Intermediate-range Climate Forecasting to Support Water Supply and Flood Control with a Regionally Focused Mesoscale Model

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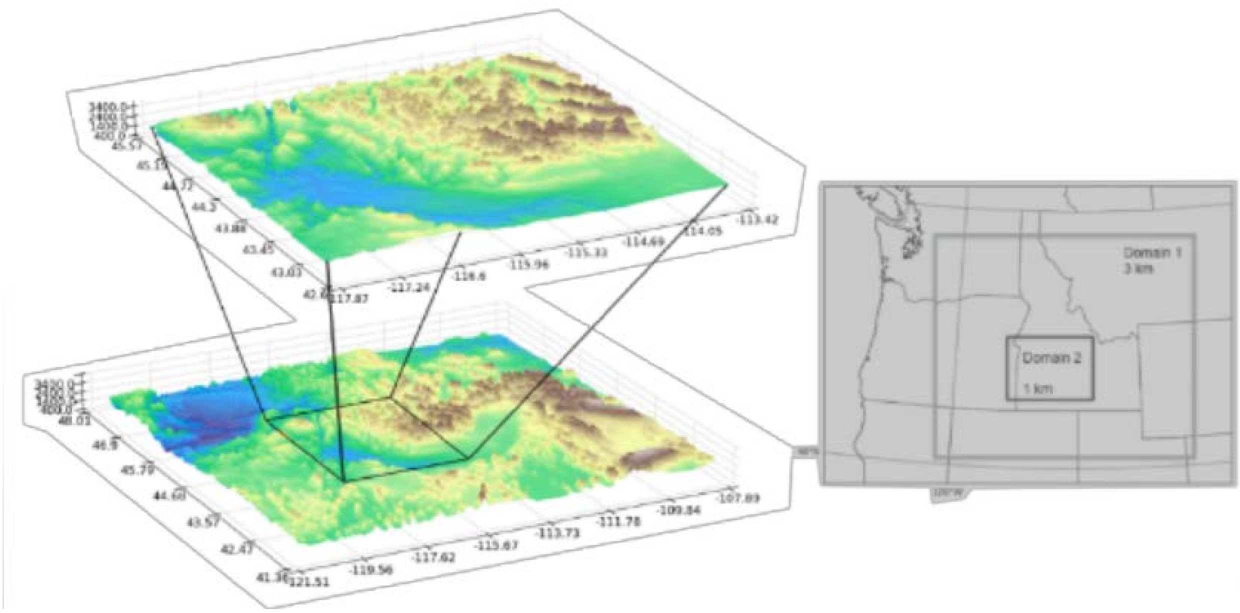

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July 2019

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14. ABSTRACT ***(Maximum 200 words)*** Reservoir operators use seasonal volume forecasts to predict the volume of water expected to arrive from spring snow melt and storms. It is difficult to predict the rate of snow melt and the quantity of additional rain that will fall because atmospheric river events are challenging to forecast and have high uncertainty. This project used an existing mesoscale numerical weather prediction model to conduct a reanalysis simulation of a June 1-5, 2010 atmospheric river event on the Boise River subbasin of the Snake River. Reforecast simulations were conducted and compared to the reanalysis simulation. It is unclear the usability of the forecast model in reservoir operations due to the significant change in the forecasted nature and severity of the event in the forecast periods leading up to the event and due to the significant data volume associated with this type of modeled forecast.

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Acronyms and Abbreviations

Acronym or Abbreviation	Description
AR	Atmospheric River
CFS	Climate Forecast System
CFSR	Climate Forecast System Reanalysis
CFSRR	Climate Forecast System Reanalysis and Reforecast
CPM	Convection-permitting models
IVT	Integrated Vapor Transport
LBC	Lateral boundary condition
LEAF	Lab for Ecohydrology and Alternative Futuring
NCEP	National Centers for Environmental Prediction
NetCDF	Network Common Data Format
Noah-MP	Noah multi-physics
S&T	Science and Technology
SNOTEL	Snow Telemetry
SRB	Snake River Basin
WRF	Weather Research and Forecasting model

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Executive Summary

Reservoirs are operated for many purposes including: water supply, flood risk management, power generation, fish and wildlife, and recreation. Operators balance the filling and drafting of reservoirs for these competing purposes and use seasonal volume forecasts to predict the timing and volume of water to be expected within the filling season. The most difficult thing to predict, however, is the rate of snow melt, and the quantity of additional rain that will fall over the spring and early summer. This is because atmospheric river events, which can produce large rain storms in the spring, can be challenging to forecast, increasing the difficulty for reservoir operators to respond.

At present, key gaps in information availability lies in the lack of information about potential weather at extended lead time (e.g., 10-30 day) and high spatial resolution (<4 km). In recent years, significant progress has been made in to improve the physical representation of atmospheric processes and the spatial resolution captured by mesoscale numerical weather prediction models, such as the Weather Research and Forecasting (WRF) model. Despite this progress, these models remain too numerically intensive to apply at continental scales while maintaining high spatial resolutions.

The objective of this project was to assess the capabilities of using mesoscale weather predictions model to provide hydroclimate forecasts data at improved accuracy and spatiotemporal coverage relative to currently available products used in real-time reservoir operations. This project was a partnership between Reclamation and the Boise State University Lab for Ecohydrology and Alternative Futuring (LEAF). BSU LEAF conducted this project using an existing mesoscale numerical weather prediction model, the WRF model, to conduct a reanalysis simulation of a June 1-5, 2010, atmospheric river event on the Boise River subbasin of the Snake River, including the months leading up to the event. The modeled states from the reanalysis simulation were then used as the initial land surface and atmospheric conditions for reforecast simulations. Forecasts were developed and conducted at lead times of 1 to 30 days and for 1 and 3 km spatial domains. Forecasts were then compared to the reanalysis simulation.

Results suggest that, for this one simulation event, the WRF-based reforecast provided some indication that a significant atmospheric river event was likely to occur well in advance (30 days) and immediately before (<10 days). Between 30-10 days, however, an event of significance disappeared from the forecast. Raising concerns that these regionally tailored models would be subject to similar uncertainties to currently produced products. Because the forecasted nature and severity of the event changed significantly in the forecast periods prior to the event, it is unclear the usability of the WRF model in real-time reservoir operations. Additionally, the substantial data volume needed to produce the forecasts at such high resolution may potentially require expensive investments in cyberinfrastructure to facilitate the effective generation, storage, and dissemination of these datasets.

Ongoing work is being conducted by LEAF seeking to identify and classify atmospheric river events and using other environmental variables to help forecast their impact.

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Intermediate-range Climate Forecasting to Support Water Supply and Flood Control with a Regionally Focused Mesoscale Model

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July 2019

Introduction

This Reclamation Science and Technology project is a partnership between the Boise State University Lab for Ecohydrology and Alternative Futuring (LEAF) and the Pacific Northwest Regional office of the US Bureau of Reclamation. LEAF identified hydrometeorological concepts and approaches to potentially address a significant scientific and management challenge faced by the Bureau of Reclamation and other water and management agencies throughout the Western US. Specifically, this project seeks to advance the potential use of regional coupled land-atmosphere models to fill in key data gaps in the availability of hydrometeorological surface forecasts in time horizons of 10-30 days.

The goals of this project are the following:

1. Examine the extent to which regional weather and climate models could skillfully predict significant management events at extended lead times (e.g., 10-30 days) and at spatiotemporal resolutions that can support reservoir operations.
2. Determine the tools, datasets, and workflows required to set up and run regional weather models at extended lead times and at spatial scales that better represent topographic processes that influence precipitation and temperature.
3. Reforecast a hydrometeorological event that challenged current reservoir operations practices in the form of an atmospheric river in June 2010 over the Snake River Basin, with focus on the Boise River subbasin.
4. Interpret the results of the reforecast experiments in the context of providing managers with improved hydrometeorological information and discuss potential workflows for the judicious use of extended-range CPM-based forecasts.

The principle findings of the project in the context of the above goals are:

1. Due to the inherent non-linearity of the atmosphere system, the accuracy of reforecasts is limited in at extended lead times when assessed using traditional metrics of accuracy in the spatiotemporal distribution of precipitation amount and phase. Extended range, high-resolution forecasts, however, ***can*** serve as a useful tool to examine the potential consequences of meteorological events that appear in global operational extended-range forecast datasets. As such, they potentially have an important role in reservoir operation workflows in providing operators a *regionally refined interpretation* of existing global forecasts.
2. Existing modeling frameworks like the Weather Research and Forecasting (WRF) model used here, extended range forecasts like the National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) also used here, along with some scripting in open-source, high-level languages (e.g., Python) can be easily configured to provide regionally refined interpretations of global forecasting datasets in ways that complement existing reservoir operations in an automated way. Although developing new operational workflows was not the focus of this Science and Technology (S&T) project, this represents a potentially important future capability for the Bureau of

Reclamation. Specifically, developing an extended range, high-resolution forecasting product would be a synthesizing activity that would serve all Reclamation Regional Offices, while also providing important linkages with NCEP, the National Weather Service, and the National Center for Atmospheric Research (the originators of the WRF model).

3. Because global forecast products like CFS can resolve phenomena like Atmospheric Rivers (ARs), which represent among the most challenging events from a reservoir operations perspective, the extended lead time dynamic forecasting capabilities like those examined in this S&T project merit continued research in the future. In particular, developing workflows to automatically detect AR events in extended-range forecasts like CFS, determine whether they intersect key regions of particular interest, and automatically develop dynamically downscaled projections of those forecasts may benefit existing workflows.
4. The volume of data produced by these regionally refined forecasts is substantial, representing between 5-16 GB of data per forecast day, depending on region and spatiotemporal resolution. Adding these forecasting capabilities to existing Reclamation's workflows may potentially require new investments in cyberinfrastructure to facilitate the effective generation, storage, and dissemination of these datasets.

Background and Scientific Motivation

Basin Context and Significance

Federal and private reservoirs are operated for a variety of purposes, these multiple uses must be considered and balanced in operational decisions. Federal projects in the Upper Snake River basin are operated for many purposes including: water supply, flood risk management, power generation, fish and wildlife, and recreation. These purposes can often conflict. For example, dams that have dedicated operations for flood risk management will generally draft in the winter and refill in the spring and early summer, these reservoirs use water supply information to determine how much 'space' or room in the reservoir is necessary to provide the flood risk management. This need can be in direct conflict with reservoir purposes that prioritize filling the reservoir such as water supply, fish, and recreation. In order to make sure dams are drafted enough but not too much, engineers create predictions of the volume of water that will run off. These predictions, called seasonal volume forecasts, are created using information such as the amount of snow on the ground upstream of a dam. The most difficult thing to predict, however, is how quickly snow will melt and how much additional rain will fall over the spring and early summer. This is one reason why managing flood risk is challenging. Reducing the drafted flood risk space too much may lead to flooding. If the drafted flood risk space increases too much, reservoirs might not fill by summer.

Reservoir operators have multiple sources of information at their disposal to make timely decisions about release schedules. Key information includes the current conditions of the reservoir (storage, inflow and outflow), water supply conditions (snow pack, runoff forecasts, which are a form of unrealized input to the reservoir), forecasts of timing of runoff, near-term weather predictions, and seasonal-scale climate guidance. Some of these pieces of information are obligatorily used in decision-making, while other information provides important context or confirmatory information.

Challenges with Current Forecast Products

A key gap in information availability lies in the lack of information about potential weather at a sub-seasonal or extended (e.g., 10-30 day) lead time. The Climate Forecast System, version 2 (CFSv2) was developed to provide global forecasts in the sub-seasonal to seasonal time scale. It was developed and is operated by the National Centers for Environmental Prediction (NCEP), an originator of weather and climate forecast data supported by the National Oceanic and Atmospheric Administration.

Although useful for identifying potential synoptic (large) scale events[1] that could bring significant precipitation to mountain snowpacks, the spatial resolution of the CFSv2 forecasts is problematic in the Western US, where the Bureau of Reclamation's primary mission lies. In particular, at its native resolution of 0.50 degrees it does not resolve topographic variability in

[1] Synoptic scale events, in meteorology, are large scale events on the order of 1000s of kilometers or more.

precipitation, temperature, and other key hydrometeorological variables in sufficient detail. As such, without additional processing, the CFSv2 data alone does not necessarily provide additional value to Reclamation reservoir operations workflows. There are two important ramifications of the relatively coarse spatial distribution of the CFSv2 forecasts in the watersheds of the Western US.

First, orographic effects of topography play a critical role in forcing the lifting of moist air parcels in mountain regions. Because CFSv2 is associated with a 0.5 degree spatial resolution: (1) the topography is significantly smoothed with respect to reality, (2) the magnitude of vertical motions in the atmosphere is underpredicted, (3) orographic lifting of moist, relatively warm air parcels higher in the atmosphere and a suppression of associated simulated precipitation amounts.

Second, the smoothing of topographic variability in the CFSv2 model is also associated with a reduction in the range of air temperatures in mountain landscapes where temperature lapse rates, coupled with large gradients in topography, lead to correspondingly large gradients in near-surface air temperature. Correspondingly, forecast models with spatial resolutions consistent with CFSv2 not only underestimate precipitation at the highest elevations, but also do not adequately partition precipitation into the correct phases.

Current Forecasting Products as Inputs to High-Resolution Regional Models

Because of the compounding precipitation-temperature effects of spatial resolution, many operational forecast products are used for statistical models to predict water supply and runoff in mountain watersheds, but too coarse to use as input to higher resolution models without additional downscaling. In recent decades, there has been significant effort devoted to developing techniques for downscaling forecast and climate projection products to resolutions capable of resolving variation in weather and climate associated with topography in mountain regions. These downscaling algorithms are of two fundamental varieties: statistical downscaling, and dynamical downscaling. In this study, we explore the use of dynamical downscaling – the use of coupled models of land-atmosphere water, energy, and momentum dynamics – to add value and context to coarse-scale, extended-range forecasts provided in the CFSv2 product.

Convection-permitting models (CPMs) like the Weather Research and Forecasting (WRF) model are capable of resolving the coupled dynamics of the land-atmosphere system at spatial resolutions of 1 km because they are associated with improved parameterizations of physical processes such as cloud microphysics and land-atmosphere exchanges of water and energy. This is a particularly critical advantage in the Western, US because of the first-order role topography plays in forcing atmospheric convection and correspondingly controlling the spatiotemporal patterns of precipitation and other surface hydrometeorological information. This enhanced spatial resolution, however, comes at the expense of increased computational requirements and larger volumes of produced data. As such, the use of these models for extended-range forecasting is restricted to specific regions or basins of interest.

Study Area and Operational Significance

The study area corresponds to the Snake River Basin (SRB), an important tributary of the Columbia River (**Figure 1**). The SRB supports large consumptive water use for food production and is an important basin for production of hydroelectric power. The SRB drains approximately 280,000 km^2, spanning an elevation range from 109 m at the confluence of the Snake and Columbia Rivers to 4,199 m in the headwaters in the Teton mountains. Mean annual precipitation ranges from approximately 210 mm/yr in the low elevation Snake River Plain to over 1500 mm/yr in the mountains.   The Snake River above Brownlee has an approximate annual runoff of 11.6 million acre-feet.

Because most agricultural productivity in the SRB coincides with the driest portion of the basin, there exists a large system of social, political, economic, and physical infrastructure to capture and store runoff from mountain watersheds. This storage is then used to supply irrigation throughout the Snake River Plain during the growing season (April through September). Physical infrastructure includes dams, reservoirs, canals and distributaries. Non-physical infrastructure includes a complex legal and administrative framework – based on the doctrine of Prior Appropriation – for supplying irrigation water to users. Federal agencies maintaining some responsibility for the maintenance, monitoring, and administration of water include the US Forest Service, Bureau of Reclamation, Army Corps of Engineers, Geological Survey, and Fish and Wildlife Service. The most significant state agency with an administrative role is the Idaho Department of Water Resources. Local organizations with administrative roles include irrigation districts of varying size, age, composition, and operating models; canal companies responsible for maintaining conveyances; and the end-users themselves (e.g., farmers and ranchers).

The Snake River system also includes several dams built either solely for the purposes of hydroelectric power generation or that produce hydroelectric power as a benefit while serving primarily as water supply reservoirs. The largest hydropower producing dams along the Snake River and its major tributaries includes the Hells Canyon complex, a sequence of three dams (Hells Canyon, Brownlee, and Oxbow dams) on the Snake River along the Idaho-Oregon border that collectively represent 1408 MW of installed capacity and four dams along the Boise River (Diversion, Arrowrock, Anderson Ranch, and Lucky Peak dams) representing 146 MW of installed capacity (EIA, 2017). The oldest of project dates to 1906 (Boise Diversion Dam) while the newest was completed in 1967 (Hells Canyon Dam).

The Boise River Basin is among the most significant of the tributaries of the Snake River and is, in many ways, a microcosm of the larger Snake River system. The Boise Basin drains an area of 11,000 km^2 with elevations ranging from 640 m at the confluence of the Boise and Snake Rivers to over 3050 m in the Sawtooth Mountains of central Idaho.   The Lower Boise, often referred to as the Treasure Valley, is home to the three largest cities in Idaho (Boise, Meridian, and Nampa). The estimated population of the Boise City-Nampa Metropolitan Statistical Area (MSA) was 676,909 as of 2015 (IDOL, 2017), an increase from 616,561 in the 2010 Census. Projections for the MSA indicate population will exceed 1 million by 2040 (COMPASS 2012). The Boise River Basin has a series of Federal Dams that provide several services, including flood risk management for the municipalities downstream, water supply (irrigation, as well as municipal and industrial uses), recreation, and fish and wildlife. Principal facilities of Arrowrock Division of the Boise Project include Reclamation's Anderson Ranch Dam and on the South Fork of the Boise River; Reclamation's Arrowrock Dam on the Boise River downstream of the confluence with the South Fork; the Corps of Engineer's Lucky Peak Dam and Reservoir, Diversion Dam a run-of-river dam that controls flows to the New York Canal and Lake Lowell (a Reclamation offstream reservoir formed by three earthfill dams enclosing a natural depression southwest of Nampa, Idaho.

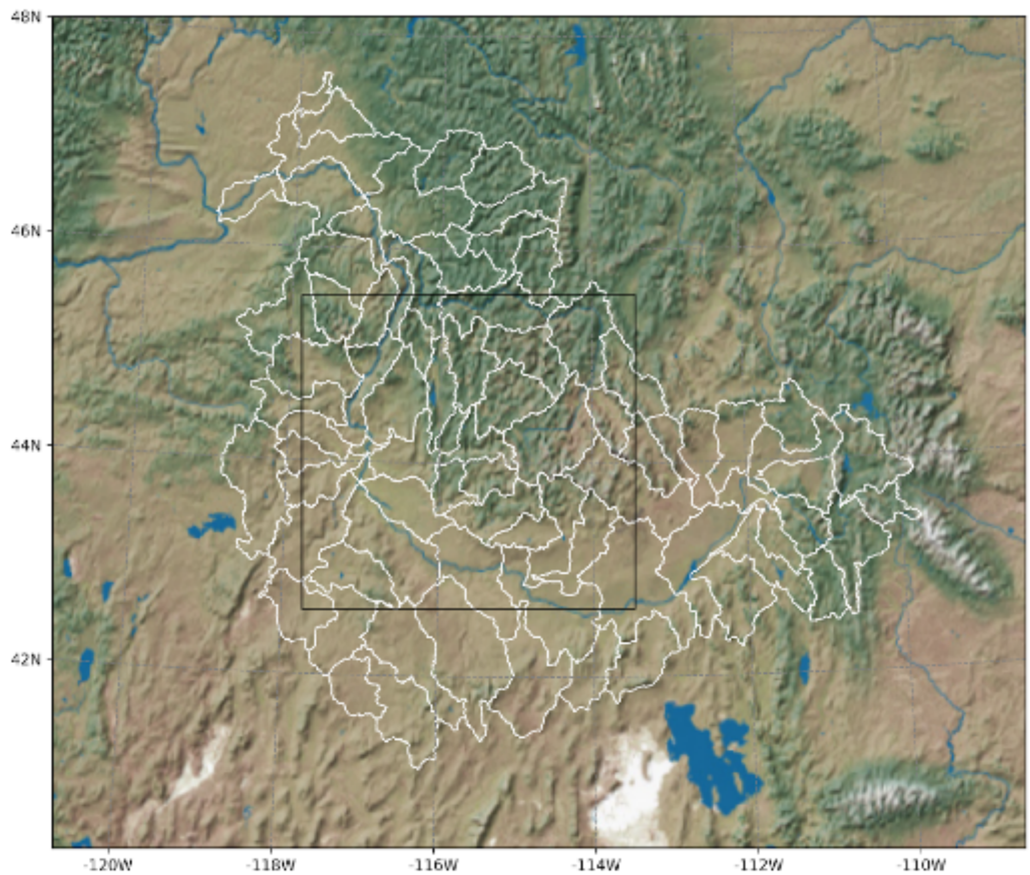


Figure 1: Map of study area. The extent of the map indicates an outer domain used in the WRF simulation (described below). A smaller, finer resolution nested domain is outlined in black. The subwatersheds of the Snake River Basin are outlined in white.

Methods

Tasks and Activities

To assess the extent to which CPMs are capable of adding significant value to existing climate forecasting products, we developed and conducted a suite of numerical experiments to assess the predictive skill of CPMs at lead times of 1- to 30-days. We selected a particularly significant management event, a June 2010 Atmospheric River (AR) that delivered significant volumes of precipitation to the Snake River Basin and the Boise River Basin at a time when the reservoir system was at or near-capacity. The bulk of the precipitation associated with the AR event occurred in the time period from June 1-5, 2010. Reforecasts of the June 1-5, 2010 over a domain in the Pacific Northwest coinciding with the Snake River Basin period were performed by using data from the Climate Forecast System Reanalysis and Reforecast (CFSRR) as the lateral boundary conditions (LBCs) to WRF and allowing the WRF model to run through June 6, 2010 at 00z.

In order to provide a meaningful comparison between the reforecasts, a reanalysis of the June 1-5 period was performed by using the Climate Forecast System Reanalysis (CFSR) data as input to WRF. As such, we produced two datasets for analysis: (1) seven forecasts corresponding to lead times ranging from 1- to 30-days prior to the onset of the atmospheric river, and (2) a reanalysis dataset against which those reforecasts are compared. Results suggest that, for this particular event, the WRF-based reforecast may have provided some indication that a significant AR event was likely to occur well in advance. However, the nature and severity of the actual event changed significantly in the forecast periods prior to the AR event and there was no clear-consensus. The reforecast at the longest lead-time (30-days) suggested a significant precipitation event. Subsequent reforecasts (25-, 20-, 15-, and 10-day lead-times) suggested a much more subdued event. The final reforecasts (5- and 1-day lead times) suggested a significant precipitation event as the atmospheric conditions associated with the synoptic setup were more closely in line with the actual atmospheric conditions. These findings suggest that long lead-time forecasting with CPMs is possible, but the nature of the information provided by them and how that information is used operationally requires significant attention. Specifically, a Western AR-watch that combines analysis of existing forecasts products from the Climate Forecast System version 2 (CFSv2) with on-demand CPM simulations in targeted regions might provide enhanced information at large lead-times without imposing significant computational and forecasting burdens.

The specific tasks associated of this suite of numerical experiments are the following:

1. Identify a historical period in the Snake River Basin (SRB) to develop and conduct a suite of numerical experiments to examine the degree to which CPMs can add value to extended-range forecast products in the context of Reclamation's mission,

2. Use the CFSRR data as input to the WRF CPM to produce high-resolution reforecasts of the identified historic event period,
3. Use the CFSR data to provide a reanalysis of the historical event period in a way that can be directly compared to the produced reforecast products, and
4. Interpret the results of the reforecast experiments in the context of providing managers with improved hydrometeorological information and discuss potential workflows for the judicious use of extended-range CPM-based forecasts.

To achieve these goals a Weather Researching and Forecasting (WRF) model was developed for the study area.

Outcomes and Data Products

This project has led to the following key products:

1. A CPM-based reanalysis of a historic atmospheric river (AR) event from June 1-5, 2010 associated with a spatial resolution of 3 km over the entire Snake River Basin and 1 km over the Boise/Payette/Big Wood River Basin and a temporal resolution of 1 hour
2. CPM-based reforecasts of the June 2010 AR event initiated at the following times: (a) May 1, 2010 12z; (b) May 6, 2010 12z; (c) May 11, 2010 12z; (d) May 16, 2010 12z; (e) May 21, 2010 12z; (f) May 26, 2010 12z; and (g) May 31, 2010 12z. These reforecasts are on the identical spatial grids as the reanalysis product and have the same 1-hour spatial resolution.
3. Input files documenting the configuration of the WRF CPM use in the reanalysis and reforecast simulations of the June 2010 AR event and associated scripts for automating reforecast and reanalysis runs.

Weather Research and Forecasting (WRF) Model

The Weather Research and Forecasting (WRF) model is a modeling framework for simulating the coupled dynamics of the land and atmosphere system (Skamarock et al., 2008). WRF simulates coupled land-atmosphere dynamics in response to input boundary and initial conditions. Atmospheric variables simulated by WRF include precipitation, air temperature, humidity, wind speed, radiant fluxes, and air pressure. WRF can refine land-atmosphere interactions in greater spatial and temporal detail in areas of interest (e.g., because of finer scale variation in topography, increased observational density, etc.) by nesting higher resolution domains within the outermost domains. Nesting can be used in a two-way fashion, in which land-atmosphere fluxes and states for coarser domains are aggregated from the simulation results of the finer domains (**Figure 2**). An increasing body of literature has demonstrated improving predictive skill in models like WRF in regions of topographic and terrain complexity. For example, Rasmussen et al. (2011) showed that WRF could accurately reproduce USDA National Resource Conservation Service SNOw TELemetry (SNOTEL) precipitation observations to within 10-15% in complex terrain, when the WRF spatial resolution was less than 6 km. We will use the Noah multi-physics (Noah-MP) land surface model (Niu et al., 2011) that is distributed with WRF. Noah-MP resolves the mass- and energy-balance of the soil, snowpack, and canopy by simulating: (1) soil moisture and temperature in four soil layers, (2) snow temperature, density, and depth in three layers, and (3) vegetation canopy temperature and water storage.

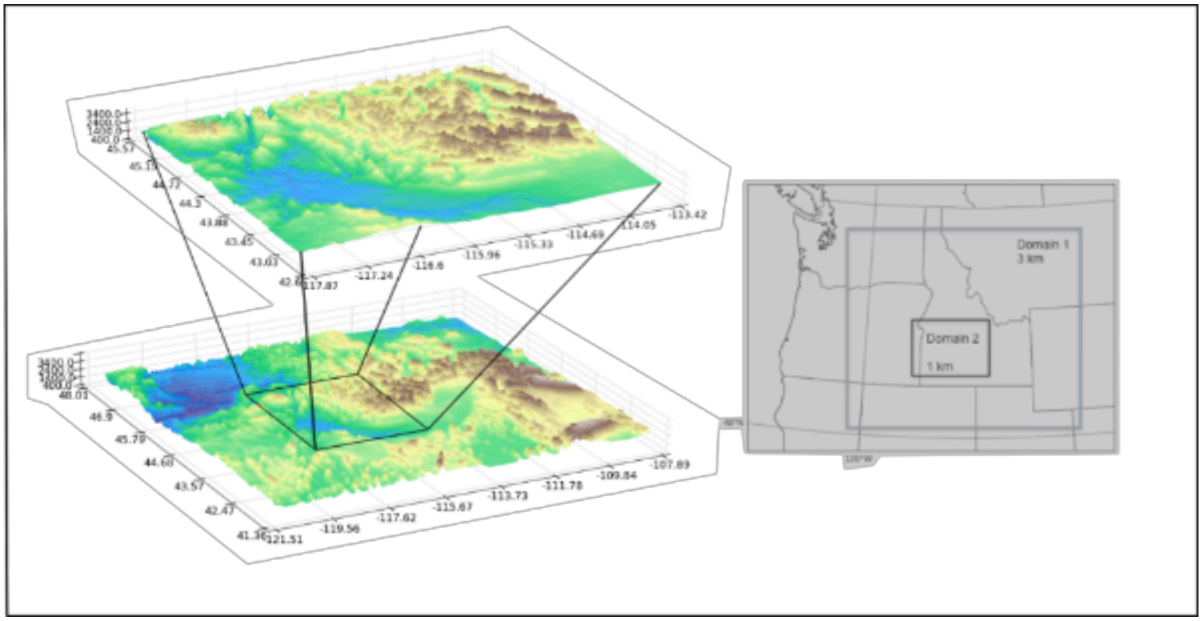


Figure 2: A conceptual illustration of the WRF simulation domains, their geographic extent, and the associated topography.

Based on prior using WRF to create long-term, high-resolution climate reconstructions (e.g., Flores et al., 2016) we have constrained the WRF physics options that lead to the greatest accuracy in predicted precipitation, temperature, and snow water equivalent in snow-dominated, mountain watersheds. This package of physics options for WRF long-term runs is shown in **Table 1** and is also largely consistent with the work of Rasmussen et al. (2011).

Table 1: WRF Physics Option Selection

Type	Parameterization Scheme	Reference
Cloud microphysics	Thompson	Thompson et al. (2008)
Planetary boundary layer	Mellor-Yamada-Janjic (MYJ)	Janjić (2002)
Longwave and shortwave radiation	Community Atmosphere Model (CAM)	Collins et al. (2004)
Land surface model	Noah-MP (default options)	Niu et al. (2011)

June 2010 Atmospheric River

Atmospheric Rivers (ARs) play a significant role in the delivery of moisture to the western Continental United States (CONUS), providing a significant fraction of precipitation in many watersheds. They are of significant importance in the context of flood protection because AR events that bring significant precipitation (typically from warm, tropical regions) to inland basins with significant seasonal snowpacks can be associated with large rain-on-snow events. These rain-on-snow events pose significant risks for floods, landslides and debris flows, and safe reservoir and spillway operations. Guan et al. (2016) found that ARs occur during 17% of all precipitation events in the Sierra Nevada, but they are associated with 50% of rain-on-snow events, so ARs are more conducive to flood generation. Complementary work to this S&T project has developed feature-based algorithms that attempt to detect ARs in global reanalysis products. The algorithm analyzes the Pacific Basin, identifying regions of high atmospheric Integrated Vapor Transport (IVT) – a measure that combines atmospheric column-integrated water vapor with wind speed – that also exhibit a high aspect ratio, reflecting the empirical observation that ARs tend to be long, narrow, coherent corridors that transport moisture from the tropics to the extra-tropics. Applying this algorithm to the CFSR data a period from 1979-2010 shows that land-falling ARs in the Pacific Basin tend to have a distinct seasonality (**Figure 3**). Specifically, ARs occur with greatest frequency in the late fall and early winter (October-February). They are almost completely absent during the Boreal summer, but approximately 20% of all land-falling ARs occur during the period from March through June. These ARs that occur at times late in the winter season when natural snowpack is near or at its maximum and reservoirs being filled in preparation for the irrigation season. Enhanced capability to predict the potential occurrence of ARs and other synoptic events capable of producing large rain-on-snow events at extended lead-times (10-30 days) could potentially give managers the ability to anticipate flooding events that may pose significant threat to filling reservoirs.

During a period from June 1-5, 2010, an AR delivered significant precipitation occurring throughout the study area. It occurred at a time when the reservoirs of the Boise & Payette River systems were significantly full (see the “Tea Cup” diagram from May 31, 2010, **Figure 4**) and at a time in which there was significant snowpack remaining in the central Idaho mountains. Since the event occurred in early June, the atmospheric setup was such that most of the precipitation fell as rain. This AR event led to significant flooding throughout southwestern Idaho, particularly in the Payette River basin. Although there were no fatalities associated with these floods, there was significant damage to homes, businesses and roads. The estimate of the amount of public assistance was greater than $5.3 million (Idaho Severe Storms and Flooding, FEMA-1927-DR).

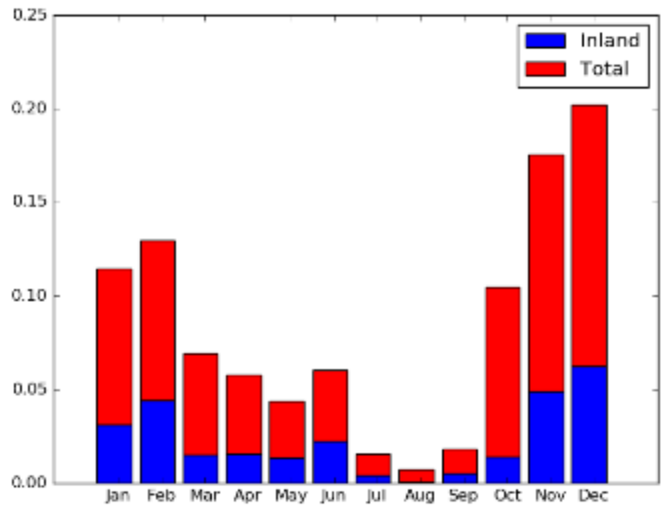


Figure 3: The empirical frequency distribution of landfalling Atmospheric River events by month for the period from 1979-2010. The subset of ARs that intersect the study domain are highlighted in blue and show a largely similar seasonal cycle to all landfalling ARs.

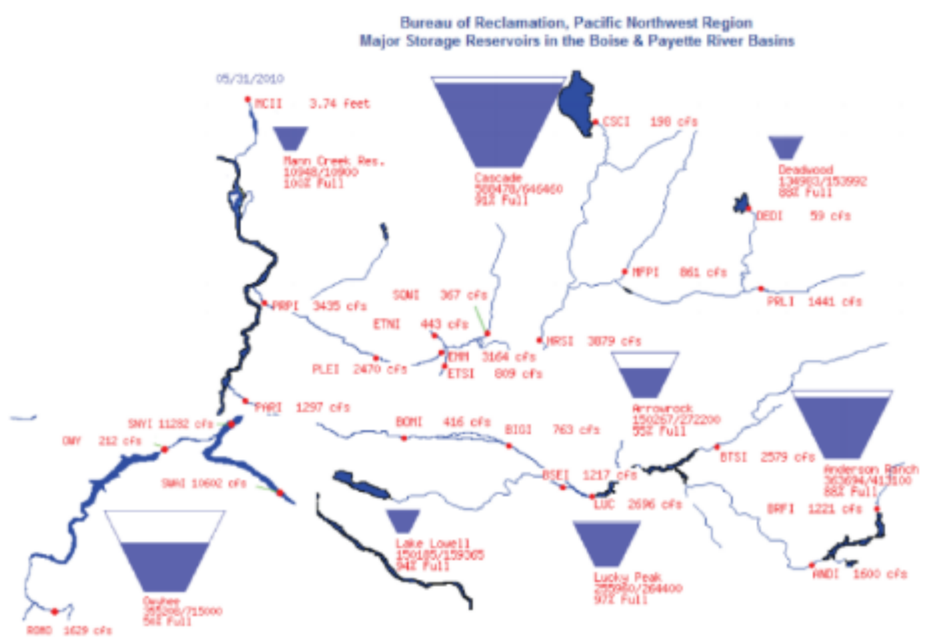


Figure 4: The Tea Cup diagram for the Boise and Payette River System on May 31, 2010, immediately prior to the onset of a significant AR that would deliver a large amount of precipitation to the watersheds of the reservoir system.

This June 2010 AR event represents a significant opportunity to understand the capabilities and limits of regionally refined CPMs in providing additional forecast information that may add in reservoir operation and flood mitigation to reservoir operators and emergency managers. It is a particularly germane event to study because: (1) its occurrence in the later portion of the season is potentially informative as an exemplar of the occurrence of ARs in a warmer climate, (2) it coincides with the availability of a CFSRR reforecast data prior to and during the event, and (3) there are a number of ancillary data products and analyses available, as well as next-generation remote sensing products, that provide additional context and data potentially useful for subsequent comparison and analysis.

Specifically, we investigate this event in detail by:

(1) Performing a WRF reanalysis simulation at convection permitting resolutions using the domains identified in **Figure 2** and physics options identified in **Table 1** for the period from June 1-5, 2010,
(2) Performing a sequence of reforecast WRF simulations, again using the domains identified in **Figure 2** and physics options identified in **Table 1**, to serve as a test of potential forecast skill in the month prior to the AR event, and
(3) Comparing the reforecast WRF simulations with the reanalysis WRF simulation as a way of determining the skill of the reforecast simulations in comparison with a similar simulation forced by reanalysis data.

Below we describe the model set-up.

Modeling Experiment Set-up

Reanalysis

A reanalysis simulation is a WRF model run that uses lateral boundary condition (LBC) data that has been conditioned on a variety of atmospheric observations derived primarily from radiosondes and remote sensing platforms. As such, it is our best representation of the actual June 2010 AR event as it occurred and will serve as a benchmark against which subsequent reforecasts can be compared. The WRF reanalysis simulation was developed by using the CFSR data to provide lateral boundary conditions (LBCs) to the outer 3 km WRF model domain from **Figure 2**. One-way coupling within the WRF model was used such that output from the WRF simulation at the boundary of the inner 1 km WRF model domain (**Figure 2**) was used as the boundary conditions for the model in the inner domain. To allow the land surface and atmospheric states in the 3 km and 1 km domain to equilibrate, we ran a spin-up simulation prior to June 1, 2010. A spin-up simulation is a simulation that is initialized with initial land surface and atmospheric conditions that are significantly coarser than the simulation domain. By running the model for an extended period of time, the states of the atmosphere and land surface are allowed to equilibrate and begin capturing spatiotemporal dynamics at the resolution of the model. Specifically, the initial land (e.g., soil moisture, etc.) and atmosphere states for the WRF simulation were obtained directly from the CFSR data and the spin-up simulation started on September 15, 2009. The motivation underlying this particularly long spin-up simulation was to obtain realistic conditions for initial snow cover and snow water equivalent prior to the onset of the June 1, 2010. This required running the spin-up simulation for the totality of the snow accumulation season and most of the melt season. Realistic spatial patterns of snow cover and snow water equivalent are desirable to capture any dynamic snow-atmosphere interactions as the synoptic conditions associated with the Atmospheric River are supplied as boundary conditions to the WRF model. The reanalysis simulation was then obtained by running the WRF model with initial conditions from the spin-up simulation on June 1, 2010 and supplying the CFSR data as input to the outer 3 km domain and allowing the model to run from June 1, 2010 to June 5, 2010.

Output of the reanalysis simulation was saved in Network Common Data Format (NetCDF) for subsequent analysis.

Reforecasts

The initialization of reforecast simulations was constrained by the availability of CFSRR data on the National Center for Environmental Prediction (NCEP) data archive. In this case, extended range reforecasts in the CFSRR repository are available in 5-day intervals prior to the June 1-5 period of interest. Specifically, the CFSRR reforecasts used to initiate WRF reforecasts were available for the following dates and forecast hours:

(1) May 1, 2010 12z,
(2) May 6, 2010 12z,
(3) May 11, 2010 12z,
(4) May 16, 2010 12z,
(5) May 21, 2010 12z,
(6) May 26, 2010 12z, and
(7) May 31, 2010 12z.

The CFSRR reforecasts were used as the LBCs to the outer 3 km WRF domain from **Figure 2**. In similar fashion to the reanalysis run, one-way coupling was used such that output from the WRF simulation on the 3 km domain was used to supply LBCs to the inner 1 km domain. The initial land surface at atmosphere conditions for the reforecast simulations corresponded to the modeled states from the reanalysis simulation at the time the reforecast simulation was initialized. For example, the May 1, 2010 12z reforecast simulation used the initial conditions from May 1, 2010 12z from the reanalysis simulation. In this way, the reforecast simulations used an initial condition that is a realistic representation of the state of the land-atmosphere system at the time the reforecast simulation began. The CFSRR data were then used as input to the outer 3 km domain and the WRF model allowed to run from the initialization date through June 5, 2010.

Output of the reforecast simulations were also saved in Network Common Data Format (NetCDF) for subsequent analysis.

Results

Reanalysis

Accumulated precipitation from the reanalysis simulation is shown for the 3 km domain in **Figure 5(a)** and for the 1 km domain in **Figure 5(b)**. The cumulative precipitation (water equivalent) reaches 100 mm or more between June 1-5 in many of the mountain ranges in the study area, including in the Teton Mountains, along the Idaho-Montana border in the Bitterroot Mountain range, in the Central Rockies within the Payette River Basin, and in the Wallowa Mountains (**Figures 5(a) and 5(b)**).

Future analyses of the output reanalysis (as well as the reforecasts discussed below) will provide quantitative comparisons to available surface observations from the SNOTEL network, as well as geostatistical interpolation products (DayMet) and reanalysis datasets (NLDAS). Furthermore, we are collaborating with colleagues from the Boise Weather Forecasting Office to analyze this reanalysis and are planning on developing a manuscript summarizing the reanalysis to be submitted to Monthly Weather Review.

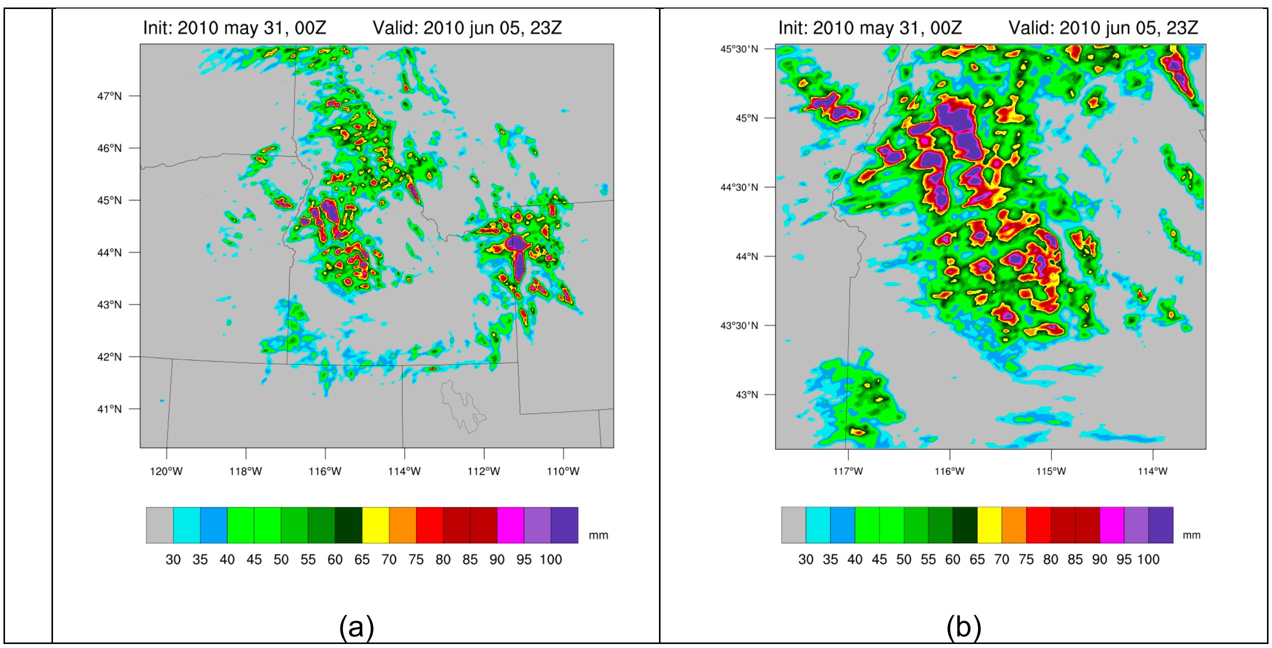
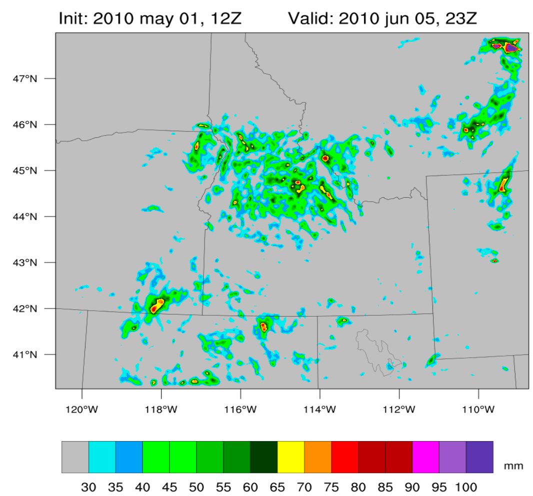
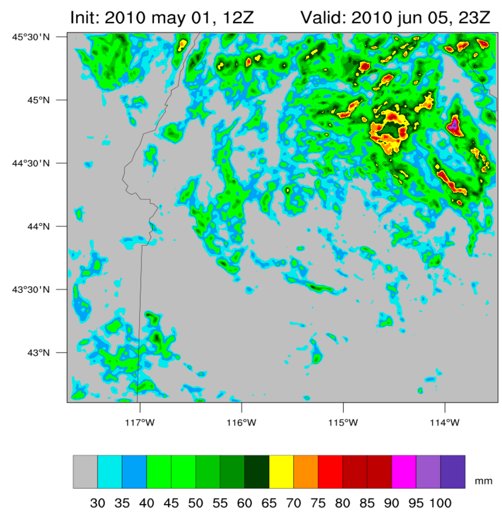
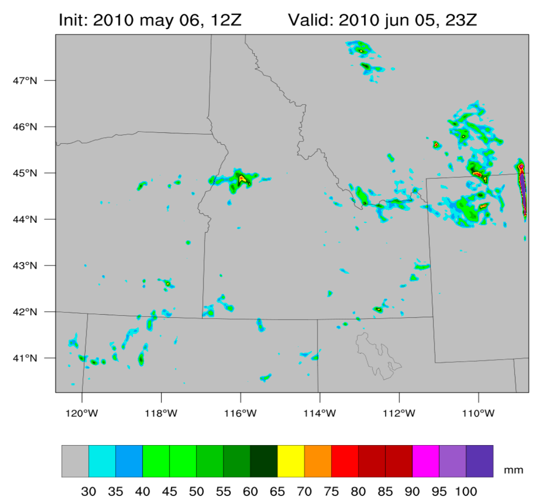
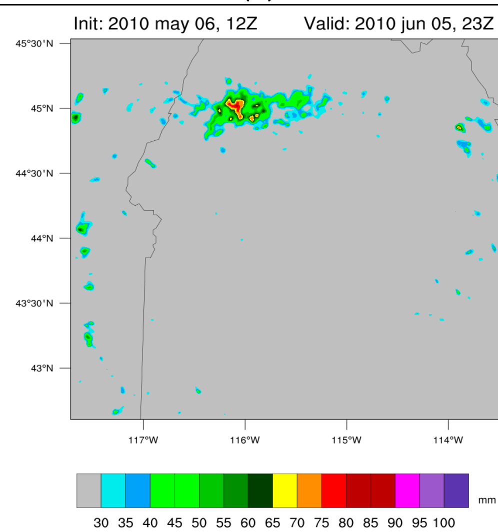


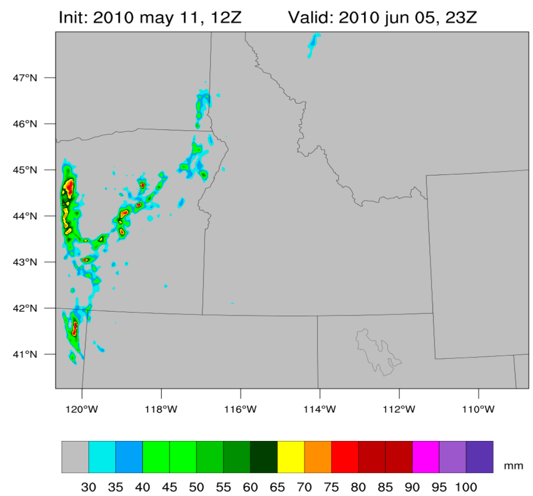
Figure 5: accumulated precipitation for the period June 1-5, 2010 for the (a) 3km domain and (b) 1 km domain

Reforecasts

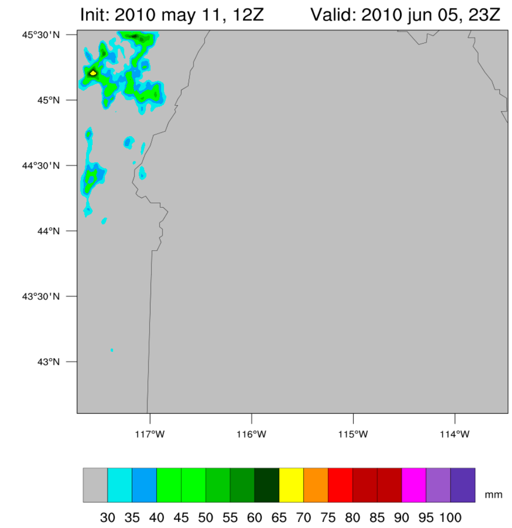
High-level insights from the reforecast simulations are summarized here. The first reforecast, which corresponds to an approximately 30-day lead-time, suggests a significant precipitation event during the period of the Atmospheric River event, but underestimates both the spatial extent of the precipitation and the total amount of precipitation. The following four reforecasts essentially miss the entirety of the precipitation event, although they do suggest some relatively minor precipitation in other parts of the outer domain. The final two reforecast simulations then suggest a significant precipitation event, with the final forecast – initialized with a lead-time of 1-day prior to the onset of the AR precipitation event – suggesting a very large precipitation event.

	3 km Domain	1 km Domain
May 01 2010 Initialization	 (a)	 (b)
May 06 2010 Initialization	 (c)	 (d)

May 11 2010 Initialization

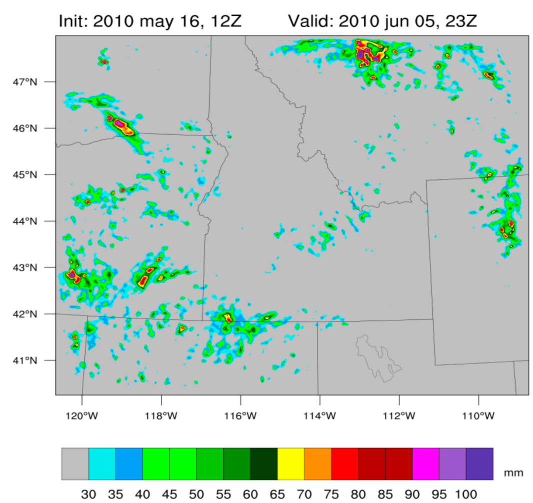


(e)

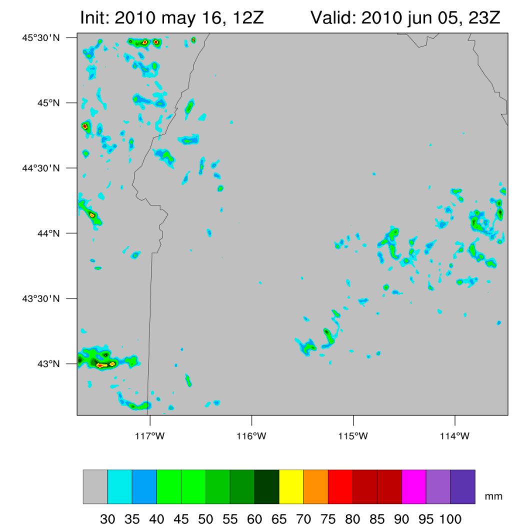


(f)

May 16 2010 Initialization

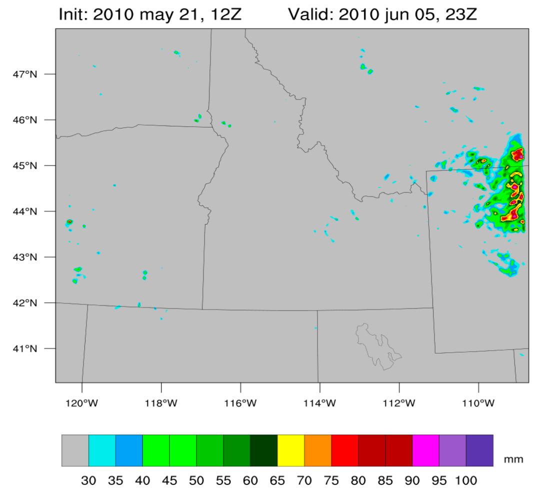


(g)

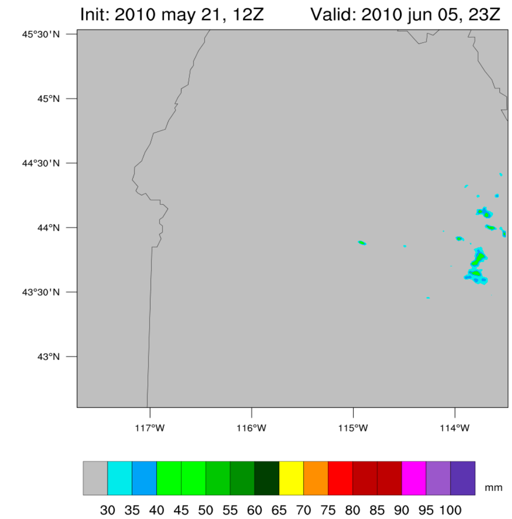


(h)

May 21 2010 Initialization

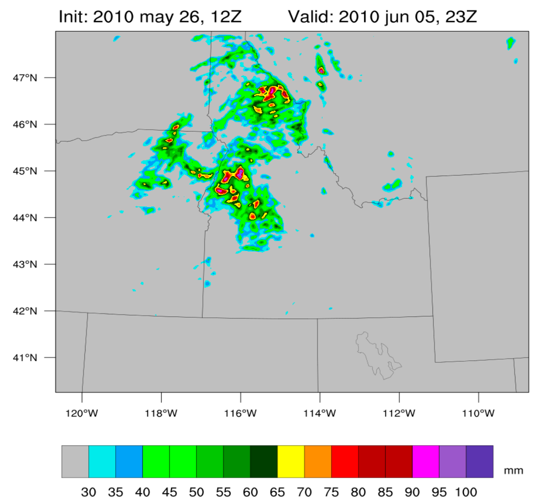


(i)

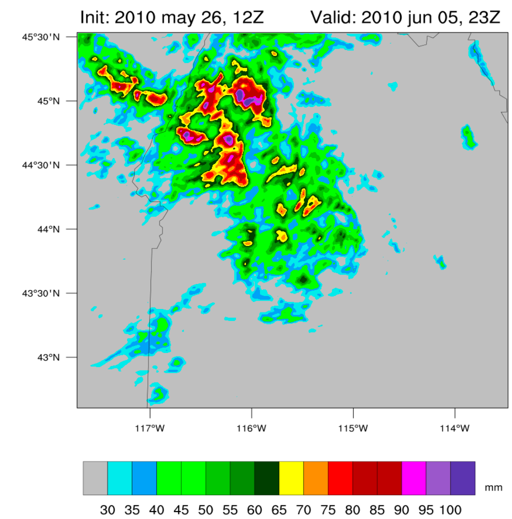


(j)

May 26 2010 Initialization

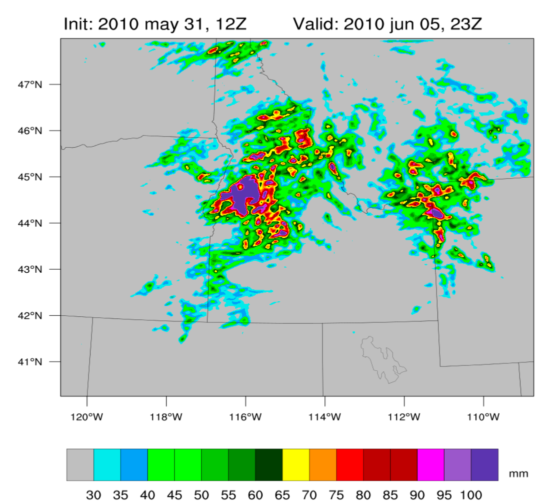


(k)

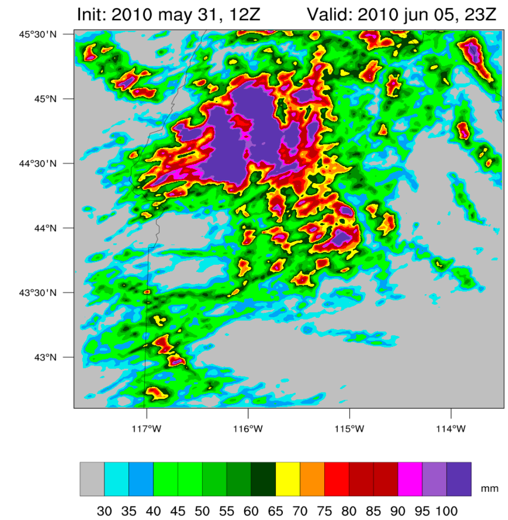


(l)

May 31 2010 Initialization



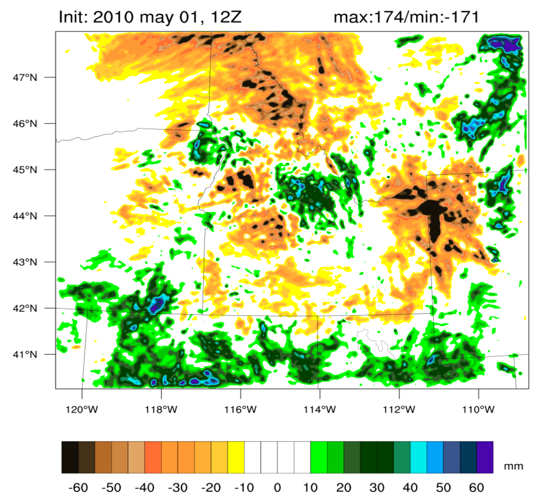
(m)

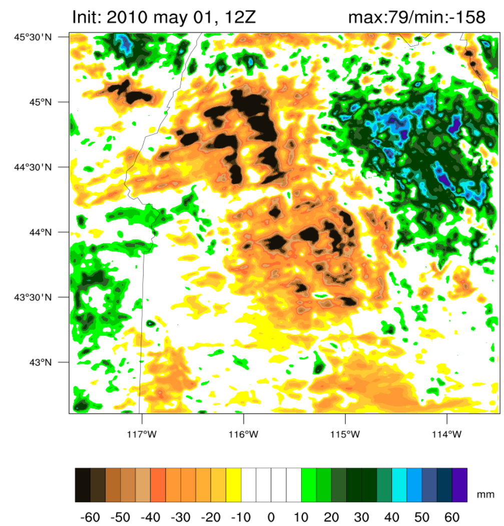


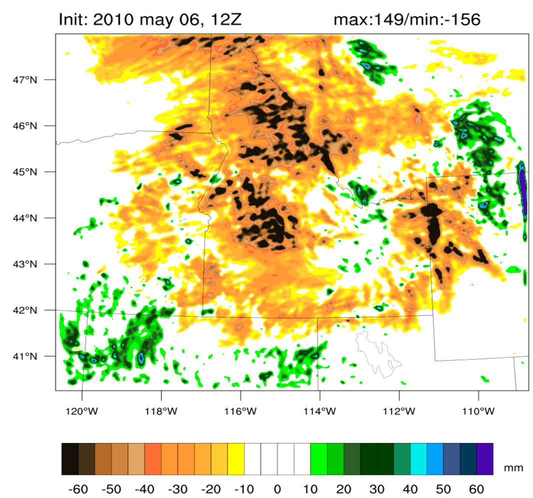
(n)

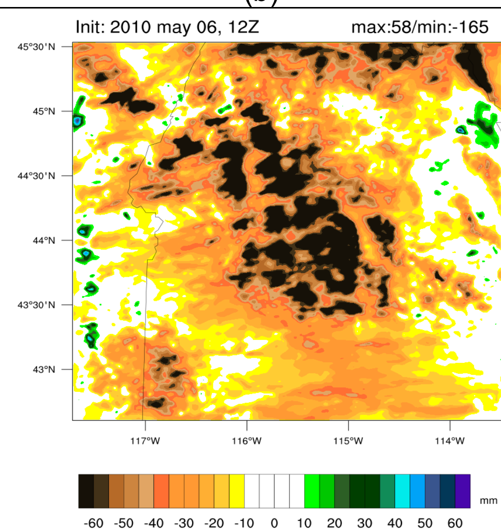
Figure 6: accumulated precipitation for the period June 1-5, 2010 for the 2010-05-01 initialization and the (a) 3km domain and (b) 1 km domain; 2010-05-06 initialization and the (c) 3km domain and (d) 1 km domain; 2010-05-11 initialization and the (e) 3km domain and (f) 1 km domain; 2010-05-16 initialization and the (g) 3km domain and (h) 1 km domain; 2010-05-21 initialization and the (i) 3km domain and (j) 1 km domain; 2010-05-26 initialization and the (k) 3km domain and (l) 1 km domain; 2010-05-31 initialization and the (m) 3km domain and (n) 1 km domain.

Comparing the reforecasts with the reanalysis by computing the difference between the reforecast and reanalysis (**Figure 7**), shows a quantitative comparison between the reanalysis and reforecast simulations. Again, these comparisons continued to be examined more closely, but important spatiotemporal patterns appear to emerge. Specifically, the most skillful reforecast simulation within the Boise-Payette River system appears to be the reforecast initiated on 2010-05-26, approximately 5 days prior to the onset of the event. Moreover, interestingly, the final reforecast simulation suggests that the reforecast overestimates precipitation in the more northern portion of the inner, 1 km domain. At the scale of the entire Snake River basin, the final forecast seems to be most skillful.

<table>
<tr><td></td><td>3 km Domain</td><td>1 km Domain</td></tr>
<tr><td>May 01 2010 Initialization</td><td>

(a)</td><td>

(b)</td></tr>
<tr><td>May 06 2010 Initialization</td><td>

(c)</td><td>

(d)</td></tr>
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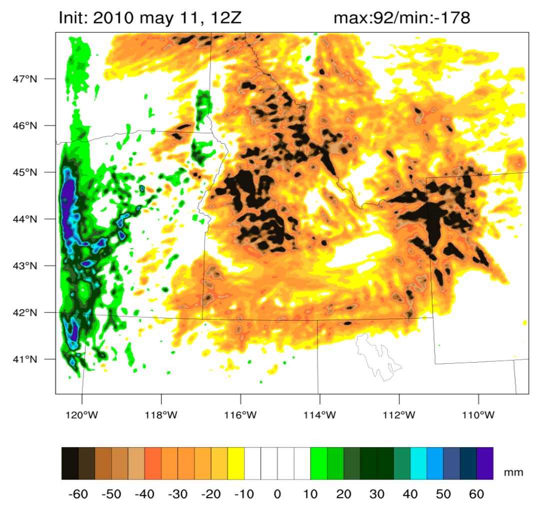
May 11 2010 Initialization



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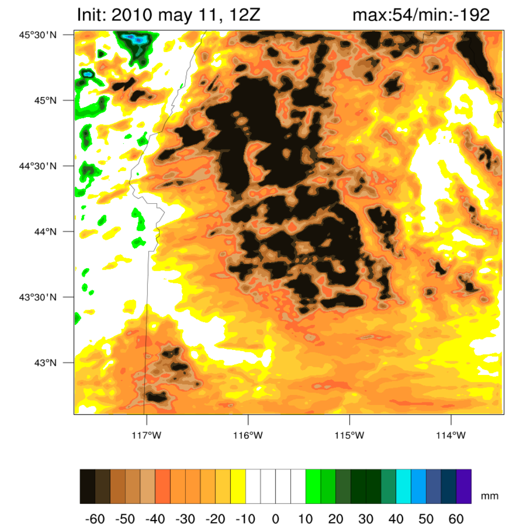
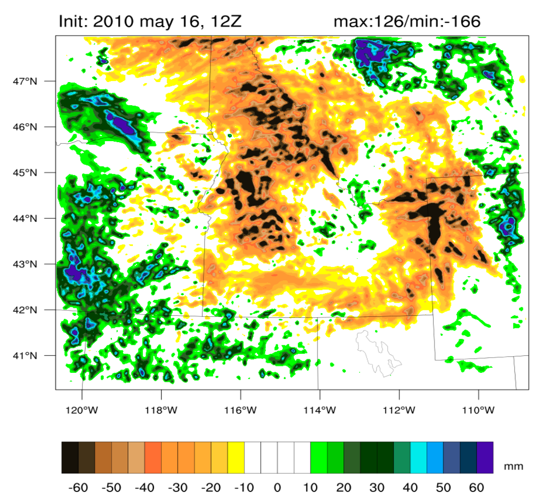


(f)

May 16 2010 Initialization



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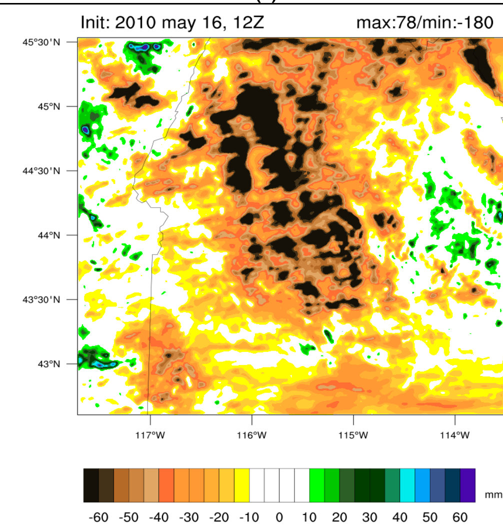
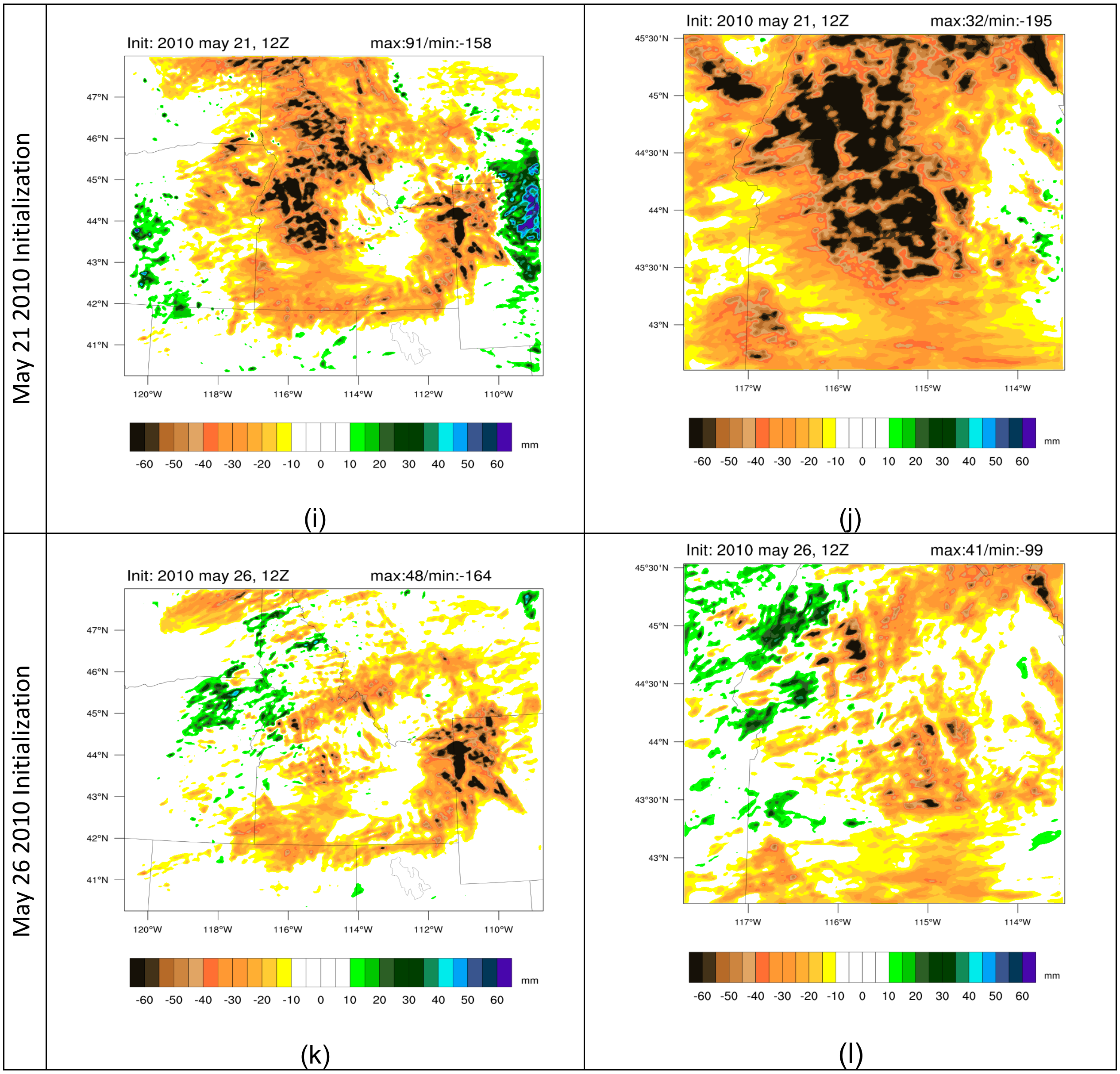


(h)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45°N
44°N
43°N
42°N
41°N
120°W 118°W 116°W 114°W 112°W 110°W
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60
mm
(i)
Init: 2010 may 21, 12Z
max:32/min:-195
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45°N
44°30'N
44°N
43°30'N
43°N
117°W 116°W 115°W 114°W
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60
mm
(j)
May 26 2010 Initialization
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46°N
45°N
44°N
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41°N
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mm
(k)
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45°N
44°30'N
44°N
43°30'N
43°N
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-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60
mm
(l)

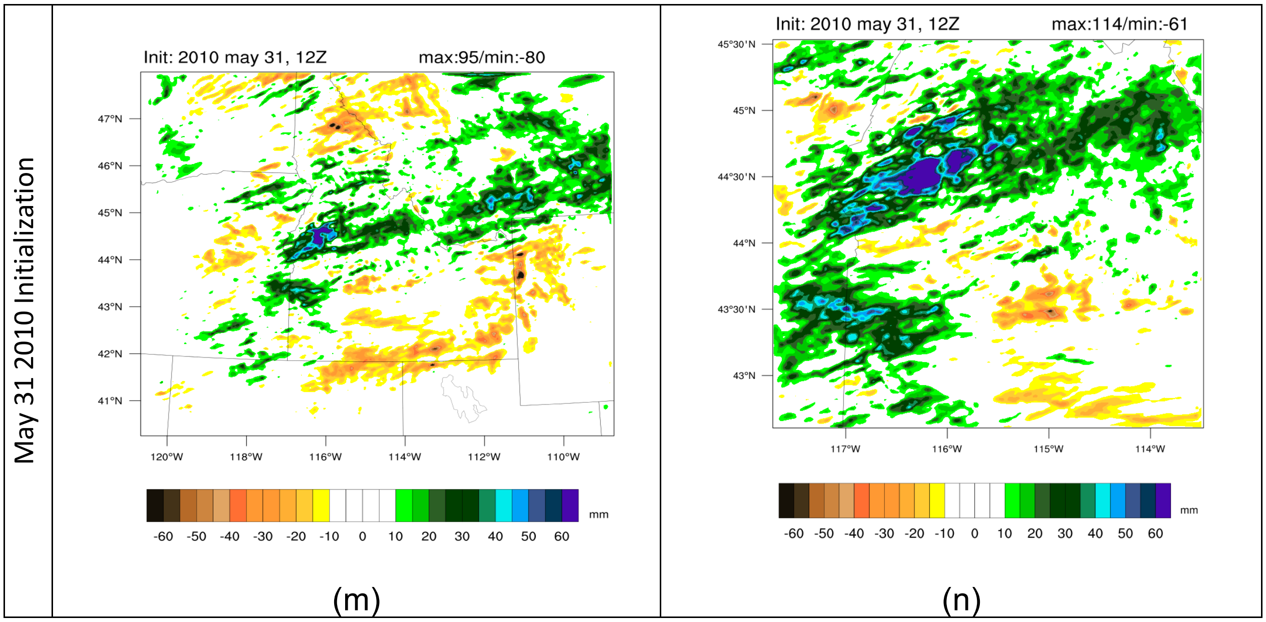

Figure 7: difference in accumulated precipitation between the reforecast and reanalysis simulations for the period June 1-5, 2010 for the 2010-05-01 initialization and the (a) 3km domain and (b) 1 km domain; 2010-05-06 initialization and the (c) 3km domain and (d) 1 km domain; 2010-05-11 initialization and the (e) 3km domain and (f) 1 km domain; 2010-05-16 initialization and the (g) 3km domain and (h) 1 km domain; 2010-05-21 initialization and the (i) 3km domain and (j) 1 km domain; 2010-05-26 initialization and the (k) 3km domain and (l) 1 km domain; 2010-05-31 initialization and the (m) 3km domain and (n) 1 km domain.

Another way of visualizing the evolution of skill between the reforecast and reanalysis simulations lies in the Taylor Diagram (**Figure 8**). The Taylor Diagram illustrates that, in comparing the accumulated event-scale precipitation, there is no reforecast that exhibits significantly high correlation with the reanalysis simulation, although the first and final reforecasts seem to be closest in reproducing the spatial variability of the reanalysis simulation.

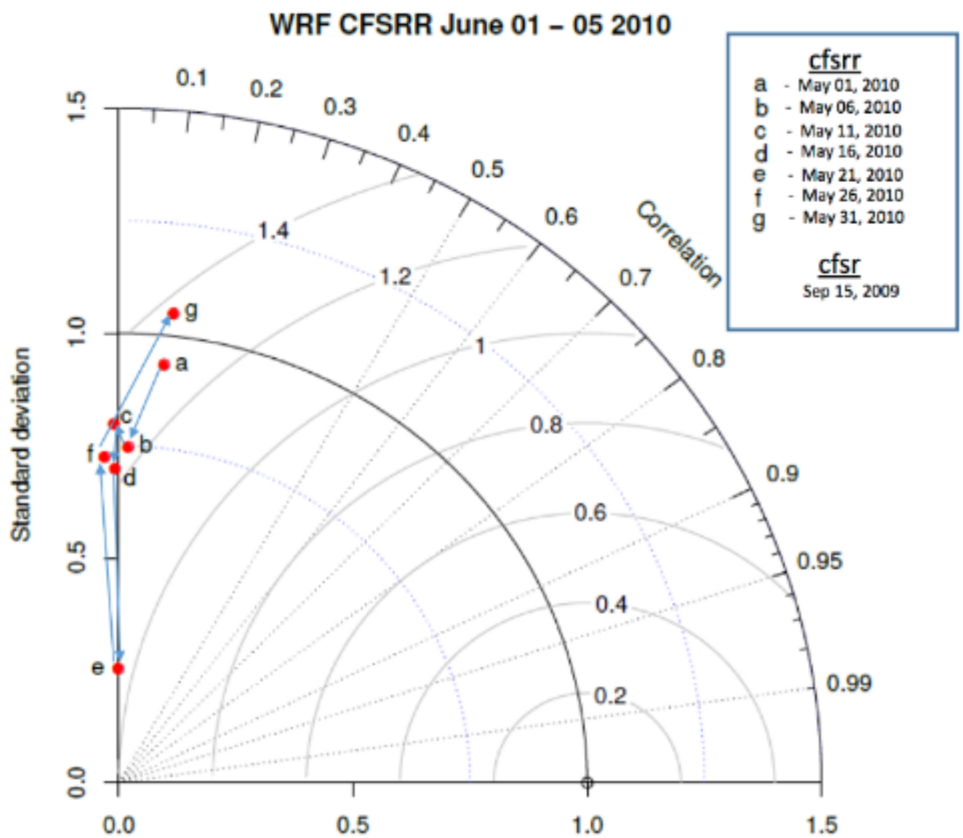

Figure 8: A Taylor Diagram showing the normalized Root Mean Squared Difference (RMSD) between accumulated precipitation in the reforecast versus reanalysis simulations, standard deviation in space of the reforecast simulations, and the correlation coefficient between the reforecast and reanalysis simulations.

Discussion and Conclusions

The produced reforecast and reanalysis datasets have yielded rich resources that we continue to examine to assess forecast skill in a variety of ways. Preliminary analyses of these datasets suggest that there may be some worthwhile information in CPM-based forecasts at intermediate lead-times in mountain watersheds. However, and importantly, the preliminary analyses shown here indicate that recovering useful information may require careful interpretation and investigation of the derived datasets. For example, the disappearance of any event of significance in the forecasts initialized between 06 May 2010 and 21 May 2010 (inclusive), in an operational setting, would likely have prompted enhanced monitoring large-scale meteorological patterns. There are two potential mechanisms by which these forecasts failed. First, the CFSRR data from 06 May to 21 May could have still contained an AR-like feature that that impacted watersheds elsewhere in the Western US and outside the spatial domains considered. In essence, absence of evidence of the occurrence of an AR event impacting the study domain in the forecasts is not evidence of absence of AR-like features in the CFSRR data. Alternatively, the CFSRR data from this period could have completely missed the presence of an AR-like feature. Continuous efforts to detect the presence of ARs in global forecasts, like that outlined below, could serve to identify times and locations where higher-resolution application of WRF (or similar models) at longer lead times would be beneficial to understanding the hydrologic consequences of these events in areas of interest. We continue to investigate the degree to which these forecasts might have yielded additional information about precipitation phase, as well as precipitation at key points within the domain such as SNOTEL sites. For example, there may have been more persistent forecasts of precipitation in mountainous portions of the domain, with significant differences between reanalyses and reforecasts arising from poor predictions at lower elevations.

We are also investigating the CFSR data for all forecasts to investigate why the four reforecasts from 2010-05-06 to 2010-05-21 suggested no precipitation. We have developed two working hypotheses regarding these reforecasts. First, it is plausible that the intervening forecasts suggested the occurrence of an AR-like event, but it either did not penetrate inland to the domain of interest or was concentrated to regions north or south of the domain. Second, the CFSRR did not predict a coherent AR-like structure in the period from 2010-05-06 to 2010-05-21. If the first working hypothesis proves more accurate, it suggests that the CFSv2 and other intermediate- and extended-range forecast products may resolve ARs and AR-like patterns at significant lead times, but their precise impacts on inland precipitation are not less well understood. This possibility opens the door to potential just-in-time monitoring and forecasting capabilities for ARs and AR-like synoptic events in the Western US. Specifically, it might be possible to analyze CFSv2 forecasts for the occurrence of potential AR-like events. The occurrence of ARs in the Pacific Basin, or the exceedance of detected ARs above some threshold, could trigger a sequence of WRF simulations at convective permitting scales to assess the likelihood that the CFSv2 forecasts may contribute to potential scenarios like large precipitation, rain-on-snow, and/or flooding events.

To this end, ongoing work being conducted by PI Flores seeks to identify and classify AR events, producing automated imagery of AR events in terms of IVT and wind field (**Figure 9**). This AR-detection scheme could be automatically applied to CFSv2 forecasts (both the deterministic and perturbed ensemble members) at limited computational cost. AR-like features exceeding a certain size or persisting in a number of sequential forecasts could then trigger a suite of CPM modeling forecasts to evaluate potential impacts. In another complementary project, we are using WRF to investigate how the presence or absence of snow cover potentially influences the onset, extent, duration, amount, and phase of AR-induced precipitation. Preliminary work suggests that the presence of a large snowpack in mountain regions can act to develop a near-surface high that can serve to block – to some degree – inland penetrating ARs.

To conclude, this work has yielded key benchmark modeling datasets and workflows using the WRF model at convection permitting scales to evaluate potential skill of extended-range forecasts using regionally refined CPMs. Preliminary analyses of these datasets suggest that regionally refined, extended-range forecasting using CPMs can potentially provide additional information and context that is of use to reservoir and emergency managers. At a minimum, they appear to be of significant value in the period within approximately 5 days of significant synoptic precipitation events. However, care should be exercise in extracting information from these regionally refined forecasts to be used in operational workflows. Moreover, the numerical expense of these simulations suggests that for the foreseeable future the use of CPMs for extended range forecasting should be triggered by significant synoptic events detected in global extended range forecasting products.

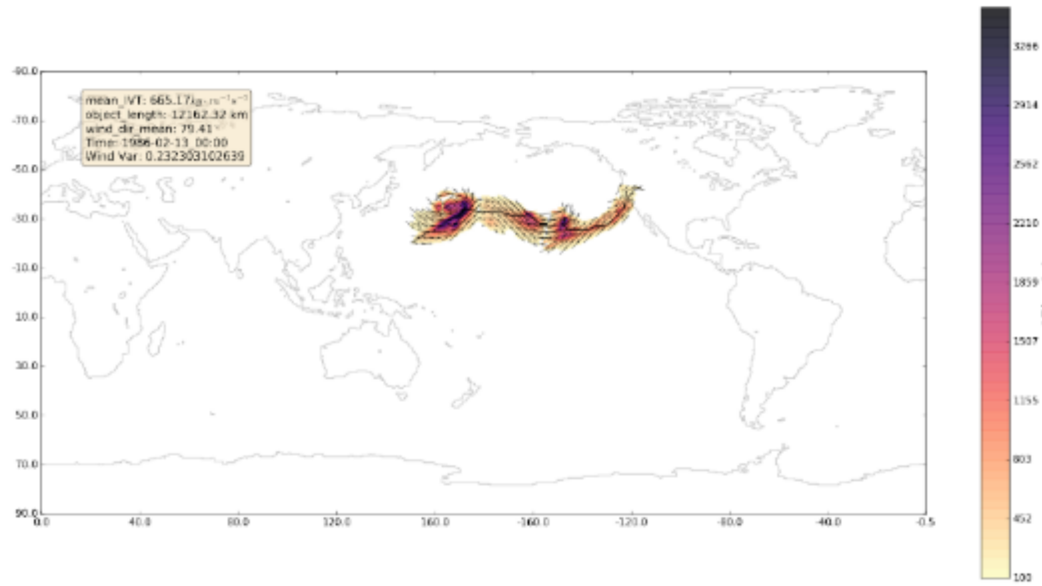

Figure 9: An example Atmospheric River event in February 1986 identified by an elongated corridor of high IVT relative to climatology in February.

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