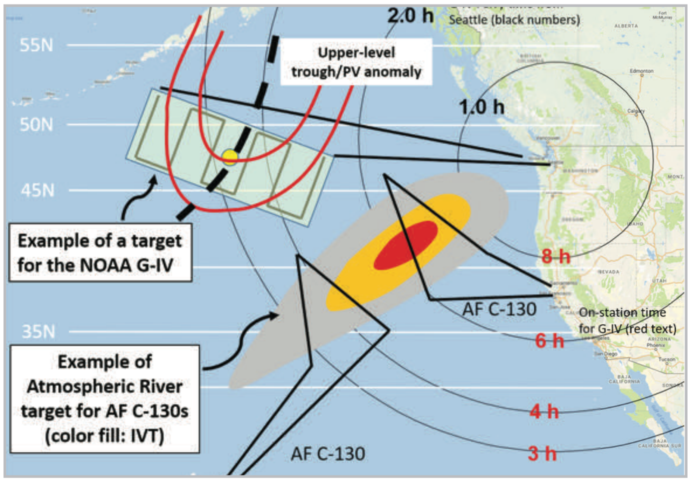
ATMOSPHERIC RIVER RECONNAISSANCE

Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

CHALLENGE

Atmospheric rivers (ARs) are the primary storms that produce both beneficial water supply (up to 50% on average) and floods (over 90% of major floods). Yet AR landfall forecasts can be off by 200-300 miles, even just 3 days before impact. AR reconnaissance (AR Recon) uses aircraft to gather data offshore to improve forecasts of landfalling ARs on the US West Coast. The Western States Water Council has recommended AR Recon for improving forecasts.[1]



Example of a flight strategy for AR Recon with the NOAA G-IV and two Air Force C-130s.

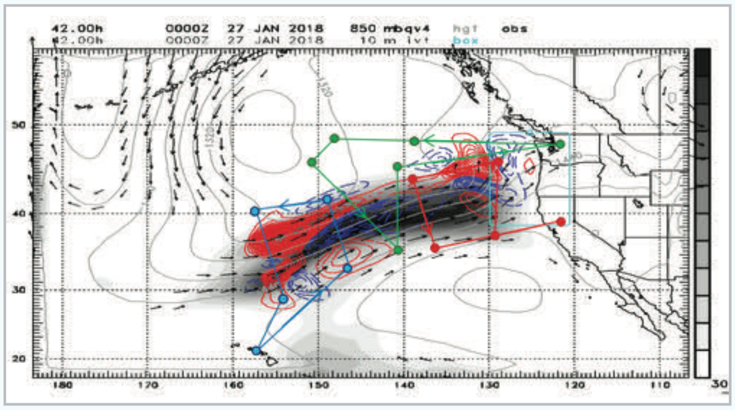
ACCOMPLISHMENTS

CW3E is the leader and catalyst for this effort, having led the deployment of a U.S. Weather Recon fleet to monitor ARs off the west coast, with 3 and 6 missions in 2016 and 2018, respectively. These campaigns serve to promote an understanding of how specific AR characteristics and forecasting methodologies affect precipitation forecasts.

AR Recon has brought together a wide range of agencies and academics, including NOAA (NWS' NCEP and Western Region, OMAO/Aircraft Operations Center), Naval Research Lab (NRL), the Air Force 53rd Weather Reconnaissance Squadron, Plymouth State University, the National Center for Atmospheric Research, the State University of New York at Albany, the University of Arizona, and the European Centre for Medium-Range Weather Forecasts. This collaborative effort demonstrates the importance of AR Recon to California and the entire West Coast of the US.

The California Department of Water Resources (DWR) supports AR Recon through funding for dropsondes (the instruments released from aircraft to obtain temperature, wind, and relative humidity). DWR's support heavily leverages

Uncertainties in atmospheric river conditions offshore impact forecasts at landfall. A model developed and run at NRL can pinpoint areas where these uncertainties have the highest impact on forecasts. In this example from 27 January 2018, the model identified locations (red and blue contours) where even a very small error in the integrated vapor transport (grey shading) can cause a significant difference in forecast precipitation in a given area (light blue box). Proposed flight tracks to sample these targeted areas are overlaid for the three aircraft (NOAA G-IV, green; Air Force C-130s, blue and red) used in AR Recon 2018. (Figure courtesy of James Doyle and Carolyn Reynolds, Naval Research Laboratory.)



funds from the US Army Corps of Engineers in support of forecast informed reservoir operations and participation of U.S. Air Force and NOAA aircraft and staff. The aircraft used for AR Recon include two C-130s and NOAA's Gulfstream IV(G-IV) jet, both of which are used for hurricane reconnaissance in the Eastern U.S.

AR field campaigns have developed new forecasting tools including the AR landfall tool and plume diagrams. These tools, available on the CW3E website, were first tested during CalWater.[2,3] Recent AR recon efforts have developed new flight planning tools and incorporated new methods to better understand what causes the greatest forecast uncertainty.

NEXT STEPS

Future AR Recon is needed to understand how observational data can improve AR forecasts, particularly the largest storms, to more accurately predict where, when and how much rain will fall. Three aircraft in each of nine storms in 2019 will provide enough cases for evaluation and refinement of the method, and for careful testing of the impact of the data on numerical weather prediction models. Additionally, new data assimilation methods are being developed and tested to optimize use of the dropsondes in regional and global weather forecast models. These efforts require large supercomputer commitments, coordination and support of a diverse team of experts, and development of forecast skill performance metrics.

Dr. Marty Ralph holding a dropsonde on the NOAA G-IV aircraft.

References

[1] Ralph et al. 2014, J. Contemporary Water Resources Research and Education, Universities Council for Water Resources.

[2] Ralph et al., 2016, Bull. American Meteorological Society.

[3] Cordeira et al., 2017, Bull. American Meteorological Society.

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A Scale to Characterize the Strength and Impacts of Atmospheric Rivers

CHALLENGE

Scales for meteorological phenomena, such as hurricanes and tornadoes, have proven very useful in raising public awareness of potentially hazardous conditions, forecasting, and conducting research. Atmospheric rivers (ARs) are the most impactful type of storm that occurs in California and along the U.S. West Coast and are a major source of extreme precipitation. Despite the widely recognized importance of ARs, until creation of this scale, no concise method had existed for conveying the possible spectrum of benefits and hazards that communities face during a particular AR event.

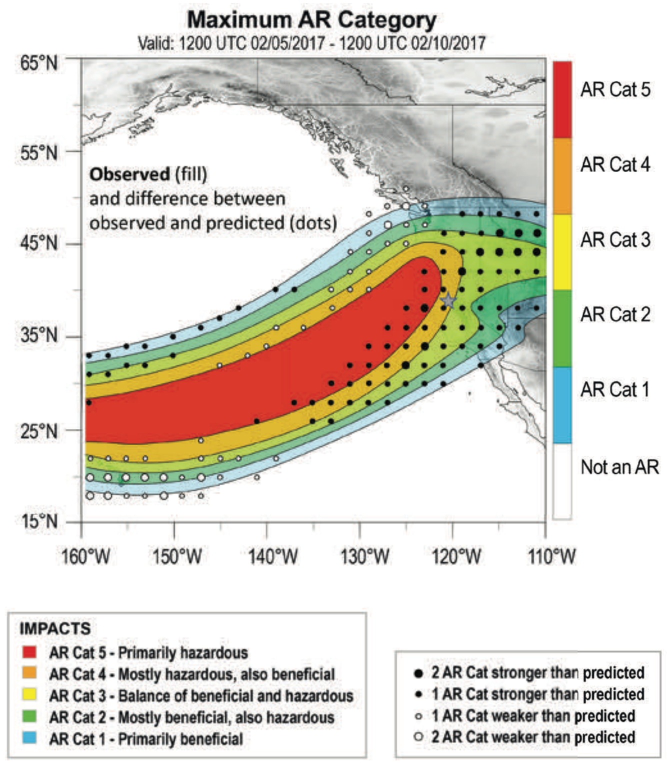

Figure 1. Top, AR CAT conditions associated with the storm that caused problems at northern California's Oroville Dam in February 2017, including evacuation of 200,000 people. Bottom, AR CAT scale and typical associated impacts.

ACCOMPLISHMENT

The Center for Western Weather and Water Extremes (CW3E) and a number of collaborators developed a scale for characterizing the strength and impacts of ARs (Figure 1). The work on this scale has occurred over several years, led by F.M. Ralph, Director of CW3E at UC San Diego's Scripps Institution of Oceanography, with input from many experts, especially from the National Weather Service (J. Rutz, C. Smallcomb), Plymouth State University (J. Cordeira), U.S. Geologically Survey (M. Dettinger), California's Department of Water Resources (M. Anderson), University of Colorado (D. Reynolds) and the U.S. Army Corps of Engineers (L. Schick, retired). It was recently formalized through acceptance of the peer-reviewed paper by Ralph et al. (2018) in the leading meteorological journal *Bulletin of the American Meteorological Society.*[1]

APPLICATIONS OF AN AR SCALE

The AR category (AR CAT) of an AR event is based on its maximum INTENSITY and DURATION (Figure 2). Intensity measures the integrated water vapor transport (IVT), or the amount of water vapor that an AR transports. Given an increased focus on AR-related science and impacts, it is likely that this AR CAT scale will be widely used to communicate the benefits and hazards associated with ARs in the western United States, where they contribute strongly to hydrological impacts. This is especially true of the hazards associated with extreme and exceptional ARs. The AR CAT scale is intended to serve the western United States, as other meteorological scales have served other parts of the nation.

DETERMINING THE AR CAT FOR AN AR EVENT[2]

Step 1: Pick a location (Figure 2, top).

Step 2: Determine a period of time when IVT ≥ 250 kg $m^{-1} s^{-1}$ (using 3 hourly data) at that location, either in the past or as a forecast. The period when IVT continuously exceeds 250 kg $m^{-1} s^{-1}$ determines the AR's start and end times, and thus also the AR duration for the AR event at that location.

Step 3: Determine AR intensity by finding maximum IVT during the AR at that location. This sets the AR intensity and preliminary AR CAT (Figure 2, bottom).

Step 4: Determine the final value of the AR CAT to assign (Figure 3).

- If the AR duration is ≥ 48 hours, then promote the value by one category.
- If the AR duration is < 24 hours, then demote the value by one category

Note: You can find AR intensity and duration forecast information on the CW3E webpage (cw3e.ucsd.edu) under "Forecasts" by selecting "AR, IWV, and IVT Forecasts."

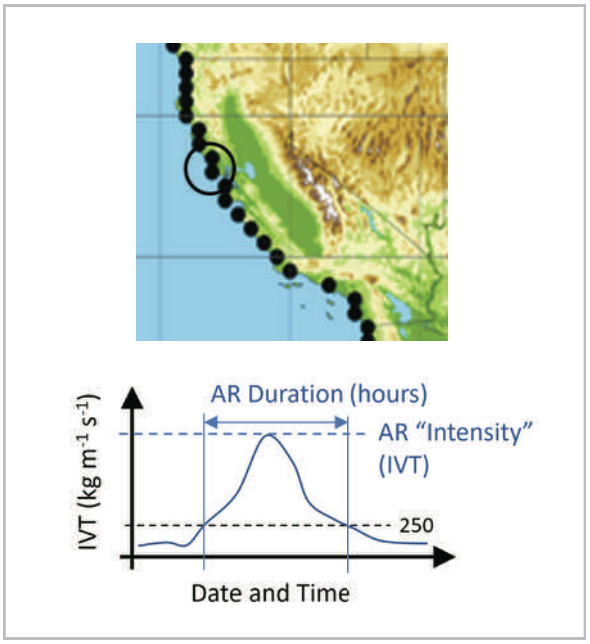

Figure 2. (top) To determine the AR location, pick a location and (bottom) then determine the maximum intensity and duration.

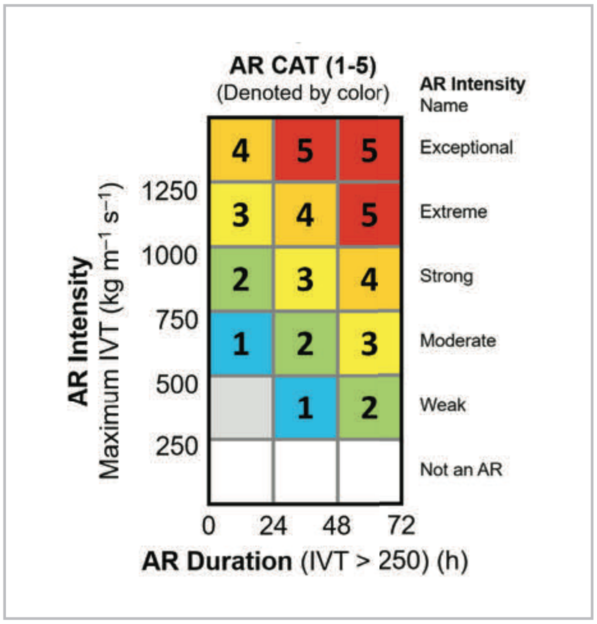

Figure 3. The AR CAT scale categorizes AR events based on the maximum instantaneous IVT associated with a period of AR conditions (i.e., (IVT ≥ 250)(h) kg m–1 s–1) and the duration of those conditions at a point.

References

[1] Ralph, F. Martin, Jonathan J. Rutz, Jason M. Cordeira, Michael Dettinger, Michael Anderson, David Reynolds, Lawrence J. Schick and Chris Smallcomb, 2018: A Scale to Characterize the Strength and Impacts of Atmospheric Rivers. Bull. Amer. Meteorol. Soc., (in press, Sept. 2018).

[2] An "AR event" refers to the existence of AR conditions at a specific location for a specific period of time.

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ATMOSPHERIC RIVER FORECASTING DECISION SUPPORT TOOLS

CHALLENGE

Atmospheric river (AR) forecasts are key to accurately predicting precipitation and flooding in California. However, standard meteorological monitoring and prediction methods and tools have not been tailored to ARs.

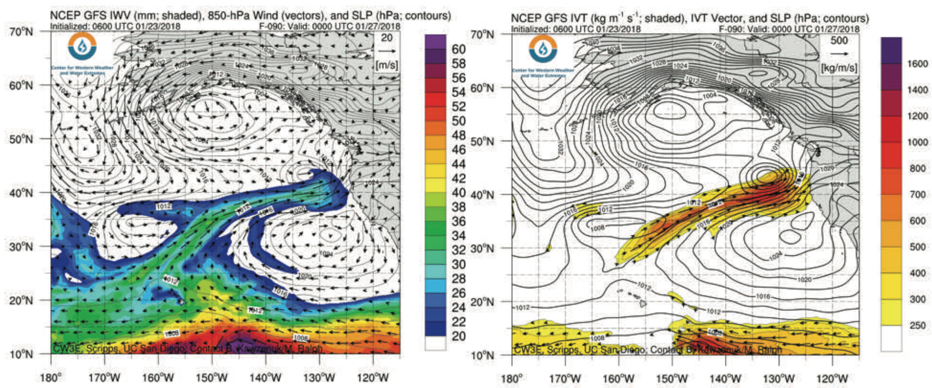
ACCOMPLISHMENTS

CW3E developed and maintains a website (http://cw3e.ucsd.edu) containing unique observations, analyses, and a comprehensive collection of tools specific to AR forecasting to help fill this gap. Many of the tools incorporate a new way of measuring and categorizing the strength and potential impacts of landfalling ARs.[1] The products developed by CW3E and partners have created new awareness of predicted AR strength, position and duration in support of water resources management, hazard mitigation, and forecasting applications for a range of users and decision makers.

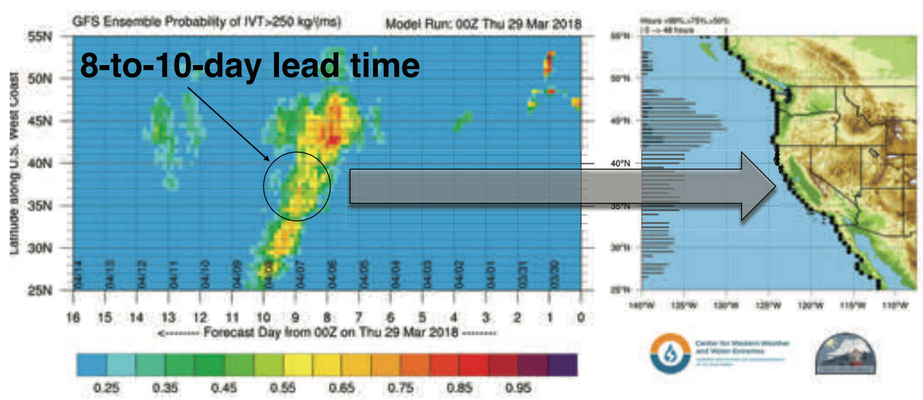
KEY ANALYSIS & FORECAST TOOLS

- **Forecast Maps** are derived from NOAA numerical weather prediction model data to predict large-scale and small-scale aspects of landfalling ARs up to 10 days in advance. These maps are a foundational component to CW3E experimental forecast outlooks.

- The **AR Landfall Tool** developed by Dr. Jay Cordeira (Plymouth State University) and Dr. Marty Ralph (CW3E) provides longer-range ensemble forecast guidance of the intensity, duration and timing of landfalling ARs up to 16 days in advance. Recent upgrades include adding AR orientation, which is a necessary parameter for diagnosing watersheds that will receive the most precipitation.



Example of CW3E forecast maps of integrated atmospheric water vapor (IWV) (left) and integrated vapor transport (IVT) (right) on 27 January 2018 prior to the landfalling of a particularly intense AR.

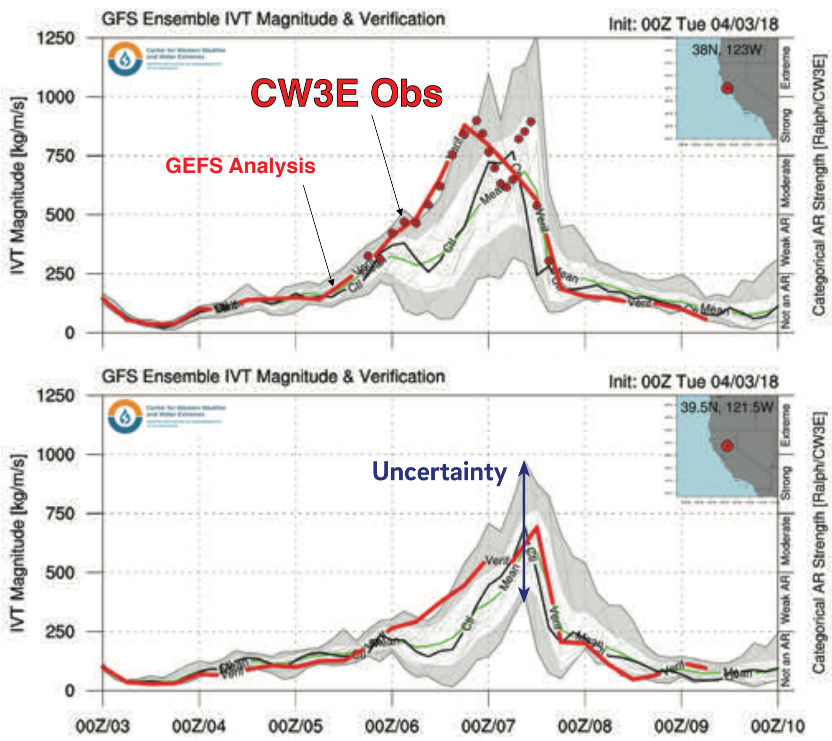


The AR Landfall Tool depicts the likelihood of an AR (shaded in colors) by latitude (y-axis) and forecast time (right to left on the x-axis) from March 29, 2018, providing forecast guidance 8-to-10 days in advance of the AR on April 7.

- **Forecast Plumes** are generated in real time on the CW3E website and are used in outlooks and storm summaries. These "plume diagrams" convey uncertainty information in the timing and intensity of landfalling ARs according to the AR Intensity scale.[2] Two types of verification of AR intensity complement the plume diagrams: (1) the model derived GEFS analysis and (2) observations collected by CW3E. These verifications show how well the AR was forecast 4 days in advance, how the AR was stronger earlier than expected, and how observations provide more accurate representation of AR intensity than the model.
- **Watershed Forecast Tools** provide forecast guidance on watershed-scale impacts of AR precipitation. One such forecast tool uses ensemble forecasts of freezing levels and NOAA/NCEP/WPC precipitation, along with a 1-km elevation model, to downscale rain-snow levels to watershed-scale, providing a forecast of how AR precipitation would be partitioned between rain and snow. The tool provides this information both as an interactive topographic map, and as detailed watershed-scale time series. The tool covers watersheds in CA, OR, WA, NV, ID and northwest MT, where rain-snow partitioning in AR storms is key to water resources operations. It provides a sense of forecast uncertainty in rain-snow levels that is important for assessing AR-driven flood and water supply risks, and is intended for water resource managers across the western United States.

NEXT STEPS

These tools are being continually improved and refined, and new tools will be developed as science advances and in response to growing demands for better forecast tools that are tailored to unique conditions of the western United States.

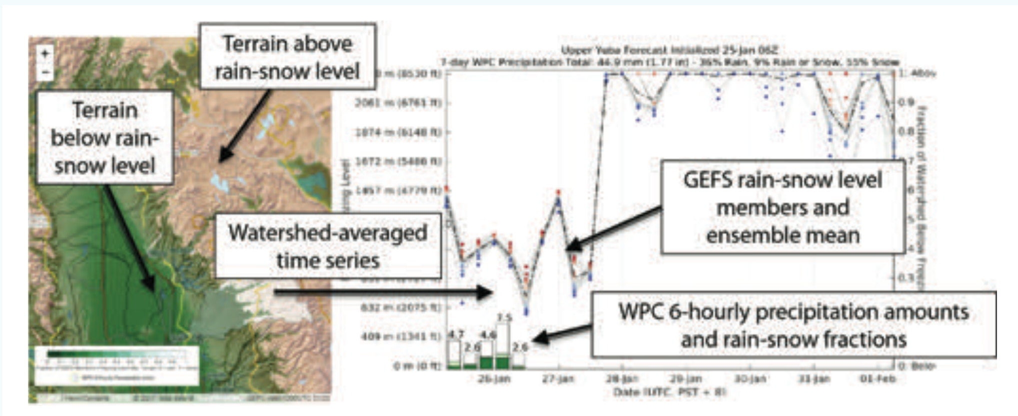


Ensemble-derived forecasts of IVT magnitude with verification (red). Each gray line is a different forecast model, green is the mean, and black is the "control" forecast. This example is for a forecast initialized on April 3, 2018 for Bodega Bay, CA and Oroville/Thermalito.

References

[1] Cordeira et al. 2017 Bull. Amer Meteorol. Soc.

[2] Ralph et al., Bull. Amer. Meteorol. Soc., *in revision*.



Rain-snow forecast tool for a forecast made on Jan 25, 2018. Left panel shows map of areas above rain-snow level (light shading), below rain-snow level (dark shading), and precipitation rates (contours). Right panel shows watershed forecast information, including time series of GFS ensemble rain-snow levels, watershed-mean precipitation rates, and fractions of precipitation falling as rain and snow.

Center for Western Weather and Water Extremes

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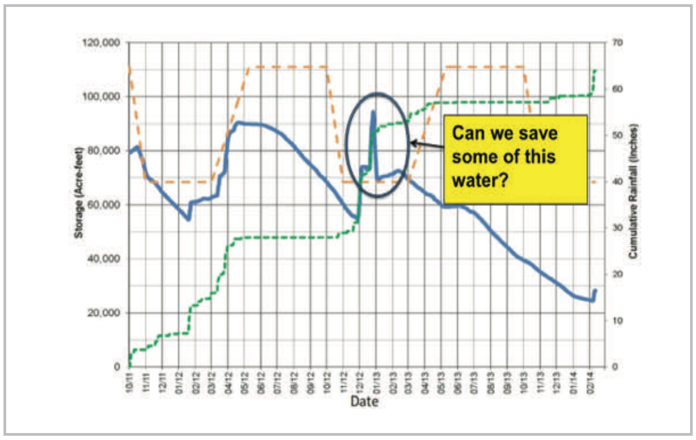
FORECAST INFORMED RESERVOIR OPERATIONS

CHALLENGE

California's water supplies rely on adequate precipitation, which is largely dependent on atmospheric rivers (ARs). The absence of AR storms often leads to drought, whereas strong ARs can cause flooding. Currently, most reservoirs are operated without the benefit of AR forecasts. However, there is now potentially useful skill in forecasting ARs. Predicting the timing and intensity of these critical precipitation events (and the lack thereof) is essential to providing water managers and dam operators with the information they need, with enough lead time, to operate reservoirs to adapt to floods and drought. Applying scientific advances in weather and streamflow prediction can lessen the impacts of weather extremes without the need for expensive infrastructure expansion. This cost-effective management approach, called Forecast Informed Reservoir Operations (FIRO), offers an opportunity to make better use of existing multi-purpose reservoirs across the state and region.

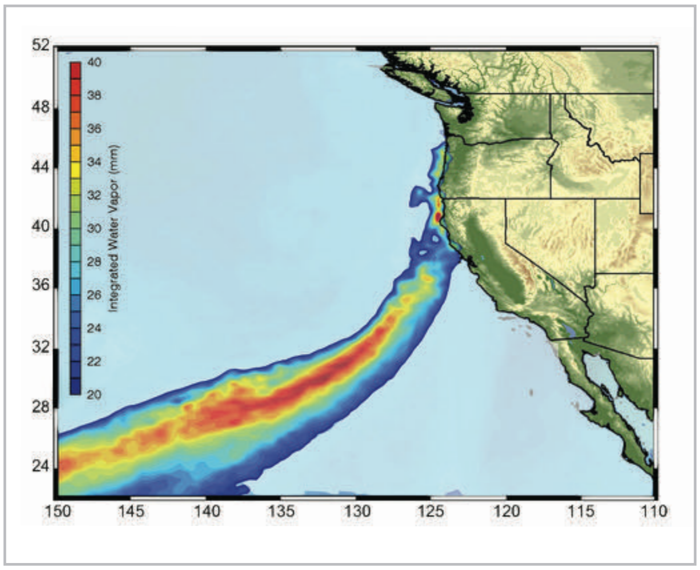


The blue line shows the actual storage in Lake Mendocino from October 2011 to February 2014. The dashed orange line represents the guide curve, or the allowed storage in Lake Mendocino determined by the U.S. Army Corps of Engineers (USACE) water control manual. The green dashed line is the accumulated rainfall during the period. December 2012 had over 15 inches of rainfall, most of which fell during four AR events. Since the storage level was above the guide curve, this water had to be released; however, over the next 13 months almost no additional rain fell.

ACCOMPLISHMENTS

FIRO, first tested at Lake Mendocino, in the Russian River watershed, has shown great promise. A Steering Committee, co-chaired by Marty Ralph (CW3E) and Jay Jasperse (Sonoma Water), is working collaboratively on this project, which has transferability potential to other reservoirs. Results from the Steering Committee's FIRO preliminary viability assessment[1] (2017) showed more than double the potential benefit to water supply as had been the goal, while not increasing flood risk and supporting salmon recovery.

- The final viability assessment is expected to be released in 2020.
- A FIRO project on Prado Dam in southern California is being scoped with a Steering Committee co-chaired by Marty Ralph (CW3E) and Greg Woodside (Orange County Water District) and including representatives of CA DWR, USACE, USFWS, NOAA, and Orange County Public Works.



The integrated water vapor for a strong AR (Feb 16, 2017) that impacted most of CA and produced 3 inches of precipitation in the coastal ranges. This was one in a series of three ARs that impacted CA in a week.

The FIRO research project is focused on improving forecasts through observations and modeling. Observations are essential for verifying and improving forecast models. Researchers at CW3E are working to understand the dynamics of ARs to better predict landfall location and the amount of precipitation that they will produce. Targeted observations have been collected in the Russian River watershed during the past three winter seasons, filling key gaps in existing observing systems to answer key science questions.

These targeted observations include two sites, one at the coast and one inland, where for the first time simultaneous radiosonde profiles were collected at high temporal resolution during AR conditions. This allows an assessment of AR characteristics, such as the vertical distribution of moisture and winds, orientation, and stability, that influence the resulting spatial patterns of precipitation and streamflow. This work also includes expanding the existing soil moisture, precipitation and streamflow monitoring networks.

Leveraging Funding: FIRO leverages funding from various partners to achieve multiple goals. FIRO was initiated via funding from Sonoma Water, followed by significant funding from the US Army Corps of Engineers. CA DWR added support for soil moisture monitoring and exploring FIRO potential at Prado Dam, which was then supplemented by funding from the Orange County Water District.

NEXT STEPS

Building on the ground-breaking Lake Mendocino FIRO pilot project, CW3E is examining the transferability potential of FIRO tools, approaches and strategies to other reservoirs and the unique meteorological, hydrological, biological and land use considerations that require tailoring for each reservoir. Work has already begun at Prado Dam, and other sites are being considered.

References

[1] FIRO Steering Committee, 2017, Preliminary viability assessment of Lake Mendocino. Available from: http://escholarship.org/uc/item/66m803p2

A CW3E researcher releases a radiosonde during a January 2017 AR at the UC Davis Bodega Marine Lab in the Russian River watershed.

The Lake Mendocino FIRO Steering Committee during a Lake Mendocino tour in January 2018. Left to right: Mike Anderson, CA DWR; Jay Jasperse, Sonoma Water; Nick Malasavage, USACE San Francisco District; Marty Ralph, CW3E; Patrick Rutten, NOAA NMFS; Robin Webb, NOAA OAR; Joseph Forbis, USACE Sacramento District; Cary Talbot, USACE ERDC. Absent: Alan Haynes, NOAA NWS and Levi Brekke, US Bureau of Reclamation.

A CW3E researcher measuring streamflow at a site in the upper Russian River watershed in March 2018.

Sonoma Water

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Image Credit: NASA

OBSERVING AND FORECASTING SNOW LEVELS

CHALLENGE

“Snow level” is the threshold elevation above which precipitation falls as snow and below which precipitation falls as rain. Determining whether a storm will produce snowpack or generate runoff is critical for understanding flood risk within a watershed.

ACCOMPLISHMENTS

Snow-level observations. One valuable observation system is the 915-MHz Doppler radar, which monitors snow levels in real time. NOAA’s HydroMeteorological Testbed (HMT) program at the Earth Systems Research Lab and University of Colorado developed a new snow level radar that is significantly less expensive than previous designs. Fifteen stations have been installed in California, mostly at the foot of major Sierra Nevada reservoirs (Figure 1). The data from these radars are currently being used for freezing-level forecast verification (see Figure 2). The radar data also allow for analysis to understand how synoptic and mesoscale features prior to and during storms affect snow levels. Forecast skill assessments have shown serious errors remain at even 1-3 days lead time, with the largest errors often associated with landfalling atmospheric river (AR) events where the predicted snow level is much lower than is observed. Recent investigations have shown that between 2008-2017, snow levels during AR events increased on average 230 feet per year and ARs are the mechanism that most often yields low-snow fraction storms.[1]

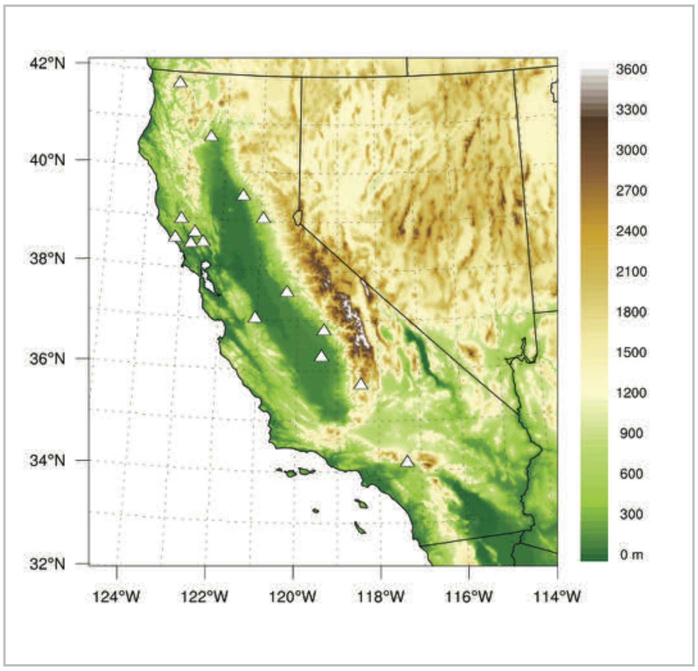

Figure 1. White triangles indicate locations of snow level radars in California

Continued research in how to improve the freezing level forecasts--using the snow level radars as verification, understanding atmospheric dynamics as it relates to snow level changes--are critical for flood preparedness and water supply planning.

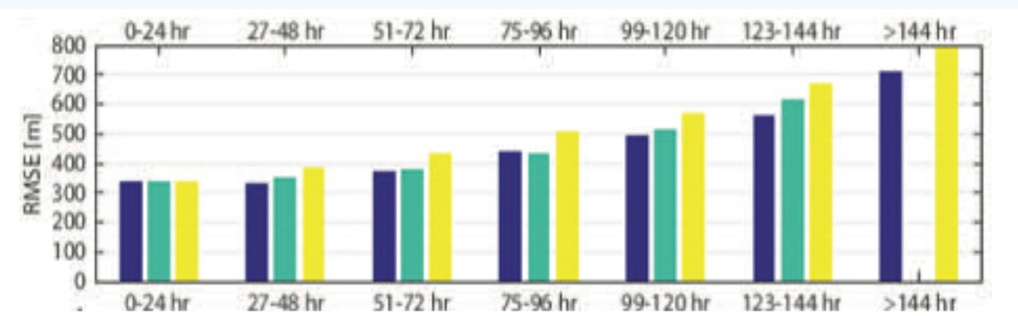

Figure 2: Root mean square error (RMSE) of rain-snow level forecasts verified at profiling radars across CA in water year 2017 sorted by lead forecast time indicated by the 3 models. Figure courtesy of B. Henn, CW3E.

Legend

West-WRF CNRFC GEFS-RV2

Snow observations. Continuous stream gauge, temperature, precipitation, and snowpack monitoring provide the historical and climate context of extreme events. Over the last 15 years, meteorological stations that include humidity, air pressure, soil moisture, solar radiation and wind (direction and speed) have provided additional data. In 2014 NASA, with support from CA DWR, created the Airborne Snow Observatory, which uses lidar to provide spatial estimates of snow water equivalent over crucial watersheds in CA.

High elevation floods. Winter floods generated in high elevations are caused by warm storms with high precipitation totals and saturated soils.[2] ARs are associated with the most extreme precipitation events in the Northern Sierra Nevada and are typically warm storms (see Figure 3). An example of this is the AR sequence that contributed to the Oroville emergency in February 2017. The ARs caused prolonged high snow levels (above 2500m) for much of a 5-day AR sequence, resulting in the Feather River watershed receiving more than 97 percent of total precipitation as rain. This event had large historical snowmelt, further contributing to inflows to Lake Oroville by ~ 10 percent (Figure 4).

Spring flooding results from large snowmelt events triggered by a rapid temperature increase. Such events have occurred 8 times between 1916-2002 that were associated with >22˚F (12˚C) increases in temperature over 5 days. These rapid warming/rapid melt events are typically associated with cooler than average March temperatures.[3] Recent research has suggested that forecasting clouds and incoming solar radiation can improve hydrological forecasts of spring melt events.

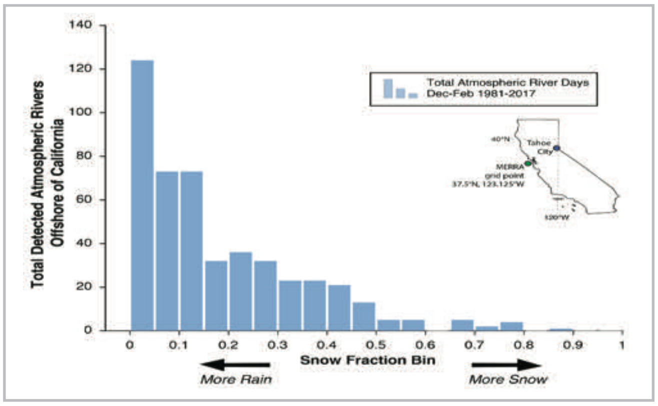

Figure 3. The fraction of precipitation that fell as snow versus rain in Tahoe City during ARs. ARs are typically warm storms with high snow levels causing more rain than snow. From Hatchett et al., 2017.

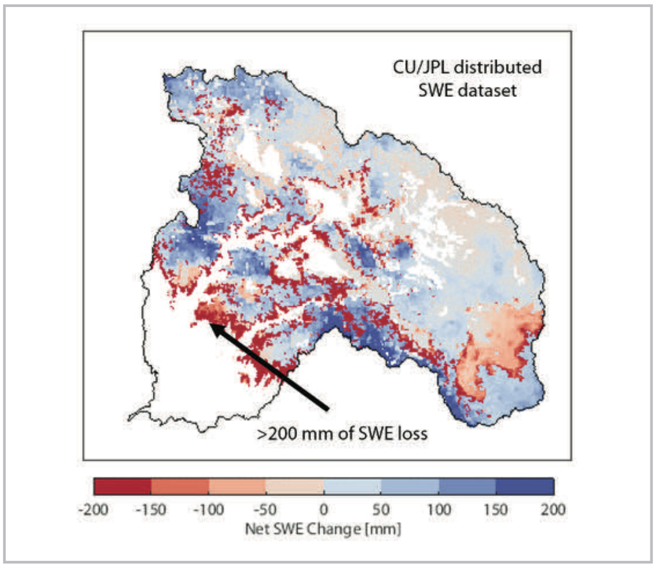

Figure 4. Feather River watershed change in snow-water equivalent (SWE) from the CU/JPL distributed snow dataset from February 6-10, 2017. Analysis and figure provided by Brian Henn, CW3E.

NEXT STEPS

Research needed to improve snow level forecasts include:

- Better tools to monitor snow level including automated methods to quantify snow-level forecast errors.
- Research to understand the physics of what controls the downward bending of the snow level during AR events over mountains.
- Improvement in West-WRF model forecasts of snow level.
- Continued and expanded monitoring to understand how variability and climate change affect flood risk.
- Enhanced GPS met stations and snow level radars that can be deployed in high elevations to provide information about the meteorological and hydrological characteristics of large events in locations where floods are generated.

Leveraging CA DWR Funding

The new observations and analyses described here would not have happened without DWR's support. DWR has leveraged its support with investments from NOAA, Scripps Institution of Oceanography and USGS. The research using data from these observations has been leveraged by other funding agencies including NOAA and NASA.

References

[1] Hatchett et al., 2017, Water.
[2] Dettinger et al., 2009, CEC-500-2009-050-D.
[3] Lundquist et al., 2004, Journal of Hydrometeorology.

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CNAP California-Nevada Climate Applications Program A NOAA RISA team

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