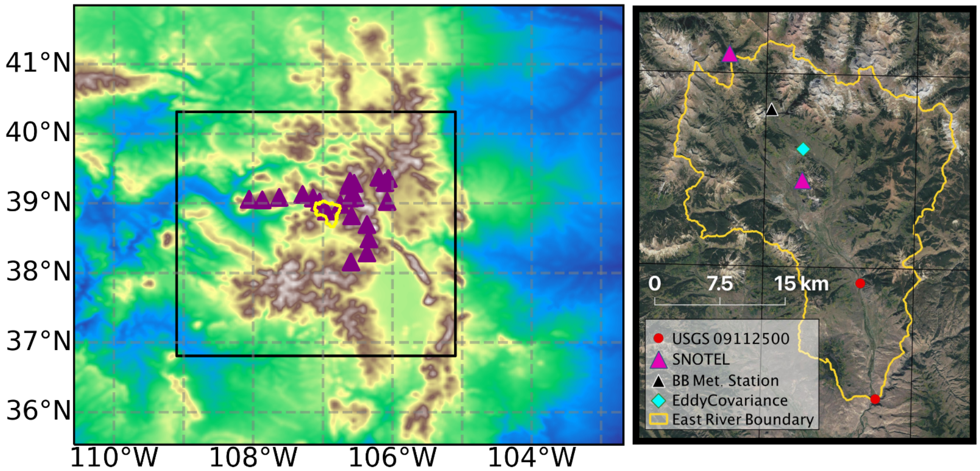
8. BUDGETARY INFORMATION:
See Submitted.

9. PROJECT OUTCOMES:

This Department of Energy Office of Science Environmental System Science project investigated how to better predict precipitation – particularly snowfall – in mountain watersheds of the western US. In much of the western US, seasonal snowpacks are a critically important natural reservoir of water that retain water in the cold, wet winter months and release water in the spring and summer months. Millions of people in the US depend on that snowmelt for their livelihoods and subsistence. Climate change is reducing the fraction of precipitation in mountains that falls as snow, and in order to understand how this impacts downstream communities, it is critical to be able to accurately predict precipitation in these landscapes. This project used computational models that simulate regional climate and water processes, data from aircraft and satellites, and data from on-the-ground observational networks to assess how accurately current models simulate precipitation, how that accuracy depends on our assumptions about the formation and change of snow and ice particles, and how consistent those predictions are with observations of the streamflow volume produced by that precipitation. During this project, activities contributed to the workforce development of three early career scientists who are now contributing in important ways to water science research and water management in the western US.






41°N
40°N
39°N
38°N
37°N
36°N
110°W
108°W
106°W
104°W
0
7.5
15 km
USGS 09112500
SNOTEL
BB Met. Station
EddyCovariance
East River Boundary