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Characterizing Snowfall Events across the Western US to Inform Water Resources Management

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14. ABSTRACT
The Bureau of Reclamation (Reclamation) Science and Technology (S&T) Program funded a scoping project (ID 20082) in October 2019 to develop a collaborative experiment to investigate atmospheric/climate drivers of hydrologic and land surface processes during drought periods and/or wet (i.e. pluvial) periods to understand the likelihood of acute or prolonged extremes and impacts on water management of Reclamation's reservoirs. The resulting project plan incorporates the approach of weather typing to understand atmospheric drivers of historical heavy snowfall events within four snowmelt-dominated watersheds that encompass a wide range of hydroclimate regions and have regional Reclamation partners who seek improved information and tools for streamflow forecasting.

15. SUBJECT TERMS
snow accumulation, weather typing, large ensemble

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Mission Statements

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Acknowledgements

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Characterizing Historical and Future Snowfall Events across the Western US to Support Informed Water Resources Management

Final Report No. 2020-20082-01

prepared by

Technical Service Center
Marketa McGuire, PE, Hydrologic Civil Engineer
Kathleen Holman, PhD, Meteorologist

Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology Program

Final Report 2020-20082-01

Characterizing Historical and Future Snowfall Events across the Western US to Support Informed Water Resources Management

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Peer Review by: Dagmar Llewellyn
Water and Planning Group Supervisor
Albuquerque Area Office

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Executive Summary

The Bureau of Reclamation (Reclamation) Science and Technology (S&T) Program funded a scoping project (ID 20082) in October 2019 to develop a collaborative experiment to investigate atmospheric/climate drivers of hydrologic and land surface processes during drought periods and/or wet (i.e. pluvial) periods to understand the likelihood of acute or prolonged extremes and impacts on water management of Reclamation's reservoirs. The primary research topics of interest were the relative roles of climate variability and long-term trends in producing extreme events. The project team aimed to leverage the joint expertise/interests at Reclamation, the University of Colorado at Boulder (CU), and the National Center for Atmospheric Research (NCAR).

The goals of this scoping project were to: 1) identify and refine the pertinent science questions, 2) identify key collaborators, and 3) develop a detailed research proposal for the fiscal year 2021 S&T proposal cycle. The scoping effort was supported by a series of meetings between Reclamation staff and possible collaborators with expertise in atmospheric science and hydrology. This scoping study final report further describes the project plan that was submitted for consideration in the fiscal year 2021 proposal cycle. Although the proposal was not selected for funding, we revised the proposal (included in this final report document) with the intention of submitting it again in the fiscal year 2022 proposal cycle.

This project plan acknowledges that winter snowpack serves as a crucial source of water that Reclamation water managers rely on to fill reservoirs and to provide water deliveries to customers across the West. At Reclamation, streamflow forecasts, which are informed in part by snowfall, are used to inform daily reservoir operations, including water-supply and flood-management operations, as well as seasonal water-supply planning, and drought contingency planning. Many researchers and practitioners have focused on understanding local and large-scale drivers of snow accumulation and melt to improve streamflow forecasts. Little attention has been given to understanding the synoptic weather conditions conducive to snowfall events across the west, knowledge that could help inform streamflow forecasts.

The project plan leverages two previously funded S&T projects focused on characterization and prediction of North American Monsoon precipitation in the southwestern US. The first project (ID 1782) sought to understand distinct atmospheric circulation patterns (i.e. weather types) associated with local precipitation in New Mexico associated with the North American Monsoon. The second project (ID 20032) sought to understand if weather types can be used to forecast monsoon precipitation on seasonal to decadal timescales.

In this study, we utilize the approach of weather typing to understand atmospheric drivers of historical heavy snowfall events within four snowmelt-dominated watersheds that encompass a wide range of hydroclimate regions. We have partnered with regional Reclamation water managers who seek improved information and tools for streamflow forecasting in order to improve their ability to meet the water demands of their customers. In addition, improved forecasting ability will allow Reclamation to improve water management decisions to benefit fish and wildlife habitat, recreation,

and hydropower production. Improving the skill of streamflow forecasts is a critical step towards improving Reclamation's ability to fulfill its mission across the western US.

Revised Final Proposal

1. Project Summary Information

TITLE (200 characters): Characterizing Historical and Future Snowfall Events across the Western US to Inform Water Resources Management

PROPOSAL TYPE: Solicited

PERFORMANCE PERIOD (END DATE): September 30, 2024 (three years FY2022-FY2024)

DESCRIPTION (10 points):
Winter snowpack serves as a crucial source of water that Reclamation water managers rely on to fill reservoirs and to provide water deliveries to customers across the West. At Reclamation, streamflow and water-supply forecasts, which are informed in part by snowfall, are used to inform daily reservoir operations, including water-supply and flood-management operations, as well as seasonal water-supply planning, and drought contingency planning. We propose to expand on previous and existing research funded through the Reclamation's Science and Technology (S&T) Program to improve understanding of the synoptic weather conditions that result in snowfall across four watersheds in the western US.

Existing research focused on understanding local and large-scale drivers of snow accumulation and melt to improve streamflow forecasts will provide a basis for this proposed study. For example, previous work has shown that local wind fields, varying precipitation totals, solar radiation intensity, and topography can influence snow accumulation and melt across individual basins (Seyfried and Wilcox 1995; Luce et al. 1998; Winstral and Marks 2002). McCabe and Dettinger (2002) reported that approximately 61% of the total variability in western US snowpack is controlled by El-Nino/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). However, while streamflow forecasts incorporating large-scale climate predictors (Mahanama et al. 2012) may improve skill in some areas, there are regions in the western US where relationships with large-scale teleconnection patterns are weak, leaving a gap in predictive capability. In this work, we aim to understand the synoptic weather conditions conducive to snowfall events across the west, knowledge that could help inform streamflow forecasts.

We will apply the weather-typing approach described by Reclamation (2019) and Prein and Mearns (2020), which uses historical reanalysis data from across the western US to characterize weather conditions under which large snowfall events have occurred. Weather typing is an objective method used to categorize the state of the atmosphere and has been used to understand historical precipitation across the US (Prein et al. 2016), historical and future variability of the North American Monsoon (ST-2019-1782-01, Reclamation 2019), and extreme precipitation events across major US watersheds (Prein and Mearns 2020). We will utilize this approach to understand atmospheric drivers of historical large snowfall events within the headwaters of each of these rivers: the Sun River in Montana, the Truckee River in Nevada, the Klamath River in Oregon, and the San Juan River in Colorado. We will focus on these river basins because they are snowmelt-dominated watersheds that have regional Reclamation partners who seek improved information and tools for streamflow forecasting, and because, together, these basins encompass a wide range of hydroclimate conditions and drivers. Snowfall events will be identified through analysis of snowpack changes in the SNOTEL dataset, supplemented by other observational datasets as they are available. We will also apply the weather-typing algorithm to output from the Community Earth System Model large ensemble (CESM LE; Kay et al. 2015), which includes 40 ensemble members of current and future climate spanning 1920 to 2100. We will explore how well the CESM LE reproduces historical weather types conducive to large snowfall events across the four basins of interest and how those weather types are projected to change through 2099.

The primary deliverable of this project will be a catalog of historical snowfall drivers across each of the four Reclamation basins of interest and a summary of how the frequency of occurrence of these snowfall drivers may change in the future. These catalogs may be used by water managers in each region to 1) understand synoptic drivers of large snowfall events in their basin, 2) explain variability in historical snowfall and streamflow, 3) inform weather and streamflow forecasts, and 4) identify use cases for long-term planning. We will collaborate with water managers from each of the four Reclamation regions (associated with the rivers listed previously) to maximize understanding and application of results. We will also partner with Andreas Prein at NCAR to provide technical guidance and facilitate transfer of existing weather typing code and data, which will expand technical capability within Reclamation to apply novel published techniques related to climate science. We will build upon S&T Project 1782 (Reclamation 2019), expand knowledge of physical drivers of snowfall events across Reclamation, and specifically address Upper Colorado Basin Region's research goal for improving understanding of snow processes in the headwaters of this basin.

TAGS: snow accumulation, snow melt, weather typing, large ensemble, machine learning.

BENEFITING REGIONS:
Missouri - Great Plains
Lower Colorado
Upper Colorado
California – Great Basin
Columbia - Pacific Northwest
Denver Office

FIELD-BASED RESEARCH LOCATION (100 Characters): This research will focus on four river basins of interest across the western US.

PROJECT TYPE: Conducting project

CONDUCTING TYPE: Development
Choose either: Applied Research, Development, Demonstration and Technology Transfer, or N/A if Scoping.

TECHNOLOGY READINESS LEVEL:
TRL 3

TECHNOLOGY TRANSFER AND INTELLECTUAL PROPERTY:
We do not anticipate needing technology transfer or intellectual property agreements.

RESEARCH AREA/CATEGORY/NEED: (5 Points, 500 characters)
In October 2019, we received FY-2020 funding for S&T scoping proposal ID 20082, "Assessing the impact of physically realized hydroclimate extremes on water supply". A reviewer recommended that we explore S&T Project 1782 (Reclamation 2019), which utilized a weather-typing algorithm to understand relationships between precipitation in the Rio Grande Basin and synoptic weather types. Conversations with Ken Nowak led us to consider applying the same algorithm to understanding snowfall across the West, largely because snowmelt is responsible for up to 70% of annual total runoff (Li et al. 2017). Therefore, this scoping report and the proposed conducting project emphasize this weather-typing approach to snowfall and snowpack accumulation.

PRIZE COMPETITIONS: (500 characters) No

SECURITY:
This proposal does not contain security sensitive information as defined by SLE 02-01 (https://www.usbr.gov/recman/sle/sle02-01.pdf).

REGIONAL DIRECTOR NEED (500 characters): (5 Points)
This project directly addresses the FY-2020 Upper Colorado Basin Region Regional Director need for improved seasonal streamflow forecasting in the Upper Rio Grande Basin. We will characterize weather types associated with snowfall events in the headwaters of the San Juan River, which provides the drinking water supply to the Rio Grande valley via the San Juan-Chama Project. We have coordinated with Dagmar Llewellyn, from the Albuquerque Area Office to ensure applicability of results to this issue in this region.

2. Research Strategy – Task Description

NEED:
Water managers need new and improved tools and methods for understanding variability and trends in streamflow, both to protect against flooding and to provide reliable water supply, particularly in a changing climate. Weather types are shown to be an effective way to characterize the large-scale atmospheric conditions that drive precipitation variability and trends. They allow for modeling of the characteristics of precipitation events, such as the frequency and magnitude, which are of interest to water managers. Algorithms that characterize weather types have been shown useful in the Rio Grande basin for characterizing monsoon precipitation events (S&T Project 1782) and are currently being used to inform prediction of these events (S&T Project 20032). In this project, we seek answers to fundamental research questions related to snow across the western US, such as whether we can characterize large-scale conditions (i.e. weather types) that are associated with large snowfall events; how long these weather types may persist; whether they are affected by large-scale modes of variability (e.g., the El Nino Southern Oscillation [ENSO] Index), and how they might change over time. By understanding the synoptic drivers of snowpack in the western US, we can demonstrate the value of this approach in providing physical context for critical variables of interest

to Reclamation, beyond monsoon precipitation in the Southwest. For example, in the Klamath River basin, which is one of many overallocated watersheds in the western US, large-scale modes of water-supply variability are not highly correlated with precipitation because the basin resides outside of the regions where correlations are significant. A catalog of historical snowfall drivers may provide new and useful information for providing irrigators with a reliable estimate of seasonal water supply, particularly in regions where snowpack comprises a substantial portion of that supply. Future studies could expand on this fundamental research to develop a framework for using weather typing to inform seasonal or even short-term streamflow forecasting.

BENEFIT:
This project represents an opportunity to bring to Reclamation a peer-reviewed scientific approach for characterizing weather types. This approach has been used to understand monsoonal precipitation in the southwestern US and a current S&T project is assisting in the use of weather typing in a predictive capacity for water management in the Rio Grande Basin. This approach is also being applied in Arizona through funding from Reclamation's Lower Colorado Region. The technical analysis has so far been performed by NCAR with Reclamation collaboration and financial support. Through this project, Reclamation has the unique opportunity to transfer this approach to our agency with in-kind support by Andreas Prein to characterize snowpack, both retrospectively using available historical data products and into the future using the CESM LE. This project will provide valuable understanding of variability, trends, and predictability of snowfall and associated snowpack accumulation. Perhaps more importantly, this project will provide each Reclamation region with a catalog of historical snowfall drivers associated with historical and projected future snowfall events. These catalogs will benefit the regions because they will be used to 1) understand synoptic-scale atmospheric drivers of historical snowfall events specific to their basin (i.e. identify weather types), 2) demonstrate how variability in weather types affects snowpack and streamflow, 3) improve weather and streamflow forecasts using knowledge of the synoptic weather drivers of snowfall events, and 4) identify future water planning applications in regions that are sensitive to snowfall.

URGENCY:
The objectives and deliverables of this work directly address multiple gaps outlined in the user needs document "Addressing Climate Change in Long-Term Water Resources Planning and Management", a document developed jointly by the US Army Corps of Engineers and Reclamation (Brekke et al. 2011). This work supports gap 3.01 (pg. 46), which is focused on understanding observed climate variability at a daily time scale to aid in the interpretation of projected future variability and its relation to water planning. The catalog of historical snowfall drivers will help enhance our understanding of the magnitude and variability of large snowfall events in the context of water management. This work also represents a major step toward addressing gap 3.06 (pg. 46), which articulates a need for new/improved methods for estimating extreme meteorological events. This methodology will allow us to document frequencies of weather types conducive to snowfall events across the western US under historical or future conditions. Future applications of this approach (not part of this project) may help us understand frequencies of extreme precipitation events of various duration, as well as any other extreme hydrometeorological variables of interest to Reclamation and water supply managers. The proposed work will make major strides toward addressing these two gaps in Reclamation's understanding of drivers affecting water supply in the Western US.

The timeline for needs outlined in Brekke et al. (2011) was listed as 5+ years. The current proposal, if funded, would begin in FY2023, more than 10 years after the initial gaps in Brekke et al. (2011) were identified and more than 5 years beyond the listed needs being met. The proposed work directly addresses two gaps identified in Brekke et al. (2011) that still exist and need to be further addressed.

PREVIOUS WORK:

Describe any previous work completed that relates to this project. This can help provide context on how this project will build on past projects to continue study on remaining research questions. Providing a note whether the work is related to a previous S&T project, other Reclamation work, or non-Reclamation work is helpful information to provide. List citations if possible.

The proposed project will leverage three known S&T projects. The first relevant S&T project (ID 1782) was led by Dagmar Llewellyn, in Reclamation's Albuquerque Area Office. This project represents the cornerstone of the proposed work. During S&T Project 1782, Dagmar partnered with two researchers from NCAR to understand dominant weather patterns associated with North American Monsoon precipitation in the Upper Rio Grande Basin. The researchers identified distinct atmospheric circulation patterns (i.e. weather types) associated with local precipitation and then used a statistical model to describe the frequency and magnitude of extreme precipitation events, how they vary with weather type, and how they may change in the future. Dagmar and the NCAR researchers submitted a follow-up proposal to the S&T Program, which was funded (S&T Project 20032), to understand if weather types can be used to forecast monsoon precipitation on seasonal to decadal timescales. These funded S&T projects rely on the approach of Prein and Mearns (2020). The proposed project builds on these efforts by continuing collaborating with Andreas Prein to support Reclamation in expanding the application potential of this algorithm to alternative variables relevant to water resources in the western US. Finally, the proposed project builds on an S&T scoping proposal (ID 20082) led by Marketa McGuire that was focused on developing a detailed collaborative experiment to advance our understanding of the intersection between hydroclimate events and water management of Reclamation's reservoirs. This scoping project also sought to investigate atmospheric/climate drivers of hydrologic and land surface processes relevant to water resources management. The proposed project builds on these three S&T projects.

Please see the "Other Comments" section for a full list of proposal citations.

RESEARCH QUESTION (5 points):

During this project, we will answer two main questions using the weather typing algorithm.

(1) Under what weather conditions (i.e., weather types) has snowpack accumulation historically occurred across the Reclamation basins of interest, particularly those that result in substantial runoff generation, and how have these patterns varied throughout the historical record?

We hypothesize that the synoptic weather conditions conducive to large snowfall events and associated snowpack accumulation include various forms of low-pressure systems, similar to Perry et al. (2010). We also expect primary snowfall drivers to vary as a function of geographic region. For example, we expect atmospheric rivers to play a larger role in snowfall events in the Klamath River basin region compared to the Sun River basin.

(2) How well does the CESM LE capture these important weather types and how are they projected to change in the future?

We hypothesize that that the CESM LE can simulate synoptic weather types associated with historical large snowfall events across the four Reclamation basins of interest. This hypothesis is supported by previous research demonstrating that global climate models are better able to reproduce large-scale features of the atmosphere-ocean system (e.g., low pressure systems, fronts) than small-scale processes that result in precipitation (McGinnis 1994). Furthermore, Prein et al. (2019) showed that the CESM LE was able to reproduce the weather types associated with historical precipitation across the continental US.

In answering these Research Questions, we hope to gain an understanding of the synoptic conditions (i.e., weather types) that are conducive to historical large snowfall events across basins of interest and to understand how those weather types may change in the future. We, as Reclamation staff, also hope to gain a familiarity with the approaches of Reclamation (2019) and Prein and Mearns (2020) in order to increase technical capacity within Reclamation. Developing this capability within Reclamation will allow for future applications of this methodology to Reclamation projects at a lower overall cost (i.e., we won't need to contract out this work).

RESEARCH METHODOLOGY (6 points):
This project will involve technical transfer of the approach of Prein and Mearns (2020) from the original NCAR authors to the Reclamation team. The weather-typing algorithm will allow the project team to develop daily weather types using any number of predictor variables, such as sea-level pressure, precipitable water, and 700 hectopascal (hPa) wind speeds. We surmise that multiple predictor variables will be useful when trying to characterize weather conditions conducive to large snowfall events, particularly in the western US, where relationships to large-scale atmospheric drivers vary (Hunter et al. 2006) and sea-level pressure does not necessarily represent surface conditions (due to elevation and topography). We will determine the set of variables with the highest predictive skill for snowfall events in each case-study basin. We will test the necessary extent of the modeling domain (i.e., basin-specific or west-wide) for weather typing, and we will determine how to identify large snowfall events (i.e., peaks over threshold, annual maximum, top 10% of events, all, etc.) based on the SNOTEL dataset. We will also test the sensitivity of weather types on to input variables.

After the modeling domain for each basin of interest has been determined, and the statistical approach selected, we will apply the optimized weather-typing algorithm to reanalysis data in order to understand the important weather types associated with historical snowfall events. This step will result in a catalog of historical weather conditions under which snowfall events have occurred across each of the identified case-study basins. This catalog will be crucial to regional applications of our results. We will characterize snowfall events by mapping each historical event to the corresponding weather type. We will focus on the number of distinct weather types, frequencies, intensities (amount of gain in snowpack), and transitions among snowfall events. We will be able to quantify the range of historical snowfall depths among each weather type, information that will be useful for future forecasting applications. All the information in the catalog will be shared with the regional partners identified as key persons.

After the analysis of historical snowfall events is complete, we will explore how the weather types associated with snowfall may change in the future. Rather than exploring output from a variety of global climate models, we will explore output from 40 ensemble members that contribute to the CESM LE. This large ensemble allows users to understand the possible range of uncertainty in future climate projections. We will focus on understanding whether the large ensemble simulates the weather types that are associated with historical snowfall events. Next, we will document how those weather types are projected to change among all ensemble members. This component of our analysis will allow us to understand changes in weather type characteristics, such as frequency, intensity, and transitional probabilities. This information will be extremely valuable to long-term water-resource planning studies in these regions.

Project results will be shared on a regular basis with regional Reclamation partners and our NCAR partners. Results will be shared with the broader reservoir operations group via a presentation during the annual Water Operations workshop, hosted by Reclamation's Water Resources and Planning Office. Results will also be shared with the broader scientific community during an annual conference (e.g., AGU or AMS) and a journal article submitted to an appropriate journal.

RESEARCH STRATEGY TASKS (6 points):

Task-0. Project management (2022 – 2024)
This task involves monitoring progress, milestones, and budget throughout the life of the project. This task also involves ensuring transfer of funds to partners in the AAO. Finally, this task includes time to respond to quarterly S&T reports.

Task-1. Coordination among partners (2022 – 2024)
This task involves scheduling update meetings with partners from each of the Reclamation basins of interest. It will also include updates to and coordination with external partners (NCAR, CU-Boulder) and other members of the TSC. Time spent on this task will assure that the project takes advantage of opportunities for technology transfer to Reclamation from our partners, and that it coordinates the applications so that they provide the most benefit to our regional partners.

Task-2. Peer review (2022 – 2024)
Peer review will take place over the course of this project, rather than as a single review of the final project report. Peer review will be performed by a selected team of reviewers from within and outside of Reclamation, including Representatives from the S&T Program. Peer review will include:

- Semi-annual (or more frequent) meetings between the identified reviewers and team members, to identify any problems or technical challenges, if they arise, as early as possible.
- Presentation and review of analysis methods and results.
- Review of all written materials generated under this project, including the final report.

Task-3. Literature review (2022 – 2022)
Team members will review previous studies that apply weather typing to understand extreme snowfall events across the west and other regions of the globe, as well as to understand other weather phenomena (such as monsoons). This review will help identify relevant predictor variables (e.g., sea-level pressure, 500 hPa geopotential height, precipitable water) to include in the weather typing algorithm. Additionally, this review will help team members understand methods for

identifying snowfall events, for example using snowfall water equivalent (Lute and Abatzoglou, 2015).

Task-4. Evaluate and run weather typing algorithm (2022 – 2022)
Task 4 includes technology transfer of the Prein et al (2016) weather-typing algorithm and testing the algorithm on various spatial extents of the horizontal domain (e.g., West-wide or basin-specific). This task will include testing of methods for identifying snowfall events in the observational SNOTEL dataset. Additional gridded datasets may be analyzed, such as SNODAS and possibly others. In this task, we will test the impact of snowfall definition on resulting weather types.

Task-5. Apply weather typing algorithm (2022 – 2023)
Under Task 5, we will apply the weather-typing algorithm to historical reanalysis data using information from the literature review. We will explore resulting event types, event frequencies, event intensities, and ways of characterizing historical events.

Task-6. Map conditions from the large ensemble (2022 – 2023)
In Task 6, we will determine how well the weather types identified within reanalysis data and historical snowfall events of interest to Reclamation are represented among members of the CESM large ensemble. We will start by focusing on historical simulations from the CESM large ensemble. We will utilize a regression analysis technique such as canonical correlation analysis (or something analogous) to identify simulated weather types that correspond to historical weather types from reanalysis data. Next, we will determine the frequency and intensity of the historical weather types during the historical period from the CESM large ensemble. Then, we will explore changes over time in the frequency, intensity, and transitional probabilities among the relevant weather types as simulated under future conditions.

Task-7. Communication platforms (2023 – 2024)
In Task 7, we will develop presentation content, including:

- a presentation for a major geophysical or meteorological conference, such as the annual American Geophysical Union meeting or the annual American Meteorological Society meeting.
- a presentation for the monthly Water Operations and Planning webinar hosted by the Research and Development Office (Ken Nowak).
- a presentation for Reclamation's Water Operations workshop hosted by the Water Resources and Planning Office.
- an article for submission to a peer-reviewed journal.

Task-8. Project closeout (2024 – 2024)
Task 8 will involve fulfilment of all project closeout requirements set forth by the S&T Program and the TSC, including a final project report that complies with the S&T Programs template, and a bulletin summarizing the importance of the project, and its methods and results.. We will engage the help of a technical writer to ensure these documents are compliant with Reclamation Visual Identity (VI) and Section 508. We will follow all open-data requirements and format the historical reanalysis datasets for inclusion in the Reclamation Information Sharing Environment (RISE) system.

3. Research Strategy – Key Persons

KEY PERSONS (10 Points):

Table 1. Summary of Key Persons.

Last Name	First Name	Tasks	Responsibilities	Expertise
Holman	Kathleen	0, 3, 4, 5, 6, 7, 8	Manage project, review previous applications of weather typing to understand snowfall events, lead application of Prein et al (2016) algorithm (testing and results), communicate with technical partner from NCAR (A. Prein), develop historical and future catalogs of weather types conducive to snowfall events across the Reclamation regions, communicate with broader TSC	Katie has more than 13 years of experience analyzing reanalysis data and climate model output (regional and global) for water resources applications. She has research and publication experience identifying relationships between large-scale atmospheric processes and regional hydrology (e.g., precipitation, evaporation, moisture fluxes, lake levels, etc). She is an expert coder in R, NCL, bash, and Matlab. In addition, she has formal coding training in Python. She also has over four years of experience managing large ($200K+) research projects
McGuire	Marketa	1, 3, 4, 5, 6, 7, 8	Review previous literature on weather typing, apply Python algorithm to historical reanalysis data and future climate projections, interact with internal and external partners, lead meetings with Reclamation area office team members, share historical and future weather catalogs,	Marketa has 20 years of experience in hydrology and water management, with 12 years of experience specifically with climate change assessments. Marketa has years of coding experience in C, Fortran and R. She has more than 9 years of experience organizing, leading, and managing research projects funded through the S&T Program.

Subhren du	Gangopadh yay	2, 7, 8	TSC peer reviewer, interact with Reclamation team members, review project results, presentations, catalog details	Subhrendu has more than 20 years of professional experience includes water resources planning and management, stochastic hydrology, applied statistics, hydroclimatology, numerical modeling in hydrology (surface and ground water), scientific computing, research and development, project management, operations management, teaching, and consulting.
Dagmar	Llewellyn	1, 3, 5, 6, 7,8	Provide experience and insights from previous applications of Prein's weather-typing methodology; assist with literature review; serve as local contact for case study on the San Juan basin; assist with presentation of results and project close-out.	Dagmar has 35 years of experience working in the water resources management community, including more than 10 years at Reclamation. Dagmar has and continues to work with Andreas Prein from NCAR to understand weather types associated with the North American Monsoon and how these weather types can be used within a forecasting framework. Dagmar also has familiarity with headwater conditions and water operations in the San Juan Basin, especially related to Reclamation's San Juan-Chama Project.
Jason	Cameron	1, 5, 6, 7		
Susan	Behery	1, 5, 6, 7		
Stephani e	Micek	1, 5, 6, 7		
Scott	Fennema	1, 5, 6, 7		

Andreas	Prein	4, 5, 6	Andreas will act as a technical specialist with the weather-typing algorithm. He will provide an overview of the Python algorithm and review methods and results from each regional study to ensure technical validity and integrity.	Andreas is a Project Scientist II working in NCAR's Capacity Center for Climate & Weather Extremes in the Mesoscale & Microscale Meteorology Lab. Andreas has over 15 years of experience in weather typing and applying weather typing to water resource questions. Andreas has worked with Reclamation in support of previous S&T funded studies and has a unique combination of technical skills that can help the proposed team and project.

4. Proposal Budget Detail

BUDGET (10 points):

Table 2. Summary of Budget by Fiscal Year.

Fiscal Year	Total Budget
2021	$84,560.00
2022	$87,060.00
2023	$98,276.00
Total	$269,896.00

Table 3. Budget Breakdown by Fiscal Year.

Fiscal Year	Office	Labor	Travel	Contracts	Contract Type	Non-Labor	Total
2021	Denver	$78,520	$0.00	$0.00		$0.00	$78,520
2021	AAO	$6,040	$0.00	$0.00		$0.00	$6,040
2022	Denver	$78,520	$2,500				$81,020
2022	AAO	$6,040	$0.00	$0.00		$0.00	$6,040
2023	Denver	$83,696	$2,500				$86,196
2023	AAO	$12,080					$12,080
Total		$264,896	$5,000				$269,896

AAO: Albuquerque Area Office

5. Partnerships

PARTNERSHIPS (15 Points):

Table 4. Summary of Partner Budget.

Fiscal Year	Reclamation	Federal Government	Non Federal Government

2021	$8,000	$0.00	$12,000
2022	$8,000	$0.00	$6,000
2023	$8,000	$0.00	$8,000
Total	$24,000	$0.00	$26,000

Table 5. Summary of Fiscal Year 2021 Partnerships.

2021					
Partner Name	**E-Mail**	**Organization Type**	**Description**	**Contribution Type**	**Amount**
Susan Novak Behery	sbehery@usbr.gov	BOR	Participate in progress discussions	In Kind - Firm	$2,000.00
Scott J. Fennema	sfennema@usbr.go·	BOR	Participate in progress discussions	In Kind - Firm	$2,000.00
Jason M. Cameron	jcameron@usbr.gov	BOR	Participate in progress discussions	In Kind - Firm	$2,000.00
Stephanie R. Micek	smicek@usbr.gov	BOR	Participate in progress discussions	In Kind - Firm	$2,000.00
Andreas Prein	prein@ucar.edu	Non Federal Government	- Provide access to the weather typing algorithm from Reclamation (2019) and Prein and Mearns (2020) - Provide technical support specific to weather typing algorithm	In Kind - Firm	$12,000.00
Jennifer Kay	jennifer.e.kay@colo	Non Federal Government	N/A	In Kind - Firm	$0.00
				Total For Fiscal Year:	$20,000.00

Table 6. Summary of Fiscal Year 2022 Partnerships.

2022					
Partner Name	**E-Mail**	**Organization Type**	**Description**	**Contribution Type**	**Amount**
Susan Novak Behery	sbehery@usbr.gov	BOR	Discuss results from historical analyses	In Kind - Firm	$2,000.00
Scott J. Fennema	sfennema@usbr.go·	BOR	Discuss results from historical analyses	In Kind - Firm	$2,000.00
Jason M. Cameron	jcameron@usbr.gov	BOR	Discuss results from historical analyses	In Kind - Firm	$2,000.00
Stephanie R. Micek	smicek@usbr.gov	BOR	Discuss results from historical analyses	In Kind - Firm	$2,000.00
Andreas Prein	prein@ucar.edu	Non Federal Government	- Provide technical support specific to weather typing algorithm - Provide technical feedback related to methodological questions	In Kind - Firm	$4,000.00
Jennifer Kay	jennifer.e.kay@colo	Non Federal Government	- Provide general feedback on large ensemble results	In Kind - Firm	$2,000.00
				Total For Fiscal Year:	$14,000.00

Table 7. Summary of Fiscal Year 2023 Partnerships.

2023					
Partner Name	**E-Mail**	**Organization Type**	**Description**	**Contribution Type**	**Amount**
Susan Novak Behery	sbehery@usbr.gov	BOR	Discuss results from CESM LE, develop future directions	In Kind - Firm	$2,000.00
Scott J. Fennema	sfennema@usbr.gov	BOR	Discuss results from CESM LE, develop future directions	In Kind - Firm	$2,000.00
Jason M. Cameron	jcameron@usbr.gov	BOR	Discuss results from CESM LE, develop future directions	In Kind - Firm	$2,000.00
Stephanie R. Micek	smicek@usbr.gov	BOR	Discuss results from CESM LE, develop future directions	In Kind - Firm	$2,000.00
Andreas Prein	prein@ucar.edu	Non Federal Government	- Provide technical support specific to weather typing algorithm - Provide technical feedback related to methodological questions	In Kind - Firm	$4,000.00
Jennifer Kay	jennifer.e.kay@colo	Non Federal Government	- Provide general feedback on large ensemble results - Help develop ideas for future CU-Boulder/ Reclamation partnership involving a student	In Kind - Firm	$4,000.00
				Total For Fiscal Year:	$16,000.00

6. Proposal Details

QUALITY CONTROL:

In order to produce high quality data and results, we have chosen to partner with people who are experts in the major themes of this proposal. For example, we will work closely with Andreas Prein to ensure proper application and interpretation of results from the weather typing algorithm. We will also work with Dagmar Llewellyn, who understands water resources concerns within the Rio Grande Basin and who has worked with results from the weather typing algorithm in the past. We have also received firm commitment of help from Professor Jen Kay. Professor Kay has worked extensively with NCAR's CESM and the CESM large ensemble. Professor Kay will provide technical feedback on the application and interpretation of ensemble results. In addition, we will meet regularly with the peer reviewer within the Technical Service Center. We will also meet regularly with partners in the area offices to ensure that results are meaningful, transferrable, and to generate ideas for future applications of weather typing results to water resources management within Reclamation headwater regions.

RISK MANAGEMENT:

The largest risk to this project is successfully running the weather typing algorithm on a local machine at Reclamation. Andreas Prein recently translated the weather typing algorithm from Fortran to Python, so we will be mimicking his Python environment. If we encounter any issues transferring this software to a local machine, we will work with Andreas and other Reclamation group members from the Water Resources Engineering and Management group who are proficient with Python.

OTHER COMMENTS:

References:

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7. Communicating Results

COMMUNICATION PLAN (5 points):
Results from the proposed project will be communicated to people within and outside of Reclamation. First, we plan on engaging regularly with team members from each of the identified regions and with folks from the Water Resources Engineering and Management group in the TSC. We will disseminate results via the standard deliverables, including a final report and bulletin. We will share the historical and future weather type catalogs with each regional key member via Kiteworks, OneDrive, or some other platform that supports large datasets. We also plan on preparing a presentation for three different venues (with differing audiences), including the S-&T webinar series, a major geophysical conference (e.g., AGU or AMS), and Reclamation's annual reservoir operators' workshop. Finally, we will prepare an article for submission to a relevant journal, such as the *Journal of Hydrometeorology* or *Journal of Geophysical Research: Atmospheres*. We have included staff days in our overall budget to ensure this communication plan is supported by project funds.

OPTIONAL DELIVERABLES:
Journal article
Conference
Powerpoint Presentation
Software
Workshop

TALKING POINTS - BOTTOM LINE:
Weather typing is a machine learning algorithm to quantitatively categorize daily atmospheric conditions. We are going to utilize weather typing to better understand historical and future variability in snowfall events across four Reclamation regions.

TALKING POINTS - BETTER, FASTER, CHEAPER (280-500 Characters):
Streamflow is impacted by snow, and snow is impacted the state of the atmosphere.

8. Implementation of Results

Results Implementation: (6 points) How is this going to get used

APPLICATION POTENTIAL:
Previous applications of weather typing have characterized precipitation associated with the North American Monsoon, suggesting that this approach may also be useful for improving our understanding of snowfall events. Additional weather typing applications beyond those outlined in the current proposal may benefit different needs within Reclamation as well. For example, members of the Technical Service Center develop basin-specific precipitation-frequency estimates across all of Reclamation. These studies typically assume that all precipitation events included in the analysis are the result of the same type of atmospheric forcing (e.g., thunderstorm, tropical cyclone, extratropical cyclone, etc.). However, these studies never actually prove the assumption of homogeneity. The weather typing algorithm could be used to develop homogeneous populations of precipitation events based on synoptic conditions for use in precipitation-frequency analyses. The proposed project will bring an advanced, machine-learning algorithm to Reclamation that can easily be adjusted.

Another future application of weather typing relates to reservoir evaporation. Previous research on Lake Superior, the large of the Great Lakes by surface area and volume, indicates that during stable atmospheric conditions, most evaporation occurs during short-term events (Spence et al. 2012). These events are typically on the order of three days long and correspond to moving air masses. Weather typing could be used to understand synoptic scale drivers of reservoir evaporation across the western US. Increasing the diversity of methods used to understand reservoir evaporation, under historical and future atmospheric conditions, can only help Reclamation prepare for future changes, whether positive or negative.

APPLICATION DESCRIPTION:

In the headwaters of major Reclamation basins, seasonal snowpack is the predominant driver of runoff. The primary deliverable from this project will include a catalog of weather types associated with historical heavy snowfall events across each of the four Reclamation regions of interest. The second important deliverable will include projections of how these weather types may change (e.g., intensity, frequency, transitional probabilities, etc.) under future climate conditions simulated by the CESM large ensemble. These catalogs can be used by water managers in each region to 1) understand synoptic-scale atmospheric drivers of heavy snowfall events particular to their basin, 2) explain historical snowfall and streamflow variability beyond the perspective of annual precipitation, 3) improve streamflow forecasts at various timescales using knowledge of the synoptic weather drivers of snowfall events, and 4) generate ideas for long-term future water planning applications in regions that are sensitive to snowfall. The project team includes key individuals (providing in-kind support) from each Reclamation region of interest in order to facilitate knowledge sharing, increase application opportunities during and after the proposed project completion date, and further explore region-specific issues that may benefit from weather typing.

FACILITATED ADOPTION:
If research finds that major snowfall events are associated with certain synoptic weather types, then this information may be incorporated into seasonal streamflow forecasting to enhance predictability and thereby provide an improved understanding of the uncertainty bounds of a forecast. It is conceivable that this information could be ingested into software such as the existing PyForecast software developed by Reclamation's Missouri Basin Region as an additional predictor variable. Alternatively, we will explore how this information may be linked to other types of seasonal streamflow forecast products used by Reclamation.

This information may also help to reduce the number of plausible seasonal streamflow forecast scenarios in the sense that current the weather type at the start of a forecast period may robustly indicate wetter than normal (or drier than normal) conditions throughout the forecast period, so corresponding forecast ensembles may be weighted more heavily. In a short-term forecasting sense, immediate operational decisions may change based on knowledge that the current weather pattern is significantly correlated with large snowfall events, for example.

IMPACT DESCRIPTION:
This research project may result in improved streamflow forecasting capability, which in turn would result in Reclamation's improved ability to deliver water to its end users. Improved forecasting ability will also allow Reclamation to modify operational decisions to make more efficient use of water supply for various other uses including fish and wildlife habitat, recreation, and hydropower. Understanding the improved skill of streamflow forecasts is a critical step towards improving Reclamation's ability to fulfill its mission across the western US.