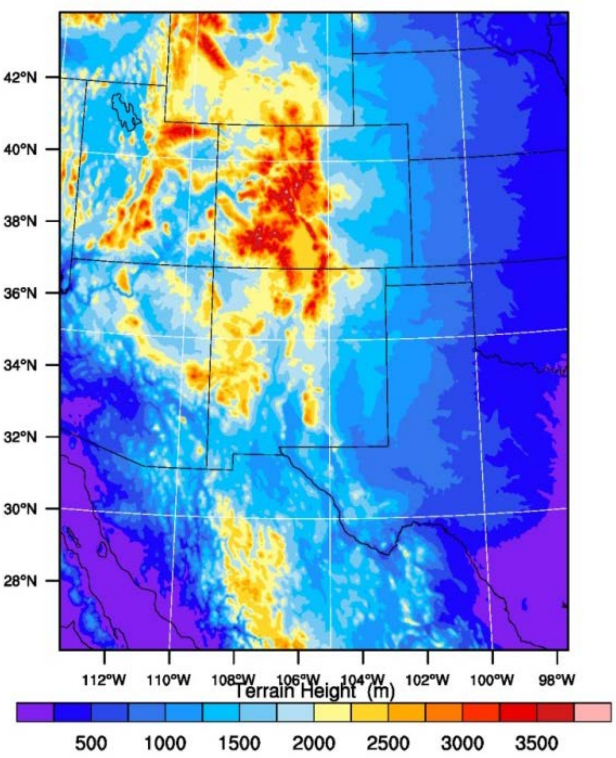
RECLAMATION

*Managing Water in the West*

## Technical Memorandum 8250-2016-004

# Application Potential for Work Processes in the Flood Hydrology and Meteorology Group




U.S. Department of the Interior
Bureau of Reclamation

July 2016

## Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

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.

# Application Potential in Flood Hydrology and Meteorology Group Work Processes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# Executive Summary

The Bureau of Reclamation's Research and Development Office established two projects (under Cooperative Agreement R11AC81334) between Reclamation and the National Oceanic and Atmospheric Administration and the University of Colorado-Boulder's Cooperative Institute for Research in Environmental Sciences for the purpose of developing advanced datasets and tools for use by Reclamation's Flood Hydrology and Meteorology Group. The first project explored the use of a high-resolution dynamical weather model, the Weather Research and Forecasting model, to simulate heavy precipitation events in the Taylor Park Dam watershed in a robust and representative manner. Small-scale physical processes that generate extreme precipitation were simulated under various atmospheric conditions by utilizing a modeling framework that simulates intense precipitation systems at cloud-scale resolution with an ensemble-based framework. The purpose of the second project was to improve understanding of the processes responsible for heavy precipitation events, including atmospheric rivers (ARs), in the intermountain west.

This report includes a brief review of those projects, along with a discussion of potential applications of the tools and methods developed under them into the workflow of the Flood Hydrology and Meteorology Group, including current and future projects. Currently, datasets and tools developed under the two projects are being used in four Reclamation Dam Safety Office studies, including a hydrologic hazard analysis at Taylor Park Dam in Colorado and a hydrologic hazard analysis at Grand Coulee Dam in Washington. Future applications of the tools and methods may be accomplished through hydrologic hazard analyses or alternative research projects.

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# 1 Introduction

## 1.1 Background and Motivation

In 2013, the Bureau of Reclamation's (Reclamation) Research and Development Office (RDO) established two projects (under Cooperative Agreement R11AC81334) between Reclamation and the National Oceanic and Atmospheric Administration (NOAA) and the University of Colorado-Boulder's Cooperative Institute for Research in Environmental Sciences (CIRES) for the purpose of developing advanced tools for use by Reclamation's Flood Hydrology and Meteorology Group (FHMG). The first project focused on improving estimation of extreme precipitation events using a high resolution numerical model, while the second project focused on diagnosing moisture sources of heavy precipitation events in the intermountain west.

This report represents a discussion of potential applications of the tools and methods developed under those two projects into the workflow of the FHMG, including current and future projects. The remainder of this section includes a review of current work processes used in the FHMG. Section 2 provides a review of the projects and associated deliverables. Current and future applications to Reclamation projects are discussed in section 3. Finally, a summary is provided in section 4.

## 1.2 Flood Hydrology and Meteorology Group

The FHMG is housed in Reclamation's Technical Service Center and completes technical investigations, reviews, and related work in flood hydrology, hydrometeorology, and meteorology. Team members provide expertise on the hydrologic components of Reclamation's Dam Safety Program, including quantifying hydrologic loads (Figure 1.1) for probabilistic risk analyses at facilities located across the western US.

The most common type of study completed by the FHMG is referred to as a Hydrologic Hazard Analysis (HHA). The purpose of HHAs, which vary in duration and complexity, is to estimate the probability of hydrologic loads on a facility. Examples of hydrologic loads include high reservoir water surface elevation, and dam overtopping. There are four different levels of dam safety studies for which HHAs are produced, including Comprehensive Reviews (CRs), Issue Evaluations (IEs), Corrective Action Studies (CASs), and Final Design (FD). Screening-level studies are referred to as CRs and typically involve no more than 15 staff days. IEs and CASs represent higher-level studies compared to CRs and typically involve more than 200 staff days. While specific details and methods vary among and within HHA categories, each analysis includes a flood frequency analysis (e.g., Figure 1.1). Physically-based rainfall-runoff models are a common component of many different HHAs.

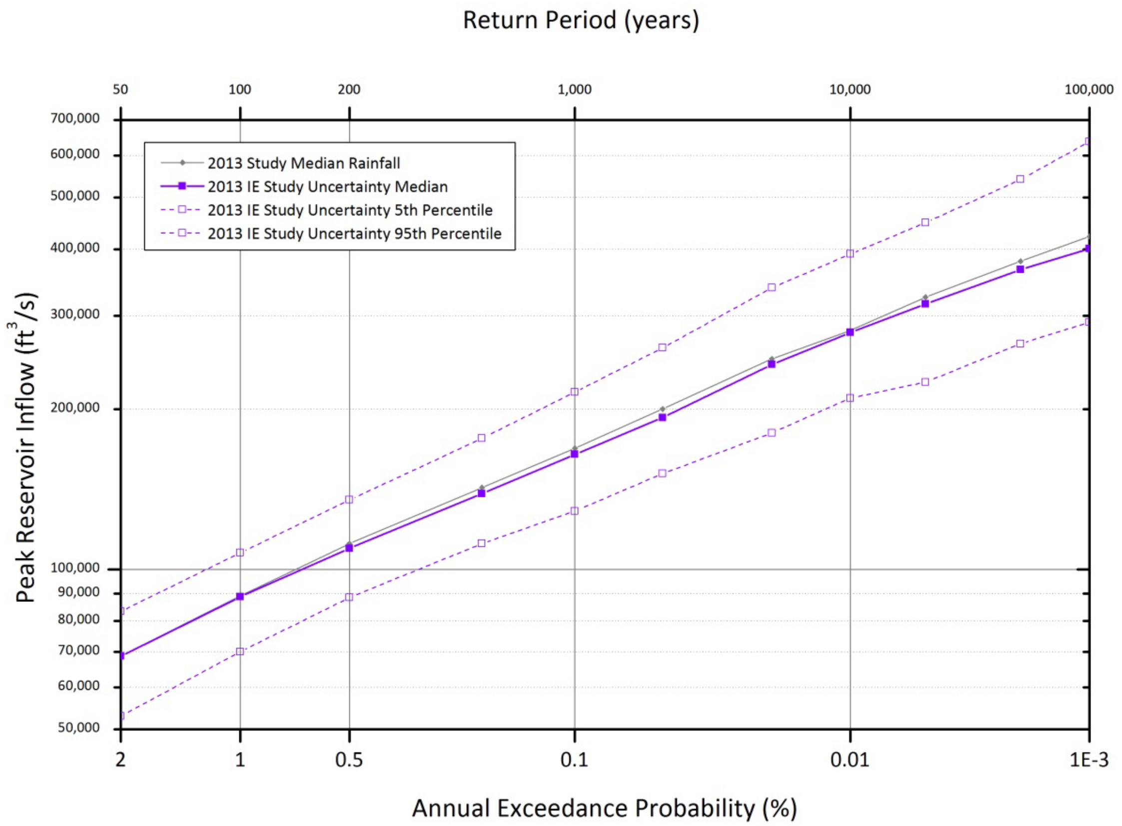


**Figure 1.1 - Example peak reservoir inflow-frequency relationship developed in an HHA (Novembre et al. 2015).**

Rainfall-runoff modeling approaches to estimate flood-frequency require a variety of meteorological inputs. Two of the most important meteorological inputs include storm patterns (both spatial and temporal) and a site-specific precipitation-frequency relationship, both of which are typically developed using historical point observations in and surrounding the watershed of interest. Storm patterns represent detailed information in space and time about precipitation totals for a specified duration (e.g., 72 hours) over a watershed. In the past, storm patterns were based on manually-generated design storms and/or spatial and temporal precipitation patterns available in Hydrometeorological Reports (HMRs). Figure 1.2 shows an example precipitation pattern developed in HMR 49 (1984).

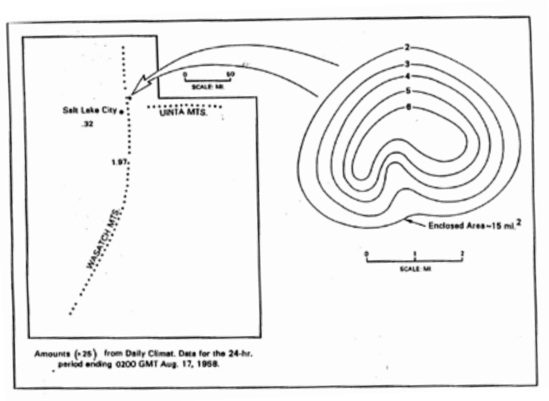


**Figure 1.2 - Isohyetal precipitation pattern based on a storm that occurred on August 16, 1958 at Morgan, Utah. Figure from HMR 49 (1984).**

Since the mid- to late-2000s, the FHMG has reduced the use of design storms and manually-developed isohyetal patterns such as the pattern shown in Figure 1.2. Instead, the group has transitioned to using a combination of point precipitation observations, various interpolation techniques, and gridded reanalysis datasets to create storm templates. Inverse Distance Weighting (IDW), a deterministic interpolation scheme that calculates values of a given variable at unknown points based on a weighted averaged of known points, is commonly used by the FHMG to estimate the spatial distribution of historical precipitation events based on point observations. Figure 1.3 shows an example spatial pattern of 72-hour total precipitation developed by applying the IDW scheme to point precipitation observations surrounding the Boise River Diversion Dam watershed in Idaho. In this case, the IDW technique produces well-known "hot spots" or "bull's eyes" around individual precipitation gauges, an artifact that is physically unrealistic (Vicente-Serrano et al. 2003; Nusret and Dug 2012).

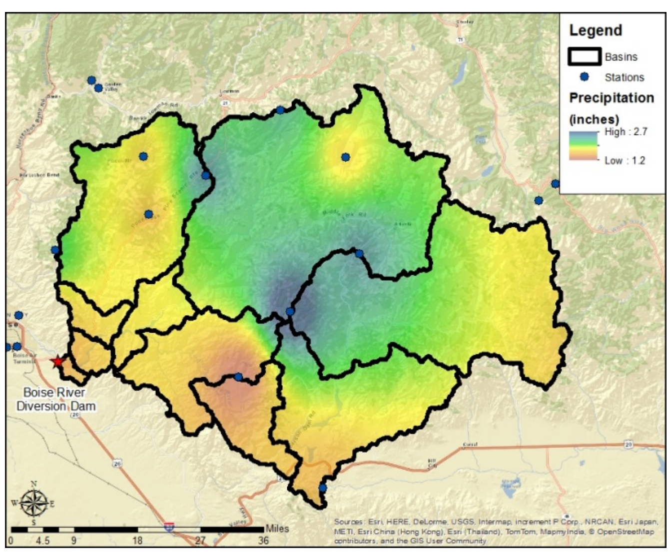


**Figure 1.3 - Seventy-two hour precipitation totals (inches) from April 25-28, 2012 based on applying the Inverse Distance Weighting technique to point observations in the Boise River Diversion Dam watershed (Keeney et al. 2015).**

Figure 1.4 shows an example of a 72-hour storm template used in a 2013 HHA for Friant Dam, located 25 miles northeast of Fresno, California (Wright et al. 2013). Precipitation totals were computed by applying isopercental analysis (Shaw et al. 2011; Micovic et al. 2015) to hourly and daily point precipitation observations surrounding the watershed. Isopercental analysis is a method used to spatially interpolate and distribute a variable that displays non-linear behavior. Isopercental analysis develops point-observation-specific relationships with a gridded precipitation field such as a map of 24-hour, 1/100 annual exceedance probability (AEP) precipitation totals. The precipitation totals in Figure 1.4 were created using a combination of point observations, Thiessen polygons (Thiessen 1911), gridded precipitation totals from the Parameter-Elevation Regression on Independent Slopes Model (PRISM), and inverse distance weighting. See Wright et al. (2013) for specifics on Figure 1.4 and Micovic et al. (2015) for a general review of the isopercental analysis procedure.

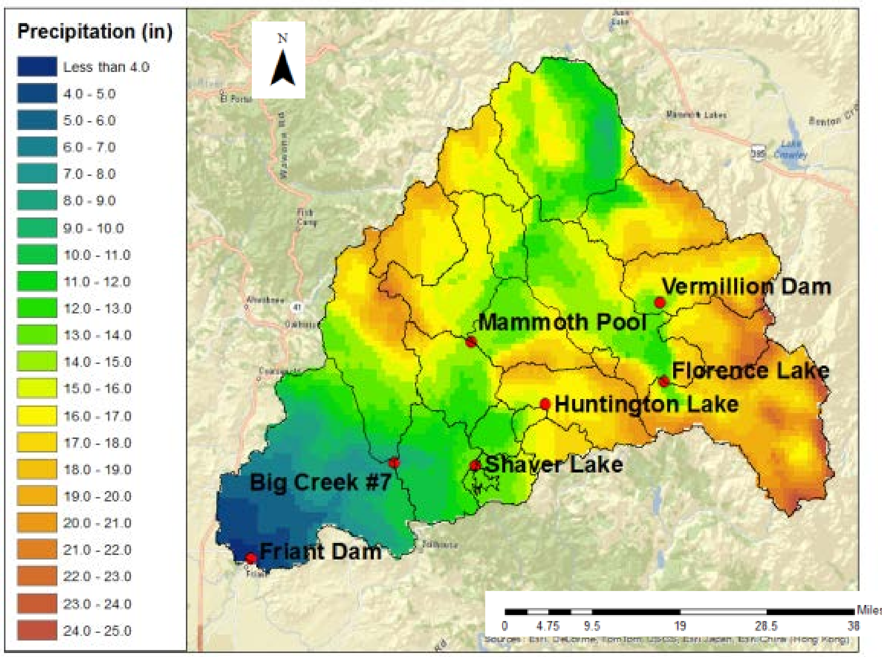


**Figure 1.4 - Seventy-two-hour precpitation totals (inches) used in a Hydrologic Hazard Analysis completed for Friant Dam (Wright et al. 2013).**

Although the spatial pattern of 72-hour precipitation totals in Figure 1.4 is not characterized by “hot spots” like Figure 1.3, there are still limitations in some methods applied during the isopercental analysis. For example, Thiessen polygons have been shown to perform poorly over rough terrain, as compared to more recent methods such as kriging and cokriging (Goovaerts 2000). There are also known issues with applying IDW to low-density precipitation networks in regions of complex terrain. Goovaerts (2000) showed that the mean square error between kriging-based monthly precipitation estimates and point observations can be up to half that based on IDW estimates.

Detailed information on the temporal distribution of precipitation during events of interest is also needed for rainfall-runoff modeling. The temporal distributions are often created using a variety of methods, depending on the region, year of event, and hydrologic modeling needs. Methods used can also vary within a study, depending on the available precipitation observations for each event of interest. Most often, hourly time series of precipitation are needed for use in rainfall-runoff models, yet hourly precipitation observations are lacking in many high-elevation regions (Daly et al. 1994). In cases where there are no hourly observations available, daily precipitation totals are disaggregated to the hourly distribution simulated by a reanalysis dataset, such as the Climate Forecast System-Reanalysis dataset (CFSR; Saha et al. 2010). Many reanalysis datasets have been designed to reanalyze historical observations using state-of-the-art modeling and data assimilation systems. CFSR is model-based reanalysis products (Silva et al. 2010) available at ~23.6 mile (~38 km) spatial resolution on an hourly time step from 1979-2013. Figure 1.5 shows an example of the location of CFSR grid cells (center of each grid cell) relative to the Lost Creek Dam watershed in Utah. Hourly precipitation totals at the basin centroid were estimated by applying IDW to the hourly precipitation totals from each of the four grid cells.

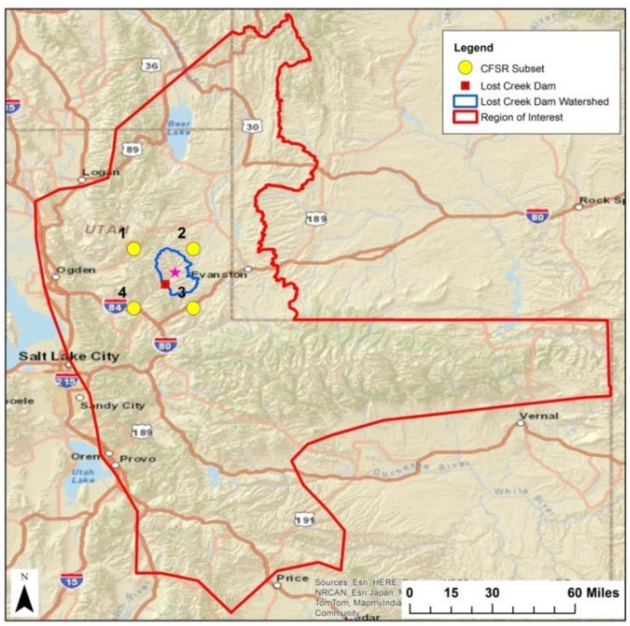


**Figure 1.5 - Location of four CFSR grid cells (yellow circles) surrounding the Lost Creek watershed (80 mi$^2$; blue outline). Figure from Holman et al. (2014).**

There are some issues with the methods used for hourly disaggregation. Most importantly, using more than one method to temporally disaggregate precipitation observations in a single study represents added uncertainty to the analysis. Although this is sometimes unavoidable, this additional source of uncertainty is never quantified. Because hourly precipitation observations are not always available in remote, high-elevation regions, additional techniques to produce consistent hourly precipitation information are needed.

The second important meteorological input needed for HHAs is a site-specific precipitation-frequency relationship. Basin-average precipitation totals from these statistical relationships are used (hundreds to hundreds of thousands of times) to scale historical precipitation events (in the form of storm templates) over the watershed of interest. Figure 1.6 shows multiple 48-hour precipitation-frequency relationships based on historical precipitation observations surrounding the Taylor Park Dam watershed, located in western-central Colorado. These precipitation-frequency relationships are based on a regional L-moments approach (Hosking and Wallis 1994; Brath et al. 2003; Bocchiola et al. 2006) from NOAA Atlas 14 (Perica et al. 2013) and a site-specific study performed by the FHMG. The regional L-moments approach is based on an assumption that one can exchange observations in space for observations in time.

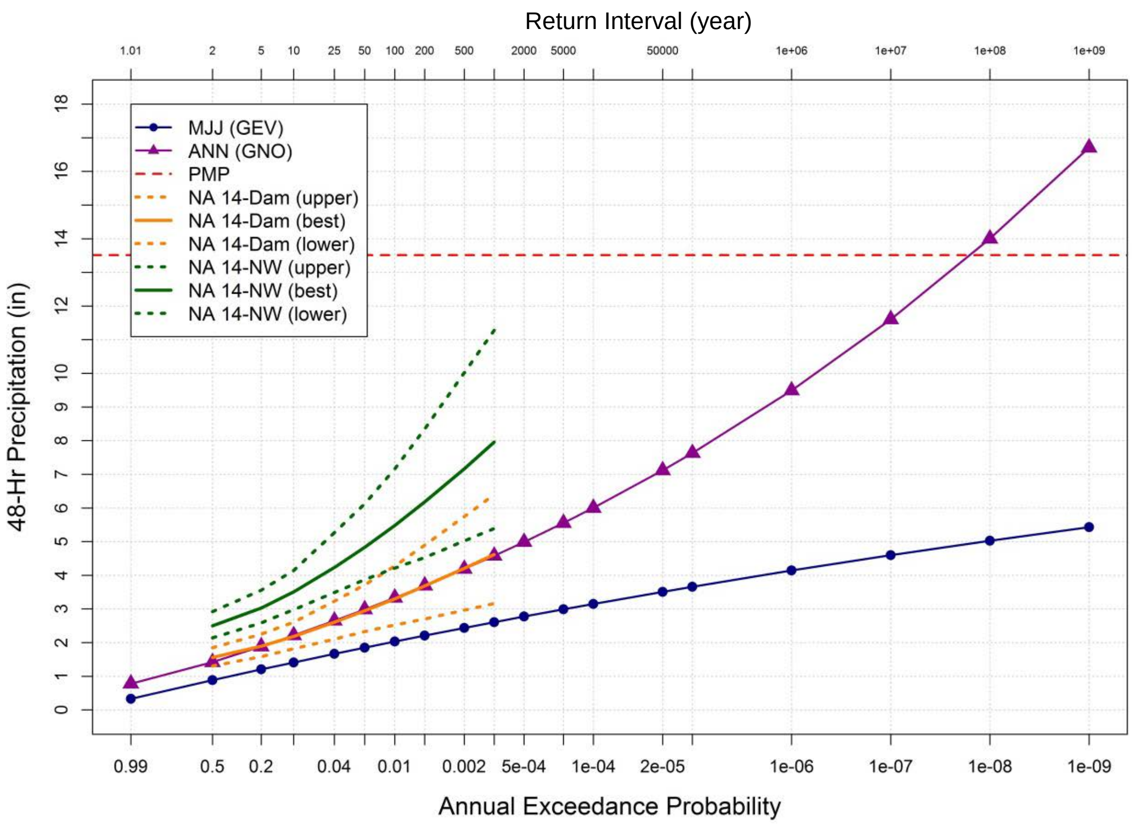


**Figure 1.6 - Basin-average 48-hour precipitation-frequency relationships for the Taylor Park Dam watershed based on annual maximum (purple, green, and gold lines) and seasonal maximum (MJJ; navy). The average May-June-July 48-hour PMP total is shown in red.**

## 1.3 Report Objectives

Acknowledging potential benefits to FHMG projects, the RDO established two collaborative projects between the FHMG and NOAA, CIRES, and NCAR. Both project work plans emphasized state-of-the-art methods, operational relevance to HHAs, communication among agencies, and research-to-operations transitions. The objective of this report is to discuss potential applications of tools and methods developed in the projects to current and future projects in the FHMG.

# 2 Overview of Projects

## 2.1 Improving Extreme Precipitation Estimation Using Regional, High-Resolution Model-Based Methods

This study explored the use of high-resolution dynamical weather models to simulate heavy precipitation events in the Taylor Park Dam watershed using a robust and representative manner. Small-scale physical processes that generate extreme precipitation and an envelope of uncertainty were simulated under various atmospheric conditions by utilizing a modeling framework that simulates intense precipitation systems at cloud-scale resolution with an "ensemble-based" framework. This project had two primary tasks, including

1) Produce high-resolution ensembles of model simulations to better estimate extreme precipitation events and the associated envelope of uncertainty (as compared with standard methods); and
2) Evaluate advantages of a distributed hydrology model to characterize extreme hydrometeorological events in dam safety decision-making.

The remainder of this section (section 2.1) reviews deliverables from this project. For additional details, see the final report, located in Appendix 1.

### 2.1.1 Produce High-Resolution Ensembles

The Weather Research and Forecast (WRF; Skamarock et al. 2007) model was used to simulate heavy precipitation events relevant to the Taylor Park Dam watershed. WRF is a state-of-the-art atmospheric modeling system that is used for both atmospheric research and operational forecasting purposes. WRF includes a fully compressible, non-hydrostatic model. WRF Version 3.6 was used for all the simulations completed in this study, with a horizontal resolution of 4 km and a vertical resolution of 54 levels. Figure 2.1 shows the extent of the simulated WRF domain.

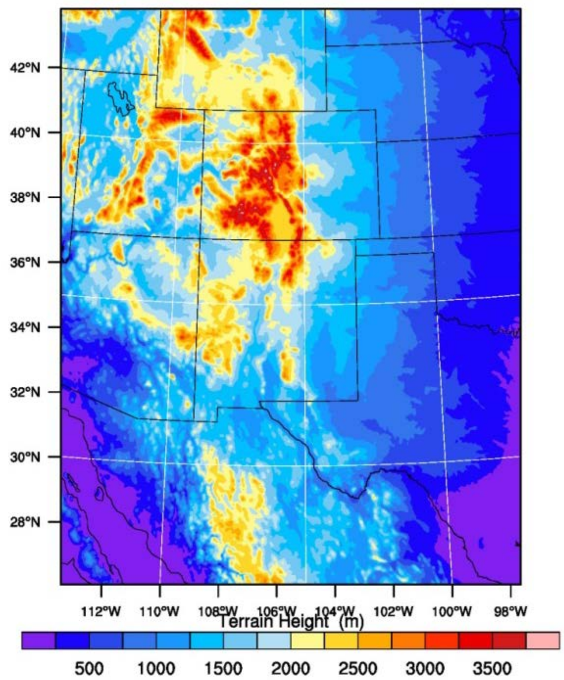


**Figure 2.1 - Terrain height (m) used in the WRF simulations based on a 4 km horizontal resolution.**

High-resolution WRF simulations were performed for each of the events listed in Table 2.1. Events were selected based on mutual interests of the FHMG and modeling team. The FHMG was interested in late-spring to summer precipitation events that were also characterized by relatively high inflows into Taylor Park reservoir. In an effort to estimate uncertainty in the spatial and temporal distribution of precipitation, ensembles consisting of 18 different members (including the control) were created for three of the seven precipitation events (indicated in Table 2.1).

**Table 2.1 - Details of historical precipitation events simulated using WRF and WRF-Hydro. Additional information is provided in section 2.1.2 and section 2.1.3.**

| Event | WRF Simulation Period | WRF Ensemble | Pseudo-Global Warming | WRF-Hydro |
|---|---|---|---|---|
| 1 | 6/17/1982 00–6/20/1982 00 UTC | | | |
| 2 | 6/05/1984 00–6/08/1984 00 UTC | | | |
| 3 | 5/25/1993 00–5/28/1993 00 UTC | | | |
| 4 | 6/16/1995 00–6/20/1995 00 UTC | X | | |
| 5 | 6/19/1996 00–6/22/1996 00 UTC | | | |
| 6 | 6/06/1997 00–6/09/1997 00 UTC | | | |
| 7 | 5/06/2000 00–5/09/2000 00 UTC | X | | X |
| 8 | 7/25/2014 00–7/28/2014 00 UTC | X | X | X |

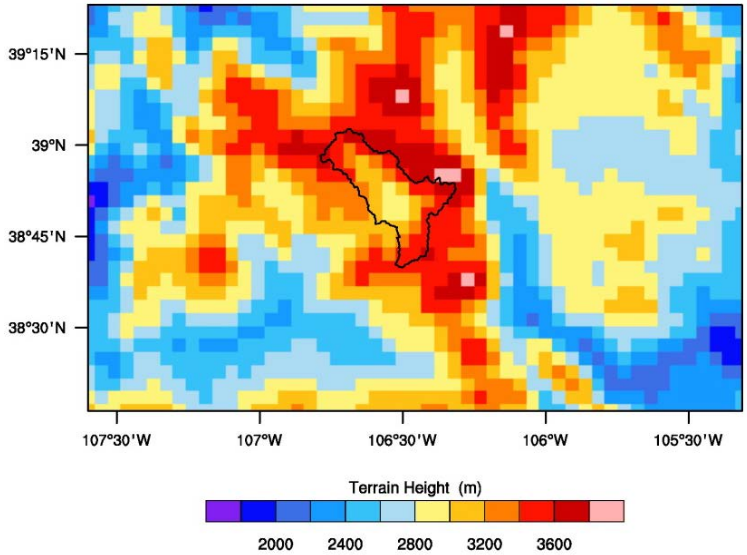


**Figure 2.2 - Terrain height (m) surrounding the Taylor Park Dam watershed based on the 4 km horizontal resolution used in the WRF simulations.**

High-resolution simulations are needed to understand how small-scale precipitation processes may change in future climates, potentially affecting the timing, distribution, and intensity of precipitation across the basin, as well as the resulting streamflow response. The ensemble approach addressed the need for multiple iterations of events in an effort to better understand the envelope of uncertainty for changes in key event types. The motivation for further developing an ensemble modeling method was born out of a previous collaborative CIRES-Reclamation project focusing on a climate change assessment of extreme precipitation for Green Mountain Dam, Colorado (Sankovich et al. 2012).

### 2.1.2 Hydrologic Model Simulations

In addition to the deliverables mentioned above, the NOAA and CIRES team partnered with NCAR to incorporate a hydrologic component to this project. In this portion of the study, NCAR team members explored the impact of WRF output on the simulated hydrologic response in the Taylor Park watershed using WRF-Hydro, an uncalibrated, spatially-distributed, and physics-based hydrologic modeling system. The primary goal of this portion of the study was to assess the impact of WRF ensemble-generated precipitation on simulated streamflow and reservoir inflow values. The second goal of this portion of the study was to explore the sensitivity of runoff generation mechanisms to surface runoff production. To accomplish these goals, WRF-Hydro simulations were performed for two ensembles listed in Table 2.1 and for a small set of experiments:

- Reduce infiltration capacity by 50% and convert forest to shrub land
- Add a domain-wide scale factor to the default quantitative precipitation estimate product of 1.1 (10% increase) and 2.0 (100% increase)
- Reduce the soil infiltration scaling parameter by 50% and 75%
- Reduce the soil infiltration scaling parameter by 50% and 75% and convert all forest in the Taylor Park watershed to shrub land

Simulated daily average streamflow from the May 2000 event is shown in Figure 2.3 (left). Results from this event indicate the existence of a positive bias in simulated flows during that year. Because WRF-Hydro simulations were produced without any model calibration, this bias could be reduced or eliminated by calibrating the hydrologic model. In addition to the positive bias, simulated flows shows greater variability than the observed flows. During the July 2014 event (Figure 2.3 right), WRF-Hydro ensemble members show a weaker positive bias as compared to the May 2000 event. In general, the ensemble values bound observations

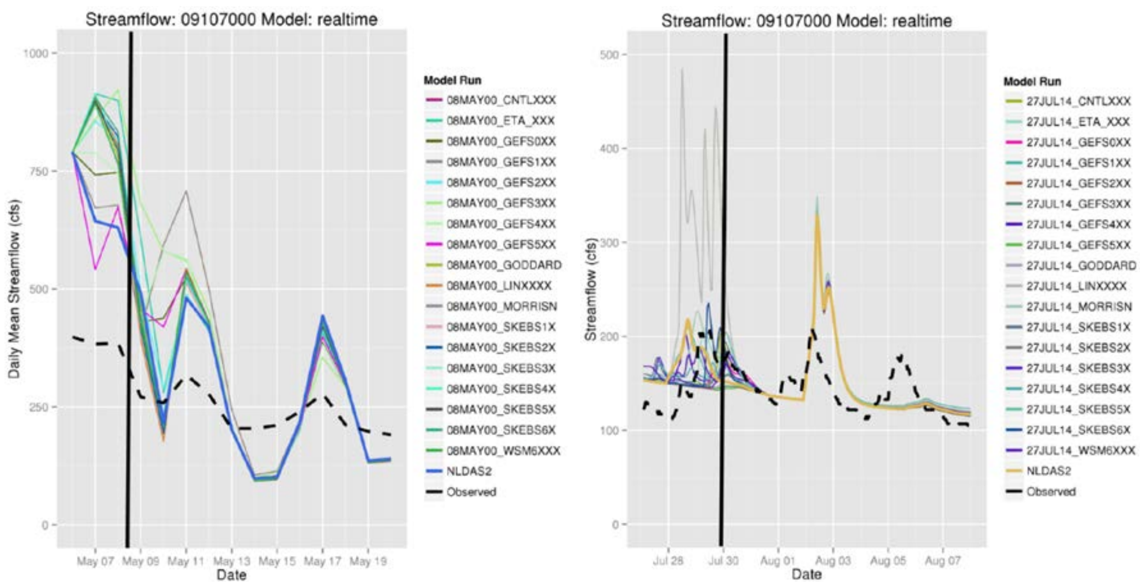


**Figure 2.3 - Simulated daily average streamflow ($ft^3\ s^{-1}$) based on the May 2000 (left) and July 2014 (right) precipitation ensemble members. Figures from David Gochis. The vertical black lines represent the end of the 96-hour WRF simulation period.**

An idealized set of hydrology simulations were performed in addition to the hydrology simulations shown in Figure 2.3. Additional details and results on these simulations, along with the full NCAR report, are located in Appendix 2.

### 2.1.3 Climate Change Simulations

The NOAA/CIRES team used a pseudo-global warming (PGW) delta method (Snover et al. 2003) to simulate changes to an observed precipitation event within a potential future climate. This was accomplished by calculating changes in air temperature and relative humidity simulated by each model of the 30-member Community Earth System Model (CESM) Large Ensemble (Kay et al. 2015). Average monthly differences in air temperature and relative humidity were calculated at each grid cell between two periods: historical (1990-1999) and future (2070-2079). The delta factors (at each grid point) were added to the initial and lateral boundary conditions used to force WRF model during the July 25-29, 2014 simulation.

Rather than using all 30 members, delta factors from four CESM-LE members were used to adjust historical conditions. The four members were selected because they simulated the smallest, largest, and middle level of warming in the low levels of the atmosphere, as well as the largest increase in relative humidity content. Figure 2.4 shows accumulated precipitation for the control simulation, along with each of the four PGW simulations, based on the July 2014 precipitation event.

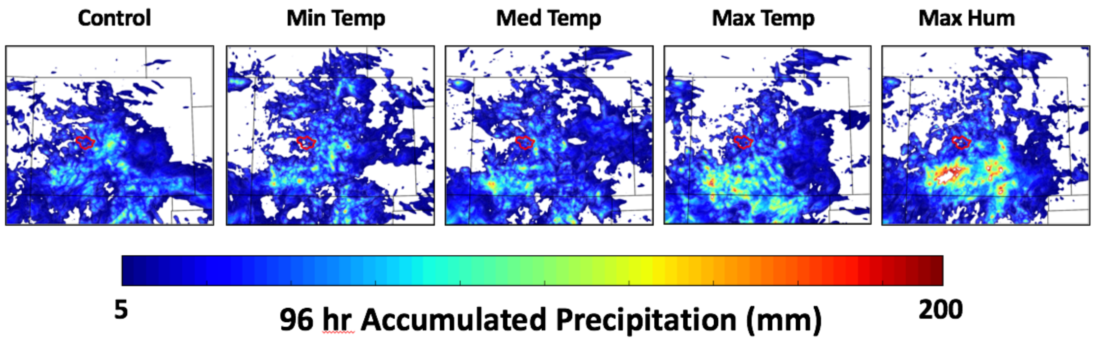


**Figure 2.4 - Accumulated 96-hour precipitation totals based on the historical control simulation from July 25-29, 2014 and four pseduo-global warming simulations (of the same event). The Taylor Park watershed is outlined in red. Figure from M. Mueller.**

## 2.2 Diagnosing the Moisture Sources for Extreme Precipitation Events in the Western US: Application to Hydrologic Hazard Analyses

The purpose of this study was to improve understanding of the processes responsible for heavy precipitation events, including atmospheric rivers (ARs), in the intermountain west. The team extended some of the techniques previously developed, including air-parcel trajectory analysis and Empirical Orthogonal Functions (EOFs, a statistical method for identifying patterns). This project had four primary tasks, including

1) Transfer data, information, methods, and documentation developed by NOAA and CIRES under the FY12/13 agreement to Reclamation;
2) Develop additional methods for diagnosing and grouping storms;
3) Generate and analyze an ensemble of high-resolution numerical simulations; and
4) Investigate impact of climate change on ARs

The remainder of this section (section 2.2) describes deliverables from each of the tasks listed above. For additional details, refer to the final project report, in Appendix 3.

### 2.2.1 Deliverables from Other Projects

The first task associated with this project was to share deliverables developed under previous projects with Reclamation staff. A gridded, high-resolution dataset containing daily precipitation, daily maximum temperature, daily minimum temperature, and daily wind speed was made available to the FHMG. The dataset is derived from approximately

20,000 NOAA stations (Livneh et al. 2015). Data are available on a 1/16° latitude-longitude grid for the years 1915-2011.

The backward air parcel trajectories during heavy precipitation events presented in Alexander et al. (2015), along with the computer code used to compute them, were shared with the FHMG. The back trajectories were computed using a modified analysis method developed at the University of Melbourne and the three-dimensional wind field from the National Center for Environmental Prediction's (NCEP) Climate Forecast System Reanalysis dataset (CFSR; Saha et al. 2010).

A Linear Model (LM) of orographic precipitation (written in Matlab) was also shared with the FHMG. The LM describes the pattern of precipitation that arises from forced ascent of saturated air over topography. The LM has been used in a number of different studies of orographic precipitation (Hughes et al. 2009; Hughes et al. 2014).

### 2.2.2 Methods for Diagnosing and Grouping Storms

The NOAA/CIRES team explored different methods to understand the climatology and variability of atmospheric conditions that lead to heavy precipitation events in the interior west. Previous work was based on applying empirical orthogonal functions (EOFs) to integrated water vapor transport (IVT). However, EOF analysis is a linear method and has known limitations. In the current project, the team used an additional method to classify and group extreme events based on Self-Organizing Maps (SOMs).

The SOMs algorithm involves an unsupervised learning algorithm that group similar input fields together and creates a composite map. The team used the SOMs algorithm to classify patterns of moisture transport into the intermountain west and explore the link between those patterns and extreme precipitation events. Additional details are available in Swales et al. (2016).

### 2.2.3 High-Resolution Numerical Simulations

In early November 2006, a major flooding event occurred in the Columbia River basin and Glacier National Park. The flooding was caused by heavy precipitation associated with a land-falling AR. Using the same WRF configuration discussed above, the team performed a six-day simulation of the AR event (November 3-9, 2006; Figure 2.5). Simulated precipitation totals in the Olympic and Cascade Ranges exceeded 400 mm.

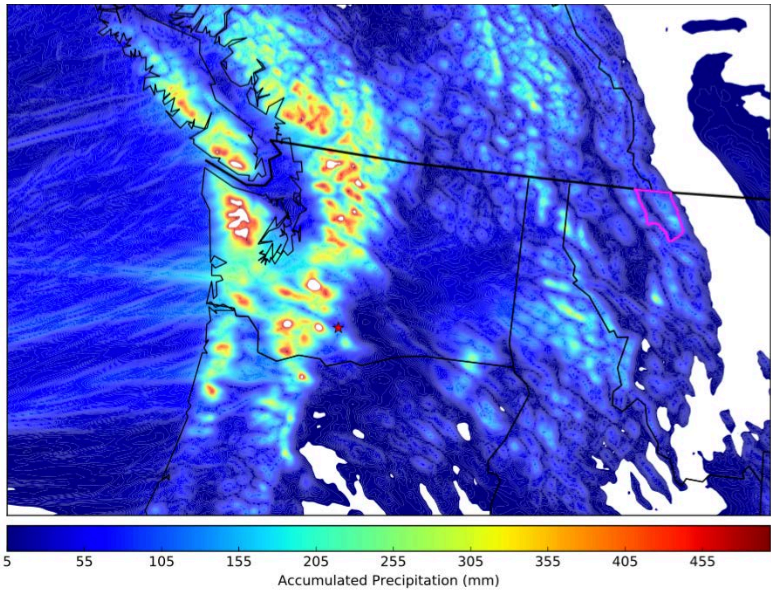


**Figure 2.5 - Simulated precipitation during totals the November 3-9, 2006 flooding event. The red outline represents Glacier National Park. Figure from M. Alexander.**

An ensemble framework was also used to explore different precipitation scenarios and to better characterize uncertainty in precipitation characteristics for this event. Potential effects of climate change were included as one of the simulation scenarios. The ensemble configuration consists of perturbations to the microphysics scheme, lateral boundary conditions, and stochastic perturbations to the temperature and wind fields.

### 2.2.4 Climate Change/Variability

The NOAA/CIRES team explored the impact of climate change on ARsand integrated water vapor transport (IVT) into the western United States and the occurrence of heavy precipitation using members NCAR's Community Earth System Model (CESM) large ensemble (LENS). The team quantified differences in average daily winter (October through March) IVT between a future (2071-2080) and historical (1990-1999) period. Their results suggest that the general pattern and direction of moisture transport from the central North Pacific Ocean towards North America does not change a great deal between these periods. However, the magnitude of the daily average IVT increases, a change that is likely the result of increases in moisture content from increased air temperatures.

In addition to exploring changes in daily average IVT, the team also investigated how future climate conditions may impact present-day ARs characteristics. Initial and lateral boundary conditions of the six-day simulation described above (section 2.2.3) were modified to represent a pseudo-global warming AR event.

# 3 Potential Applications to Hydrologic Hazard Analyses

As discussed in section 1.2, two of the most important meteorological inputs to hydrologic hazard analyses performed by the FHMG include storm patterns (both spatial and temporal) and a site-specific precipitation-frequency relationship. Some of the current methods used to develop these meteorological inputs have known shortcomings, which could be mitigated by using the updated datasets and methods developed by the NOAA and CIRES teams. This chapter discusses current and future applications of the NOAA and CIRES deliverables to the FHMG workflow. See Table 2 for a summary of the application potential of those deliverables.

**Table 2 - Application potential of NOAA and CIRES deliverables to meteorological inputs needed by the FHMG.**

| Deliverable | Storm Templates (spatial and temporal) | Precipitation-Frequency Analyses |
|---|---|---|
| WRF Output | X | |
| Livneh Dataset | X | |
| Back-Trajectories | X | X |
| Linear Model of Orographic Precipitation | | X |
| Self-Organizing Maps | X | X |
| Columbia River AR Simulations | X | |
| Climate Change Simulations | X | |

## 3.1 WRF Output

Hourly output from the high-resolution WRF simulations is currently being used in two studies underway for Taylor Park Dam. The first study is an IE-level HHA requested and funded by Reclamation's Dam Safety Office (DSO). The purpose of this study is to produce probabilistic estimates of reservoir elevation. Precipitation output from the WRF simulations, including ensemble members, is being used to develop the spatial and temporal storm templates needed. Output from the control simulations is being used to calibrate a lumped rainfall-runoff model, HEC-HMS (Hydrologic Engineering Center Hydrologic Modeling System; USACE-HEC 2010; Figure 3.1). In addition, the control simulations and ensemble members will be used for production runs, which are used to simulate the runoff response after calibration is complete. Simulated results from the production runs are used to develop the flood-frequency estimates at the reservoir, which will ultimately be used in a risk assessment for the dam.

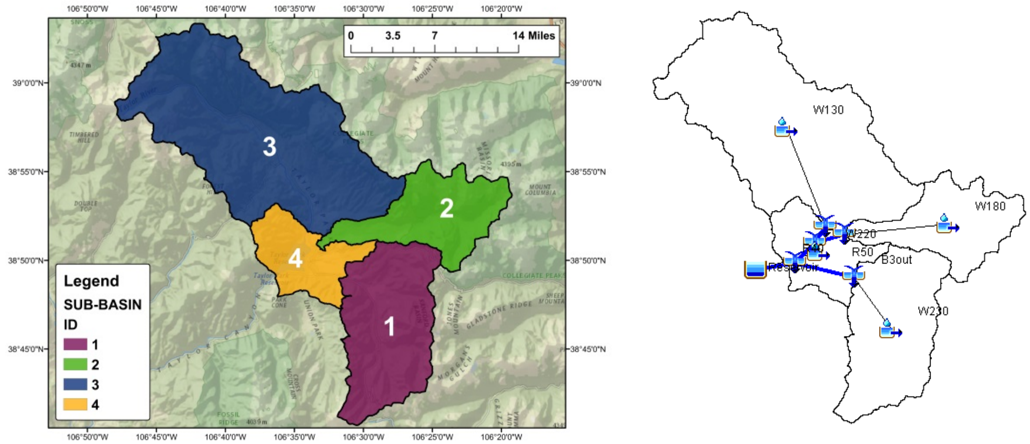


**Figure 3.1 - Two schematics showing the delineations of subbasins in the Taylor Park Dam watershed, based on a lumped rainfall-runoff model shown on the right.**

The second study in which WRF output is being used is a research project funded by Reclamation's Dam Safety Technology Development Program. This project is focused on exploring the use of distributed rainfall-runoff models within the FHMG. Hydrologists in the FHMG are currently exploring the use of WRF-Hydro (Gochis et al. 2013) and gridded HEC-HMS (USACE-HEC 2010) to develop flood-frequency estimates. As with the IE-level HHA discussed above, precipitation output from the WRF simulations can be used as inputs to the hydrology models used as part of this Dam Safety Technology Development project. WRF output could also be used as forcing for additional gridded hydrology models, such as the Variable Infiltration Capacity model (VIC; Liang et al. 1994; 1996) and the Two-Dimensional Runoff Erosion and Export model (TREX; Velleux et al. 2008; England et al. 2007).

Output from the WRF simulations, which is available on an hourly time step at 2.49 mi (4 km) horizontal resolution, provides many benefits to the FHMG. For example, the precipitation data are already available in gridded format. As a result, FHMG members do not have to apply an interpolation scheme to point observations (which typically vary by event) in order to produce the spatial patterns of historical precipitation needed for inputs to the rainfall-runoff model. In addition, the group does not have to temporally disaggregate daily precipitation observations to an hourly time step because WRF output is available at that temporal resolution. These benefits produce consistent results among the precipitation events chosen, which represents a large improvement over previous techniques. Beyond the benefits of data structure, the WRF ensemble members can be used to demonstrate the uncertainty surrounding historical precipitation events and how that uncertainty is translated into the runoff response. Uncertainty in storm templates (spatially and temporally) is not currently considered in HHAs.

While the use of WRF output has added benefits, there are some concerns for widespread future use. For example, running and storing output from the WRF simulations is computationally expensive. There is also a relatively large learning curve for processing and analyzing the output. In addition, output from the WRF simulations cannot be directly ingested by HEC-HMS (or any other HEC product). Instead, the FHMG developed a software module to translate the native WRF output structure to that required of HEC-HMS (*.dss; see Figure 3.2). While this tool is already built, it represents an additional data processing step for using the WRF output.

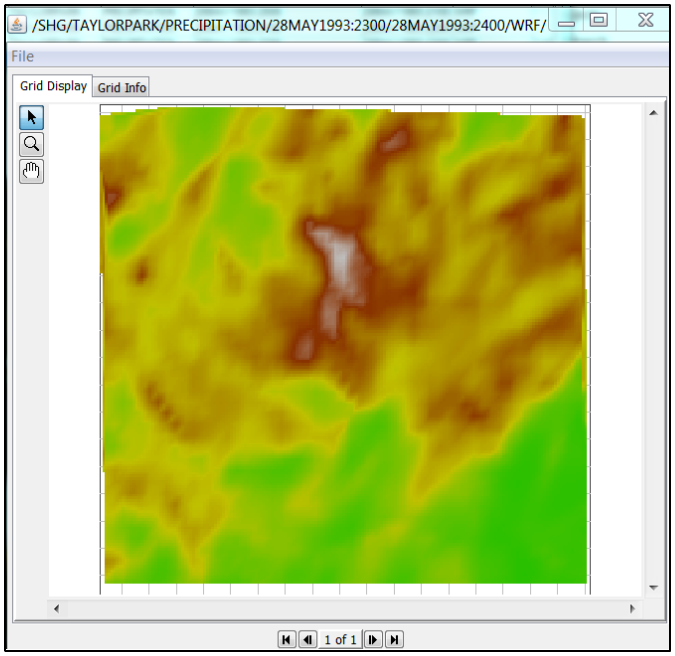


**Figure 3.2 - Sample screenshot of the software program, HEC-DSSVue 2.0.1, which is required to visualize .dss files used in HEC-HMS modeling.**

## 3.2 Livneh Dataset

The Livneh et al. (2013) dataset (hereafter referred to as the Livneh dataset) represents a long-term, gridded, observational dataset of precipitation, maximum temperature, minimum temperature, and wind speed available on a daily time step and 1/16°latitude × longitude horizontal resolution (approximately 6.94 km or 4.3 miles). This dataset is currently being used in two different FHMG projects; however the potential for application extends beyond these projects.

Currently, there is a multi-agency effort to produce an HHA for Grand Coulee Dam. The study is unique because members of the FHMG are using an existing VIC model developed by the University of Washington to calculate flood frequency estimates at the dam. The VIC model is a distributed hydrology model and requires distributed precipitation inputs. Daily precipitation totals from the Livneh dataset will be used to create storm templates for the Grand Coulee Dam HHA. Although individual precipitation events have not been identified for the HHA yet, the FHMG has begun exploring precipitation totals in and around the Grand Coulee Dam watershed. Figure 3.3 shows the average top 1% (N=355) of three-day precipitation totals between 1915 and 2011 based on the Livneh dataset surrounding the Grand Coulee Dam watershed. This information is helpful because it demonstrates the clear spatial variability in heavy precipitation totals throughout the watershed. As the Grand Coulee Dam project moves forward, members of the FHMG will identify historical precipitation events of interest and use totals from Livneh dataset as inputs to the VIC model.

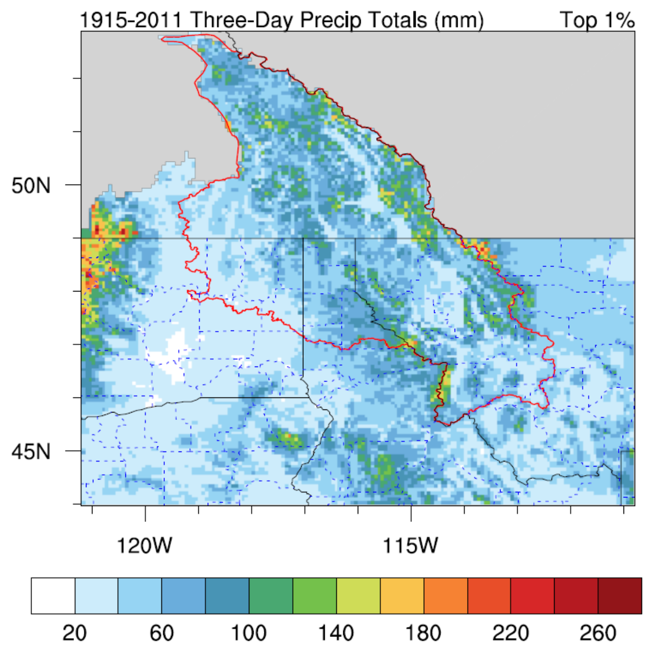


**Figure 3.3 - Average three-day precipitation totals (mm) during the top 1% of events (at each grid cell separately) around the Grand Coulee Dam watershed based on the Livneh dataset.**

The second FHMG project currently utilizing the Livneh dataset is a project underway for Taylor Park Dam, which is funded through the Dam Safety Technology Development. This project is focused on characterizing flood seasonality in the Taylor Park Dam watershed using observations and gridded datasets. Figure 3.4 shows a composite of average daily precipitation (mm) from the Livneh dataset during annual maximum inflow events to the Taylor Park reservoir between 1963 and 2011. The low average daily precipitation totals (~ 3 mm) in the watershed during large inflow events suggest precipitation is not the dominant cause of high flows.

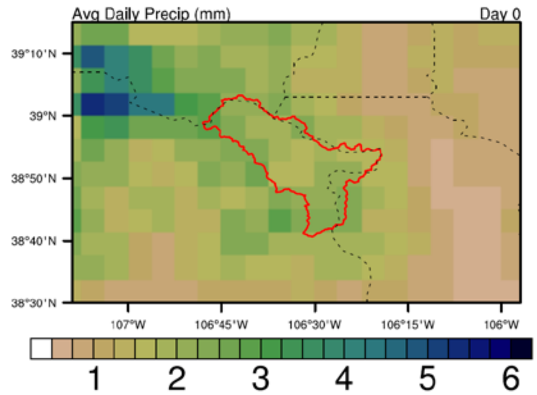


**Figure 3.4 - Average daily precipitation (mm) during annual maximum inflow events to the Taylor Park reservoir between 1963 and 2011. The Taylor Park Dam watershed (255 $mi^2$) is outlined in red. Black dashed lines represent county boundaries available in NCL[1].**

## 3.3 Back-Trajectories

Back-trajectories can be useful to determine the source(s) of moisture and the pathway(s) the moisture took during an extreme precipitation event (Alexander et al. 2015). This is useful information because the source and path of moisture in many extreme precipitation events across the Intermountain west of the United States are not obvious and are sometimes based on speculation (HMR 49 1984). Determining the moisture sources and pathways during extreme precipitation events can be beneficial by providing the FHMG a broader context of historical events of interest.

Figure 3.5 shows an example back-trajectory analysis valid during the extreme precipitation event that occurred along the Front Range of Colorado in September 2013. The figure shows the moisture pathways of parcels located at different vertical levels (indicated by the streamline colors) of the atmosphere during the event. This figure shows that there were two apparent moisture sources during the precipitation event. Low-level moisture originated over the Gulf of Mexico (pressure levels greater than 700 mb), while the upper-level air (pressure levels lower than 400 mb) originated over the Pacific Ocean.

[1] https://www.ncl.ucar.edu/Document/HLUs/Classes/MapPlotData4_1_earth_2.shtml

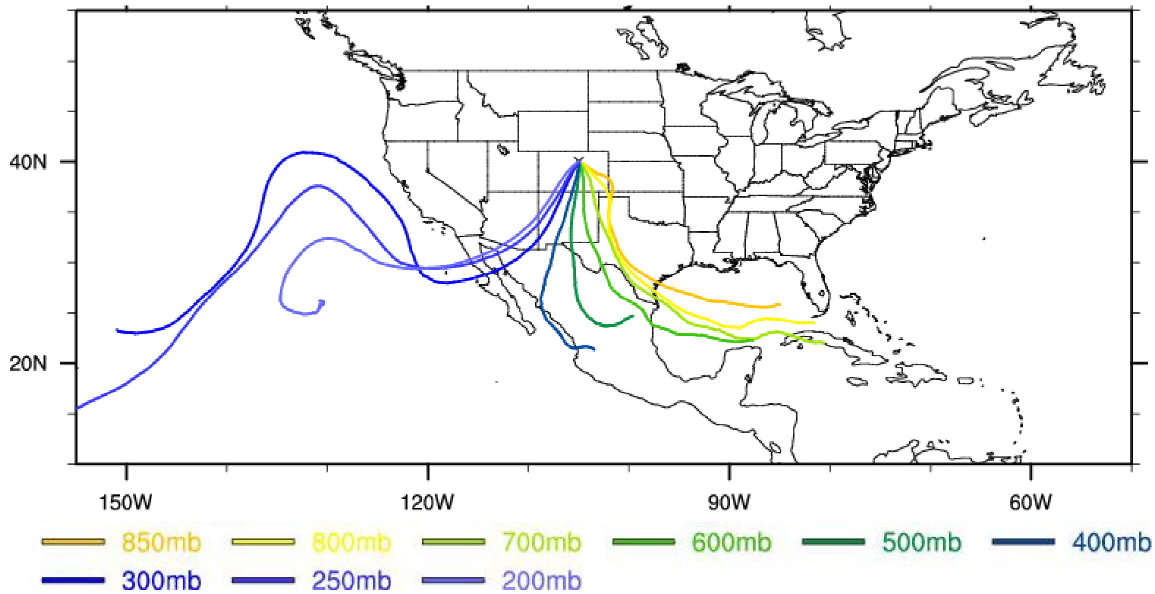


**Figure 3.5 - Backward air parcel trajectories based on the NCEP/NCAR Reanalysis I showing the moisture pathways from September 10-12, 2013 during the extreme precipitation event over the Front Range of Colorado. The "x" indicates Boulder, Colorado. Image provided by the NOAA-ESRL Physical Sciences Division, Boulder, Colorado, from their Web site at http://www.esrl.noaa.gov/psd/.**

In future studies, the back-trajectory tool could be used to categorize or label precipitation events based on the moisture source region(s). If, for example, back trajectories are computed for all the heavy precipitation events of interest to a dam site, the FHMG could use this information to select a subset of events with differing source regions. Rather than selecting many events with moisture sources over the Pacific Ocean, the group could use the back trajectory information to diversify events used in an HHA. In addition, the FHMG could also use the back-trajectories to define transposition limits on historical precipitation events. For example, back trajectories of a single event could be used to restrict transposition limits. The FHMG could define transposition limits to the historical trajectory path observed. Alternatively, the FHMG could use back trajectories to identify precipitation events that resulted in precipitation outside the watershed, but that tracked over or near the watershed.

While the back-trajectory code provided by the NOAA/CIRES team has many potential applications, there are some limitations. For example, to run the FORTRAN code locally, the user needs to be comfortable working in a linux environment and should be somewhat familiar with FORTRAN code. Furthermore, the user must have access to the CFSR dataset, which requires a large amount of storage space. The NOAA/CIRES team also provided the FHMG with some software scripts to plot results from the back-trajectory analysis. However, these scripts are written in a different language than FORTRAN, namely NCL, which represents another small hurdle to wide-spread application of the tools.

## 3.4 Linear Model of Orographic Precipitation

The linear model of orographic precipitation provided by the NOAA/CIRES team was developed to predict the precipitation response resulting from the ascent of saturated air over topography. The model includes airflow dynamics, cloud time scales and advection, and downslope evaporation (Smith and Barstad 2004). The model is vertically integrated and uses average values of time-constant variables that are representative of the entire atmospheric column. Input parameters include background precipitation rate, horizontal wind components, air temperature, moist stability frequency, conversion time scale (cloud water to hydrometeors), timescale of hydrometeor fallout, and a measure of the vertical structure of the atmosphere.

Broadly speaking, the LM could be used in a number of different types of studies. For example, members of the FHMG could use the LM to identify the wind direction that results in the greatest amount of precipitation at a site of interest located in or around topography. This type of analysis could be performed at many locations of interest to Reclamation along the western U.S. In addition, members of the FHMG could use the LM to explore some of the founding assumptions and concepts used in the development of PMP in HMRs. These explorations would likely take the form of internal research projects.

Although this tool is extremely useful for theoretical considerations and exploration, widespread application in the FHMG may be challenging. Currently, the LM is written in Matlab (The MathWorks, Inc), which must be purchased.

## 3.5 Self-Organizing Maps

Published work by the NOAA/CIRES team (Swales et al. 2015) is based on a publicly-available software package written in MATLAB (The MathWorks, Inc) to compute self-organizing maps (SOMs). The SOM algorithm is an objective way of grouping multi-dimension variables (e.g., precipitation totals in time and space). Members of the FHMG could apply the SOMs algorithm to develop spatial patterns of precipitation resulting from different moisture transport trajectories, similar to the analysis by the NOAA/CIRES team. However, there are additional potential applications.

The Grand Coulee Dam HHA is an example of a study for which the SOMs algorithm could be useful. The Grand Coulee Dam watershed is extremely large (approximately 75,000 $mi^2$) compared to other Reclamation drainage areas, which may aide in the usefulness of results from a SOMs analysis. The FHMG is currently working on implementing a new distributed land-surface model in the study. Specifically, members of the FHMG are using the Variable Infiltration Capacity model (VIC) to estimate the flood frequency relationship in the watershed. Spatial and temporal precipitation information (i.e., storm templates) is also needed for this study. Members of the FHMG can utilize the SOMS algorithm to develop subsets, or pools, of precipitation events by mapping precipitation totals to daily integrated water vapor transport (IVT) patterns developed using the SOMs algorithm. Heavy or extreme precipitation events can be selected based on membership to these different pools of IVT. Figure 3.6 shows a schematic of precipitation patterns mapped to patterns of IVT.

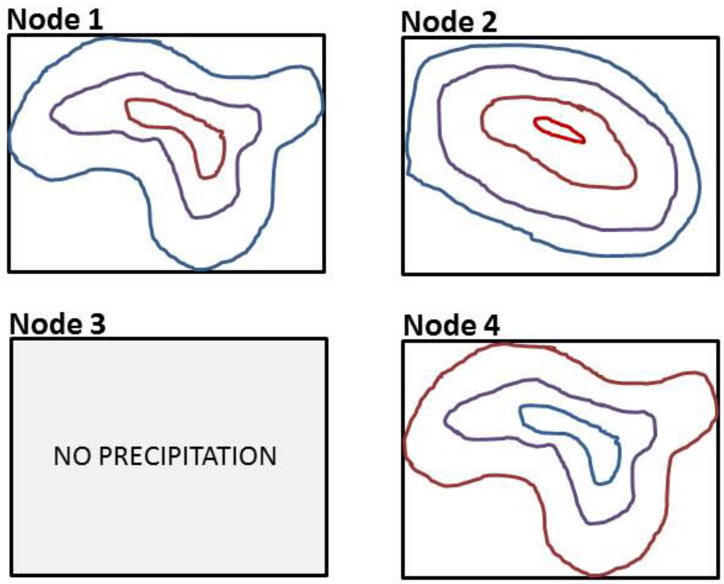


**Figure 3.6 - Schematic of average multi-day precipitation totals (in space) mapped to the results from the SOMs algorithm applied to IVT anomalies for some region of interest.**

In addition to developing subsets of precipitation events to use as storm templates, the SOMs algorithm can also be applied to historical precipitation observations to more objectively define the homogeneous region used to develop precipitation-frequency analyses (e.g., Figure 1.6). Lin and Chen (2006) defined homogenous regions for precipitation frequency analyses by applying the SOMs algorithm to 17 variables that included elevation, mean annual precipitation, standard deviation of annual precipitation total, and average monthly precipitation for each month. The authors used a measure of heterogeneity presented in Hosking and Wallis (1997) to test if resulting regions were homogenous. Using the SOMs algorithm, Lin and Chen (2006) identified eight clusters (or groups) of precipitation across all of Taiwan. The FHMG could use the SOMs algorithm as an alternative method for defining or identifying homogeneous regions needed in regional precipitation frequency analyses.

The SOMs algorithm can also be used to identify regions of homogenous snow characteristics and behavior. Fassnacht and Derry (2010) used the SOMs algorithm to define similar regions of snow throughout the Colorado River basin. The authors identified regions based on similarities in peak SWE, cumulative SWE, date of peak SWE, and length of snow season (Figure 3.7) using daily, weekly, monthly, and yearly snow water equivalent (SWE) observations. The FHMG could apply the SOMs algorithm to all available SWE observations in a region to determine which stations behave similarly to a site of interest. This type of analysis could be used in any study where snow plays an important role in annual flooding.

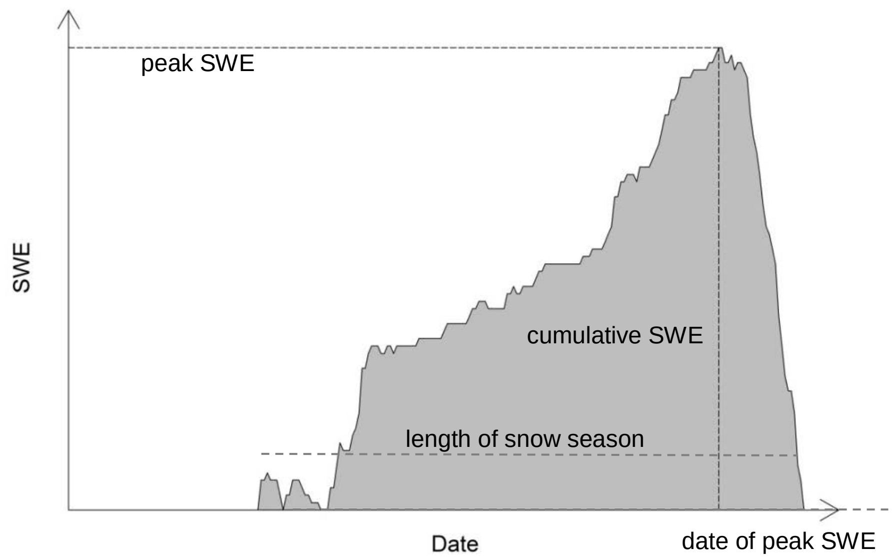


**Figure 3.7 - Example niveograph, which shows daily SWE versus time for a single water year. The four variables of interest to Fassnacht and Derry (2010) are represented by this figure. Figure adapted from Fassnacht and Derry (2010).**

## 3.6 Columbia River AR Simulations

The high-resolution (spatially and temporally) WRF ensemble simulations of the November 2006 AR event may be used in a number of future HHAs that require storm templates (e.g., IEs or CASs). Figure 3.8 shows the location of Reclamation dams in the northwestern United States. Members of the FHMG will explore precipitation totals from the WRF simulations to ensure that the site of interest received precipitation. Output from the ensemble can be used in conjunction with storm templates developed in any number of traditional ways, or independently, depending the number of storm templates needed.

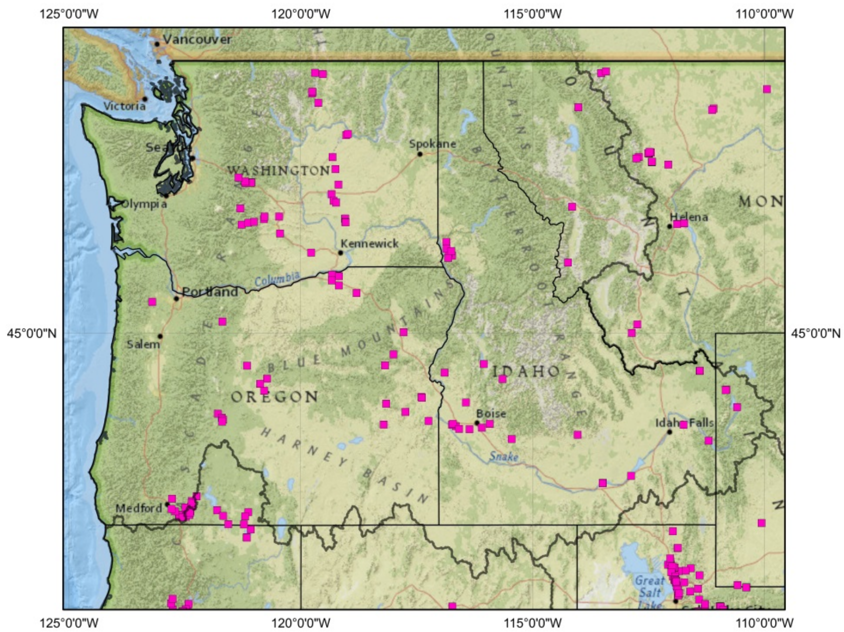


**Figure 3.8 - Reclamation dams (magenta squares) located in the Pacific Northwest. Reclamation region boundaries are shown in black.**

## 3.7 Climate Change Simulations

In 2009, Congress passed the SECURE Water Act, which authorizes the cooperation between Federal water agencies and scientific agencies to work together with State and local water managers to plan for climate change. Specifically, Omnibus Public Land Management of 2009 (Public Law 111-11) Subtitle F – SECURE Water Section 9503 Part (c)(1) instructs Reclamation to report "each effect of, and risk resulting from, global climate change with respect to the quantity of water resources located in each major Reclamation river basin." In an effort to meet this directive, the 'SECURE Water Act Proposed Stage 2 Implementation Strategies' document proposes to incorporate climate change analyses into new areas of emphasis, including dam safety. Since then, DSO has discussed the potential for multiple climate change pilot projects in order to evaluate the utility of incorporating climate change information into the Dam Safety risk assessment framework.

Recently, The DSO funded a two-part climate change pilot study for Friant Dam, in California (Bahls et al. 2014; Novembre et al. 2015). The first part of the study developed a methodology to create climate-adjusted hydrometeorological model inputs, while the second part used the climate-adjusted inputs in the Stochastic Event Flood Model (SEFM; Schaefer and Barker 2002;2009). The FHMG members adjusted historical precipitation and temperature observations (excluding the spatial distribution of historical precipitation events) using monthly delta factors (Sankovich et al. 2013) developed using the Bias-Corrected, Spatially-Downscaled CMIP5 dataset (BCSD5). The climate-adjusted hydrometeorological inputs were used to estimate climate-adjusted flood frequency relationships (Novembre et al. 2015).

Since the completion of the Friant climate change pilot project, the DSO has expressed interest in funding additional climate change pilot projects that explore alternative methods for incorporating climate change projections into flood-frequency and hydrologic hazard analyses. The NOAA/CIRES team provided the FHMG two sets of pseudo-global warming simulations. The first set of simulations involves an adjusted precipitation event from the Taylor Park Dam watershed, while the second set of simulations involves adjusting an AR event that affected Glacier National Park in November 2006. The pseudo-global warming simulations of precipitation events in the Taylor Park Dam watershed can be used as climate-adjusted storm templates. This represents an alternative approach to the Friant climate change study, where the spatial and temporal patterns of precipitation were not modified based on climate projections (Bahls et al. 2014). Consequently, using climate-adjusted storm templates represents an alternative to the approach taken in the Friant Dam pilot project. A climate change pilot project for Taylor Park Dam is a natural extension to the HHA currently underway. Furthermore, the pseudo-global warming simulations of the AR event that impacted the northwest U.S. may be used in any additional climate change pilot projects established in Reclamation's Pacific-Northwest region (Figure 3.8).

# 4 Summary

In 2013, Reclamation's RDO established two projects (under Cooperative Agreement R11AC81334) between Reclamation and NOAA and the University of Colorado-Boulder's CIRES for the purpose of developing advanced tools for use by Reclamation's FHMG. The first project focused on improving estimation of extreme precipitation events using a high resolution numerical model, while the second project focused on diagnosing moisture sources of heavy precipitation events in the intermountain west. The tools and products resulting from these projects have great potential for use in the FHMG.

Output from the WRF simulations has many applications to FHMG work processes. For example, simulated precipitation and temperature data are currently being used in a HHA for Taylor Park Dam. WRF outputs are also being used in a Dam Safety research project on Taylor Park Dam watershed, exploring the use of distributed hydrology models for flood frequency analyses. The WRF climate change simulations from the Taylor Park region are a valuable asset to a potential climate change pilot project at that facility. In addition, the WRF-Hydro simulations are a valuable demonstration of advanced hydrologic methods that may be used in future flood frequency analyses.

Other deliverables also benefit the FHMG. For example, the Livneh dataset is currently being used in a Dam Safety research project focused on flood seasonality in the Taylor Park Dam watershed. The dataset is also being used in the HHA underway for Grand Coulee Dam. Similarly, the SOMs algorithm has many potential applications to FHMG work processes. This algorithm may be used to identify storm templates, delineate homogeneous regions for precipitation-frequency analyses, or identify regions of homogeneous snow behavior.

Collectively, the tools and products developed under the two projects with NOAA and CIRES have many benefits to the FHMG. The FHMG will continue to use these deliverables and explore additional applications under new project agreements.

# 5 Acknowledgements

The majority of this report was prepared by Kathleen D. Holman, Ph.D., from the Flood Hydrology and Meteorology Group of the Bureau of Reclamation's Technical Service Center in Denver, Colorado. Additional Flood Hydrology and Meteorology Group employees at Reclamation contributed to this report, including: meteorologist, David Keeney and hydrologic engineer, Nicole Novembre, P.E.. TSC peer review was completed by Joseph Wright, P.E.. The NOAA, CIRES, and NCAR team provided the data, tools, and analysis results in the text and appendices. Discussions with the personnel from the Reclamation Science and Technology Program were also helpful.

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# Appendix 1 Improving Extreme Precipitation Estimation Using Regional, High-Resolution Model-Based Methods

**Improving extreme precipitation estimation using regional, high-resolution model-based methods:**
**Final summary for performance period February 2014 - 2016 CIRES-Reclamation Cooperative Agreement R11AC81334**

**Background**

The Bureau of Reclamation (Reclamation) Flood Hydrology & Meteorology Group (FHMG) is tasked with evaluating probabilistic precipitation and reservoir inflows for use in Dam Safety Risk Analyses. The FHMG is currently working on a study to assess the probability of overtopping of Taylor Park Dam in Colorado. Of particular interest is improving precipitation inputs to rainfall runoff models used to estimate reservoir inflows.

In this study we have developed a numerical model-based framework to provide superior precipitation data as input to Reclamation hydrologic models, and more generally improve understanding of heavy precipitation events and processes as they relate to Reclamation sites of interest in the western US. The study addresses the uncertain nature of precipitation estimates by employing an ensemble modeling framework to produce a range of physically-realistic precipitation scenarios. The impact of climate change was also addressed by modifying the model's environment according to anticipated changes in temperature and moisture.

A significant challenge faced by hydrologists is the estimation of heavy precipitation potential in the western US. A key limitation is inadequate distribution of point precipitation data. Lack of data inhibits the ability to generate spatially- and temporally- explicit precipitation estimates. Detailed estimates in both space and time are critical to accurately assessing heavy precipitation and flood potential at a specific location. Many methods that are currently used to extrapolate limited observations across complex terrain may under- or overestimate precipitation due to assumptions required to smooth the existing data. Particularly for small regions of interest, a greater reliance on approximations and outdated estimation methods may result in precipitation estimation errors. The fundamental weakness of smoothing and statistically-based extrapolation methods is that they are not based on physical relationships and are prone to being unrealistic. This is especially true in regions of complex terrain where precipitation can exhibit sharp gradients.

In this study, we have explored methods to address some of these limitations using a high-resolution dynamical weather model to simulate precipitation across multiple realizations of a given event (i.e., an ensemble of model simulations). We used the Weather Research and Forecasting (WRF) model to produce highly-detailed, physically-consistent precipitation estimates for several cases at Taylor Park Dam and the East-Taylor (USGS Hydrologic Unit Code 14020001) watershed (Figs. 1a-b). Taylor Park watershed is a remote location in central

Colorado at an elevation ranging from 8,500 to 13,000 feet. To estimate case-specific uncertainty associated with these estimates, WRF was run in an ensemble framework. The WRF ensemble configuration was developed and tested using select events of interest at the watershed. This document will detail how each of the tasks from the 2014 project management plan were addressed over the performance period.

**Task 1: Produce high-resolution ensembles of model simulations to better estimate extreme precipitation events and their associated envelope of uncertainty for a given region of Reclamation interest. Design and manipulate the suite of model simulations to produce continuous, high-resolution, probabilistic gridded output that can be directly used in Reclamation studies and evaluations.**

**Task 1.1** Select events of interest based on historical cases already included in ongoing Reclamation work, in addition to cases identified by newer datasets such as CFSR, NARR, Stage IV, etc. (*CIRES lead*)

Test cases were chosen based upon two criteria: streamflow on the Taylor River and the magnitude of precipitation over the associated East-Taylor watershed. These factors maximize overlap between Reclamation and CIRES/NOAA needs and applications, as well as data availability. Moreover, emphasis on both streamflow and precipitation enables examination of the relationship between streamflow and factors such as precipitation magnitude, distribution and type, in addition to snowpack and snowmelt. Two datasets were used to evaluate these criteria and select test cases.

First, daily streamflow from the USGS gage on the Taylor River was analyzed for 1962-2015. This data is available at http://water.weather.gov/ahps2/hydrograph.php?wfo=gjt&gage=trac2. It should be noted that the Taylor River accounts for only a portion of inflows at the reservoir (128 of the 254 sq mile Taylor Park watershed area). Calculated daily reservoir inflow is available from Reclamation at http://www.usbr.gov/rsvrWater/faces/rvrOSMP.xhtml. Figure 2a shows the climatology of heaviest streamflow days along the river. The heaviest 1000 events were clustered exclusively during May-July. This result was not surprising given the known impact of seasonal snowmelt on observed streamflow in the region. This key finding was also reflected in a list of 10 cases of interest provided by Reclamation. The list included both heavy precipitation and high Taylor Park reservoir inflow events (see Appendix). Each of these events occurred during May-July. Ensemble case selection was restricted to these months due to the central importance of reservoir inflow.

Second, CIRES/NOAA created a precipitation climatology for the East-Taylor watershed to gain insight into heavy precipitation events in the region. The East-Taylor watershed was used instead of the Taylor Park watershed for this part of the meteorological assessment to increase the sample size of available observations, and to better represent the types of events that cause precipitation in the general region (as opposed to unnecessarily limiting case selection to events occurring directly over the very small Taylor Park watershed.) The climatology was constructed using a 1/16 degree gridded observation-based precipitation dataset (Livneh et al. 2013). This dataset is based on observations from 20,000 NOAA Cooperative Observer (COOP) stations. Data from 1968-2011 was used to develop the climatology. Gridded daily precipitation was averaged over the watershed and the top events ranked. Figure 2b shows the monthly distribution of the 500 heaviest precipitation days at the East-Taylor watershed. It reveals the vast majority of heavy precipitation days occur during the cool season (October - April). That the peaks in annual precipitation and streamflow are out of phase suggests cool season precipitation falls predominantly as snow and does not immediately contribute to runoff. This is a reasonable expectation given the high elevation of the watershed. The water is stored as snowpack until temperatures warm and snow melts in May-July.

Another consideration is precipitation changing from solid to liquid form as temperatures increase by late spring. This can have profound impacts on runoff as rain may accelerate snowmelt and contribute immediately to runoff. Thus, precipitation events during the May-July period were given top priority during the test case selection process. Events were sorted into monthly rankings to gain clarity on the heaviest events during the critical late spring - early summer period. Precipitation rankings were cross-referenced with the top streamflow days on the Taylor River. Analysis showed the top streamflow day occurred on 18 June 1995, one day after the 12th largest June precipitation day. This result informed the selection of 18 June 1995 as the first test case used during the study.

Background knowledge about the antecedent hydrology and meteorology for the 18 June 1995 case also informed the selection of other cases for ensemble testing. Ensemble performance and spread depend on the sources of uncertainty in the simulation, so a variety of weather environments were desired to more robustly develop and test the ensemble configuration. Summer convection-driven (27 July 2014) and early season (8 May 2000) cases were chosen to supplement the frontally-forced precipitation case of 18 June 1995 in the ensemble tests.

**Task 1.2** Using a small collection of representative cases (most likely less than 5 cases per site), produce control simulations using reanalysis data to achieve an acceptable representation of the event compared to observations. (Single simulations of a larger set of events (on the order of 10 storms) can also be produced if a larger sample of cases is advantageous for a given location.) (*CIRES lead*)

The Weather Research and Forecasting (WRF) modeling system Version 3.6 was used to generate control simulations for 8 events (including the 3 events chosen for ensemble testing): 19 June 1982, 7 June 1984, 27 May 1993, 18 June 1995, 21 June 1996, 8 June 1997, 8 May 2000, and 27 July 2014. Event selection was based on the Reclamation event list and was constrained by availability of data for initial and lateral boundary conditions. Initial and lateral boundary conditions to drive the model were provided by the Climate Forecast System Reanalysis (CFSR) dataset. Each simulation was conducted during a 96 hour period centered on 00 UTC of the event day. This was a compromise designed to capture precipitation prior to the event and to conserve computing resources needed to conduct simulations for multiple cases. A single domain with 4km grid spacing was established over the Intermountain West. Figure 3 shows the extent of the domain with the East-Taylor watershed outlined for context. Data from the 8 control simulations were disseminated to Reclamation via a CIRES/NOAA FTP site. Further information regarding specifics of the control simulations can be found in the Appendix.

**Task 1.3** Introduce perturbations to create an ensemble of simulations using some combination of methods (CIRES lead; the exact number and type of perturbations will likely depend on the site being studied and the appropriateness of the permutations for the Reclamation needs being addressed)

A suite of ensemble perturbations were used to generate a range of physically-consistent precipitation scenarios for three 96-hour cases: 16-20 June 1995, 6-10 May 2000, and 25-29 July 2014. Case selection was driven by USGS streamflow data (1962-2015), a precipitation climatology of the East-Taylor watershed (1968-2011), and the objective of investigating and including events from a diverse range of weather conditions. Eighteen ensemble members were generated by perturbing microphysical parameterization schemes (6 members, including the control), adding stochastic perturbations during simulation to account for energy transfers from unresolved to resolved scales (six members), and perturbing lateral boundary conditions (six members).

These perturbation groups were chosen to represent a range of model uncertainties that are particularly important for precipitation simulation. Microphysics schemes are used by the model to parameterize unresolved physical processes important for the development of precipitation. The six microphysics schemes were chosen for applicability to the type of cloud processes common to the region (i.e. “cold-cloud processes” that apply to clouds that contain both frozen and liquid water). Stochastic perturbations were generated using the Stochastic Kinetic Energy Backscatter Scheme (SKEBS). This method pseudo-randomly modifies temperature and wind fields to mimic the impact of unresolved turbulent energy cascades on resolved processes. The package was available within the WRF code and has been used in recent publications concerning precipitation systems (e.g. Berner et al. 2011, Duda et al. 2016). Details of ensemble members can be found in the Appendix.

Initial results with the original 12 ensemble members showed the envelop of scenarios failing with respect to observations at the Global Historical Climatology Network (GHCN) station (Station ID: USC00058184) at the Taylor Park Dam. (Fig. 4). Due to underperforming spread, CIRES/NOAA held internal meetings in which the issue was determined to be lack of variation in the lateral boundary conditions. This suppressed spread because the CFSR data guided each simulation toward a single solution. To account for uncertainty at the boundaries, 6 members from the Global Ensemble Forecast System (GEFS) Reforecast dataset were used as lateral boundary conditions in the place of a single CFSR state (Figs. 5a-b). The GEFS reforecast dataset is a retrospective ensemble forecast system (1984-present) that uses a fixed numerical forecast model, but also uses perturbed initial and boundary conditions to generate an envelope of possible atmospheric responses to a given initial environment. It is run at relatively coarse resolution (Hamill et al. 2013), but is useful for gauging a spread of potential large-scale environmental states preceding the heavy precipitation events of interest for this work. Using the GEFS members as initial and lateral boundary conditions to our high-resolution simulations increased spread in this case, a result that argued strongly for adopting a GEFS-supplemented 18 member ensemble for subsequent cases.

This ensemble configuration was used for the following two test cases. Figures 6a-b show spatial and temporal precipitation distributions for the 6-10 May 2000 case. As in June 1995, most precipitation fell in a 12-15 hour period. Microphysics and stochastic members capture this event quite well compared to observations at the Taylor Park Dam. In this case, lateral boundary condition members diverged with other members, showing precipitation onset 9-12 hours later than the other 12 members, adding temporal diversity to the envelope of solutions. The scenarios provided by GEFS appear to have degraded the forecast at the watershed with respect to CFSR-driven simulations, but with fairly coarse observations one may also view this discrepancy as a potentially valuable addition of ensemble spread.

Results from 25-29 July 2014 are shown in Figures 7a-b. Unlike the other cases, precipitation fell each afternoon and evening of the period. This is a clear indication of convective precipitation which is often strongly influenced by land surface features such as mountains. In such cases, the gradient between no precipitation and a heavy, prolonged event can be sharp and driven by circulations related to complex terrain. The importance of a high-resolution dynamically realistic precipitation estimation method is underscored by this event. Spatial precipitation distributions show the highly localized nature of convective precipitation and the importance of mountain terrain. The heaviest precipitation estimates were in southwestern Colorado near the San Juan mountains. Microphysics members produced the largest spread and better approximated the observed precipitation over the watershed. In contrast to the June 1995 case, microphysics perturbations likely performed best due to the prime importance of cloud process uncertainty in convective systems.

Beyond simply producing multiple precipitation scenarios, the ensemble approach is useful due to derived products such as maximum precipitation (Fig. 8). This product yields the maximum precipitation of all members at each grid point in the model domain. Since it is a type of “composite” of all members, it is not itself a physically-consistent scenario; however, it can be considered as an ensemble-generated “upper bound” of precipitation for a given case. For heavy precipitation events, this is one way to anticipate how much precipitation could fall given specific, fixed environmental constraints. This type of analysis would not be possible with only a single deterministic model simulation and highlights the enhanced range of information available through ensemble methods. Other derived products may include probability of exceeding a threshold, mean, spread and probability distribution functions. Future innovative research is needed to explore how best to use such products to improve streamflow modeling.

Climate change was also considered as part of this study. To simulate precipitation events within a potential future climate, CIRES/NOAA used a pseudo-global warming (PGW) delta method. This was accomplished by calculating temperature and relative humidity changes (i.e. deltas) in the 30-member Community Earth System Model (CESM) Large Ensemble (Kay et al. 2014). Deltas were calculated by subtracting monthly temperatures and moisture at each individual gridpoint using a "past period" of 1990-1999 and a future period of 2070-2079. The deltas were added to WRF initial and lateral boundary conditions to simulate a recent case within the environment of the 2070-2079 climate. The most recent case 25-29 July 2014 was chosen to test this method. To conserve computing resources, deltas from 4 members were used - minimum, maximum, and middle-of-the-road warming in the low levels of the atmosphere and the maximum increase in atmospheric moisture content (Fig. 9a).

Figure 9b shows watershed averaged precipitation for the control and four PGW simulations. At the watershed, the climate perturbations had a diverse effect on precipitation totals. This demonstrates that large-scale climate change does not necessarily project linearly onto finer scales, and particularly not uniformly in space and time. Case-to-case variability and localized physics continue to be a dominant factor determining precipitation magnitudes and distributions over a relatively small region of interest. When we considered a wider area, however, precipitation increases were apparent in southern and southwestern Colorado (Fig. 9c). The increases coincide with the area of greatest precipitation in the control simulation, roughly along the San Juan mountains. The greatest precipitation increases occurred in the warmest and most moist scenarios. The maximum moisture increase scenario was especially striking with widespread precipitation exceeding 200mm in southwestern Colorado.

**Summary**

In this study, a high-resolution dynamical model ensemble framework has been used to produce precipitation estimates for eight cases at the Taylor Park Dam and East-Taylor watershed. Three cases were selected to develop and test the 18-member ensemble designed to generate a range of precipitation scenarios. This framework was created to demonstrate potential improvements over current methods of heavy precipitation estimation such as smoothing of sparse observations and storm transposition. Improving upon existing methods is desirable because current methods are not constrained by physical laws and they fail to reproduce detailed spatial and temporal distributions in complex terrain. Challenges with the current state-of-the-practice stem mainly from a fundamental lack of observations in many areas of the western United States. The new method shows promise in providing physically-realistic estimates on a high resolution grid set up over such sparsely observed areas.

As results from ensemble testing confirm, the model produced sufficient spread for each case over the East-Taylor watershed. The range of precipitation scenarios produced can be used as input to hydrologic models to anticipate an associated range of streamflow. Further, the ensemble can be used to derive other quantities such as maximum precipitation, probability distribution functions, or probability of exceeding a given threshold. These products may be used in innovative ways in the future to further improve precipitation and streamflow estimation. Another concern for watersheds across the western United States is the impact of global climate change on localized heavy precipitation events. We have demonstrated a method to augment model initial and lateral boundary conditions to assess how precipitation events evolve in different climates. Preliminary findings suggest warmer environments trigger heavier precipitation in preferred areas and that the largest impacts appear to stem from moisture increases relative to temperature increases. The relationship between temperature and moisture increases as it pertains to small-scale storms and heavy precipitation events warrant future investigation.

**Figure 1a:** Location of the East-Taylor (black outline) and Taylor Park (magenta outline) watersheds within Colorado.

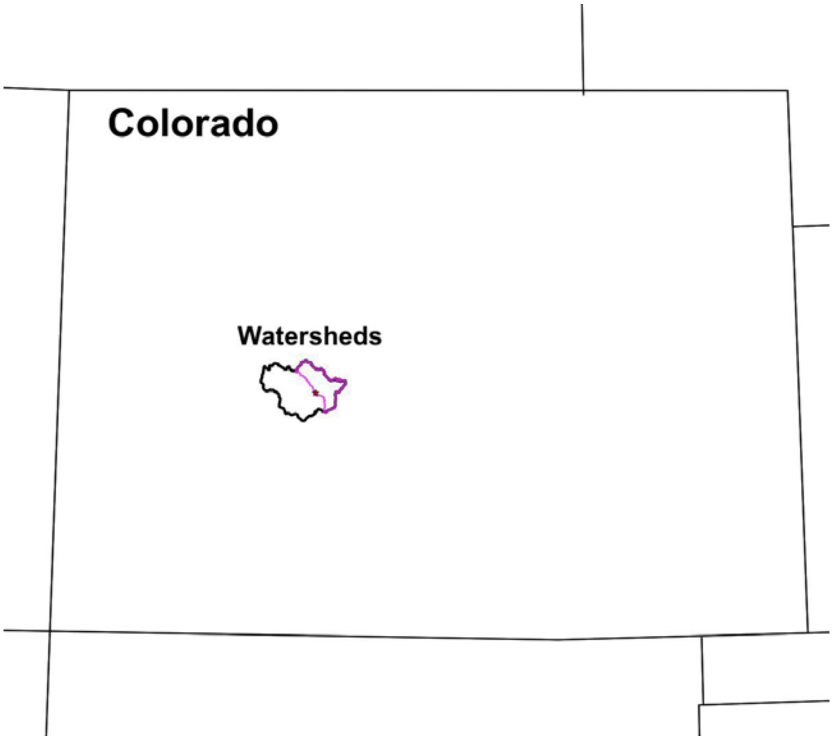



**Figure 1b:** Closer view of the East-Taylor (black outline) and Taylor Park (magenta outline) watersheds with Taylor Park Dam denoted by the red star. The Taylor Park watershed is a subset of the larger East-Taylor watershed. The larger East-Taylor watershed is used to calculate the basin-averaged precipitation in this report.

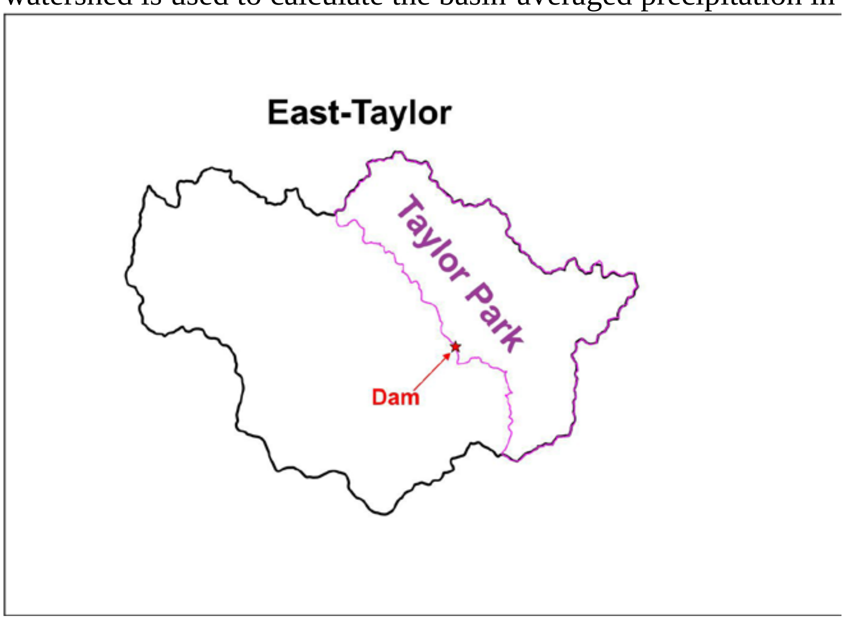


**Figure 2a:** Histogram of the heaviest 50, 100, 250, 500, and 1000 streamflow events at the USGS gage on the Taylor River.

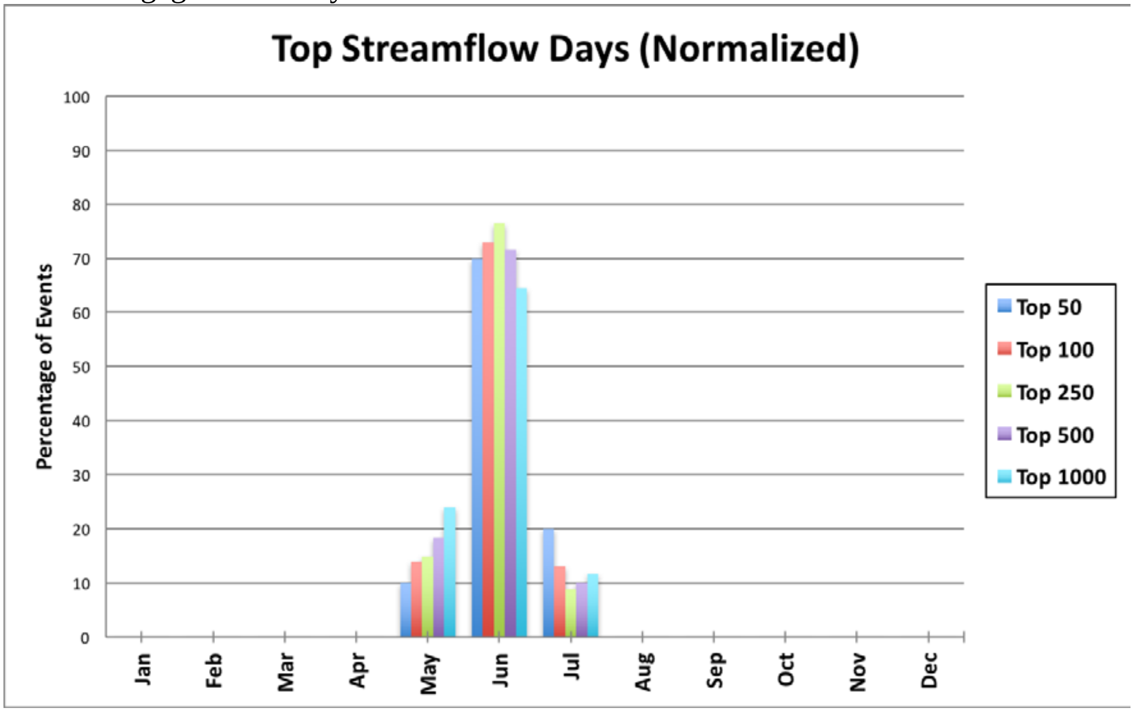



**Figure 2b:** Histogram showing the monthly distribution of heaviest basin-averaged precipitation days at the East-Taylor watershed.

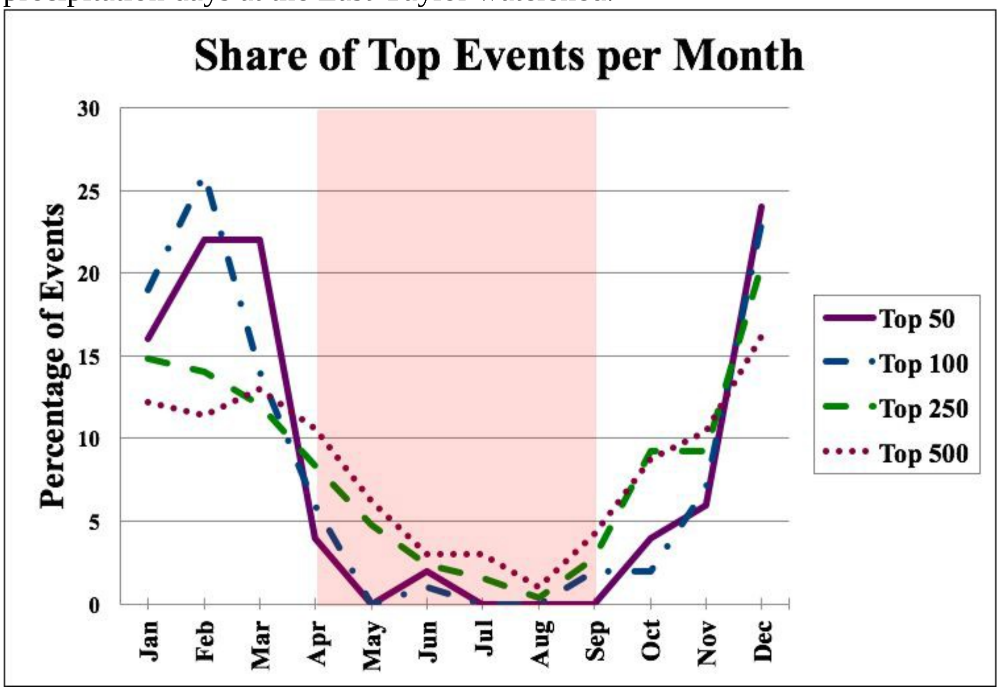


**Figure 3:** Areal extent of WRF model simulation domain. Also plotted are the East-Taylor watershed and Taylor Park Dam (red dot).

**Figure 4:** East-Taylor watershed-averaged precipitation plumes for the 16-20 June 1995 case. Ensemble members belong to microphysics (red) and stochastic (blue) perturbation families. Black dotted line denotes control member. Cyan line is observed precipitation at Taylor Park Dam.

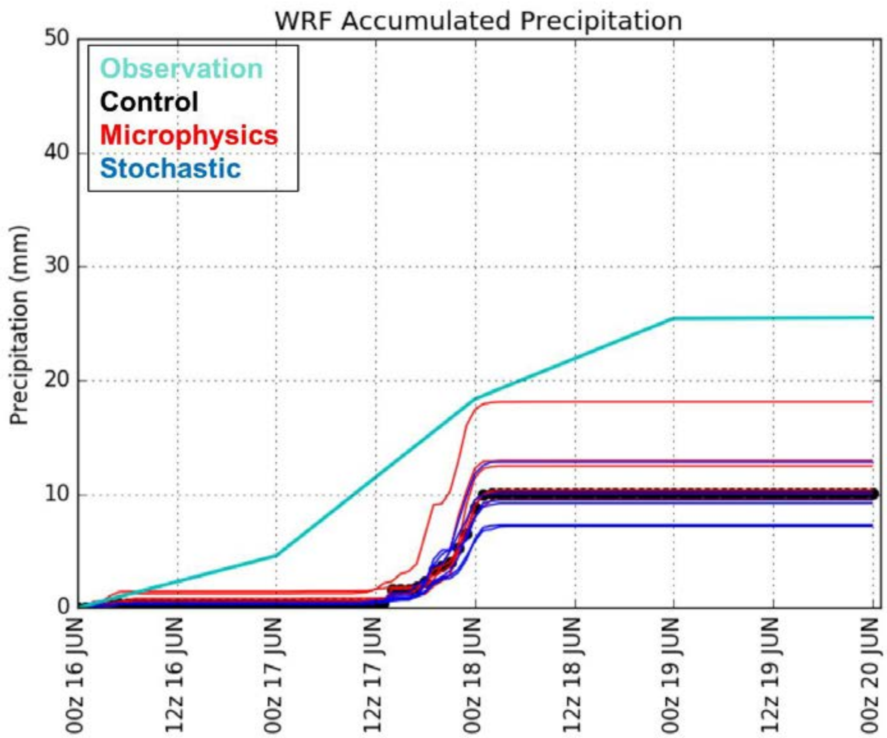


**Figure 5a:** Thumbnails of precipitation across Colorado for the 16-20 June 1995 case. Members were generated through microphysics (top row), stochastic (middle row), and lateral boundary condition (bottom row) perturbations. Red outline denotes East-Taylor watershed.

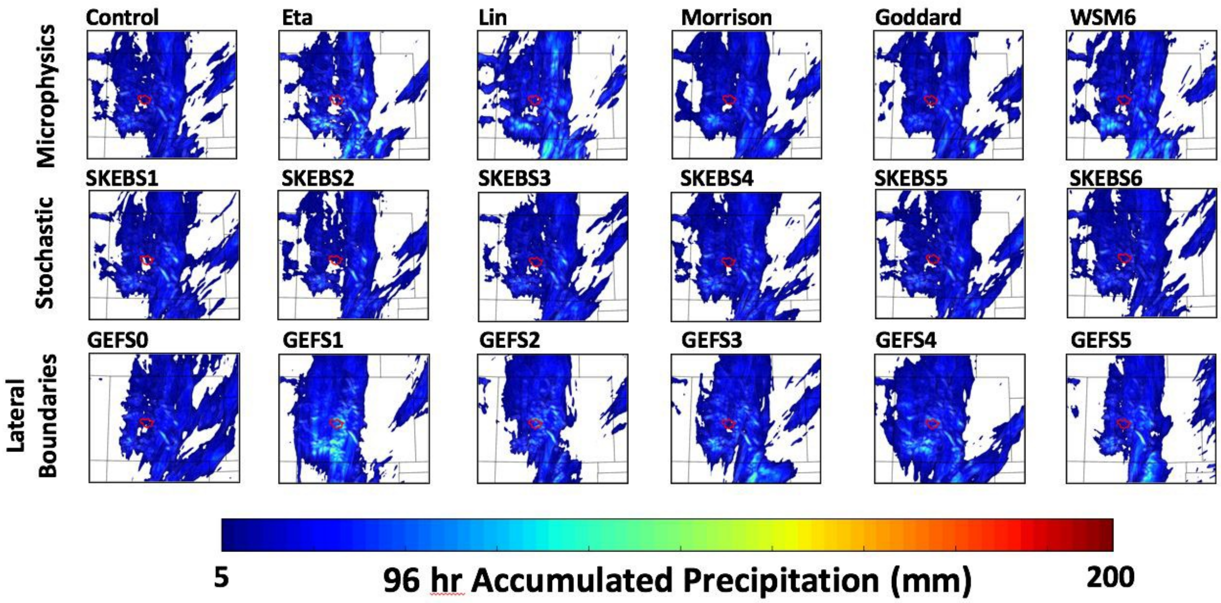


**Figure 5b:** Same as figure 4 with lateral boundary condition perturbation members (green) added.

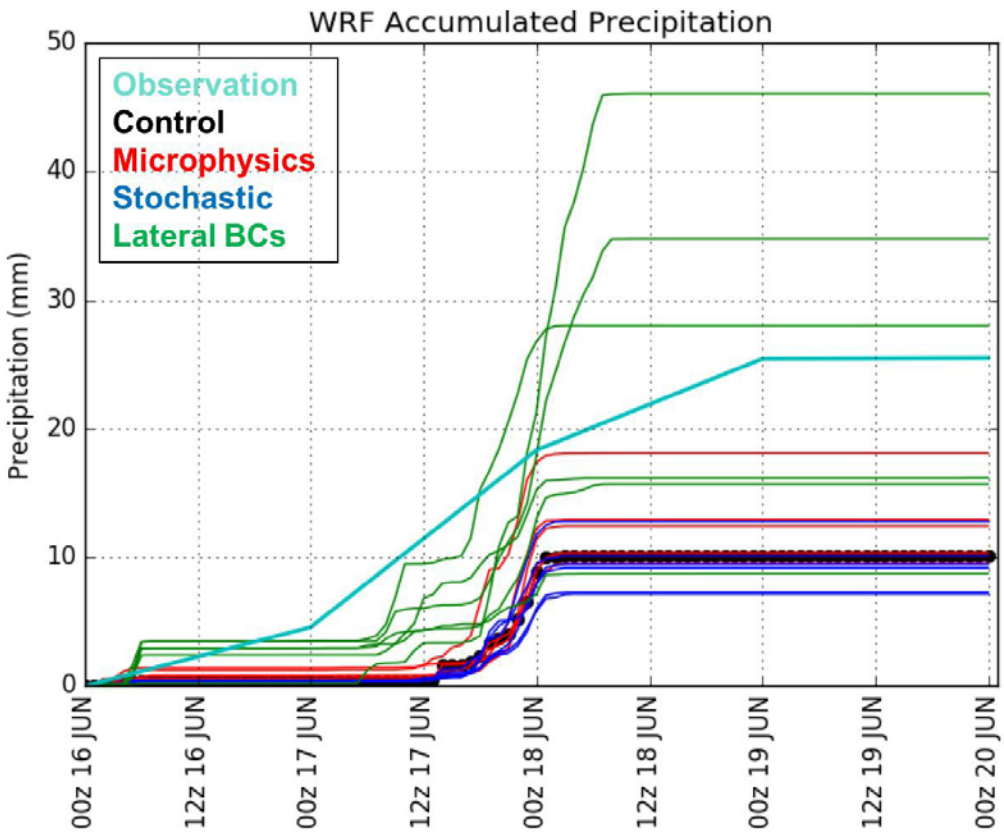


**Figure 6a:** Same as Figure 5a, except for the 6-10 May 2000 case.

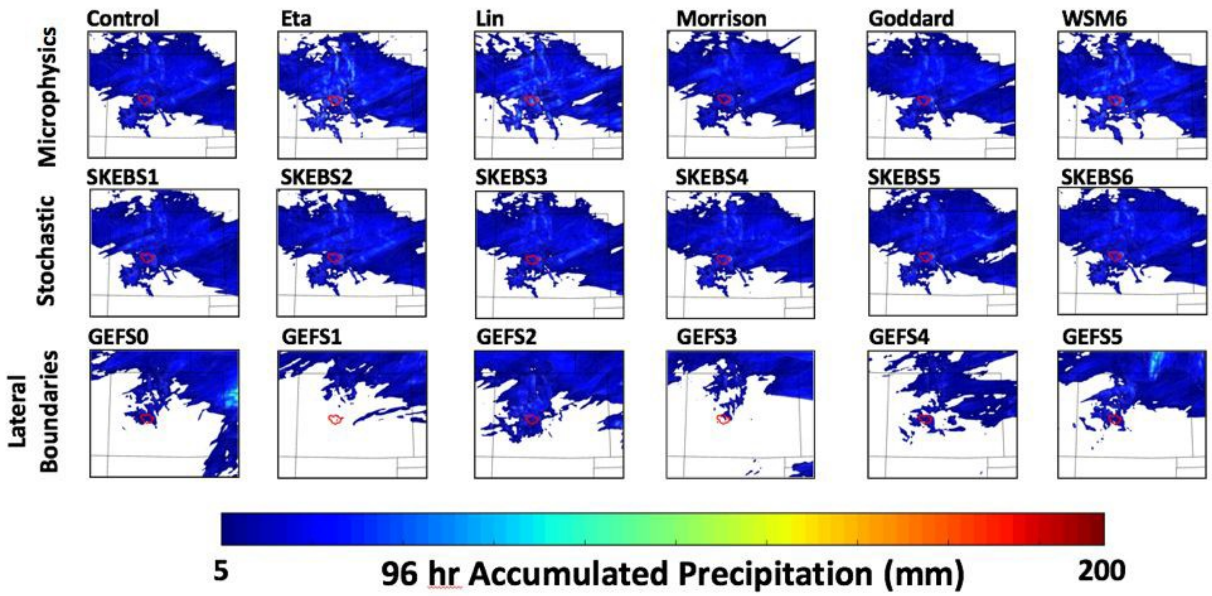


**Figure 6b:** Same as Figure 5b, except for the 6-10 May 2000 case.

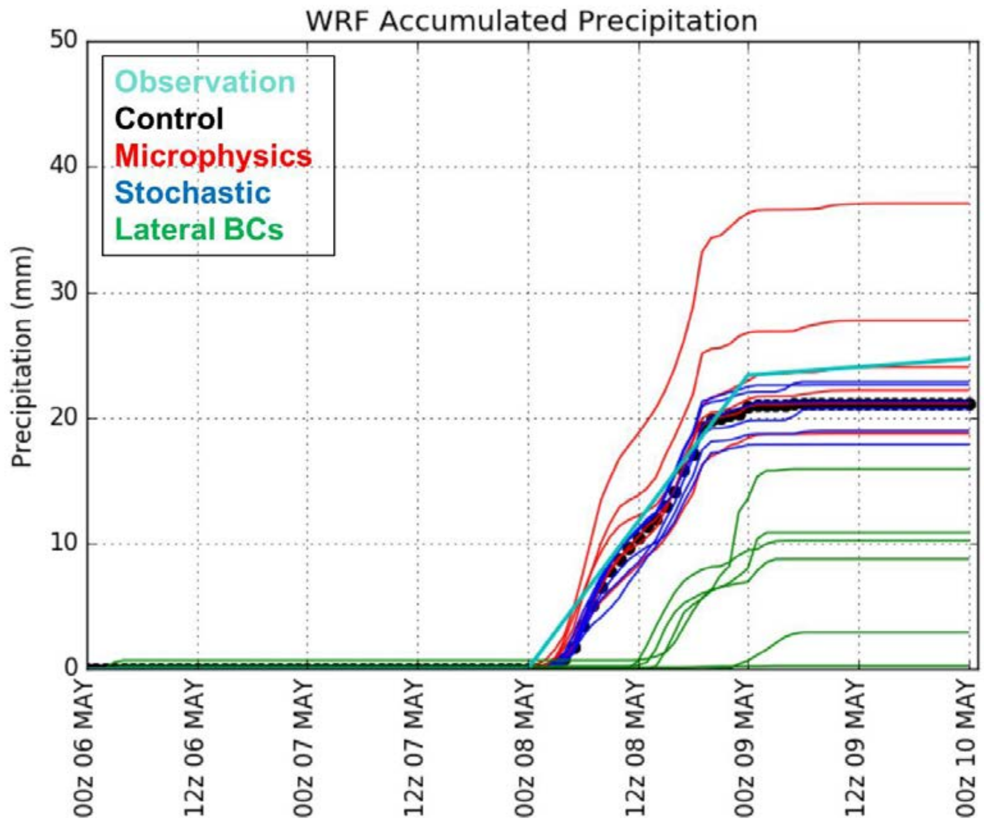



**Figure 7a:** Same as Figure 5a, but for the 25-29 July 2014 case.

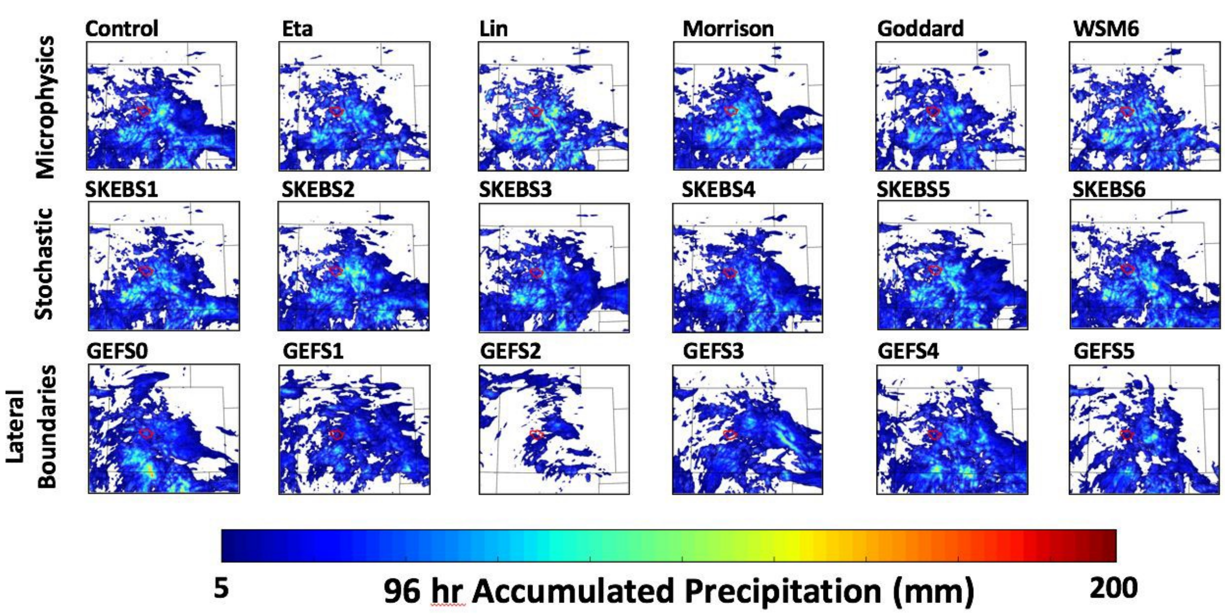


**Figure 7b:** Same as Figure 5b, but for the 25-29 July 2014 case.

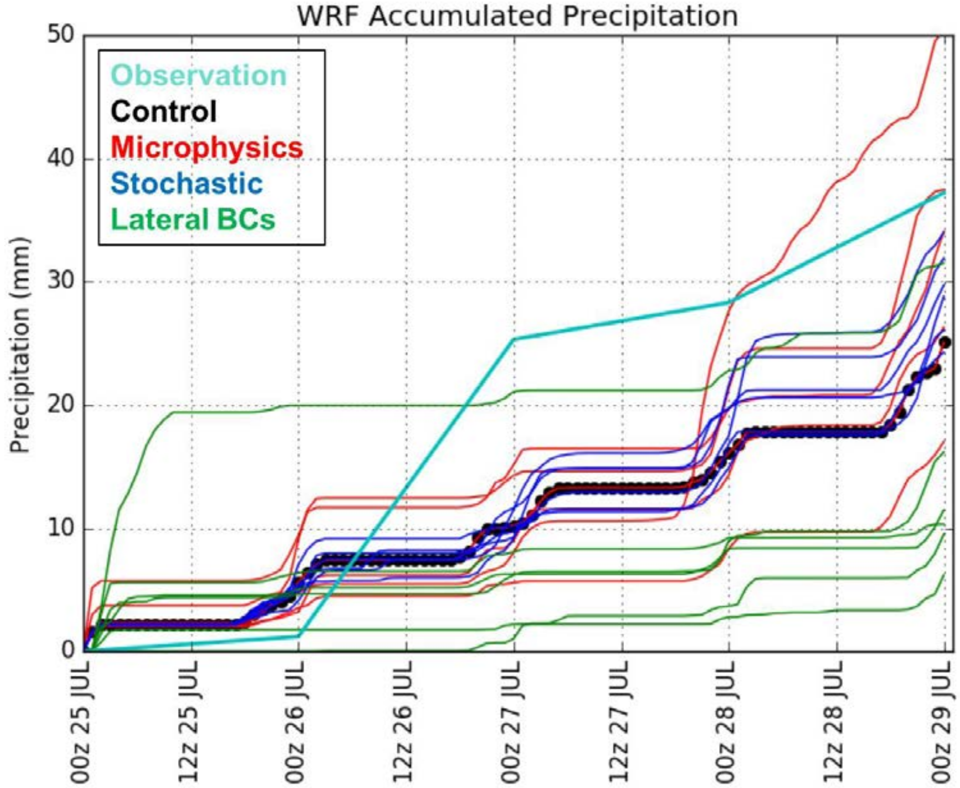



**Figure 8:** Maximum precipitation from all 18 ensemble members at each grid point.

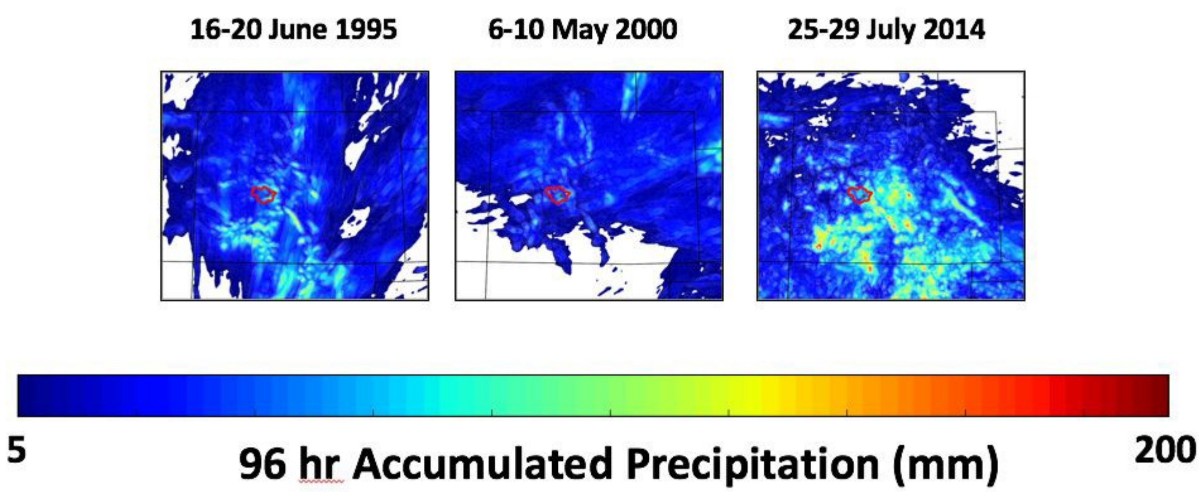


**Figure 9a:** Temperature (T) and specific humidity (Q) deltas at 700hPa for the four CESM members used. Note even the minimum temperature increase scenario increases temperatures 3-4C.

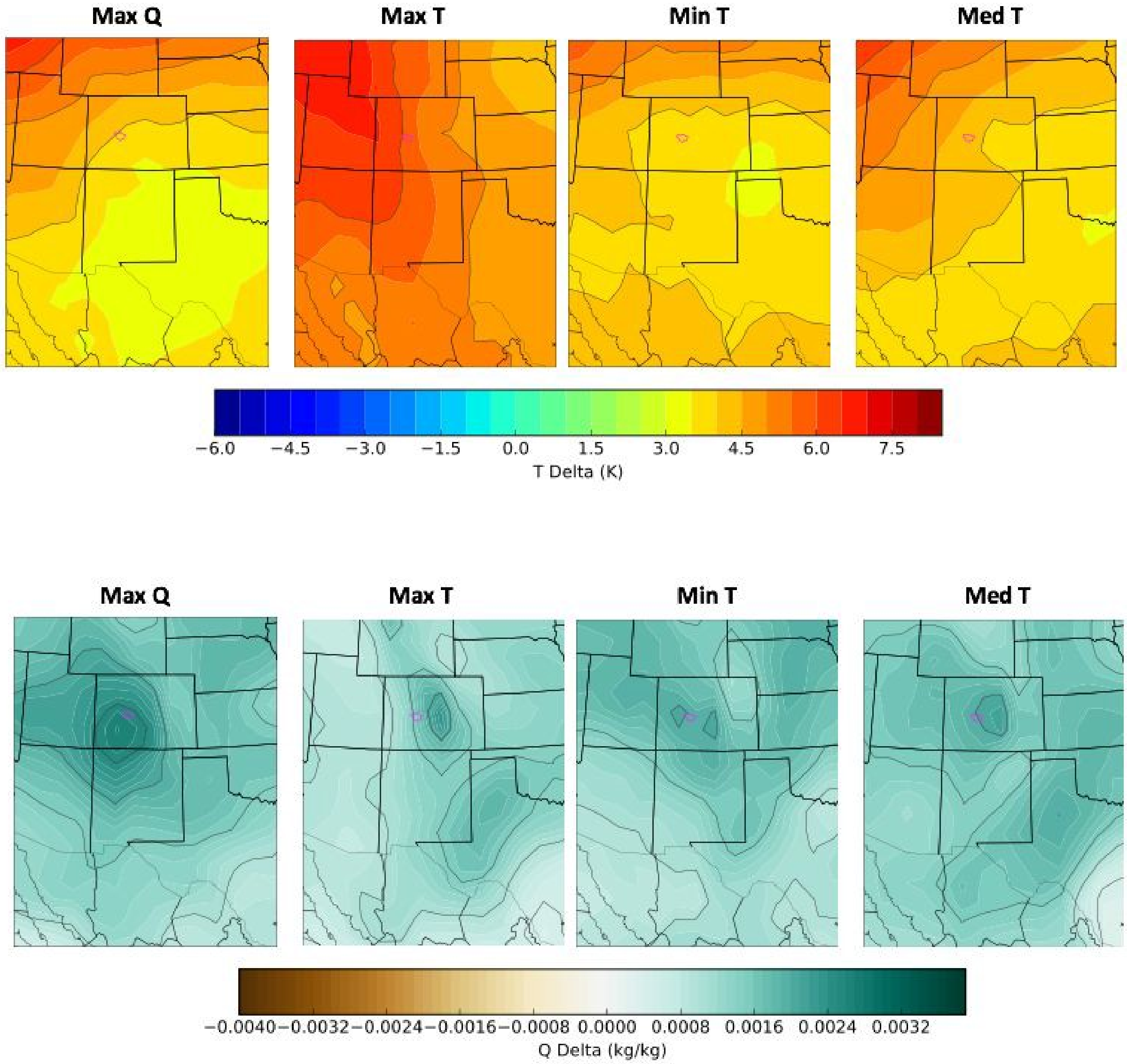


**Figure 9b:** East-Taylor watershed-averaged precipitation plumes for the pseudo global warming members (magenta lines) during the 25-29 July 2014 case. Cyan line denotes daily observations at Taylor Park Dam. The control run is shown as a black dotted line.

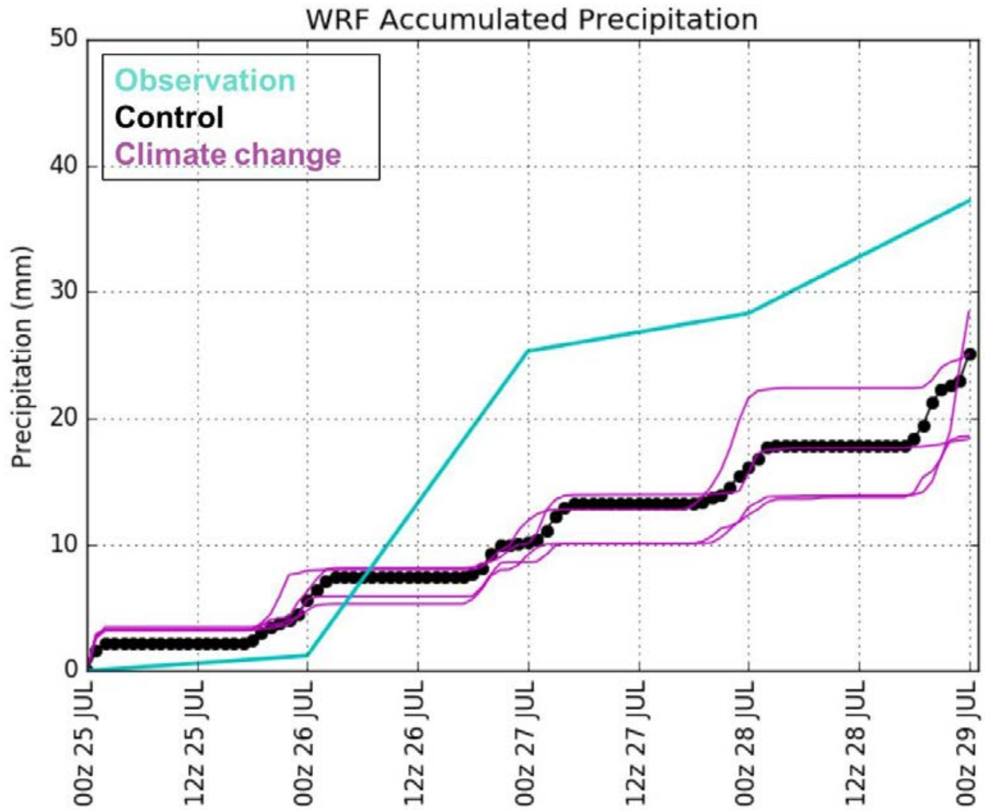
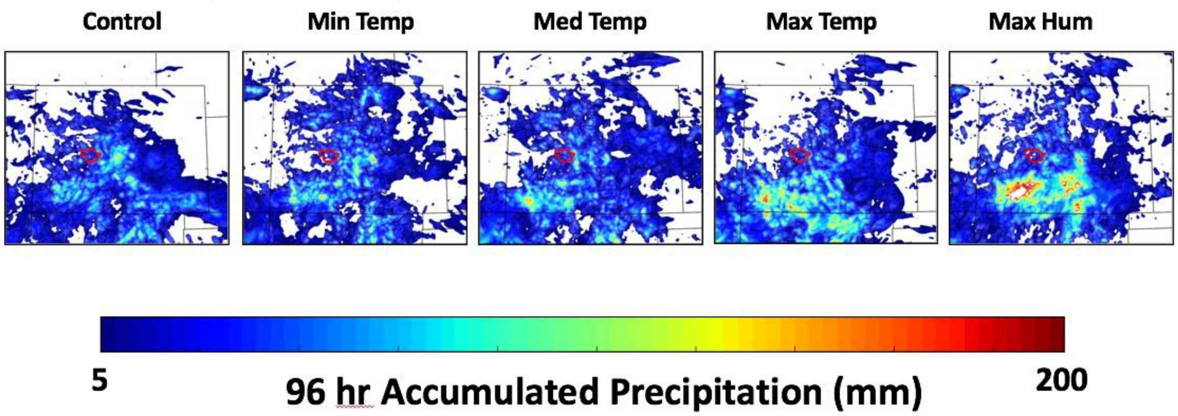



**Figure 9c:** Total (96-hour) precipitation for control and four pseudo global warming simulations during the 25-29 July 2014 event.



## Appendix

Reclamation Events of Interest

Reclamation provided a 10-event list of suggested test cases. These cases were: 13 June 1965, 19 June 1982, 7 June 1984, 27 May 1993, 18 June 1995, 21 June 1996, 8 June 1997, 8 May 2000, 2 June 2008, and 27 July 2014.

WRF Control Details

The control runs for this study were conducted using the Weather Research and Forecasting (WRF) model Version 3.6. Each case was 96 hours, centered on 00 UTC the day of the event. Initial and lateral boundary conditions were provided by 6-hourly Climate Forecast System Reanalysis (CFSR) data. The grid spacing of the simulation domain (4km) enabled explicit simulation of cumulus convective processes. Microphysics was parameterized by the new Thompson scheme. Noah land surface model and Yonsei planetary boundary layer physics parameterizations were also used.

Ensemble Member Details

An ensemble of 18 WRF members was developed and tested during this research. Ensemble members were designated as among three perturbation groups: Microphysics, Stochastic and Lateral Boundary Conditions. Microphysics members were produced using different microphysical parameterization schemes: Thompson (control), new Eta, Lin, Goddard GCE, Morrison and WSM 6-class graupel scheme. These members differed from control in no other way except microphysics scheme. Stochastic members were created by invoking the Stochastic Kinetic Energy Backscatter Scheme (SKEBS) in the model. To generate 6 different members, seed numbers (1,2,3,4,5 and 6) were supplied to the pseudo-random number generator within the SKEBS package. Lateral boundary condition members replaced CFSR lateral boundary conditions with data from Global Ensemble Forecast System members 0,1,2,3,4 and 5. The GEFS members were based on randomized perturbations. All members were the same as control except for their perturbations.

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# Appendix 2 NCAR Study on the Hydrologic Consequences of Using WRF-Modeled Heavy Precipitation Ensembles

**Improving extreme precipitation estimation using regional, high-resolution model-based methods:**

**Final summary for performance period February 2014 - 2016 CIRES-Reclamation Cooperative Agreement R11AC81334**

**ADDENDUM TO FINAL REPORT: NCAR Study on the hydrologic consequences of using WRF-modeled heavy precipitation ensembles**

**Submitted by: D. Gochis, A. Dugger and L. Karsten (NCAR)**

**Overview:**

The Taylor Park Reservoir serves as an important high elevation water resource reservoir for the Upper Gunnison River Basin Water Conservancy District. The dam was constructed to capture and store seasonal snowmelt and release that water for irrigation use to farmers further downstream in the Taylor-East River and Upper Gunnison River valleys. As discussed in the main NOAA/CIRES report a majority of annual precipitation falls during the cool season months of October-April. Months in which the heaviest precipitation rates are found are also found during these months. Conversely, high streamflow values contributing to total reservoir inflows into the Taylor Park Reservoir tend to peak during the months of May-July as seasonal snowpack melts. From these basic hydroclimatic considerations, it is assumed that a primary risk for severe flooding and possible reservoir spills or dam overtopping exists when heavy rainfall during the late spring or summer occurs in the watershed on top of peak seasonal streamflow values. The NOAA/CIRES climatological analysis revealed 3 event days from the core risk season for additional study using a the Weather Research and Forecasting (WRF) model as a dynamical downscaling tool:

June 18 1995
May 9 2000
July 27 2014

The primary NOAA/CIRES report details the justification for using an ensemble-based dynamical downscaling approach in the characterization of heavy rainfall uncertainty. The uncertainties in atmospheric processes contributing to heavy rainfall in sparse terrain are manifold and include uncertainties in cloud and precipitation microphysical processes, dynamical and thermodynamical initial condition uncertainty and uncertainty in model domain lateral boundary forcing. To address these uncertainties the

NOAA/CIRES team generated a set of 18 WRF model ensembles for each of the event days above and analyzed the resulting basin-averaged precipitation. For the 27July 2014 event they also generated an additional ensemble member that emulated a warmer climate by using the so-called ‘pseudo-global warming’ (PGW) approach. The results of those analyses are provided in the NOAA/CIRES approach.

In this Addendum, we explore the impact of the NOAA/CIRES WRF model scenarios on simulated hydrologic responses using an uncalibrated physics-based, spatially-distributed hydrologic modeling system called WRF-Hydro. The details of the hydrologic model implementation are provided below in the Task description. The goals of the hydrologic modeling study were to:

- Provide a baseline assessment of simulated runoff sensitivity from the WRF model against a limited set of hydrologic process scenarios due to vegetation disturbance and reduced infiltration due to frozen soils
- Assess the impact of the WRF-model generated precipitation ensembles on model simulated streamflow and reservoir inflow values

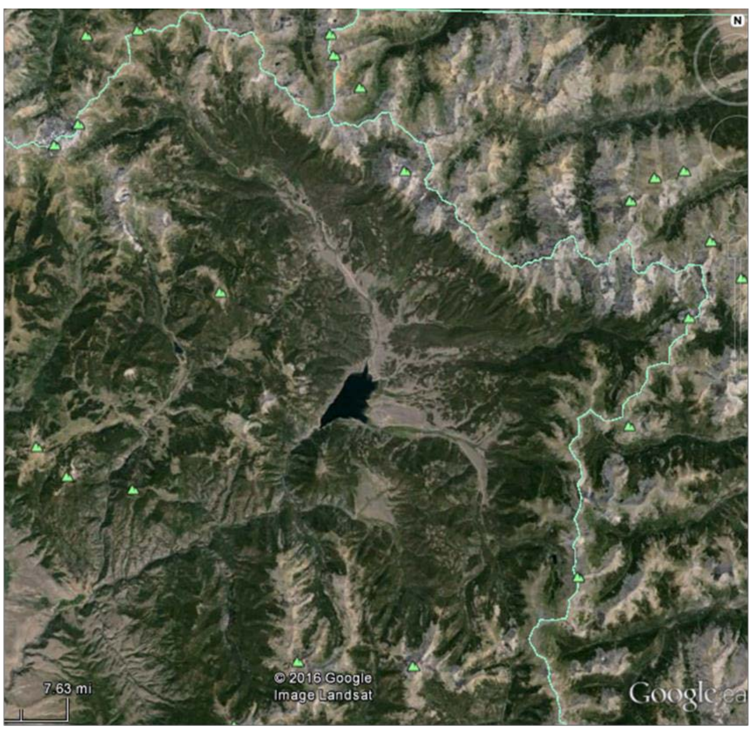



Figure 1: GoogleEarth View of the Taylor Park Reservoir and basin

The watershed contributing to flow into the Taylor Park Reservoir is dominated by steep terrain ranging from approximately 8,500’ to over 13,000’ and land cover is typically alpine and sub-alpine ecosystems on steep mountain slopes along with some lower elevation pasture and wetlands surrounding the Taylor Park reservoir. (See Fig. 1) Primary runoff generation mechanisms in the basin result from snowmelt inputs that fill soils and bedrock fractures, heavy rainfall on sloping terrain, and limitations in soil infiltration due to wildland fire, frozen soils or other land surface disturbances. Due to a paucity of important hydrologic observations in this region there is significant uncertainty as to exactly how and when such processes are important. Therefore, to place the WRF model ensemble precipitation analyses in context with associated uncertainties in hydrologic processes we have developed a set of simple 'end- member' experiments with the WRF-Hydro system to explore the impact of these hydrologic model uncertainties. In our findings below, we present results from a small set of experiments which modify the hydrologic model configuration and parameter specification as follows:

1. Reduce infiltration capacity by 50% AND convert forest to shrubland
2. Add a 'domain-wide' multiplier to the default quantitative precipitation estimate product used of 1.1 (plus 10%) and 2.0 (plus 100%). The WRF-Hydro simulated streamflow results from these artificially perturbed precipitation values will be compared against those from the WRF model ensembles.
3. Reducing a soil infiltration scaling parameter in WRF-Hydro by 50% and 75% percent from its default value.
4. Reducing a soil infiltration scaling parameter in WRF-Hydro by 50% and 75% percent from its default value and converting all forests in the Taylor Park watershed to shrubland to mimic the influence of widespread forest mortality such as from fire.

These latter 2 modifications are intentionally 'extreme' in order to better understand the sensitivity of runoff generation mechanisms related to surface runoff production.

**Tasks and Findings:**

The goal of the WRF-Hydro modeling effort was to explore the modeled hydrologic response to variable inputs of precipitation from WRF model ensembles and from the specification of uncertain hydrologic parameters. Our reference simulation for this work used a configuration of the WRF-Hydro system that was previously set up for a seasonal water supply forecasting project funded by the Colorado Water Conservation Board. (See Appendix for details on the model set up.) The long term retrospective model dataset used meteorological analyses provided by the 1/8th degree NCEP/NASA National Land Data Assimilation System v2. This dataset provides a long term set of hourly meteorological forcings required by the land surface models within the WRF-Hydro modeling system. [We note that NLDAS2 is somewhat different from the 1/16th degree Livneh et al. dataset but that we could not use the Livneh dataset for driving WRF-Hydro due to the fact that it only had daily values of precipitation and other meteorological variables.] Once reasonable long-term model performance was demonstrated we executed the various ensemble simulation experiments as discussed above. The details of the task description and results are provided below. It is noted there that *no basic-specific model calibration work was performed for the Taylor Park implementation*. All results were achieved using the implementation of the WRF-Hydro model that has been used for the aforementioned seasonal water supply forecasting project. Hence the results shown do exhibit some underlying biases but we believe those bias structures do not significantly detract from assessing the model sensitivity in the various set of ensemble simulation experiments.

**Task 1: Conduct a set of hydrologic model ensemble simulations using existing quantitative precipitation estimates to establish the sensitivity of runoff responses to precipitation and hydrologic model parameters (Note that this Task as stated is an amalgamation of Tasks 2.1-2.5 from the original Statement of Work):**

The results of the WRF model precipitation ensembles were provided in the main project report from NOAA-CIRES. Results from the daily-averaged streamflow analysis for the May 8 2000 event (Figure 3) indicated there is an underlying positive bias in streamflow in the uncalibrated WRF-Hydro model during that year. This bias appears to come from diurnally-driven snowmelt runoff as evidenced by the strong diurnal cycle in simulated flows early in the simulation period (not shown, but available). This bias could potentially be eliminated via calibration of the hydrologic model. Overall, while the correlation in modeled vs. observed streamflow is good during the principle simulation period, the modeled flows exhibit much greater variability than do the observations. Specifically, streamflow tends to decrease aggressively during the first several days, even during the precipitation event suggesting that precipitation during this event may have been more snow than rain and that cooler temperatures during the event may have acted to slow snowmelt. The modeled flows then increase more aggressively compared to observed flows. Rains for the May 2000 event fall largely on the eighth. There is very little runoff response in the observations until May 11 when there is a slight uptick in flow from 250 to approximately 300 cfs. Most of the WRF-model ensembles show this aggressive variability. Exceptions to this behavior include the GEFS-driven WRF ensembles (see the raster timeseries in the left panel for a clearer view) while other WRF-model ensembles tend to decrease and increase more aggressively. Beyond the primary event period (right of the black line) all results begin to become more similar to each other since they are all driven by the same NLDAS2 forcings. Overall, both the observed flows and the model runs decrease during the event and the event pulses appear to be a fairly minor anomaly on the seasonal cycle during this melt year.

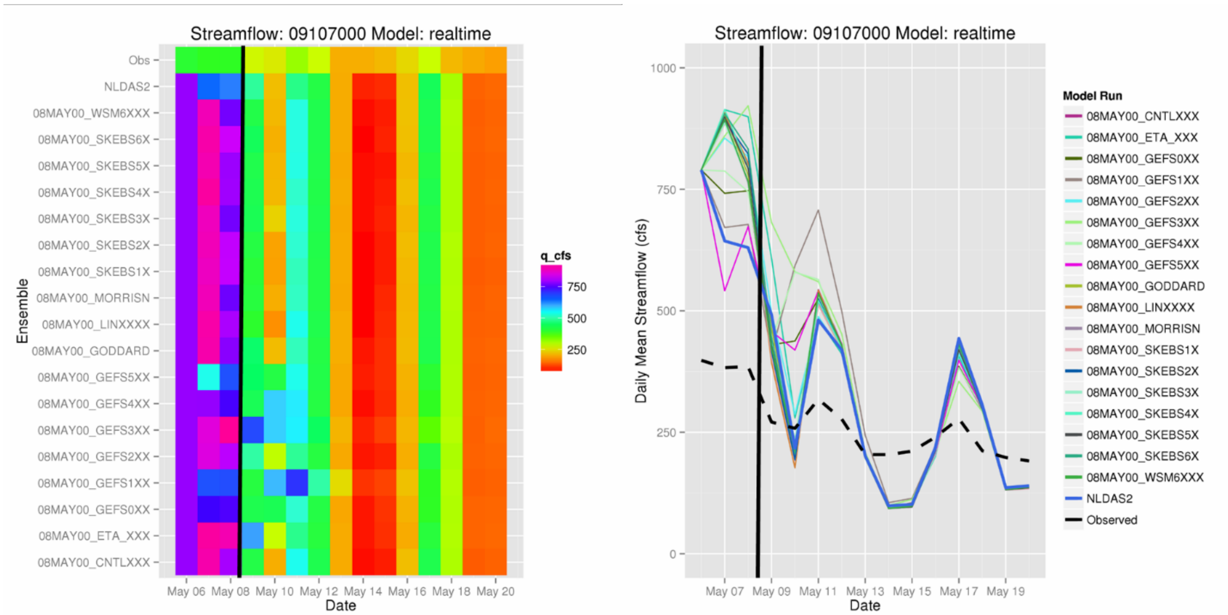



Figure 3: (left) Raster time-series of observed, NLDAS-driven and WRF-model ensemble driven daily-average streamflow values, and (right) Standard 'spaghetti' plot of observed and simulated streamflow for the May 8 2000 runoff event. Vertical black lines indicates the end of the 96-hr WRF model simulation period.

Observed streamflow into Taylor Park Reservoir, WRF-Hydro default streamflow simulation results and WRF model ensemble-forced for the 28 July 2014 case are shown in Figure 4. In contrast to the May 2000 case there is only slight positive bias at the time of model initialization. All observations and the WRF- model ensemble members then increase in response to the heavy rainfall event then slowly recess over the next 2-3 days. The ensemble streamflow values generally bound the observed flow conditions with members both higher and lower than the observed peak flow value. The ensemble raster timeseries plot in Fig. 4 shows that the NLDAS2 analysis, SKEBS6, MORRISON and ETA WRF-ensemble members tended to show the most similar peak flow values as did the observations. The LIN mircophysics ensemble member appears to be the lone outline of this event generating a peak flow value well in excess of 2 times the observed peak flow. Rainfall plots from that ensemble member from the primary NOAA/CIRES report suggest a strong, localized maximum in the Taylor Park region. Following the WRF model ensemble simulations streamflow fall into a very similar pattern. A large event on Aug. 2 also occurred as evidenced in the streamflow observations but the NLDAS2 forcing appeared to generate too extreme of a streamflow response. Conversely later on Aug. 6-7 another event occurred although this latter event tended to be underestimated by the NLDAS driven WRF-Hydro simulation. In summary, the combined WRF model precipitation ensembles and WRF-Hydro modeling system appeared to provide reasonably skillful representations of the July 27, 2014 high flow event. Although magnitudes of streamflow increases in the model were not as pronounced as observed flows, there appears to be reasonably good correlation of the flow values in time.

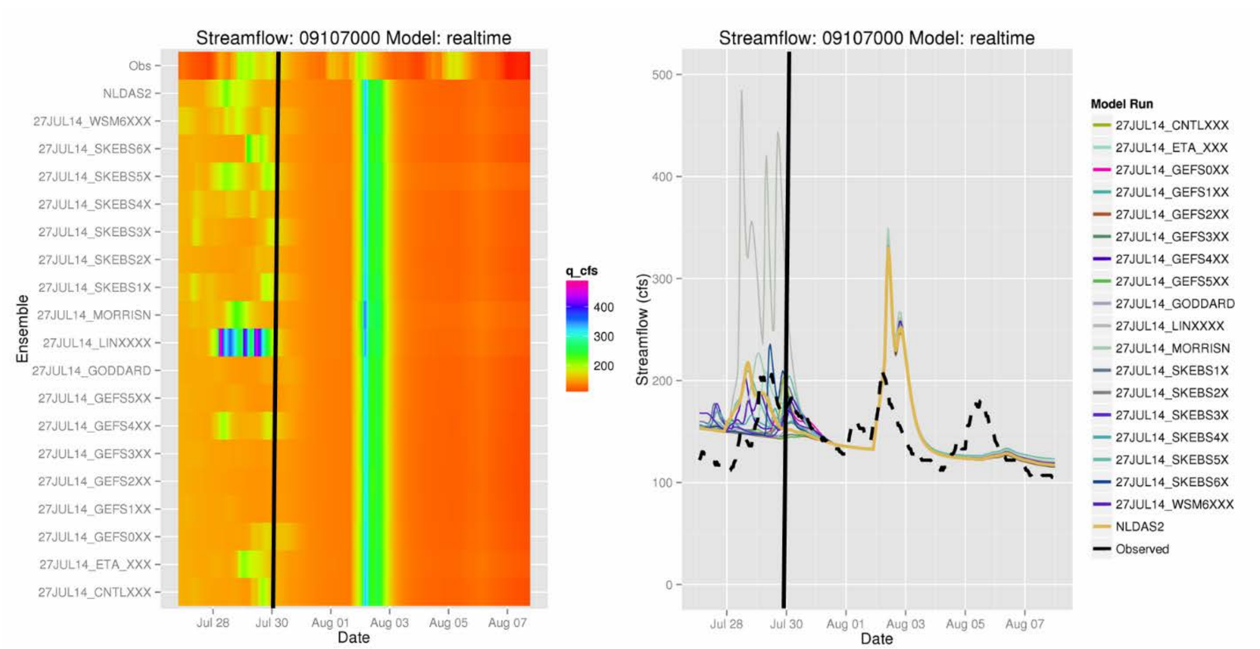



Figure 4: (left) Raster time-series of observed, NLDAS-driven and WRF-model ensemble driven daily-average streamflow values, and (right) Standard 'spaghetti' plot of observed and simulated streamflow for the 28 July 2014 runoff event. Vertical black lines indicates the end of the 96-hr WRF model simulation period.

**Task 2: Conduct a set of hydrologic model ensemble simulations using NOAA/CIRES generated WRF model precipitation ensembles to assess the viability of using WRF model precipitation ensembles in dam safety studies in remote mountain regions:**

In addition to the WRF ensemble simulations a set of idealized hydrological model and forcing perturbation experiments were also conducted to explore some of the inherent model sensitivities and to try to bound the responses seen in the model with some fairly extreme scenarios. The results of these experiments for the runoff season leading up to the July 27 2014 event are shown in Figure 5 where the default or 'control' run is the unperturbed NLDAS-driven run from Fig. 4 above.

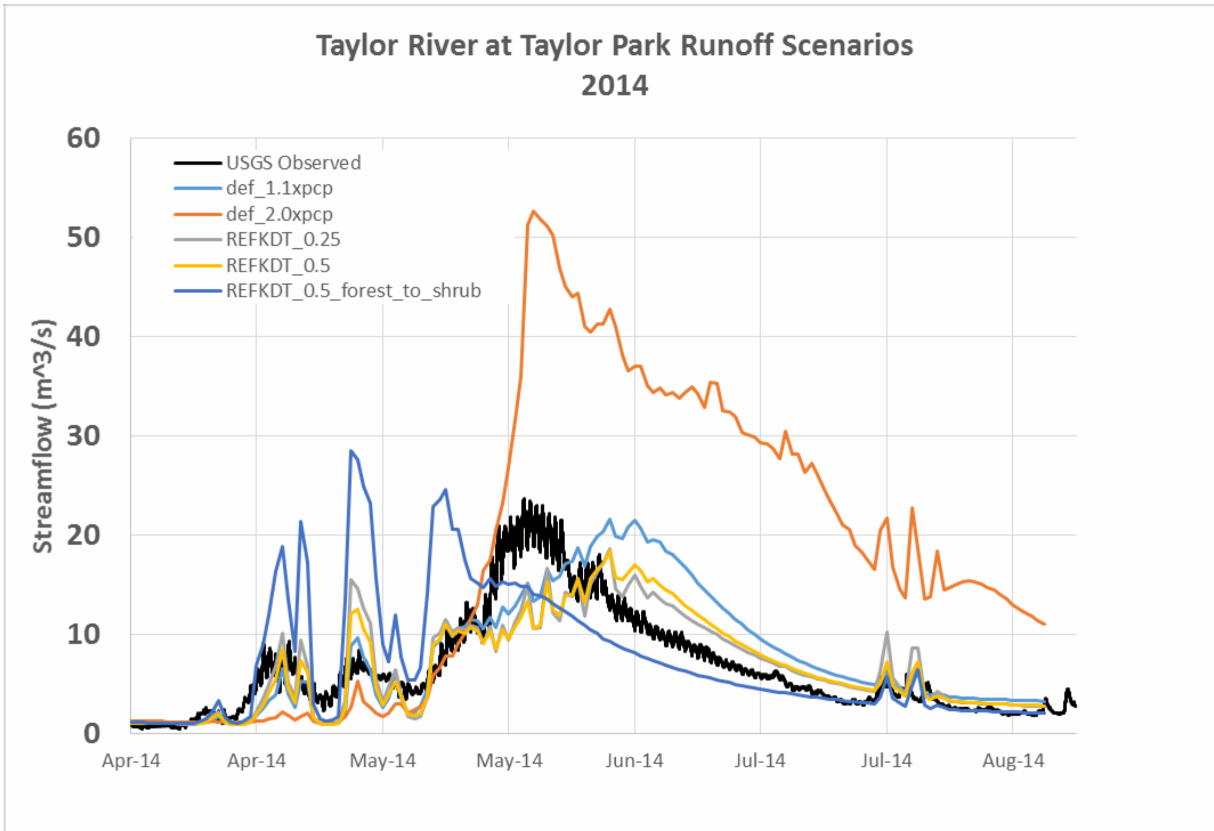



Figure 5: Simulated hydrographs from idealized WRF-Hydro model perturbation experiments for the season leading up to the July 28 2014 event. [Note units are in cubic meters per second.

The main findings from the sensitivity experiments are as follows:

1. The doubling of precipitation values across the simulation period clearly have the largest impact in both timing and runoff amount with large peak summer flow. The large amount of precipitation in that run appears to have delayed snowmelt runoff responses to some degree resulting in diminished spring runoff but dramatically larger summer peak flow. Peak flow values form this run in excess of 1,700 cfs (50 cms) are significantly larger than observed and modeled peak flows of either of the other events suggesting that high precipitation values play a very important role in peak streamflow conditions but potentially in an indirect or time-delayed fashion.
2. Precipitation multiplier value of 1.1 to season long precipitation as well as modest changes to the infiltration capacity scaling factor (REFKDT) imparts a small to modest sensitivity to simulated streamflow.

3. Reduction in infiltration capacity scaling factor, from 0.5 to 0.25, increases individual event peaks but decreases peak seasonal flow and seasonal recession flows in June 2014. This behavior implies that only modest changes in surface versus subsurface runoff partitioning are found under this range of this parameter.
4. Conversion from forest to shrub appears to accentuate snowmelt as well as further reduce spring infiltration increasing spring event peaks but dampens summer peak
5. The runoff events in July 2014 appear to be most sensitive to the precipitation doubling scenario and the model experiment with the smallest value of the infiltration scaling factor.

Overall this very basic sensitivity experiment suggests that fairly large perturbations to precipitation and/or fairly dramatic reductions in infiltration capacity would be needed to generate appreciable differences in event-scale runoff responses. Additionally, these perturbations still produce fairly modest increases in summer event streamflow for the July 2014 event compared to the magnitude of normal peak flow values already observed during the peak spring runoff period.

**Summary:**

Overall the WRF-model ensembles tended to produce events that corresponded well in time with observed rain pulses (as described in the NOAA/CIRES report) and thus produced runoff events that correlated well with observed runoff events. For the May 2000 event the uncalibrated WRF-Hydro model exhibited a significant positive bias in initial flow conditions and larger variability than observed flows but flow peaks and recession characteristics were well matched in time with observations. The cause of the strong initial condition bias is not known but could be related to a lack of model calibration or biased forcing data leading up to the event period.
Observed and modeled flow correspondence during the Jul 2014 event was also good. During this latter event, the WRF-model driven ensembles appeared to bound the observed flow conditions fairly well. One extreme model outlier, from the LIN microphysics ensemble member, exists for the 2014 event.
This reasonable modeled flow behavior suggests the following conclusions:

- The WRF model ensembles appear able to produce forcings of reasonable timing and intensity as do observations.
- The WRF-Hydro model appears to reasonably translate the WRF-Model meteorological forcings into hydrologic responses that have good correlation with observed flows.
- Initial condition biases in the May 2000 event appear to condition the model states to produce excessive runoff variability compared to observations although the impact of this reduces as time proceeds in the simulation. Such a bias or excess variability was not present in the Jul 2014 case.

Idealized WRF-Hydro model sensitivity tests showed that the model responds most significantly to high precipitation perturbations. Reductions in infiltration capacity in this snowmelt dominated system did change runoff partitioning behavior between fast surface runoff and baseflow processes but the overall impact of the partitioning changes explored here were not very large. Changing forest to shrubland along with a modest reduction in infiltration capacity appeared to produce strong springtime melt pulses and decreased summer flows. As such, a large scale vegetation conversion such as this may suggest that there is increased vulnerability to high flow events in the springtime but potentially less in the summer.

Overall the proposed method of using WRF model meteorological ensembles along with a physics based hydrological model appears to provide a feasible means of assessing certain aspects of hydrologic risk and understanding the impact of uncertainty in precipitation forcings on simulated streamflow. However, more detailed quantification of risk requires additional work in hydrologic model calibration and in understanding the particular risk thresholds for the infrastructure in question.

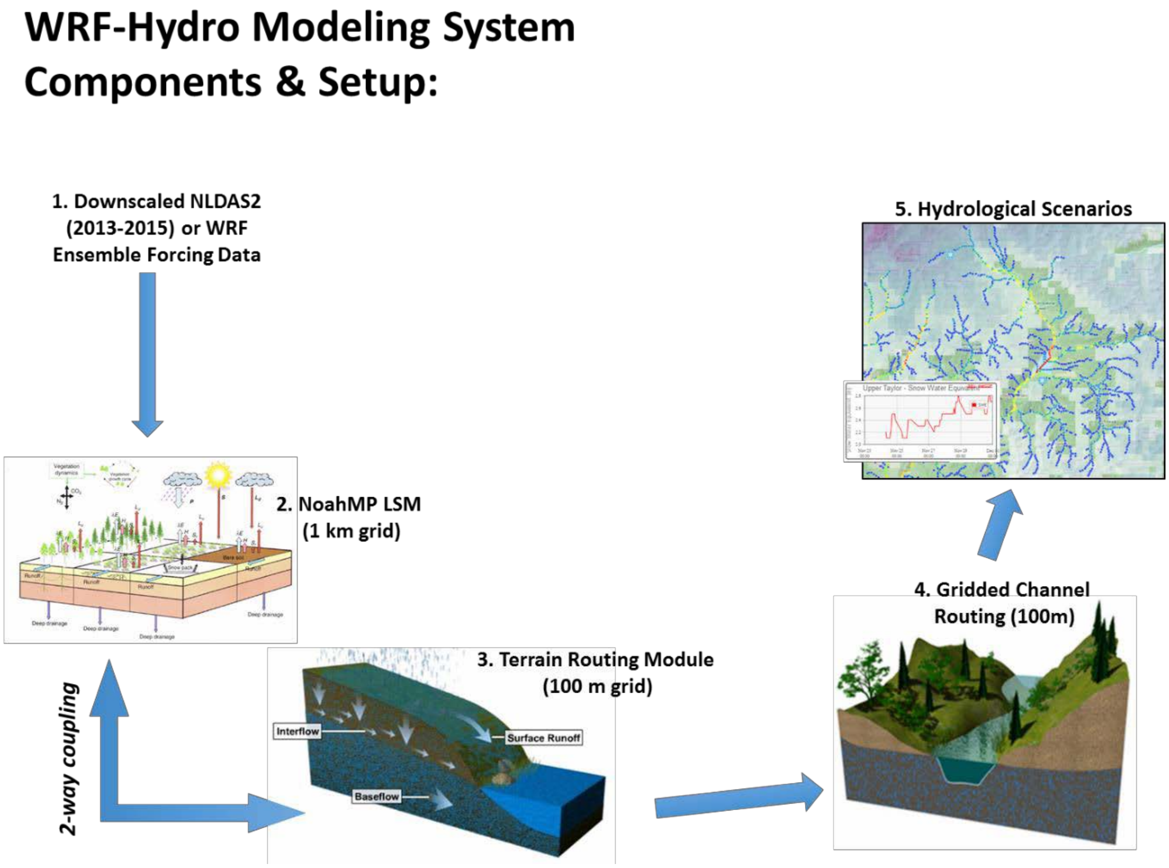
**APPENDIX:**

As part of a broader project funded by the State of Colorado and the Bureau of Reclamation WaterSMART program, the community WRF-Hydro modeling system was set up to simulate terrestrial hydrologic processes for a large region of southern Colorado and New Mexico. This model domain encompassed the Taylor Park and East River basins. WRF-Hydro is a multi-scale modeling system and the column land surface model was set up at a 1km resolution on a regular grid while terrain and channel routing processes were set up to run on a 100m grid. The main modeling workflow was setup as is shown in Appendix figure below. The default model runs were driven by topographically downscaled by NLDAS2 meteorological forcing data and the model was spun up for a 3 years prior to the primary event periods. WRF-Hydro has multiple physics options for its configuration. For this study we used the following physics options:

- NoahMP column land surface model
- Diffusive wave overland flow
- Saturated subsurface flow
- Empirical exponential baseflow parameterization
- Gridded diffusive wave channel flow

For the default model run, driven by NLDAS, the long-term model execution was used. For all other WRF- model ensemble-driven runs, the WRF-Hydro restart file created from the long-term spinup at a time 6 hours into the WRF model forecast was used as the initial conditions for the ensemble member simulation. Similarly we discarded the first 6 hours of the WRF model simulation to minimize the effects of atmospheric spinup. The WRF-model driven runs were then executed forward for 90 more hours to the end of the WRF model simulation. After 90 hrs, the NLDAS forcing was used again as forcings for the next 11 days for all model simulations in order to let the event fully drain out.

Therefore, simulation results following the 96 hr period of WRF forcings used become increasingly similar. Modeled streamflow data and land surface model data were output from WRF-Hydro hourly.



# Appendix 3 Diagnosing the Moisture Sources for Extreme Precipitation Events in the Western US: Application to Hydrologic Hazard Analyses

Final report for COLLABORATIVE PROJECT between CIRES and the Bureau of Reclamation: FY14/15

**Diagnosing the moisture sources for extreme precipitation events in the western US: Application to hydrologic hazard analyses**

**March 28,2016**

**1. Background**

It is important to both scientists and water managers to better understand the synoptic (weather-related) and climatic processes that influence heavy precipitation events in the US intermountain west (IMW). This research has the potential to better inform decisions about dam safety and flood hydrology, for example by helping to guide storm transposition for estimating maximum precipitation. In addition, there is the potential to improve longer-term outlooks through a better understanding of how these extreme events are related to climate variability and change.

Atmospheric rivers (ARs), long narrow bands of enhanced water vapor transport, are the dominant mechanism for generating intense precipitation events along the west coast of the US during winter. While studies have extensively explored the impact of ARs on the temperature and precipitation west of the Sierra Nevada and Cascade mountain ranges, the influence of ARs on the weather in the intermountain west remains an open question. For example, does much of the moisture transport occur through narrow gaps in the mountains or can it remain in the atmosphere after passing over higher topography? ARs primarily occur in winter but does their impact on precipitation in the interior west vary from fall to spring? Are the heavy precipitation events always associated with ARs or are their other ways to generate them?

Findings from the previous project with Reclamation in FY12/F13 demonstrated that air parcels take unique pathways and/or have multiple moisture sources to retain enough water vapor to have intense precipitation events in states such as Arizona, Colorado, Idaho and Utah. We continued our investigation of extreme precipitation events and their relation to ARs in the US intermountain west, with a focus on watersheds/facilities that are of interest to Reclamation. The methods developed are applicable at many sites throughout the West such that the actual site of interest can be defined by Reclamation based on dam safety priorities.

**2. Purpose**

The purpose of our study was to address questions related to Reclamation and NOAA/CIRES research needs in the area of understanding extreme precipitation events in the western US, including:

1) How can the results best be used to address water resource management and dam safety issues? What information, technology and data need to be transferred from CIRES/NOAA to Reclamation to facilitate this process?
2) What are the preferred pathways for moisture to reach the inter-mountain west?
3) How do the moisture sources and synoptic processes, especially ARs, influence extreme precipitation events over key dam locations and the surrounding watersheds?
4) Is there utility in using ensembles of model simulations to explore the range of plausible storm outcomes? Can they provide improved estimates of very heavy precipitation amounts? Can they provide guidance on different path of storms and provide guidance on regions where storm translation is physically plausible?
5) How are the pathways/extreme events influenced by climate factors including global warming?

**3. Tasks**

**Task 1: Transfer to Reclamation the data, information, methods and documentation developed by CIRES and NOAA under the FY12/13 CIRES agreement to study extreme events**

The original AR/trajectory in FY12/13 research developed the knowledge base and prototype tools to diagnose the causes of heavy precipitation. The following analysis tools and datasets were developed from this effort and transferred or made available to Reclamation in FY14/15:

*1) Heavy Precipitation from Station Data:*

a) 1-Day Maximum events:

This is an analysis of 2167 "reliable" stations (obtained from the Global Historical Climatology Network (http://www.ncdc.noaa. gov/oa/climate/ghcn-daily/) in the western US that had reported at least 80% of days during 30 consecutive years. The maximum 1-day precipitation total is reported at each station and then the stations are sorted in ascending order from smallest to largest event. There are different arrays for the precipitation total, station name, latitude, longitude, elevation and the year month day of the event. This was done by month, 3 month season (DJF, MAM, JJA, SON) and cold season (Oct-Apr).

b) 3-Day Maximum events:

Similar to the 1-day events, the same 2167 stations were sorted based on 3-day precipitation totals.  This was done with the same cold season, seasonal, and monthly breakdown.

c) Percent Annual precipitation events (1-day and 3-day):
This is an analysis of the same data, except maximum events are determined not by the total precipitation, but by the percent of the annual climatology the event registered (100* total precipitation / annual mean). Similarly these files are restricted by month, season or cold season.

d) Regional 1-day events:
These are the precipitation events we used in the "Moisture Pathways" paper for 6 intermountain west regions (see Fig. 2 in Alexander et al. 2015, J. Hydromet.). In this analysis all stations in the designated region are considered and the top 350 regional events are sorted by 1-day maximum precipitation totals. The same station can repeat in the top 150 many times.

*2) Access to the Livneh precipitation data set:*

Gridded precipitation from a high-resolution (1/16 °) dataset recently developed by Livneh et al. (2013) was made available to Reclamation over the conterminous United States and the Columbia River watershed in southwestern Canada for the years 1915–2011. It is derived using daily observations from approximately 20,000 NOAA Cooperative Observer stations. The daily data are rescaled so that the long-term monthly climatology equals that from the Parameter-Elevation Relationships on Independent Slopes Model (PRISM; Daly et al. 1994, J. Applied Meteorology). The Livneh dataset likely provides a reasonably good representation of precipitation in the IMW because of its higher resolution and explicit treatment of topography.

Livneh, B., E. A. Rosenberg, C. Lin, B. Nijssen, V. Mishra, K. M. Andreadis, E. P. Maurer, and D. P. Lettenmaier, 2013: A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States: Update and extensions. J. Climate, 26, 9384–9392, doi:10.1175/JCLI-D-12-00508.1.

Livneh B**.**, T.J. Bohn, D.S. Pierce, F. Munoz-Ariola, B. Nijssen, R. Vose, D. Cayan, and L.D. Brekke, **2015**: A spatially comprehensive, hydrometeorological data set for Mexico, the U.S., and southern Canada 1950-2013, *Nature Scientific Data*, 5:150042, doi:10.1038/sdata.2015.42.

The data is available through: http://www.colorado.edu/lab/livneh/data

*3) Back Trajectories*

Backward (in time) air parcel trajectories, based on the three-dimensional wind field obtained from CFSR were computed using a method originally developed at the University of Melbourne (http://www.cycstats.org/trajectories/trajhome.htm;, which we modified to provide additional output including the surface pressure. Trajectories were computed for the top 150 one-day precipitation totals that occurred at stations within each of the six regions shown in in Fig. 2 of Alexander et al. (2015, J. Hydromet). The trajectories were initiated from the four Climate Forecast System Reanalysis (CFSR) grid points surrounding the station that recorded extreme precipitation event and were initiated at the four 6-hour intervals on the day the event occurred. We used trajectories starting at a single pressure level located between 50 and 100 hPa above (at a lower pressure than) the surface. For example, if the surface pressure was 827 hPa, trajectories were initiated at 750 hPa level. We chose this level, which is generally located in the upper boundary layer/lower free troposphere, because it was high enough so that nearly all (> 99%) of the trajectories remained above the surface over North America but was low enough to be located within the region of strong water vapor transport. A total of 2400 trajectories (150 independent events **x** 4 CFSR grid points **x** 4 times per day) were initiated in each region. The position of a trajectory is computed backwards in time over the five previous days at one-hour intervals using the six-hourly three-dimensional CFSR wind fields.

Alexander M. A., J. D. Scott, D. Swales, M. Hughes, K. Mahoney, C. A. Smith, 2014: Moisture Pathways into the US Intermountain West Associated with Heavy Winter Precipitation Events. Journal of Hydrometeorology, 16, 1184-1206, doi: http://dx.doi.org/10.1175/JHM-D-14-0139.1. (June issue).

The following was delivered to Reclamation:

a) The 2400 back trajectories at one-hour intervals back 5 days for each of the six IMW regions
b) The code used to compute the trajectories
c) The code used to plot the trajectories
d) Portable code: Dustin Swales (PSD) worked closely with Katie Holman (Reclamation) to ensure that Reclamation was able to run these codes on their computer system.

4) *Linear model (LM) of orographic precipitation was provided to Reclamation*

The linear describes the pattern of precipitation arising from forced ascent of saturated air over topography, where the vertical rate of ascent is determined from linear mountain wave theory. Forced ascent in the LM converts moist air to cloud water, is subsequently converted to hydrometeors with timescale $\tau_c$ and fall out with timescale $\tau_f$. The hydrometeors and cloud water are advected by a mean wind $\mathbf{U}=U\mathbf{i}+V\mathbf{j}$. The LM also includes a gravity wave term allowing the mountain-wave-induced change of vertical velocity with height to cause precipitation to fall upstream of topography gradients. Thus in the LM, precipitation broadly scales with the gradient of the terrain, modified by advection and gravity wave processes. For convenience the LM operates in Fourier space, where representations of physical processes can be combined into a single transfer function. A background precipitation rate, representing the precipitation falling at zero elevation far from topographical influence, is then added to the inverse Fourier transform. The solution is then truncated to eliminate negative values.

5) *Advanced Pattern techniques.*

In the FY12/13 project Empirical Orthogonal Functions (EOFs) were used to find weather patterns that were associated with strong moisture transport into the IMW. In the

FY14/15, a nonlinear technique called “Self- Organizing Maps” (SOMs) was used to identify patterns of moisture transport and the associated heavy precipitation. We confirmed the Reclamation had general software available to use both of these analysis techniques.

*6) Web-based application for plotting trajectories*

A web based tool for plotting trajectories has been developed and is operational at PSD see: http://www.esrl.noaa.gov/psd/cgi-bin/data/trajtool/traj.pl

A user is able to plot both forward and backward trajectories and initialize the trajectories as a function of location and height.

**Task 2: Develop additional methods for diagnosing and grouping storms**

We explored different methods to document the climatology and variability of conditions that lead to heavy precipitation events in the interior west. One method we used in the FY 12/13 grant is based on empirical orthogonal functions (EOFs) of the integrated water vapor transport (IVT). EOF analysis is a linear method and has some known weaknesses (e.g. some patterns can be unrealistic due to the constraint that the patterns/time series are orthogonal (uncorrelated) to each other. Thus, we used additional statistical methods to classify and group extreme events including two additional nonlinear methods to address the questions proposed here:

*1) Develop a Trajectory Similarity Score, based on cluster analysis*

From Joe Barsugli

*2) Self-Organizing Maps*

Self-organizing maps (SOMs) is an unsupervised learning algorithm that provides a method to visualize large amounts of data in a much reduced dimension, often a set of 2-D fields. SOMs have two phases: a learning phase that employs a competitive process to derive a training set of maps and prediction phase in which new vectors are given a location on a map, classifying the data. Put more simply, an iterative approach is used to group similar maps together and then a composite map is made from the average of those maps. The resulting maps are situated in a matrix relative to one another according to their similarity, with additional information about frequency of each node, and frequency of node transitions (i.e., how often one pattern transitions to another).

We used SOMs to classify patterns of moisture transport into the intermountain west and their link to extreme precipitation events based on a "two-step" approach. Step 1 used a low-order 2x2 SOM to filter out dry-days and step 2 used a 3x3 SOM on the remaining moist days. The 3x3 SOM SOMs highlighted different moisture pathways into the western US. We then mapped extreme precipitation events, obtained from the Livneh dataset, to the SOM patterns.

Details of the method and results can be found in:

Swales, D., M. A. Alexander and M. Hughes, 2016: Examining Moisture Pathways and Extreme Precipitation in the U.S. Intermountain West using Self-Organizing Maps. *Geophysical Research Letters*, **43**, 1727–1735, doi:10.1002/2015GL067478.

We also participated in a study lead by Cameron Bracken (Reclamation & University of Colorado), which examined the characteristics of three-day total extreme precipitation in the western United States. Coherent seasonal spatial patterns of timing and magnitude are evident in the data, motivating a seasonally based analysis. While Alexander et al. 2015 used a subjective method for identifying regions and only examined winter precipitation, this study used a clustering method that is consistent with extreme value theory to identify coherent regions and then used these regions to initialize back trajectories over the course of the seasonal cycle. The trajectory analysis demonstrated unique moisture sources and dominant moisture pathways for each spatial region. In the winter the Pacific Ocean is the dominant moisture source across the west, but in other seasons the Gulf of Mexico, the Gulf of California, and the land surface over the midwestern U.S. play an important role.

For more information see:

Bracken, C., B. Rajagopalan, M. Alexander, and S. Gangopadhyay, 2015: Spatial Variability of Seasonal Extreme Precipitation in the Western United States, *J. Geophys. Res. Atmos.*, **120**, 4522-4533, doi:10.1002/2015JD023205.

**Task 3: Generate and analyze an ensemble of high-resolution simulations**

We used an ensemble approach to generate a suite of Weather Research and Forecast (WRF) simulations of strong AR events that generate heavy precipitation over a critical watershed and infrastructure for Reclamation.

**Columbia River drainage and Glacier National Park study**

There are multiple dams and other structures operated by Reclamation in the Columbia River Basin and further east in western Montana. Glacier National Park in Montana was the site of extensive flooding in November 2006. The flooding was caused by heavy rainfall associated with a land-falling atmospheric river in the Pacific Northwest. This event produced heavy rain throughout the northwestern US, especially in the Cascade Mountains and northern Rocky Mountains. To better understand the processes by which moisture from a Pacific AR was transported that far inland, we performed a 6-day simulation (3-9 November 2006) using WRF (the model is described in detail in the companion project report “Improving extreme precipitation estimation using regional, high-resolution model-based methods”). We used a 4-kmilometer grid over a domain that includes much of the Pacific coast of North America. The simulated precipitation in the Olympic and Cascade Ranges exceeds 400mm, while higher elevation portions of Glacier

National Park region received 150-200mm of precipitation (Fig. 2). However, the precipitation totals fell short of 280mm (11 inches) observed in the park at Flattop Mountain.

Over the next 1-2 months, an ensemble framework will be used to explore multiple precipitation scenarios, including those indicated under future climate scenarios (e.g., pseudo global warming simulations). The ensemble configuration will consist of perturbations to microphysics scheme, lateral boundary conditions and stochastic perturbations to temperature and wind fields.

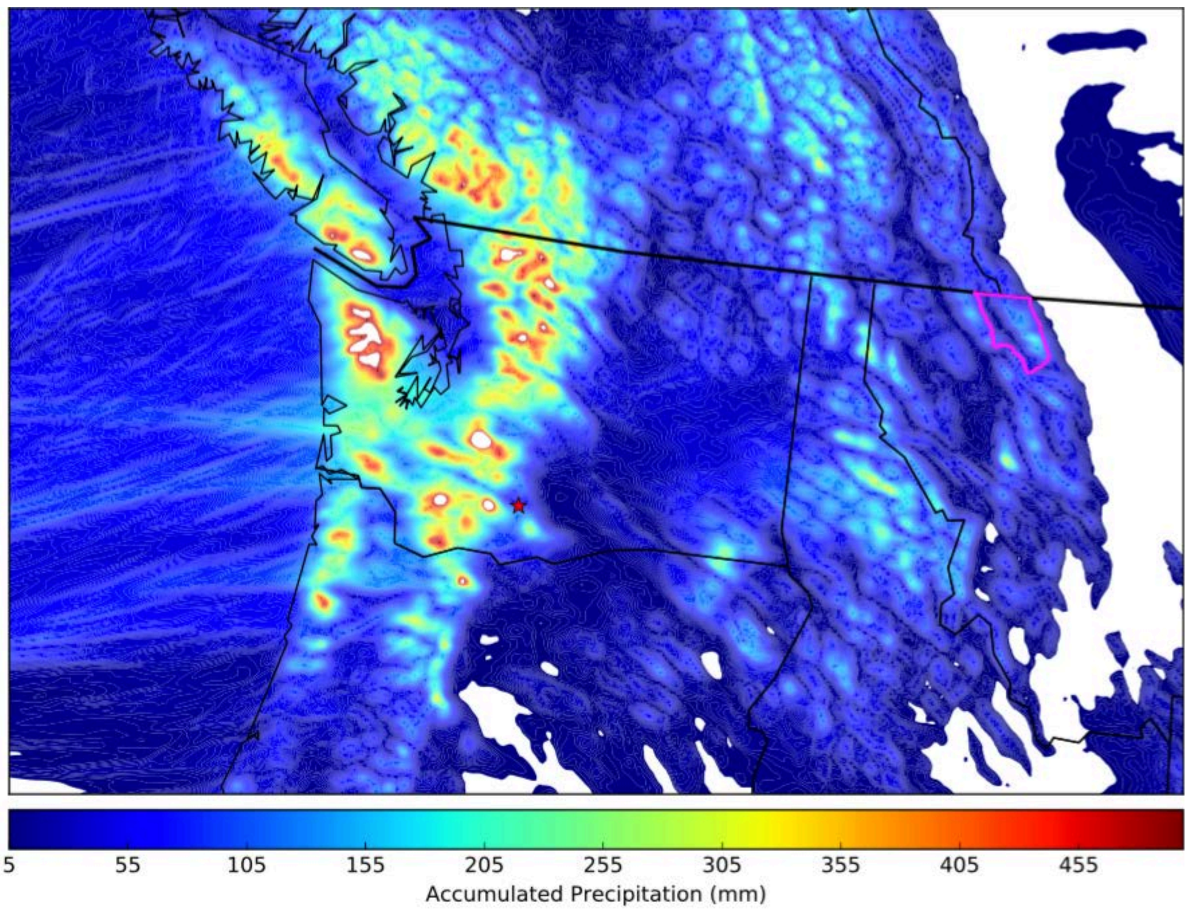



Fig. 1: Accumulated precipitation during 3-9 November 2006 (6-day) over Pacific Northwest simulated by the WRF model. Glacier National Park in northwestern Montana is outlined in purple.

**Task 4: Climate Change/Variability**

Factors internal to the climate system, such as ENSO, and climate change driven by an increase in greenhouse gases, will influence ARs and the resulting precipitation across the western US.

**Examine ARs and how they change due to greenhouse gas forcing**

We investigated the impact of climate change on atmospheric rivers and the integrated water vapor transport (IVT) into the western United States. We obtained the climate change signal from the NCAR Community Earth System Model (CESM) large ensemble (LENS) and used 30 ensemble members that were initialized in 1920 with slightly different initial conditions. The simulations were run for 160 years to 2080 using the RCP8.5 scenario for greenhouse gases after 2005.

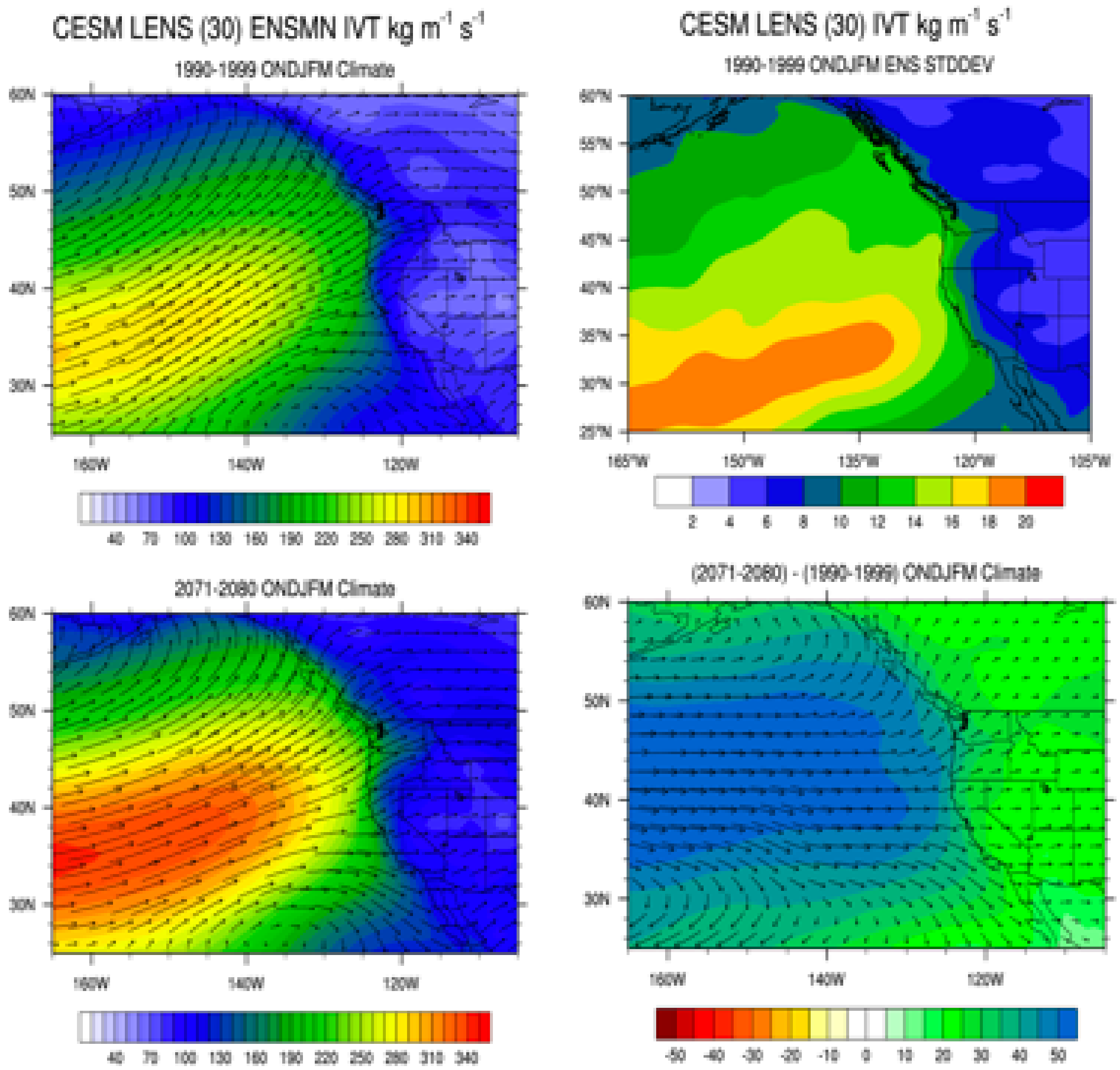



Fig. 2. IVT from the 30 CESM-LENS simulations magnitude (shading and direction vectors: top-left) ensemble mean for the period 1990-1999; bottom left) ensemble mean for the period 2071-2080; upper right) standard deviation of IVT averaged over 1990-1999 among the 30 simulations and lower right) difference (Δ or “delta”) between 2071-2080 and 1990-1999 (i.e. a-b).

The daily IVT from LENS for two 10 year time periods: 2071-2080 and 1990-1999 and their difference are shown in Fig. 2. The results from CESM-LENS experiments shows the general pattern and direction of moisture transport from the central North Pacific towards North America does not change substantially between 2071-2080 and 1990-2090. In addition, the leading patterns of IVT variability over the western US during 1990-1999, which are well simulated by the CESM, remained relatively unchanged during 2071-2080 (not shown). However, the magnitude of the IVT increases, likely due to the ability for a warmer atmosphere to carry more moisture, and as a result there is a potential for stronger ARs and thus more heavy precipitation and flooding as the 21$^{st}$ century progresses.

Experiments of future AR-related storms will be conducted using the "pseudo global warming" (or "delta") method. In these experiments, differences (or deltas) in long-term averages obtained from the climate models are added to the present day weather conditions. Taking the difference between the two periods removes the mean model bias. The difference values can then be added to a present day AR event and a suite of simulations conducted using WRF ensemble methodology described in Task 3, which will be done for 2006 Glacier National Park storm.

**Explore the role of climate variability**

We investigated how the three phases of ENSO (i.e., eastern Pacific and central Pacific El Niños as well as La Niña; EPEN, CPEN, and NINA, respectively) modulate the atmospheric circulation and thereby change the water vapor transport into western North America. In EPEN, large positive integrated water vapor transport (IVT) anomalies extend northeastward from the subtropical Pacific into the northwestern United States following the flow around an anomalously deep Aleutian low. In CPEN, a southward shift of the cyclonic circulation over the North Pacific, which extends toward California, induces moisture transport into the southwestern United States. There is also a second IVT pathway into North America during CPEN; that is, moisture from the eastern tropical Pacific is transported across Mexico and into the southwestern United States. For NINA, the opposite circulation arises with an anticyclonic anomaly over the North Pacific and significant negative IVT anomalies at approximately 30°N on the southern side of this anticyclone.

For a full description of this research see:

Kim, H-M., and M. A. Alexander, 2015: ENSO's Modulation of Water Vapor Transport over the Pacific North America Region. *Journal of Climate*, 28, 3846-3856. doi: http://dx.doi.org/10.1175/JCLI-D-14-00725.1

**Task 5: Final Assessment, Publications, and Next Steps**

A number of tools were developed and a wide array of research was conducted for this project. We have transferred the data and computer code to Reclamation necessary to conduct the types of analyses we performed. Our work led to a better understanding of inland penetration of atmospheric rivers and the extent to which ARs are influenced by climate variability and change.

**Publications:**

Alexander M. A., J. D. Scott, D. Swales, M. Hughes, K. Mahoney, C. A. Smith, 2015: Moisture Pathways into the US Intermountain West Associated with Heavy Winter Precipitation Events. *Journal of Hydrometeorology*, **16**, 1184-1206, doi: http://dx.doi.org/10.1175/JHM-D-14-0139.1. (June issue).

Bracken C., B. Rajagopalan, S. Gangopadhyay, and M. Alexander. Supporting Information for Spatial Variability of Seasonal Extreme Precipitation in the Western United States. *Journal of Geophysical Research – Atmospheres*, **120**, Issue 10, 27 May 2015, Pages: 4522–4533.

Hughes, M., K. M. Mahoney, P. J. Neiman, B. J. Moore, M. Alexander, F. M. Ralph, 2014: The Landfall and Inland Penetration of a Flood-Producing Atmospheric River in Arizona. Part II: Sensitivity of modeled precipitation to terrain height and atmospheric river orientation, *Journal of Hydrometeorology*, **15**, 1954-1974. (This study was mainly performed in FY12-13 put some additional work was needed to get it into publishable form during FY14-15).

Kim, H-M., and M. A. Alexander, 2015: ENSO's Modulation of Water Vapor Transport over the Pacific North America Region. *Journal of Climate*, **28**, 3846-3856. doi: http://dx.doi.org/10.1175/JCLI-D-14-00725.1

Swales, D., M. A. Alexander and M. Hughes, 2016: Examining Moisture Pathways and Extreme Precipitation in the U.S. Intermountain West using Self-Organizing Maps. *Geophysical Research Letters*, **43**, 1727–1735, doi:10.1002/2015GL067478.

We are happy to continue working with Reclamation so they can best utilize the tools and knowledge gained from our research.