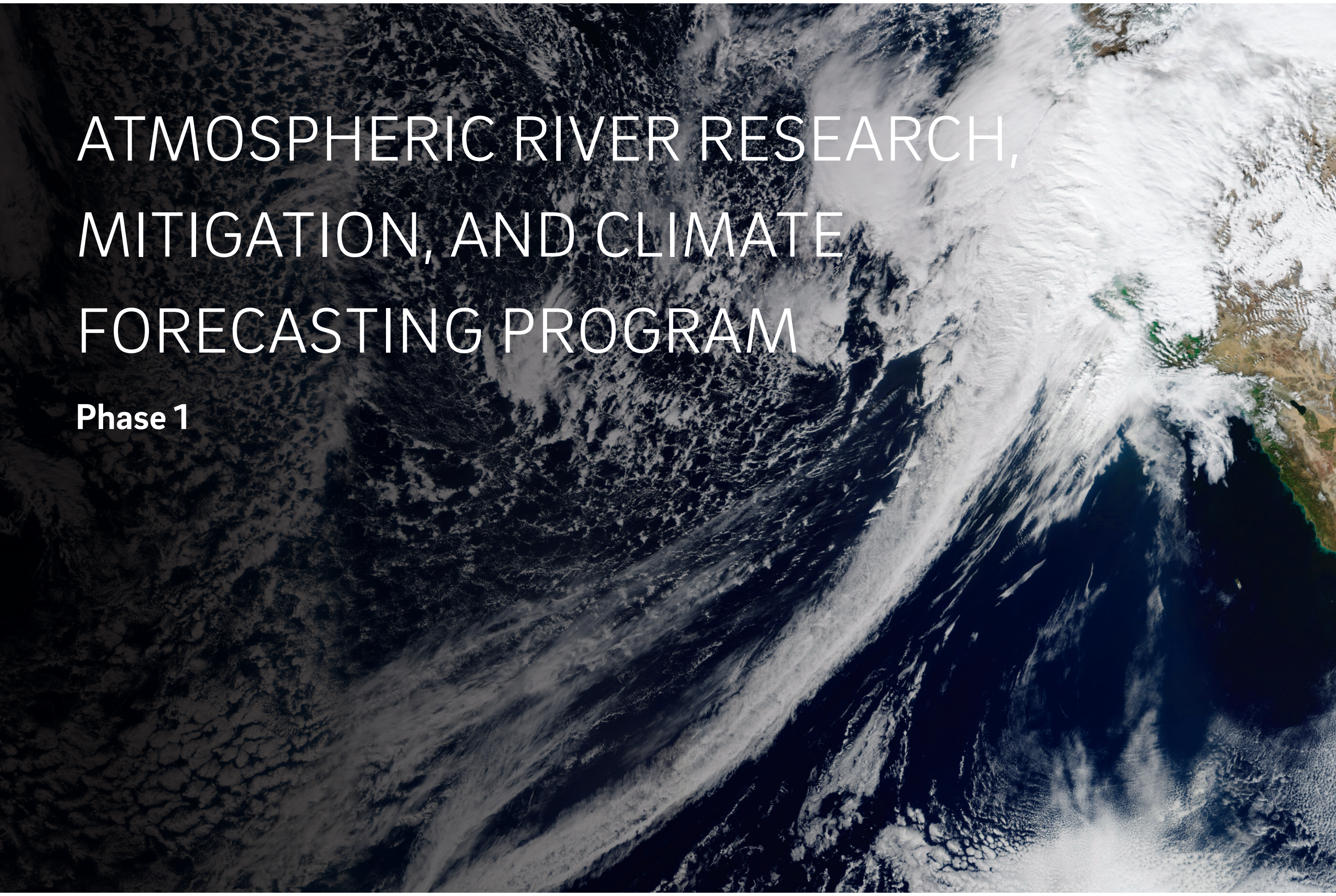
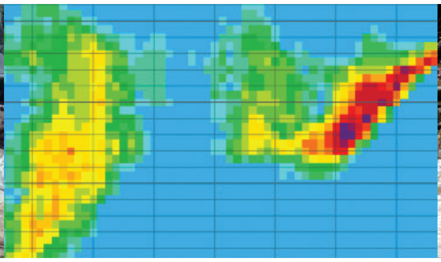


ATMOSPHERIC RIVER RESEARCH, MITIGATION, AND CLIMATE FORECASTING PROGRAM

Phase 1



Final Report* | *April 2019

Center for Western Weather and Water Extremes

UC San Diego

SCRIPPS INSTITUTION OF OCEANOGRAPHY

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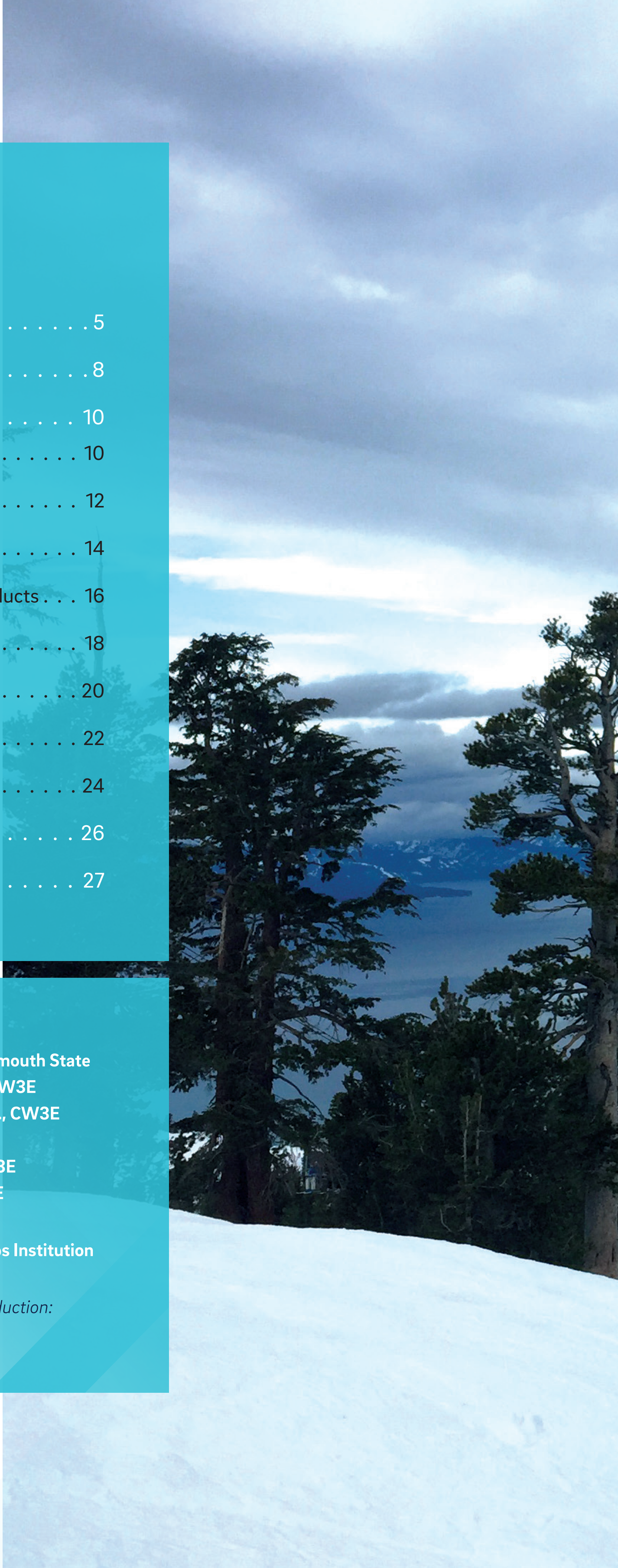

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EXECUTIVE SUMMARY

Context

California faces serious water management challenges. The state must not only balance many competing demands for water, but also do so in a climate that fluctuates tremendously between wet and dry extremes. California has more year-to-year variability in annual precipitation than any other part of the United States (Figure 1E). The recent severe drought from 2012 to 2015, followed by the wettest water year on record for the 8-station index in 2017 illustrates the large swings of precipitation that California experiences. Given this unique variability, many of the forecasting tools developed on a national level do not adequately support forecasting and preparedness for extreme precipitation events in California. Because this variability is driven by the presence or absence of a few large storms (Figure 2E)—which are most often caused by landfalling atmospheric rivers (ARs)—forecasting tools, observations, and research that focus on ARs are critical to supporting both water management and flood preparedness. This focus on ARs also supports climate resilience and serves to inform adaptation, as global climate models project a future with an even more variable precipitation regime that includes extended dry periods punctuated by more extreme events[1], most of which are ARs.

Coefficients of variation of total precipitation, WY 1951-2008

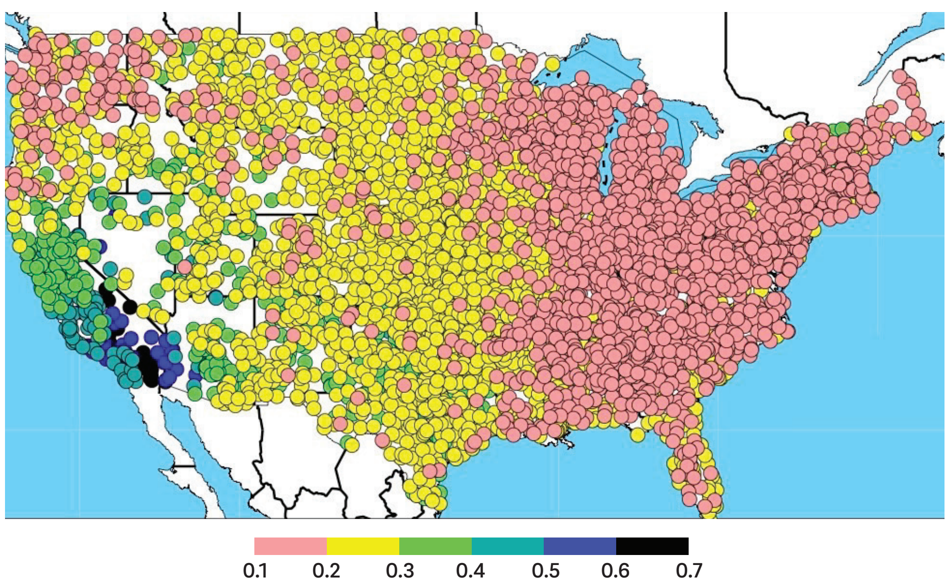


Figure 1E. Observation stations throughout the contiguous United States showing the coefficient of variation for precipitation. A value of 0.5 means that the year-to-year variability is 50 percent of the yearly average. California has the highest variability on the map. Figure from Dettinger et al., 2011.

[1] Pierce et al., 2018.

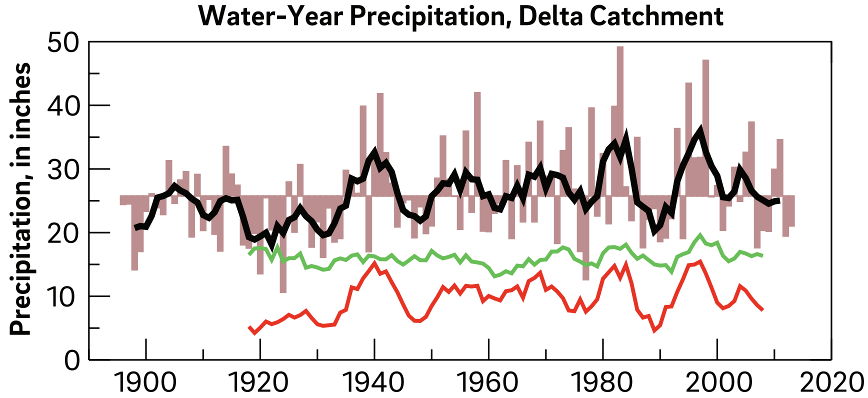


Figure 2E. Water-year precipitation totals in the Delta's catchment area from 1895 to 2019. The brown bars show annual totals and whether they are above or below the long-term average (about 25 inches per year). The lines are five-year moving averages that show total precipitation (black), the amount that fell in the wettest 5% of wet days (red, representing the heaviest storms) and all other wet days (green). Figure from Dettinger and Cayan, 2014.

Purpose

The ultimate goal of the "Atmospheric Rivers Research, Mitigation, and Climate Forecasting Program" (AR Program) is to enable substantially greater water supply reliability and flood mitigation capacity across the state. To do this, the AR Program requires innovations in meteorology, hydrology, climate science, oceanography, civil engineering, water resources management, fisheries management, and decision support systems. The AR Program develops core tools and capabilities to support forecast-informed reservoir operations (FIRO) and water management decisions at lead times from days to months, as well as flood mitigation and debris flow hazard reduction. Key tools and capabilities created during Phase I include a weather forecasting model optimized to predict ARs and associated conditions out to several days lead time, better observations to help monitor and predict ARs and their impacts, a system that leverages federal weather reconnaissance aircraft to improve AR forecasts, usable precipitation outlooks from weeks to months ahead, decision support tools for statewide and regional applications, and improved climate projections of annual precipitation. Phase I of the AR Program built a framework and brought together teams, methods, partnerships, and relationships that will be foundational to subsequent phases of the AR Program.

AR PROGRAM **PHASE I ACCOMPLISHMENTS**

FORECAST-INFORMED RESERVOIR OPERATIONS	
Better tools for reservoir managers can help to increase water supply reliability.	A preliminary FIRO assessment at a test reservoir, Lake Mendocino, shows enough improvement in reliability to increase water supply by an average of 20,000 acre feet per year, or the equivalent of 50,000 homes. The AR Program has been a key partner in this multi-agency cross-disciplinary effort on Northern California's Lake Mendocino and recently on Southern California's Prado Dam.
FORECASTING AND DECISION SUPPORT TOOLS	
AR forecasts can feed into tools that inform emergency managers, water managers, and the public.	CW3E has developed AR tools with rapid response capabilities. These tools have been used to support DWR during extreme storms. New products show snow level forecasts and uncertainty at the watershed scale. Snow level is the altitude above which precipitation falls as snow in a storm.
ATMOSPHERIC RIVER SCALE	
Numbered category scales help forecasters communicate the severity of weather phenomena.	The AR Program has developed a user-friendly scale to classify and communicate the strength and potential impacts of ARs. It was tested for the first time winter 2019.
SUBSEASONAL-TO-SEASONAL FORECASTING AND EXPERIMENTAL PRODUCTS	
Water resource managers and other users can benefit from AR outlooks with lead times of two weeks to seasons.	AR outlooks looking two to three weeks into the future have been developed and are now being validated in partnership with NASA's Jet Propulsion Laboratory (JPL). A water year precipitation outlook has been created and is updated monthly.
REGIONAL ATMOSPHERIC RIVER FORECASTING	
Regional models can be tailored for weather prediction in California.	CW3E created the West-WRF model to better forecast ARs and associated extreme precipitation. West-WRF now has better skill for ARs and snow-level forecasts than the national model.
ATMOSPHERIC RIVER RECONNAISSANCE AND DATA ASSIMILATION	
Better observations of ARs offshore and improved data assimilation methods could lead to more accurate landfall predictions.	The AR Program coordinated with the USACE FIRO Program to create an AR Recon airborne field effort using Air Force and NOAA aircraft to test its feasibility and impact. CW3E coordinated the deployment of 32 drifting buoys with pressure sensors to help fill gaps in surface observations throughout the North Pacific. CW3E and multiple operational weather forecasting centers are working to study the impact of AR reconnaissance on forecasts through data
LANDSLIDES AND POST-FIRE DEBRIS FLOWS	
Better understanding of the conditions that lead to these hazards can lead to improved forecasts.	During this phase of work, the AR Program has built on previous interdisciplinary efforts to characterize the meteorological conditions that can lead to impactful debris flows and landslides. AR Program research has found that 76% of shallow, storm-driven landslides in northern California are associated with ARs.
OBSERVING SYSTEMS NETWORK	
A robust monitoring system can help to address water resources and emergency management challenges.	The AR Program conducted a comprehensive evaluation of the state of a selection of sensor networks. The evaluation identified gaps in data continuity and access, offered recommendations for improvement, and highlighted a well observed watershed that could be used as a model for others.

INTRODUCTION

The Importance of Atmospheric Rivers

California faces serious water management challenges. The state must not only balance many competing demands for water, but also do so in a climate that fluctuates tremendously between wet and dry extremes. Research during the last decade has shown that California has more year-to-year variability in annual precipitation than anywhere else in the contiguous United States.[2] This variability is driven by the presence or absence of a few large storms, which are most often caused by landfalling atmospheric rivers (ARs) (Figure 1). ARs are long, narrow, transient corridors of strong horizontal water vapor transport that can cause heavy precipitation as they are forced upward, often by mountains. ARs are the largest "rivers" of fresh water on Earth, averaging more than double the flow rate of the Amazon River (see table below).[3] Water year 2017 was an example of a wet year that resulted from 56 ARs impacting California (Figure 2).

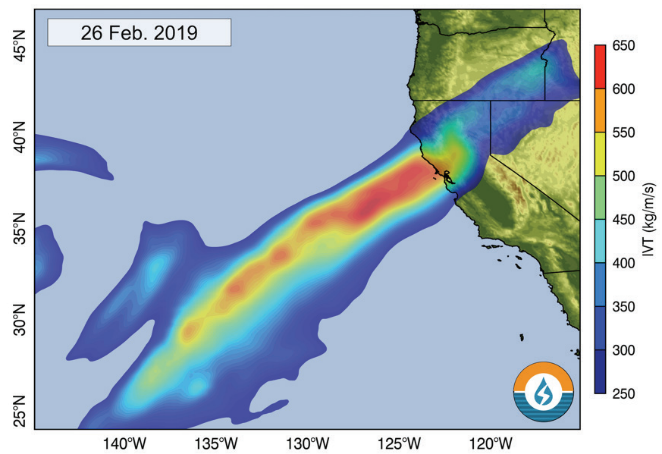


Figure 1. An AR making landfall on February 26, 2019, near the Russian River watershed in Northern California. The color scale represents integrated water vapor transport, a metric used to measure the strength of ARs.

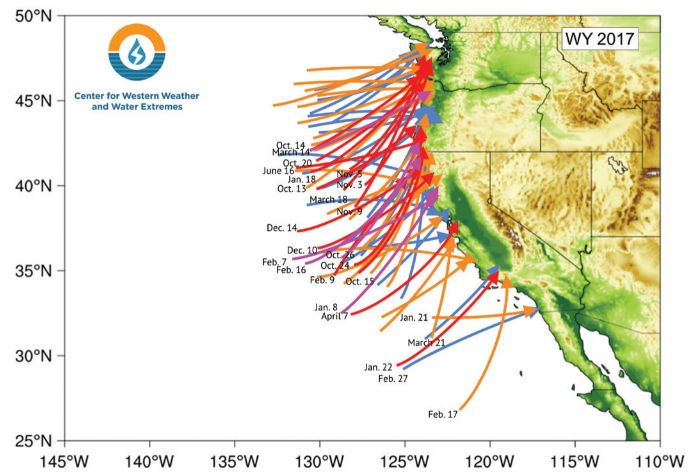


Figure 2. A map of the ARs that made landfall along the U.S. West Coast during water year 2017. Each line represents one AR. The colors indicate the strength of the AR. Each line shows the axis of maximum vapor transport (the AR "core") at the time of landfall. This map does not show the width of each AR or the size of the region affected by it.

ARs provide 30–60% of California's total annual precipitation, with higher percentages in the northern part of the state.[4] Thus, they are extremely important for water supply and water resources. However, strong ARs and long-duration ARs can also cause hazardous flooding. California suffers an average of $475 million in flood damages per year, and more than 93% of these damages are associated with ARs.[5] Improved AR forecasts can benefit public safety by providing earlier warning of potentially hazardous conditions. Better near-term to seasonal AR forecasts can also support water management decisions by providing guidance on whether reservoir operators should retain or release water to prepare for a dry or wet month.

Mean transport of water by an AR (as water vapor) and the major terrestrial rivers (as liquid)

	10^9 M^3 DAY^{-1}	10^6 ACRE FEET DAY^{-1}	MULTIPLIER
Average AR	39.7	32.2	1 AR = *X* rivers
Amazon River	15.1	12.3	2.6
Congo River	3.6	2.9	11.0
Mississippi River	1.5	1.2	27.4

Comparison of the mean flow rates between ARs and major river systems. Adapted from Ralph et al., 2017 a result of early AR research supported by DWR.

[2] Dettinger et al., 2011.
[3] Ralph et al., 2017.
[4] Gershunov et al., 2017.
[5] Downton et al., 2005, along with a forthcoming review of National Flood Insurance Program insured losses from 1978 to 2017.

Current Forecast Skill

A decade of research has shown that ARs can be predicted several days ahead of landfall on the West Coast, but forecasting tools still have major shortcomings. For example, forecasts of where the AR core will make landfall are critical to predicting precipitation, yet landfall predictions with a three-day lead time are currently off by an average of about 200 miles.[6] These forecast errors propagate through the representation of streamflow processes, which leads to uncertainty in streamflow forecasts and potential flooding hazards (Figure 3). Further, the accuracy of AR forecasts (i.e., "forecast skill") rapidly decreases with lead time, such that with a lead time of eight days or more, forecasts are just slightly better than any random forecast. However, there are certain conditions, such as during both an El Niño and a positive Pacific/North American teleconnection, during which long-range (seven- to 10-day) AR forecasts are more reliable.[7] Similarly, forecast skill for the subseasonal timeframe, with three-week lead times, is affected by certain phases of the Madden–Julian Oscillation, a tropical climate oscillation. Recent research results, such as those discussed above, illustrate the need for new approaches to understand AR forecast skill under variable climate states to better inform water management decisions.

About the Atmospheric Rivers Program

The "Atmospheric Rivers Research, Mitigation, and Climate Forecasting Program" (AR Program) originated in October 2015 with the passage of California State Senate Bill SB-758. This bill appropriated $3M to the California Department of Water Resources (DWR) to oversee the AR Program, which supports research at the University of California (UC). F. Martin Ralph (UC San Diego, Scripps Institution of Oceanography, Center for Western Weather and Water Extremes) is the principal investigator and leads the program implementation. The AR Program develops core tools and capabilities to support forecast-informed reservoir operations (FIRO) and water management decisions at lead times from days to months, as well as flood mitigation and debris flow hazard reduction. The section below highlights accomplishments from the AR Program Phase I.

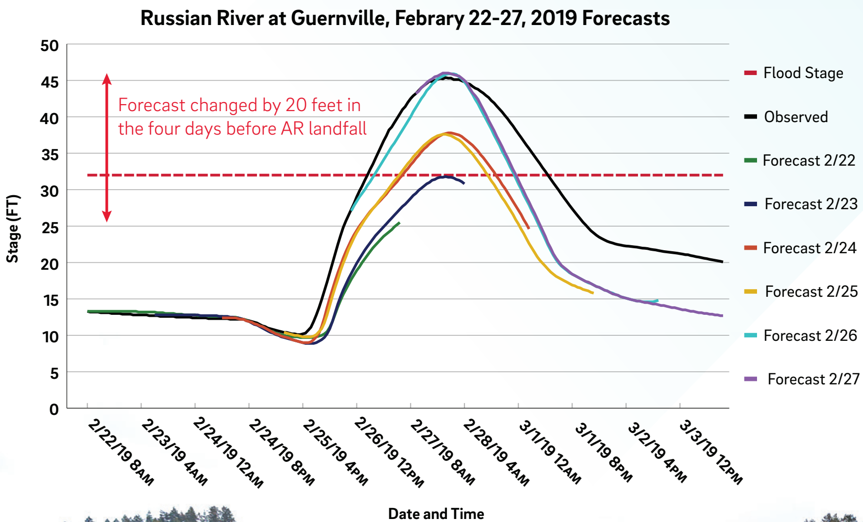


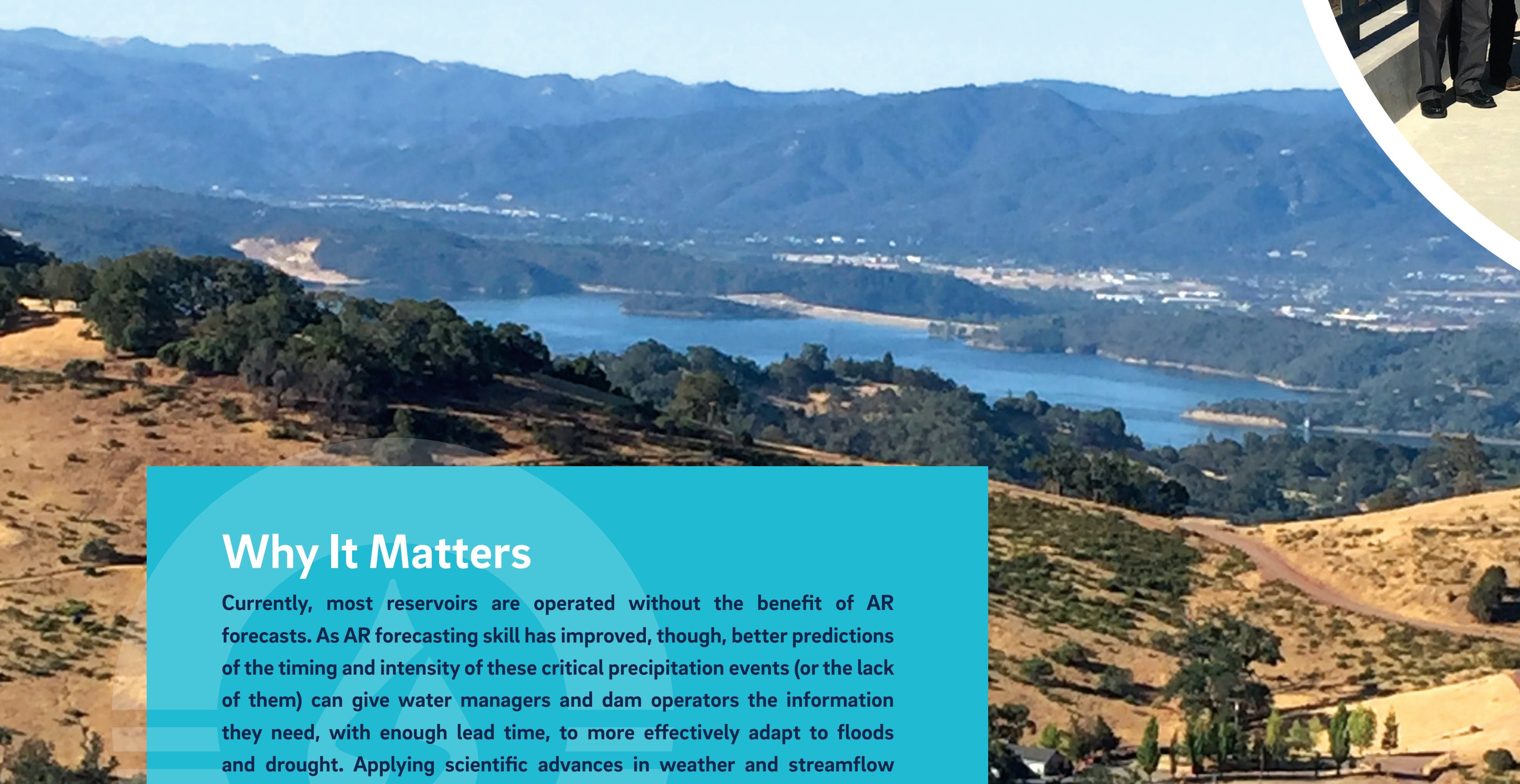
Figure 3. Left: A comparison of streamflow forecasts provided by the National Weather Service's California Nevada River Forecast System for Guerneville for the five days before the peak streamflow that caused widespread flooding throughout the region in February 2019. The streamflow forecasts varied by over seven feet, which was the difference of being above and below flood stage. Uncertainty in precipitation forecasts contributed to uncertainty in streamflow forecasts. Below: A photo of the flooding at Monte Rio, five miles downstream of Guerneville, from the same storm. Photo credit: Sonoma Water Agency.

[6] Nardi et al., 2018.
[7] DeFlorio et al., 2019.

ACCOMPLISHMENTS

FORECAST INFORMED RESERVOIR OPERATIONS

FIRO has shown great promise during initial testing at Lake Mendocino in the Russian River watershed. A steering committee, co-chaired by F. Martin Ralph (CW3E) and Jay Jasperse (Sonoma Water), is working collaboratively on this project. Results from the FIRO Preliminary Viability Assessment (2017) showed more than double the potential benefit to water supply than had been the goal, and these benefits are possible without increasing flood risk. FIRO also supports salmon recovery. The final viability assessment for FIRO at Lake Mendocino is expected to be released in 2020.



Why It Matters

Currently, most reservoirs are operated without the benefit of AR forecasts. As AR forecasting skill has improved, though, better predictions of the timing and intensity of these critical precipitation events (or the lack of them) can give water managers and dam operators the information they need, with enough lead time, to more effectively 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 FIRO, offers an opportunity to make better use of existing multi-purpose reservoirs across California and other western states.

FIRO work on Lake Mendocino has demonstrated improved water supply reliability and lower flood risk.

Left: Members of the Prado Dam FIRO steering committee, including representatives from CW3E, Orange County Water District, DWR, USACE, FWS, NOAA, and Orange County Public Works.

Strategies and lessons from the Lake Mendocino pilot project may be transferable to other reservoirs. For example, a steering committee co-chaired by F. Martin Ralph (CW3E) and Greg Woodside (Orange County Water District) with representatives from DWR, the U.S. Army Corps of Engineers (USACE), the U.S. Fish and Wildlife Service (FWS), NOAA, and Orange County Public Works is scoping a FIRO project at Prado Dam in southern California. As part of the scoping process, CW3E published an analysis of ARs and the different dynamics that are associated with extreme precipitation in the Santa Ana River watershed.

The AR Program's FIRO research aims to improve forecasts through observations and modeling. These components work hand-in-hand, as observations are essential for verifying and improving forecast models. Program partners have collected observations in the Russian River watershed during the past three winter seasons, expanding existing observing systems to fill key gaps and answer science questions. These efforts have included expanding the existing soil moisture, precipitation, and streamflow monitoring networks. Researchers made specific efforts to collect data at two locations during AR events, which has allowed the AR Program to assess how AR characteristics, such as the vertical distribution of moisture and winds, orientation, and stability, influence the resulting spatial patterns of precipitation and streamflow.

FIRO has been developed as a collaborative effort between local (Sonoma Water and Orange County Water District), state (DWR), and federal (USACE) agencies as well as academic institutions. Funding from all agencies has contributed to FIRO. The AR Program is the state's investment in this promising new approach.

FORECASTING AND DECISION SUPPORT TOOLS

Forecasting Tools

The AR Program team has developed a comprehensive set of decision support tools that government agencies and academics actively use to support water resources management, hazard mitigation, and other forecasting applications. Many of these tools are available for public access at cw3e.ucsd.edu. They include a collection of graphics that illustrate forecasts of landfalling ARs one to two weeks in advance from a variety of numerical weather prediction models. Examples of these tools include the AR Landfall Tool, AR Plume Diagrams, and Watershed Forecast Tools.

The **AR Landfall Tool** was created by Jason Cordeira (Plymouth State University) and F. Martin Ralph (CW3E) during a project that preceded the AR Program. It communicates the predicted intensity, duration, timing, and location of landfalling ARs up to 16 days in advance based on an ensemble of forecasts. This tool was upgraded during the AR Program to include forecast information every three hours (instead of six hours) and every 0.5° latitude along the coast (instead of 1.0°). Figure 4 shows how the AR Landfall Tool provided advanced warning of a landfalling AR along the California coast in April 2018. The AR Program team also modified the AR Landfall Tool to display forecast information for week 3 as part of an effort to develop subseasonal-to-seasonal outlooks.

Why It Matters

The ability to forecast the occurrence of extreme precipitation related to ARs is critical for planning for the beneficial impacts of this precipitation on water supply, as well as mitigating the detrimental impacts of flooding. Better situational awareness of incoming ARs by emergency managers, water managers, and the general public can lead to better decision-making.

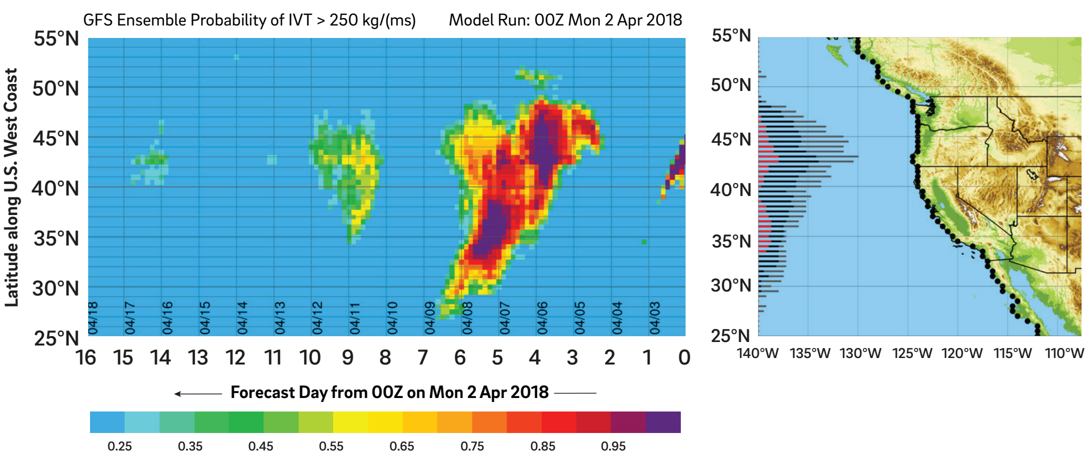


Figure 4. The AR Landfall Tool shows the likelihood of an AR by latitude and by forecast time (from right to left, in the panel on the left). The horizontal bars next to the map show the likelihood of AR landfall by latitude.

The **AR Plume Diagram,** also developed before the AR Program, conveys uncertainty in the timing and intensity of landfalling ARs at a particular location. Like the AR Landfall Tool, the AR Plume Diagram was upgraded during the AR Program to

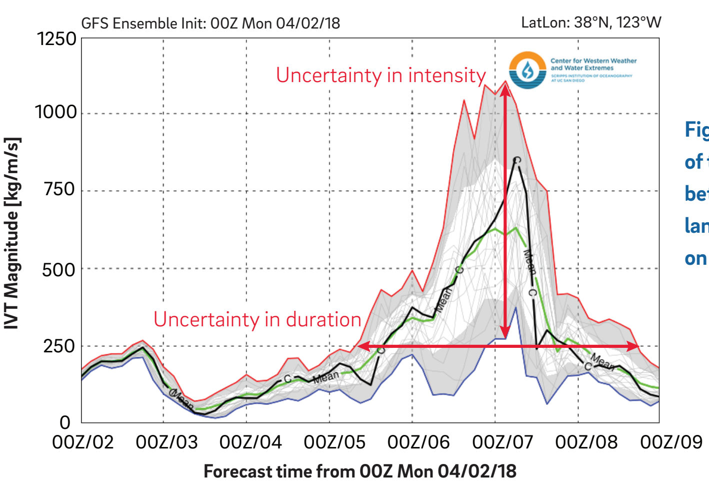


Figure 5. Example of an AR Plume Diagram for a location near the mouth of the Russian River in April 2018. In this case, the peak in the black line between April 7 and 8 indicates a strong AR that is expected to make landfall. The red, green, blue, and gray features show uncertainty, based on a range of alternative forecast scenarios.

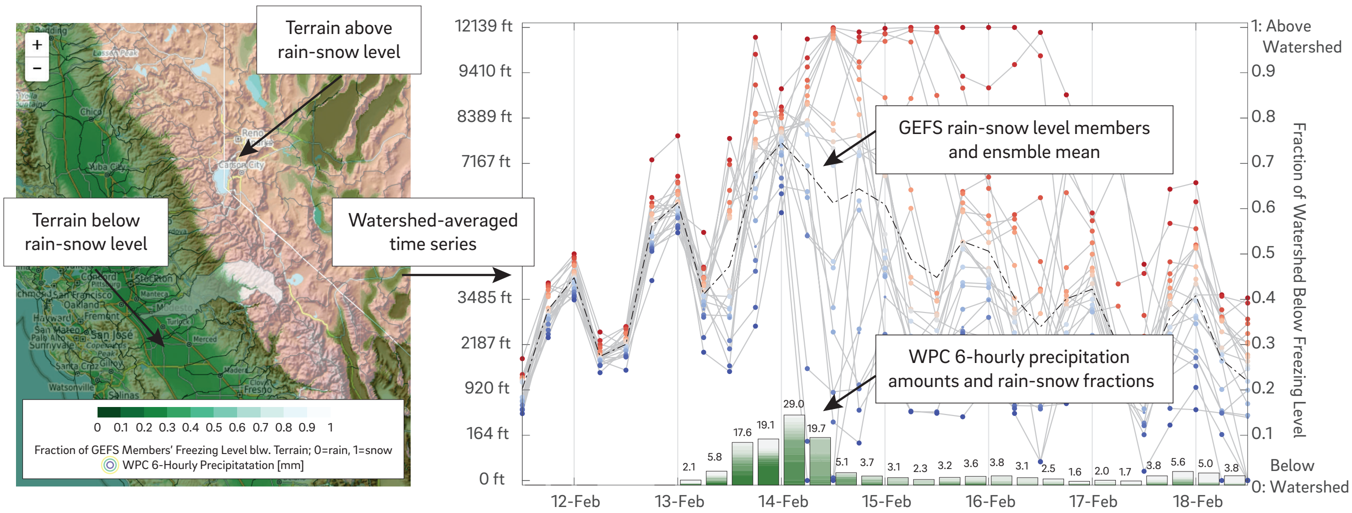


Figure 6. The Watershed Forecast Tool illustrates areas above the rain-snow level (light shading), areas below the rain-snow level (dark shading), and precipitation rates (contours on the map); its graphs show rain-snow levels, average precipitation rates, and fractions of precipitation falling as rain and snow. The tool utilizes the Global Ensemble Forecast System (GEFS) forecasts for snow level and the Weather Prediction Center (WPC) for precipitation forcasts.

include forecast information every three hours (instead of six hours) and every 0.5° latitude along the coast (instead of 1.0°). Figure 5 shows an example of the AR Plume Diagram for a location near the mouth of the Russian River.

Watershed forecast tools grew out of a previous project to develop geospatial forecast tools. The AR Program supported the development of watershed-average precipitation and freezing-level forecasts. The freezing-level tool provides maps and graphs that show how AR precipitation will be partitioned between rain and snow in a given watershed (Figure 6). This tool also characterizes uncertainty from an ensemble of rain-snow level forecasts. The watershed forecast tools provide more information to help water resource managers in snow-affected regions throughout the U.S. West Coast anticipate AR-driven flood and water supply risks.

Oroville Rapid Response

In a rapid response to the extremely wet February 2017 and the Oroville spillway collapse, CW3E provided daily updates on AR forecasts during and immediately after the Oroville event. CW3E's AR expertise and forecasting tools provided important information and context to support decision-making. CW3E also analyzed seasonal patterns in AR intensity at Oroville to support decision-making after the event.

AR Information Distribution

As part of the AR Program, CW3E provides decision support resources by communicating forecast information through forecast outlooks, updates, and post-event summaries (see the table below). CW3E's "AR Forecast Tools" website received 7,236 page views between December 1, 2017, and February 28, 2018, and 14,916 views for the same period in winter 2018–2019—an 106% increase. CW3E is also working to reach a larger audience via social media by increasing its Twitter following to more than 750 as of March 2019 (@CW3E_Scripps). The increase in communication products, webpage visits, and social media presence highlights the ability of CW3E to increase situational awareness of ARs during the months of the most extreme precipitation in California.

Information on the number of communication products produced by CW3E for each water year and overall.

WEBSITE NEWS ITEM	TOTAL	WATER YEAR 2018	WATER YEAR 2019
Outlooks/quick looks	38	20	18
Post-event summaries	14	6	8
Summaries of landfalling ARs	7	1	6
Odds of reaching normal water year precipitation	9	4	5

ATMOSPHERIC RIVER SCALE

Why It Matters

Scales for meteorological phenomena, such as hurricanes and tornadoes, have proven useful in raising public awareness of potentially hazardous conditions. Despite the widely recognized importance of ARs, until the creation of the AR scale, no concise method had existed for conveying the possible spectrum of benefits and hazards that communities face during a particular AR.

CW3E and several collaborators set out to develop a scale to characterize the strength and impacts of ARs. This work resulted in development of the AR scale (Figure 7), which classifies each AR into one of five severity categories based on two factors: the maximum intensity of water vapor transport and the duration of the event.

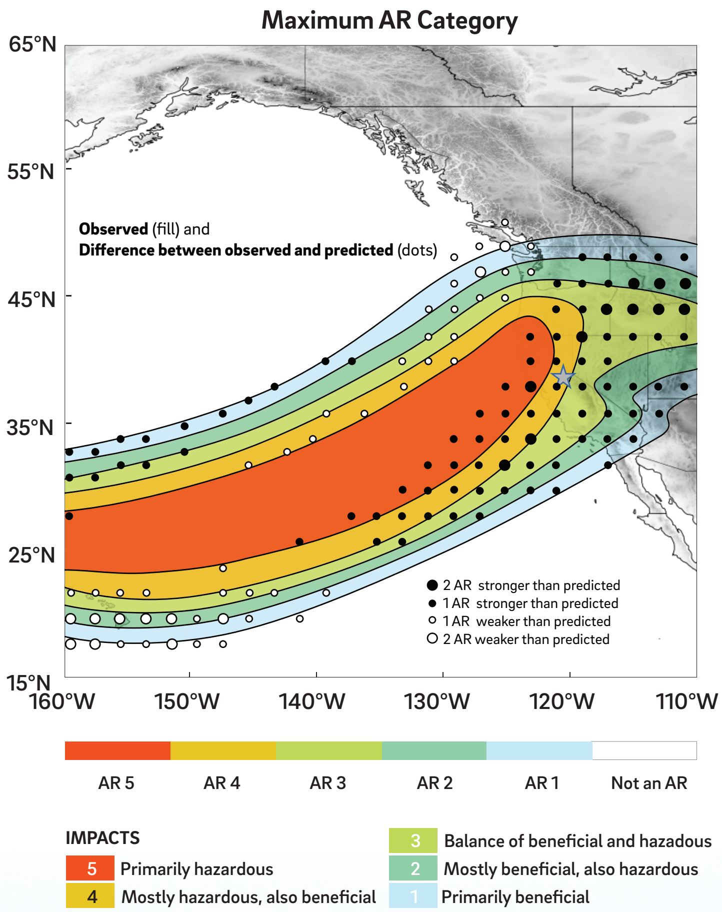


Figure 7. AR scale and typical associated impacts.

The AR Scale: A Team Effort

Work on the AR scale has occurred over several years, led by F. Martin Ralph at CW3E with input from many experts:

- **National Weather Service** *(Jon Rutz, Chris Smallcomb)*
- **Plymouth State University** *(Jason Cordeira)*
- **U.S. Geological Survey** *(Michael Dettinger)*
- **California Department of Water Resources** *(Michael Anderson)*
- **University of Colorado** *(David Reynolds)*
- **U.S. Army Corps of Engineers** *(Larry Schick, retired)*

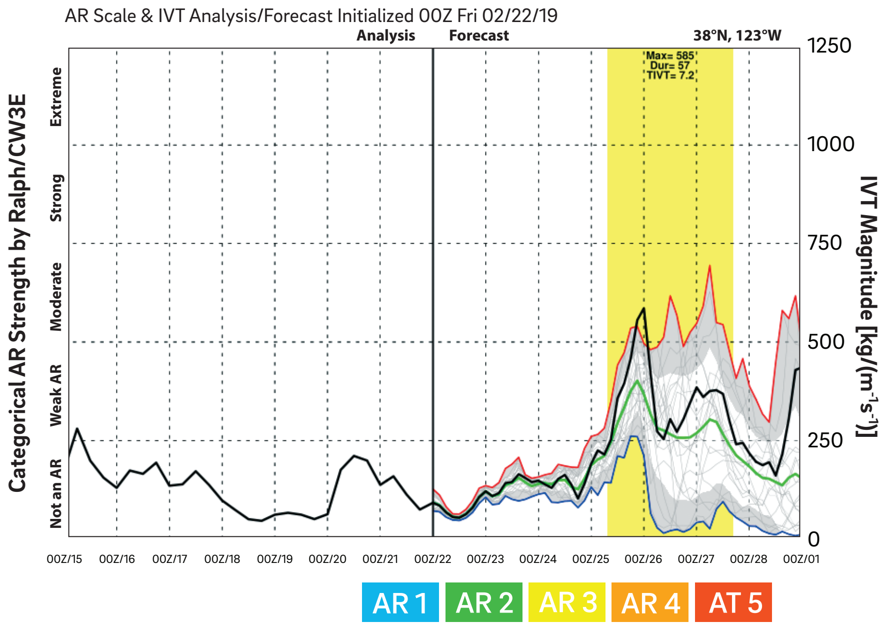


Figure 8. AR Plume Diagram for the Russian River area in February 2019. This enhanced tool shows a AR 3 that is forecast to make landfall (yellow shading). It also shows observed conditions over the previous seven days.

The AR scale ranges from 1 to 5. AR values of 1 and 2 mostly bring beneficial moisture, whereas values of 3 to 5 are increasingly hazardous because they contribute to impacts such as floods. This is especially true if a strong AR occurs when soils have already been saturated by recent precipitation, which means more of the new precipitation will run off instead of being absorbed. For example, streamflow data associated with nine recent AR 5 events in the Russian River watershed showed that six of these events led to major flooding, while the other three struck either early in the season or during a major drought when dry soils reduced runoff. The AR scale methodology has been formalized through publication of a peer-reviewed paper in the leading meteorological journal *Bulletin of the American Meteorological Society.*[8]

The AR scale fills a critical communication gap by providing a concise way to convey the possible spectrum of benefits and hazards that communities face during a particular AR event. Given an increased focus on AR-related science and impacts, the AR scale will be widely used to communicate the benefits and hazards associated with ARs in the western United States. In the winter of 2019, the AR scale was mentioned in local and national newspapers, as well as in radio and television broadcasts.

During the AR Program, the AR Plume Diagram (described above) was enhanced to display AR scale information for a seven-day forecast as well as the observed conditions over the previous seven days (Figure 8)—thus tying together two of the program's most useful tools.

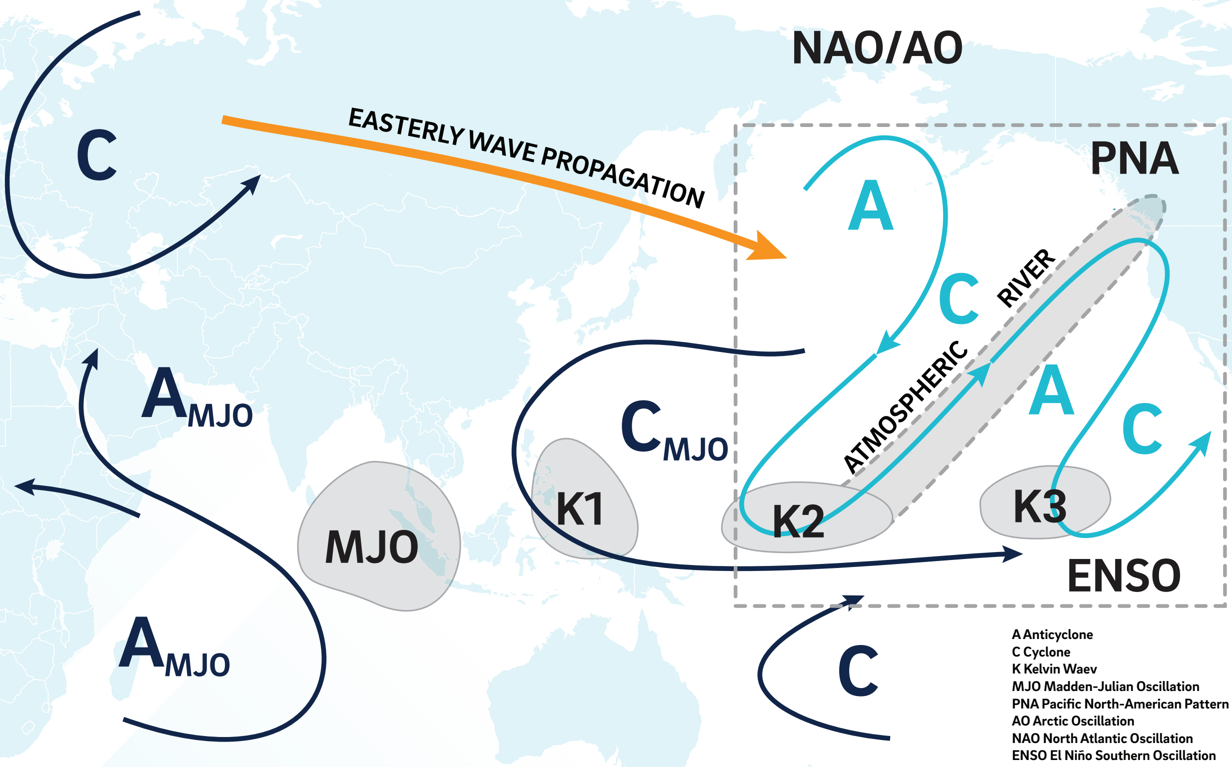
[8] Ralph et al., 2019.

SUBSEASONAL-TO-SEASONAL FORECASTING AND EXPERIMENTAL PRODUCTS

In partnership with NASA's Jet Propulsion Laboratory (JPL), researchers at CW3E have investigated a suite of S2S-related research topics for ARs. These topics include a multi-model dynamic hindcast skill assessment of S2S AR activity, design of a statistical model based on historical atmospheric circulation data to forecast S2S AR activity along the western U.S. coastline, ridging (mid-level high pressure) events over the western United States and North Pacific, and application of artificial intelligence and post-processing techniques to improve S2S AR prediction skill. The CW3E/JPL team continues to investigate these areas in order to improve prediction of AR activity over the western United States.

Why It Matters

Subseasonal-to-seasonal (S2S) lead times of two weeks to two years represent critical decision-making windows for water resource managers and other end-users of weather and climate information. This is especially true in the western United States because of the region's high year-to-year variability in precipitation.



Example of the multiple climate and weather interactions that affect S2S forecasts adapted from Ralph et al., 2011.

Multi-Model Experimental Week-3 Forecast of AR Activity: March 7, 2019

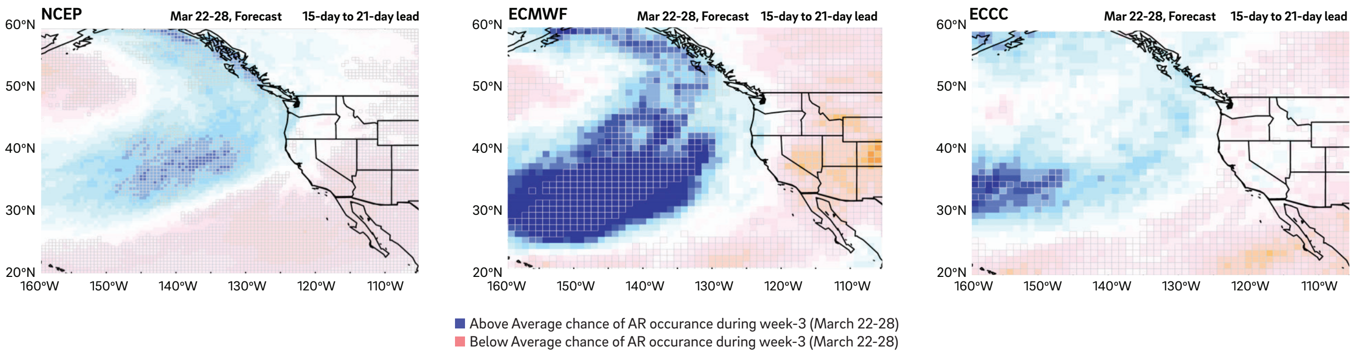


Figure 9. Results from a multi-model experimental week three (15–21 days lead) AR forecast. A forecast of AR occurrence (defined as the number of AR days per week) is shown above for the March 7, 2019 model runs from the European Centre for Medium-Range Weather Forecasts (ECMWF), the US National Centers for Environmental Prediction(NCEP), and the Environment and Climate Change Canada (ECCC). Blue values represent higher-than-average AR activity predicted and red/orange values represent lower-than-average AR activity predicted. Grey rectangles surround grid cells where more than 75 percent of forecast ensemble members agree on the sign of the anomaly. These regions can be interpreted as having higher confidence in their prediction of week-three AR occurrence.

CW3E and its partners have also developed a suite of S2S experimental AR outlook products that generate probabilistic forecasts from dynamical models run at leading forecasting centers, including the European Centre for Medium-Range Weather Forecasts (ECMWF), the U.S. National Centers for Environmental Prediction (NCEP), and Environment and Climate Change Canada (ECCC). These forecasts are updated every Friday morning, with another update for the ECMWF product every Tuesday. During initial development of these products, the team obtained feedback from stakeholders at DWR to make sure the results were useful and understandable to a broad audience. Figures 9 shows an example of one of these products, which resides in a password-protected portion of the CW3E website so it can be vetted and evaluated.

The S2S Research Team and Advisory Panel

S2S research under the AR Program has benefited from robust collaboration among a team of academic institutions and government agencies in the United States and beyond.

An advisory panel of experts from CW3E and JPL guides the team's S2S research and the development of experimental S2S AR products. Going forward, the S2S Advisory Panel will supervise a broad array of ongoing research and offer guidance on which experimental products to provide to the public.

REGIONAL ATMOSPHERIC RIVER FORECASTING

Why It Matters

Most global weather models focus on accuracy at large spatial scales appropriate for the continental United States and for events such as nor'easters, hurricanes, and tornadoes. These models are not as well suited for forecasting ARs, which are key to predicting precipitation, snow, rain, and flooding in California. Similar to what has been done for hurricane forecasts, CW3E has developed a regional weather forecast model, West-WRF, that is tailored to forecasting extreme precipitation events in the western United States—particularly landfalling ARs.

West-WRF is a version of the Weather Research and Forecasting (WRF) model developed at CW3E and tailored toward accurate predictions of ARs and precipitation over the western United States. It provides near-real-time forecasting by simulating the formation and dynamic evolution of horizontal vapor transport in ARs and their interactions with terrain over California. West-WRF has a 3-kilometer resolution throughout California and has been run daily each winter (December through March) since December 2015. During each forecast season, West-WRF products are publicly available on the CW3E website.

West-WRF captures AR dynamics and associated precipitation more effectively than the Global Forecast System (GFS) model. In particular, West-WRF represents the uplift of the AR and the corresponding precipitation more accurately than the GFS model at three to four days' lead time.[9] West-WRF is also better able to capture narrow cold-frontal rain bands, an extreme precipitation phenomenon (Figure 10). West-WRF is in continuous development, not only with the support of DWR, but also leveraging funding from USACE. Efforts are ongoing to improve several aspects of West-WRF's configuration.

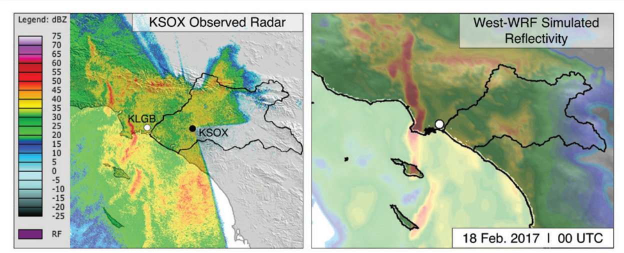


Figure 10: An example of West-WRF's ability to simulate narrow cold-frontal rain band development, which is a challenging process to predict accurately. This phenomenon is associated with intense precipitation events over land.

West-WRF also predicts freezing level heights at a high resolution, which allows researchers to analyze snow versus rain impacts at a watershed scale. The freezing level height is the height at which falling precipitation changes from solid to liquid. The elevation of a location relative to this height will help determine whether that location will receive snow or rain during a given storm. Forecasting the freezing level height is also critical for predicting runoff impacts, because snow will typically accumulate in a layer on the surface, called snowpack, and will generally have a slower runoff response than rain. However, if rain falls on top of existing snowpack, it can accelerate melting and increase rapid runoff. West-WRF has been shown to be as skillful or better at predicting freezing level variations compared with NOAA's Reforecasted v2 Global Ensemble Forecast System (GEFSRv2) and the California-Nevada River Forecast Center (CNRFC) forecast products (Figure 11).

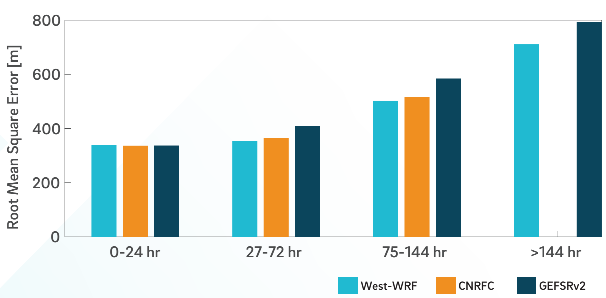


Figure 11. Comparison of three models' ability to accurately forecast freezing level heights for AR events at 19 stations in California in 2016 and 2017, at lead times ranging from one to seven days. West-WRF had a slightly lower root mean square error than the other models, which means it came closest to predicting actual freezing level heights. Adapted from Henn et al., in review.

[9] Martin et al., 2018.


403 WG
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ATMOSPHERIC RIVER RECONNAISSANCE AND DATA ASSIMILATION

Why It Matters

Forecasting ARs is a challenge, and significant errors remain in forecasts from operational centers. For ARs that affect California, limited observations over the Pacific Ocean pose a particular challenge, as they reduce scientists' ability to properly initialize forecast models with the current state of the atmosphere. Satellite data have improved coverage, but often have gaps in the most sensitive areas for AR forecasts because of the inability to sample regions with deep cloudiness and precipitation, as well as limited vertical resolution. Methods to assimilate these observations into weather forecast models remain an active area of research.

Atmospheric River Reconnaissance

To investigate key upstream atmospheric conditions in the data-sparse northeastern Pacific, the AR Program deployed aircraft in 2018 and 2019 to collect observations over the ocean. This campaign, called AR Recon, involved two of the Air Force 53rd Weather Reconnaissance Squadron's WC-130J Hurricane Hunter aircraft, along with NOAA's Gulfstream IV in 2018. The team collected data by releasing dropsondes, which record temperature, pressure, wind, and relative humidity at high resolution as they descend through the atmosphere.

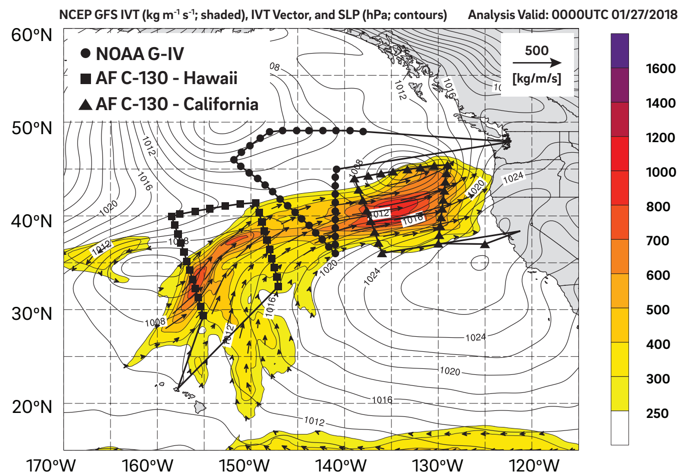


Figure 12. Flight tracks with dropsonde release (dots) locations from an AR Recon mission in January 2018. The background shows integrated vapor transport (color shading) and sea level pressure (contours).

AR Recon focused on collecting data in areas that would provide the most value for forecasting precipitation and its impacts in California. To this end, CW3E worked with experts from the Naval Research Laboratory (NRL), NCEP, and SUNY Albany to use objective, quantitative techniques to pinpoint locations of greatest sensitivity in the forecast—in this case, largely centered on the AR core. The field campaign combined this information with knowledge of important meteorological features such as the upper-level jet stream, potential vorticity anomalies, and cold-air troughs to specify each mission's flight path (Figure 12).

The targeted dropsonde profiles collected by AR Recon may help improve AR predictability. Not only were these data incorporated into operational forecast models and CW3E modeling tools, but they will also be used in research studies to further understand the dynamic processes that drive key AR characteristics such as strength, position, length, orientation, and duration.

Drifting Buoys

In January 2019, the AR Program deployed 32 drifting buoys with air pressure sensors in the northeastern Pacific Ocean. Drifting buoy pressure measurements are important for improving weather prediction because they can improve the representation of large-scale circulations in global weather prediction models, they fill data gaps over the ocean, and they can be used to correct biases in satellite measurements—which improves their added value. The deployment of these new buoys was made possible through a collaborative effort led by CW3E (sponsored by DWR and USACE) and including the Lagrangian Drifter Laboratory at Scripps (sponsored by NOAA's Global Drifter Program), ECMWF, the AR Recon Modeling and Data Assimilation Steering Committee, and the Air Force.

Data Assimilation Studies

Data assimilation refers to the process of blending information from a range of observing platforms with a model's first guess, giving more weight to the observations where they are dense, and relying more heavily on the model in data-sparse regions. This assures that the model is initialized properly to reflect current atmospheric conditions and to then generate accurate predictions. Observations can come from multiple sources, including surface, upper-air, remote sensing, and satellite measurements.

In collaboration with leading centers around the world, including NCEP, ECMWF, NRL, and the National Center for Atmospheric Research, CW3E is exploring cutting-edge data assimilation techniques to improve the accuracy of predictions of ARs and precipitation over California. Research advances continue to lead to new data assimilation methods. CW3E has implemented state-of-the-science data assimilation systems tailored to ARs and precipitation over California, including advanced three- and four-dimensional hybrid-variational and ensemble-based methods. The latter approach in particular has shown that the assimilation of dropsondes significantly improves the prediction accuracy for the majority of AR Recon intensive observation periods in 2018 and 2019 (Figure 13).

Moreover, the AR Program's Global Positioning System radio occultation (GPS RO) data assimilation experiments investigated how assimilation of datasets with high vertical resolution would affect forecasts of precipitation under different experimental conditions. The emphasis on high vertical resolution in the data comes from the fact that ARs produce precipitation when they interact with topography, which means precipitation will be highly sensitive to the vertical distribution of moisture as the AR encounters mountains. A case study of an AR event in 2009 showed that in areas where GPS RO data were assimilated into forecast models, the models' estimates of moisture were consistent with satellite observations.

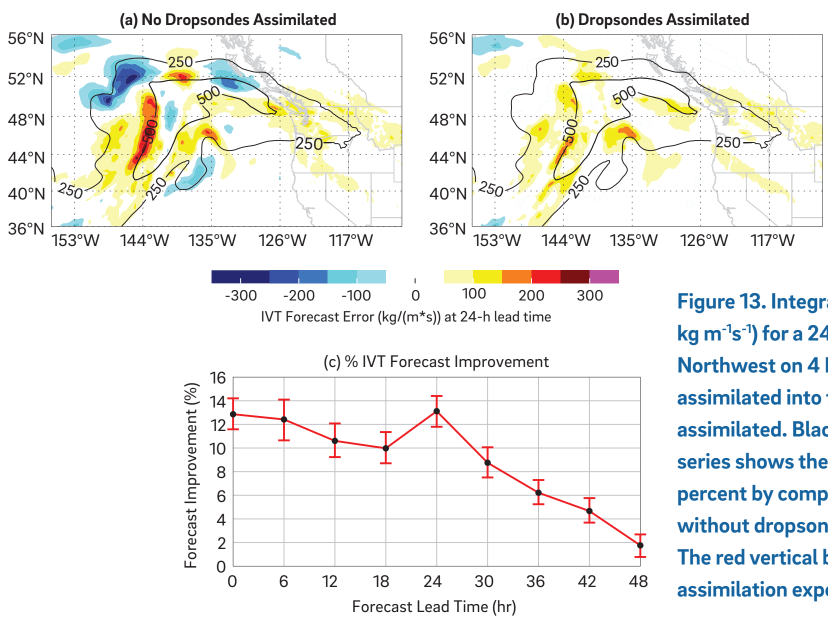


Figure 13. Integrated water vapor transport (IVT) forecast error (filled, kg $m^{-1}s^{-1}$) for a 24-hour forecast of an AR that made landfall in the Pacific Northwest on 4 February 2018 (a) without the data from the dropsondes assimilated into the forecast and (b) with the data from the dropsondes assimilated. Black contours in (a) and (b) are the estimated IVT. The time series shows the IVT forecast root mean square error improvement as a percent by comparing the forecasting with droposondes assimilated and without dropsondes assimilated at forecast lead times from 0-48 hours. The red vertical bar represents the 95% confidence interval. Both data assimilation experiments are initialized 3 February 2018.

Leveraging Resources for AR Recon

The AR Recon program makes efficient use of existing infrastructure by using aircraft that are mostly dedicated to hurricane reconnaissance during summer and fall, but can help in winter with ARs. The program also uses money from many sources to supplement AR Program funds. For example, the Air Force provides funding for the flights and the flight team, while the dropsondes have been purchased with a combination of AR Program and USACE funding. These federal agencies have contributed about $4.5 million to support AR Recon for 2018–2019. In addition, highly respected weather forecasting agencies, such as NCEP, ECMWF, NRL, and the National Center for Atmospheric Research, have contributed their time, significant computational resources, and expertise to the effort.

LANDSLIDES AND POST-FIRE DEBRIS FLOWS

The AR Program's interdisciplinary approach has given the research and forecasting community new information to improve forecasting of hazards. Recent work on landslides and post-fire debris flows has produced several publications that interpret and share results, building on a prior phase of funding from DWR. The prior and current funding supported a close collaboration between the California Geological Survey, USGS, and CW3E. This collaboration produced several multidisciplinary studies that improved scientists' understanding of the meteorological and geomorphic conditions that most often lead to landslides and post-fire debris flows.

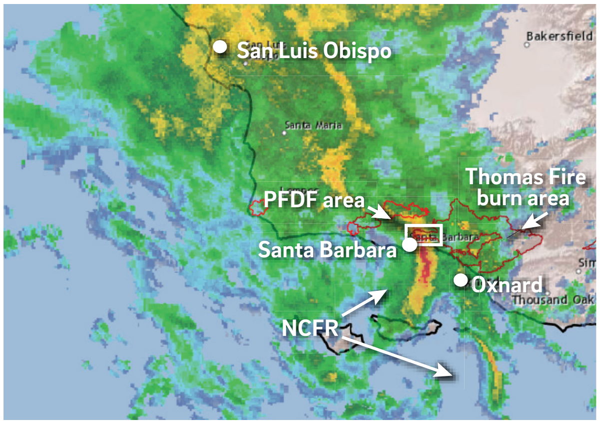


Figure 14. Radar imagery showing precipitation at the time of a post-fire debris flow in the Thomas Fire burn area in Montecito in January 2018. Yellow to red colors in the radar map indicate higher-intensity precipitation. The narrow cold frontal rain band (NCFR) and the post fire debris flow location (PFDF) are labeled on the map. Figure adapted from Oakley et al., 2018.

Studies by the team identified weather conditions that are often associated with post-fire debris flows—including large-scale features, such as ARs, and intermediate-scale features, such as narrow cold frontal rain bands. The role of narrow cold frontal rain bands as a

Homes and streets of a neighborhood affected by the Santa Barbara County mudslides in Santa Barbara, California are shown, Jan. 9, 2018, from the perspective of a Coast Guard MH-65 Dolphin helicopter crew involved in rescuing injured and stranded victims. Coast Guard helicopters were dispatched from Los Angeles-Long Beach and San Diego to assist local first responders with rescue efforts. (U.S. Coast Guard photo)

Why It Matters

High-intensity rain events can lead to landslides and post-fire debris flows. These events pose significant threats to many California communities—threats that are growing as climate change increases the potential for extreme rainfall, large wildfires become more common, and urban development expands in high-risk areas. Applied science professionals, such as engineering geologists and operational meteorologists, face the challenge of having to rapidly characterize an area's potential to generate debris flows using historical rainfall and impact data, along with forecasting tools that provide sufficient lead time and accuracy to be used in National Weather Service "watches" and "warnings" and ultimately evacuation notifications.

catalyst for debris flows was highlighted in a case study of a deadly event in Montecito in January 2018 (Figure 14). AR Program research has shown the importance of well documented observations to help scientists understand intermediate-scale atmospheric conditions and localized precipitation data. However, the research has also revealed the difficulty of obtaining such data, along with a lack of robust documentation of post-fire debris flow impacts. Better information in these areas will help emergency managers anticipate the potential magnitude and severity of impacts due to incoming storms, and it will help atmospheric scientists evaluate the types of storms that trigger debris flows.

Like post-fire debris flows, shallow landslides are often triggered by high-intensity rain. However, existing soil moisture conditions play a critical role in determining whether new rain will trigger a landslide. The AR Program's multidisciplinary collaboration led to a new method to determine the probability that a particular amount of precipitation will exceed a soil moisture threshold above which landslides have been known to occur. Using an inverse approach, USGS researchers also developed maps that show where no landslide will occur, based on slope and soil thickness. This approach showed that 58 percent of California's land area is not susceptible to shallow, storm-driven landslides—information that can help state and local officials focus attention on areas with landslide risks (Figure 15).

Figure 15. White areas show regions of California that are not susceptible to landslide due to slope and soil characteristics.

OBSERVING SYSTEMS NETWORK

Why It Matters

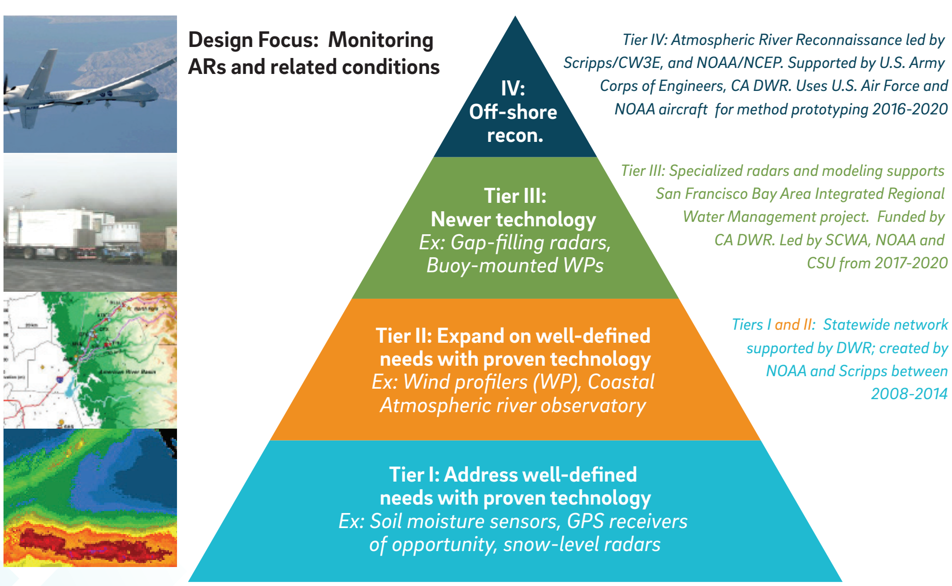
About 10 years ago, DWR, the Western States Water Council, and the Western Governors' Association collaborated to develop a vision for observation networks in the West. The overarching motivation was to be better prepared for extreme precipitation and flooding events. The vision involved a tiered implementation (Figure 16), with installation in stages to begin with lower-cost networks where users were already familiar with the data that would be collected in new, targeted areas. This tiered observation network has now been successfully installed, which is a major accomplishment. The next challenge is to evaluate how well the objectives of the vision have been met, identify remaining gaps, and identify where new objectives and efforts may be needed.

The AR Program team conducted a detailed review of sensor networks throughout California (Figure 17), starting with a summary of active stations. Some networks (e.g., GPS-Meteorology, Sierra snowpack, soil moisture, and the Russian River testbed) have stations operated by many different agencies, while others are more centralized. The overview aimed to answer fundamental questions such as who pays for, runs, and maintains the networks; what users they serve; what requirements they help to meet; and what decisions informing science they enable. The AR Program also sought to evaluate technical details such as the adequacy of support for station maintenance and data processing, archiving, and dissemination; as well as higher-level strategic considerations such as whether the networks are sufficient for their stated objectives and for new objectives that may have emerged. The evaluation identified gaps in data continuity or access. Ultimately, the AR Program sought to assess how well all these networks support the fundamental goal of improving decision-making and preparedness for extreme precipitation and flooding events. The review also examined how well the networks work together to provide an integrated, comprehensive picture of the hydroclimate in California.

To help evaluate sensor networks, the AR Program conducted a wide-ranging survey of end users, including the research community, operational forecasters (via dissemination to Weather Forecast Offices and River Forecast Centers through the NWS Western Region), floodplain managers (via the Floodplain Management Association list), and

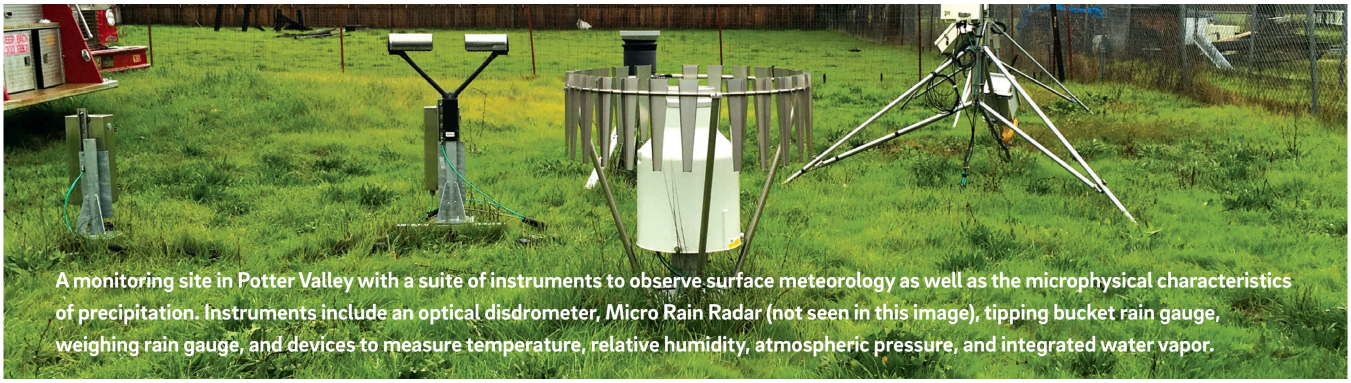
Sensor Networks Evaluated

- GPS meteorology
- Soil moisture
- AR observatories
- Advanced Quantitative Precipitation Information (AQPI) Radar
- Snow level radar
- Sierra snowpack
- AR Recon
- Russian River testbed



**Derived from Ralph et al. 2008 proposal from NOAA to California Dept. of Water Resources (DWR) based on findings from CalJet, PacJet and HMT. Developed in collaboration with Scripps Inst. of Oceanography and USGS. Major elements are included in Ralph et al. (2014) Univ. Council on Water Resources report for the Western States Water Council.*

Figure 16. A Vision for next-generation observations to help address CA's water resource issues (Ralph et al. 2008*): A tiered approach to implement a robust statewide monitoring network to support water resource management. This vision was developed in 2008, and it included implementation actions through 2020.



A monitoring site in Potter Valley with a suite of instruments to observe surface meteorology as well as the microphysical characteristics of precipitation. Instruments include an optical disdrometer, Micro Rain Radar (not seen in this image), tipping bucket rain gauge, weighing rain gauge, and devices to measure temperature, relative humidity, atmospheric pressure, and integrated water vapor.

others. Major survey findings indicate that, while the monitoring capabilities provided by these networks are useful for many applications, there are significant opportunities for gap-filling, modernization, and better integration of data from different networks. Continuity and data access are particularly critical. Enhancements such as backup systems for real-time data dissemination could help to ensure data are always available when they are needed.

The team also prepared a case study of the Valentine's Day 2019 AR storm to evaluate how well the observing system provides critical real-time information to help decision-makers reduce damage to life and property during extreme hydrometeorological events. During this particular storm, soil moisture station data indicated that California was in prime position to produce runoff and snow level radars at several locations observed highly varying snow levels, providing a high-resolution look at the timing of snow level variations relative to heavy precipitation. The observations recorded an extreme snowfall event in Redding that was not forecast well.

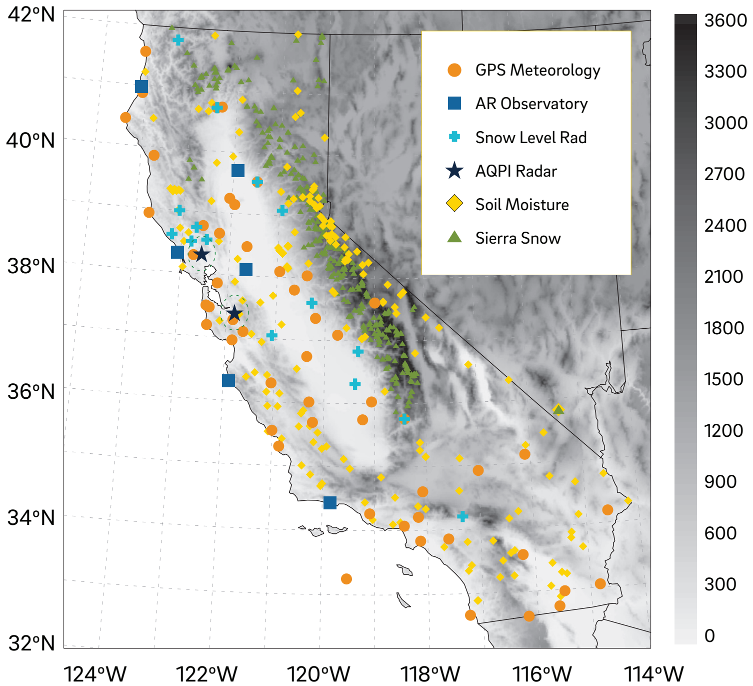


Figure 17. Locations of many of the sensors that were included in the sensor network evaluation.

A Collaborative Evaluation

Several key mentors guided the AR Program's sensor network evaluation:

SENSOR NETWORK OR PROJECT COMPONENT	LEAD
GPS meteorology	Jennifer Haase, Ph.D., Scripps/IGPP
Soil moisture	Dennis Lettenmaier, Ph.D., UCLA
AR observatories and AQPI	David Reynolds, CIRES
Snow level radars, user surveys, and case study	Ben Hatchett, Ph.D., DRI
Sierra snowpack	Mike Dettinger, Ph.D., USGS
AR Recon and Russian River testbed	F. Martin Ralph, Ph.D., CW3E

In addition to these researchers, Jon Rutz (NWS's Western Region) provided critical support reviewing and disseminating the user survey.

NEXT STEPS

The AR Program has made great strides for California, but even more needs to be done to realize the full range of potential benefits for informed decision-making. Phase I of the AR Program has laid an important foundation for Phase II by demonstrating early successes and building organizational and technical capacity. With research frameworks, skills, and partnerships developed under Phase I, and with ongoing support, the AR Program will help give California substantially greater water supply reliability and flood protection. The program will develop new capabilities and tools to support FIRO, water management decisions at various time scales, groundwater recharge, flood protection, and debris flow hazard reduction.

Program investment areas will:

- Work with water managers to further explore FIRO at California reservoirs, leveraging ongoing federal investment.
- Advance the science of how ARs form and impact conditions in California.
- Determine what causes errors in AR forecasts (including conditions that inhibit ARs) at time scales from hours to days, weeks, months, and seasons, and in climate projections.
- Produce near-real-time information supporting California water decisions, including tailored forecast products, models and observations.
- Provide rapid-response science and forecasting capability supporting information needs in the face of natural hazards, such as floods, post-fire debris flows, and landslides.
- Advance the science of how ARs form and impact conditions in California.

Capabilities and tools to be developed in Phase II will include:

- An enhanced weather forecasting model optimized to predict ARs and associated conditions with several days' lead time.
- Better observations for monitoring and predicting ARs; a system leveraging federal weather reconnaissance aircraft to improve AR predictions.
- Precipitation outlooks from weeks to months ahead with usable skill.
- Machine learnig algorithms leveraging model predictions and available observations to further improve forecast skills.
- Decision support tools for statewide and regional applications (debris flow warnings, urban flood issues in the Bay area, flood-managed aquifer recharge).
- Improved climate projections of annual precipitation.

REFERENCES

DeFlorio, M. J., Waliser, D. E., Guan, B., Ralph, F. M., & Vitart, F. (2019). Global evaluation of atmospheric river subseasonal prediction skill. *Climate Dynamics,* **52**(5), 3039–3060. https://doi.org/10.1007/s00382-018-4309-x

Dettinger, M., & Cayan, D. (2014). Drought and the California delta—a matter of extremes. *San Francisco Estuary and Watershed Science,* **12**(2), 6p. https://doi.org/10.15447/sfews.2014v12iss2art4

Dettinger, M. D., Ralph, F. M., Das, T., Neiman, P. J., & Cayan, D. R. (2011). Atmospheric rivers, floods and the water resources of California. *Water,* **3**(4), 445–478. https://doi.org/10.3390/w3020445

Downton, M. W., Barnard-Miller, J. Z., & Pielke, R. A. (2005). Reanalysis of U.S. National Weather Service Flood Loss Database. *Natural Hazards Review,* **6**(1), 13–22. https://doi.org/10.1061/(ASCE)1527-6988(2005)6:1(13)

Gershunov, A., Shulgina, T., Ralph, F. M., Lavers, D. A., & Rutz, J. J. (2017). Assessing the climate-scale variability of atmospheric rivers affecting western North America. *Geophysical Research Letters,* **44**(15), 7900–7908. https://doi.org/10.1002/2017GL074175

Henn, B., Weihs, R., Martin, A., Ralph, F. M., & Osborne, T. (Accepted, pending revision). Skill of rain-snow level forecasts for landfalling atmospheric rivers: A multi-model model assessment using California's network of vertically profiling radars. *Journal of Hydrometeorology.*

Martin, A., Ralph, F. M., Demirdjian, R., DeHaan, L., Weihs, R., Helly, J., ... Iacobellis, S. (2018). Evaluation of atmospheric river predictions by the WRF model using aircraft and regional mesonet observations of orographic precipitation and its forcing. *Journal of Hydrometeorology,* **19**(7), 1097–1113. https://doi.org/10.1175/JHM-D-17-0098.1

Nardi, K. M., Barnes, E. A., & Ralph, F. M. (2018). Assessment of numerical weather prediction model reforecasts of the occurrence, intensity, and location of atmospheric rivers along the West Coast of North America. *Monthly Weather Review,* **146**(10), 3343–3362. https://doi.org/10.1175/MWR-D-18-0060.1

Oakley, N. S., Cannon, F., Munroe, R., Lancaster, J. T., Gomberg, D., & Ralph, F. M. (2018). Brief communication: Meteorological and climatological conditions associated with the 9 January 2018 post-fire debris flows in Montecito and Carpinteria, California, USA. *Natural Hazards and Earth System Sciences,* **18**(11), 3037–3043. https://doi.org/10.5194/nhess-18-3037-2018

Pierce, D. W., Kalansky J. F., & Cayan D. R. (2018). *Climate, drought, and sea level rise scenarios for California's Fourth California Climate Assessment.* California Energy Commission. Publication Number: CCCA4-CEC-2018-006. http://climateassessment.ca.gov/techreports/docs/20180827-Projections_CCCA4-CEC-2018-006.pdf

Ralph, F.M., Dettinger, M. D., White, A., Reynolds, D., Cayan, D., Schneider, T., ... Wick, G. (2014). A vision for future observations for Western U.S. extreme precipitation and flooding. *Journal of Contemporary Water Research and Education*, **153**, 16-32.

Ralph, F. M., Dettinger, M. D., White, A., Cayan D., (2008). Development of a 21st Century Statewide Hydrometeorological Observations Mesonetwork in support of California's Enhanced Flood Response and Emergency Preparedness Program (EFREP). Submitted to California Department of Water Resources.

Ralph, F. M., Iacobellis, S. F. , Neiman, P. J., Cordeira, J. M., Spackman, J. R., Waliser, D. E., ... Fairall, C. (2017). Dropsonde Observations of Total Integrated Water Vapor Transport within North Pacific Atmospheric Rivers. *Journal of Hydrometeorology,* **18**, 2577–2596. https://doi.org/10.1175/JHM-D-17-0036.1

Ralph, F. M., Neiman, P. J., Kiladis, G. N., Weickmann K., Reynolds, D. W. (2011). A Multiscale Observational Case Study of a Pacific Atmospheric River Exhibiting Tropical–Extratropical Connections and a Mesoscale Frontal Wave. *Monthly Weather Review,* **139**, 1169–1189. https://doi.org/10.1175/2010MWR3596.1

Ralph, F. M., Rutz, J. J., Cordeira, J. M., Dettinger, M., Anderson, M., Reynolds, D., ... Smallcomb, C. (2019). A scale to characterize the strength and impacts of atmospheric rivers. *Bulletin of the American Meteorological Society,* **100**(2), 269–289. https://doi.org/10.1175/BAMS-D-18-0023.1

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