Five-Year Strategic Plan

2025–2029

Center for Western Weather and Water Extremes

UC San Diego | SCRIPPS INSTITUTION OF OCEANOGRAPHY

Message from the Director, Dr. Marty Ralph

Dr. Marty Ralph. Photo by Dr. Cary Talbot.

I am grateful and humbled to celebrate the 10th anniversary of the Center for Western Weather and Water Extremes (CW3E). At this milestone, I want to take a moment to reflect on our accomplishments, refresh our objectives, and look ahead to the challenges before us. In our first 10 years, we have established ourselves as a leader in Forecast Informed Reservoir Operations and in forecasting atmospheric rivers. CW3E's innovations would not have been possible without the strong support of our primary partners: the California Department of Water Resources and the U.S. Army Corps of Engineers. Foundational to CW3E's approach is a symbiotic and collaborative relationship between research and operations, coined "Research and Operations Partnership (RAOP)," which has enabled us to test new ideas in support of California's water resilience goals. Our success in California has prompted interest nationwide.

I'm proud of our many accomplishments, and I'm excited for what the future holds. We will strengthen the RAOP by exploring different time scales and storm types, including their underlying science, and making our forecasting products more responsive to our partners' needs. While education has been a core part of CW3E from the start, I'm thrilled to expand our capabilities to train the next generation of leaders on the complexities of extreme weather and water management. Additionally, we will expand our services to help new regions better manage their water resources. The spirit of collaboration has been a hallmark of our success. By serving as a hub for collaborative partnerships between scientists, engineers, water managers, and policymakers, we pursue multidisciplinary scientific advances, develop new technology and methods, and produce practical solutions to solve extreme weather and water challenges in the West and elsewhere.

These problems are a uniting force that drive the culture of collaboration among our talented graduate students, postdoctoral scholars, staff, and partners, without whom our accomplishments would not have been possible. We are also grateful for the incredible support we have received from the Scripps Director's Office, the Scripps Business Office, our state and local water agency partners, and our federal sponsors and funders, all of whom are acknowledged on page 16. Continued collaboration will help the water management community face the challenges of climate change and find solutions together. We've developed this strategic plan to help guide these future endeavors.

Introduction

In 2014, the Center for Western Weather and Water Extremes (CW3E) was launched at Scripps Institution of Oceanography at the University of California San Diego to better understand, predict, and apply extreme weather forecasting capabilities tailored to the unique meteorological conditions of the western United States. In its first 10 years, CW3E has become a global leader in cutting-edge research on the science of extreme weather caused by atmospheric rivers (ARs), as well as the practical applications of this research.

CW3E pioneered the Research and Operations Partnership (RAOP) approach—a symbiotic relationship between scientists and operational agencies that conduct or support water management, in which operational needs guide research direction and science informs operational decisions (i.e., moving from use-inspired research to science-inspired use).

Integrating science into water management and weather prediction enterprises provides a conduit for CW3E's research, tools, and new technologies to directly impact people's lives and livelihoods.

This strategic plan lays out four priorities for the next five years of CW3E's continued growth:

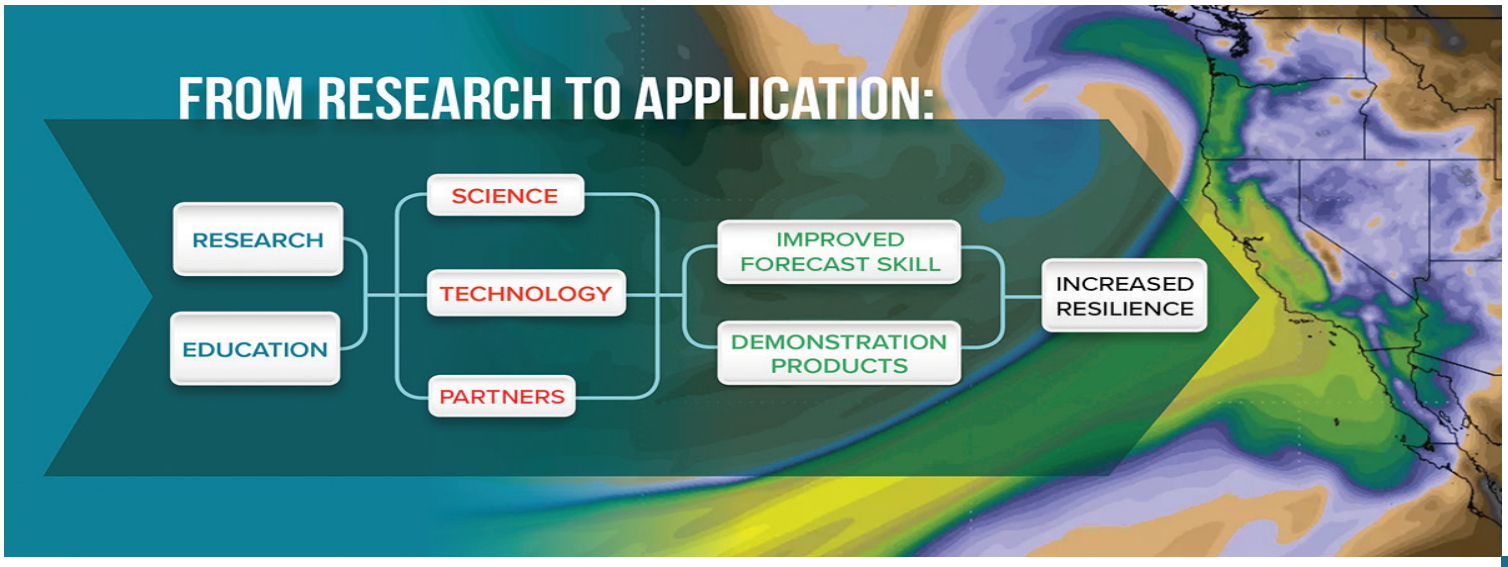
1. Atmospheric Rivers and Extreme Precipitation Research, Prediction, and Applications
2. Forecast Informed Reservoir Operations (FIRO): Resilient Water Management
3. Novel Observations
4. Advanced Precipitation and Streamflow Prediction

> "CW3E is a model for science communication. If science isn't effectively communicated to people beyond our sphere, we are nothing more than another ivory tower."
>
> – **Dr. Jack Gilbert,** Director of Research, Scripps Institution of Oceanography, UC San Diego

CW3E implements these priorities in three ways:

- **Research**. CW3E will strengthen and grow its FIRO RAOP to extend the benefits of FIRO nationwide, and we will innovate with our partners to accelerate forecast skill improvement at different time scales, which is foundational for FIRO's success.
- **Education**. We will expand educational offerings and extend our impact by teaching the next generation the multiple disciplines needed to manage weather and water extremes.
- **Service delivery**. We will pursue opportunities to apply proven strategies that lead to research and technology integration within the weather and water forecasting enterprise.

Focusing on one storm type (ARs) has been very effective in improving forecasts and developing the tools needed to better manage water in the West. We will selectively apply this storm-specific approach to other parts of the United States and beyond. This plan articulates goals for all priorities and how we can achieve them together. As we look to the next five years, our core values, our focus on priorities, and our dedicated and talented staff will be the pillars to achieve CW3E's vision of enhanced resilience.



Vision, Mission, and Goal

CW3E's vision, mission, and goal reflect its growth and evolution. They will serve as the fundamental underpinnings of our organization for the next five years.

Vision

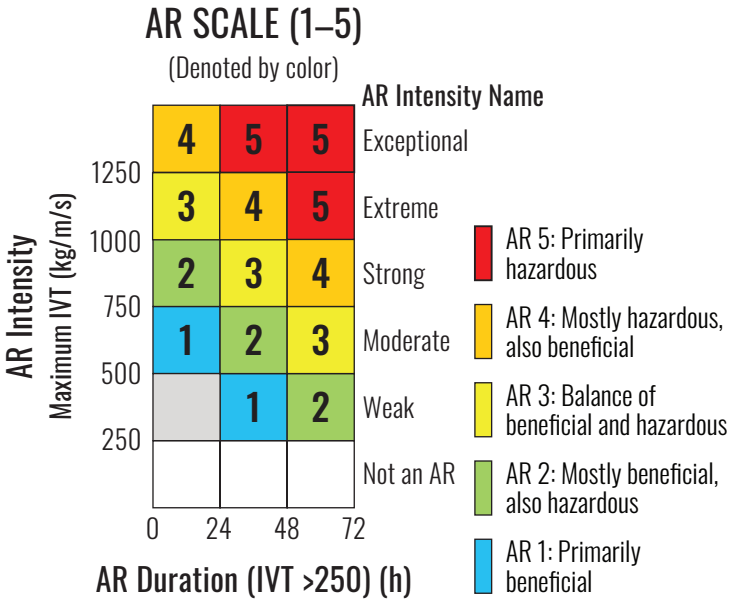
Use CW3E innovations to enhance the resilience of natural and socioeconomic systems to extreme weather and water events, changing weather patterns, and the effects of these events and patterns on water supply and flooding.

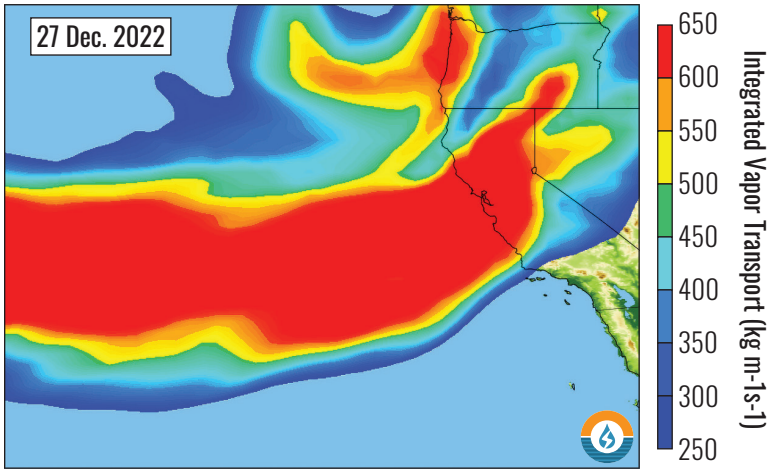
Mission

Pioneer advanced water cycle science, technology, products, and education to support effective policies and practices that address the impacts of extreme weather and water events on communities and environments.

Goal

Revolutionize the science, prediction, and fundamental understanding of extreme weather and water events across time scales, focusing on the impacts of these events on society in the context of climate change.





Top: The AR Scale, developed by Ralph et al. 2019. This tool helps to communicate the intensity and duration of ARs to a wide audience. Bottom: The first AR in a family of nine ARs that occurred in quick succession in California in water year 2023, bringing a record-breaking duration of AR conditions.

Core Values

CW3E's core values are central to its success. The Center keeps these values at the forefront of strategic planning and reinforces them in day-to-day operations:

- **Student and staff growth.** Promote a work environment that aligns with CW3E's goals while enabling professional development, growth, and well-being of all team members.
- **Discovery and emerging technologies.** Explore new ideas and pioneer new approaches that use the latest methods, technologies, and supercomputing to answer complex questions.
- **Practical applications.** Create pathways to apply CW3E's science, products, and services worldwide in partnership with collaborators and stakeholders.
- **Collaboration.** Cultivate RAOPs by bringing together thought leaders and practitioners to provide research that meets operational needs and informs operational decisions with the best possible science.
- **Outreach.** Communicate and promote our science clearly to policymakers, water managers, mainstream media, students, and the public to support informed decision-making, awareness, and education to support effective policies and practices that address the impacts of extreme weather and water events on the environment, people, and the economy.
- **Diversity.** Achieve success by valuing and including a diverse workforce and continually seeking to expand the representation of people from diverse backgrounds at CW3E.
- **Incremental and transformational change.** Intentionally engage, support, and pursue both incremental and transformational approaches to research and applications.

CW3E engages with a group of 5th grade students and works with them to collect weather observations and create a weather report for their peers based on real-time data as part of an outreach day in the Yampa River Basin in Colorado.

> "By bringing together modelers, observationalists, technologists, and stakeholders for the atmospheric river–related seamless understanding, prediction, and reservoir operation, CW3E has created a new model for science application integration, leading to better returns on the science investment."
>
> – **Dr. Xubin Zeng,** Director, Climate Dynamics and Hydrometeorology Center, University of Arizona

CW3E, Colorado Mountain College, and Yampa Valley Sustainability Council team members assemble the tower for meteorological sensors at the Lower Elk Station.

Highlights: Past Accomplishments and Aspirational Goals

CW3E's innovative partnerships with operational agencies are leading to transformative change.

Looking Back: Key Accomplishments from the Last Five Years

- Helped California address record wet and dry extremes.
- Expanded FIRO pilots from one to six dams and demonstrated major FIRO benefits in both dry and wet years.
- Grew AR Reconnaissance (AR Recon) fourfold, from an average of 8 to 33 missions per year.
- Developed the AR Scale and tools.
- Developed the best AR forecasts with a 200-member ensemble regional model, the West Weather Research and Forecasting (West-WRF).
- Increased computing by more than an order of magnitude and shared computing resources with partners.
- Formed the Water Affiliates Group, which consists of leading water agencies that interact with CW3E regularly.
- Forged the RAOP approach.
- Embedded staff with the California Department of Water Resources (DWR) and the National Weather Service (NWS) to integrate innovative tools into operations.
- Expanded CW3E's impact nationwide and globally.
- Collaborated with over 30 institutions, agencies, and private-sector companies.
- Recognized by the Public Relations Society of America for coverage in over 1,500 news stories.
- Integrated CW3E's AR observational data into the Global Forecasting System.
- Received an endorsement for AR Recon by the World Weather Research Programme.

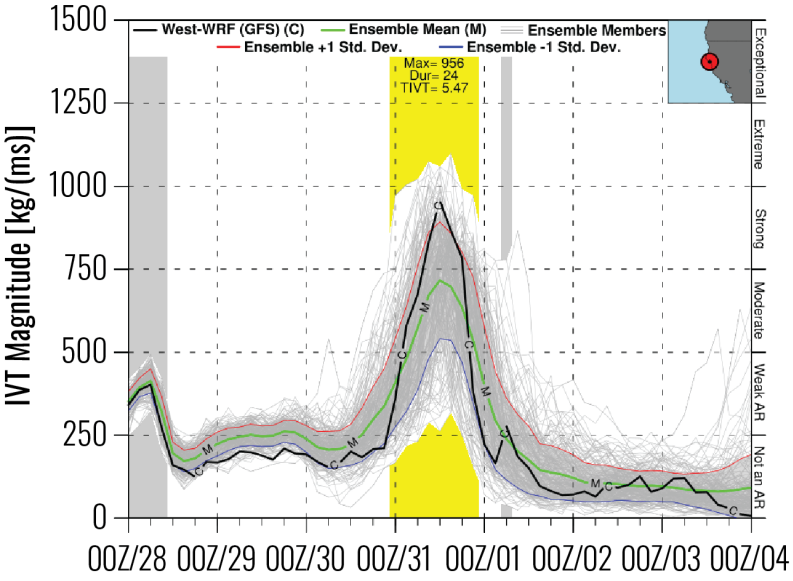
Looking Ahead: Key Aspirations for the Next Five Years

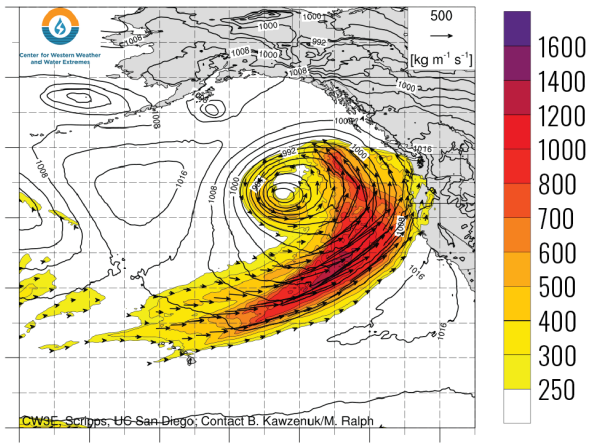
- Expand AR Recon to 60 missions per year throughout the northeastern Pacific Ocean as a national operational requirement.
- Integrate CW3E forecast tools further into operations at DWR, the U.S. Army Corps of Engineers (USACE), and NWS.
- Improve AR forecasts by a one-day lead time over the next 10 years using West-WRF.
- Expand AR Recon beyond the western United States.
- Explore forecast improvements for three other storm types in the West: cutoff lows, narrow cold frontal rainbands, and monsoons.
- Apply machine learning methods to improve weather and streamflow prediction.
- Develop a regional gap-filling radar demonstration program to support water and emergency management agencies.
- Enhance soil moisture monitoring in the Colorado River Basin to improve water supply forecasts.
- Grow FIRO from six to 24 dams.
- Complete FIRO screenings at over 500 USACE dams and document FIRO methods and pathways to support FIRO implementation.
- Partner with DWR on a statewide FIRO strategy for California.
- Provide education and training to build capacity for implementing FIRO nationwide.
- Effectively communicate CW3E's research results via publications and other media.

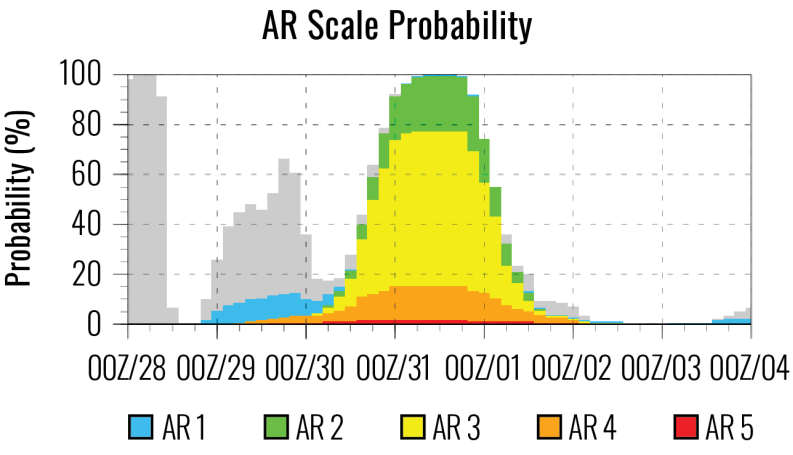
In 2020, CW3E launched the Water Affiliates Group, which consists of leaders in the water management industry. The group helps facilitate transferring information and technical knowledge among members and between CW3E and members. This exchange promotes sharing successes and challenges faced by leading water agencies and connects members more closely with CW3E to shape research strategies and operational tools, advance understanding of ARs and droughts, improve water management, mitigate flood risk, and increase water supply reliability. The group consists of 19 members across California, Arizona, and Washington that meet regularly to learn about the latest research tools and forecasts, as well as to share their perspectives to help CW3E tailor weather information and products to meet operational needs. The open discussion between the water agencies and CW3E facilitates knowledge transfer and supports innovation for both CW3E and Water Affiliates Group members.

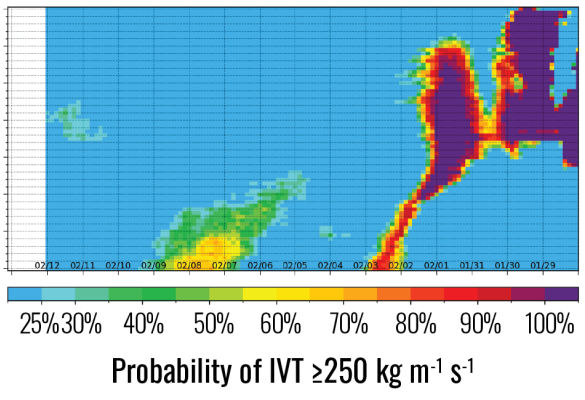
CW3E has developed several forecast tools that are used by emergency managers, water managers, and dam operators to raise awareness and plan for incoming AR storms.

A selection of forecast products and tools developed by CW3E. These four snapshots show the forecast on January 28, 2024, and are intended to illustrate the utility and range of the tools made available by CW3E. Top left: CW3E's West-WRF AR Scale with the AR strength represented by integrated water vapor transport (IVT) forecast. Top right: Vertical IVT forecast with magnitude shaded in kilogram-meters per second (kg m^{-1} s^{-1}). Bottom left: Shading represents the probability of AR Scale conditions at the given location, calculated by the number of ensemble members predicting a given AR Scale at each forecast lead time. Bottom right: The probability CW3E AR Landfall Tool, which displays the likelihood of AR conditions.









Five-Year Priorities

Over the next five years, CW3E will focus on four priority areas:

- Atmospheric Rivers and Extreme Precipitation Research, Prediction, and Applications
- FIRO: Resilient Water Management
- Novel Observations
- Advanced Precipitation and Streamflow Prediction

The following sections outline past accomplishments, objectives, goals, and next steps within each of these priority areas.

PRIORITY AREA:

Atmospheric Rivers and Extreme Precipitation Research, Prediction, and Applications

Goal

Continue to innovate and lead research on ARs, extreme precipitation, and their impacts.

CW3E's research will leverage novel observations, modeling, and innovations in forecast verification to advance our understanding of ARs, extreme precipitation, and their associated impacts. These discoveries will become the basis for decision support tools that will enhance RAOPs.

Accomplishments

- Developed an AR Scale to characterize the intensity and duration of ARs and their potential to impact the environment and society.
- Developed forecast tools, including the AR Landfall Tool and multi-model watershed precipitation forecasts, to support AR and extreme precipitation forecasting activities.
- Engaged with local, state, and federal partners—including an embedded CW3E meteorologist at DWR—to conduct research supporting water resources management.
- Fostered international collaboration on ARs through the International AR Conference, AR Colloquium, and AR Recon workshop.
- Published 150+ peer-reviewed journal articles on ARs and AR-related science with CW3E authors or co-authors.
- Received an endorsement for AR Recon by the World Weather Research Programme.

Key Objectives

- Use AR Recon observations and advanced modeling techniques, such as West-WRF, to better understand the science of ARs and extreme precipitation, including physical processes, forecasting, and impacts.
- Engage with the international community by publishing results in peer-reviewed journals, organizing the International AR Conference, and hosting colloquia.
- Expand research and forecast verification efforts on ARs and the different storm types responsible for extreme precipitation in the western United States in concert with the National FIRO Expansion Pathfinder Program run in partnership with USACE.
- Work with strategic partners in atmospheric science, water resources, and emergency management to develop and improve AR and extreme precipitation forecast methods, services, and applications to meet user needs.
- Support accessible and tailored information on ARs and extreme precipitation by improving CW3E's website, forecast tools, training activities, social media, briefings, and digital media.

Opportunities and Challenges

CW3E has demonstrated that enhanced observations, scientific understanding, and model development focused on ARs can move the needle on precipitation forecast skill across the western United States. CW3E will use this AR-centered framework to improve scientific understanding of extreme precipitation and associated forecast skill throughout the United States and globally by focusing on extremes related to ARs.

Our experience improving AR forecasts has shown that advancing forecast skill requires accurately diagnosing the dynamics of specific storm types. To expand its scope, CW3E will build staff expertise, ground and airborne observational networks, and modeling capacity for ARs and different storm types impacting the West. RAOPs with academic partners, government entities, and operational centers will be necessary to further enhance research-based products in support of improved forecasting and more flexible water resource management, as well as to increase public awareness of extreme precipitation.

An AR family occurs when a series of ARs strike in quick succession. This map shows the location and maximum strength of the nine ARs, according to the AR Scale, as they made landfall in California in December 2022 and January 2023. AR families can amplify impacts by saturating soil and filling up reservoirs. Briefings by the embedded meteorologist at DWR and the AR forecast products supported the prepositioning of emergency management services based on anticipated AR impacts.

> "The ability to leverage newer technology and [knowledge] as it pertains to weather forecasts enhances our ability to safely deliver the multiple missions at Lake Mendocino."
>
> – **Dr. Nick Malasavage,** Chief, Operations and Readiness Division, USACE San Francisco District

A WC130-J "Hurricane Hunter" plane used to collect observations to support AR forecasts. Photo by Erik Jepsen.

Strategies to Achieve Priority Area Objectives

- Collaborate with academic institutions to develop CW3E-led strategic hubs for increased research capacity and productivity on ARs and extreme precipitation throughout the United States and globally.
- Focus on research by storm type and features to better predict these events by integrating modeling and observations.
- Develop and tailor new decision support and forecast tools to enhance AR prediction in collaboration with the water resources management community, including DWR, the National Oceanic and Atmospheric Administration (NOAA), and USACE.

PRIORITY AREA:

FIRO: Resilient Water Management

Goal

Strengthen CW3E's role in enhancing water resources management by accelerating the pace and scope of FIRO—in collaboration with DWR, USACE, and other partners—as a cost-effective approach for increasing resilience to droughts and floods.

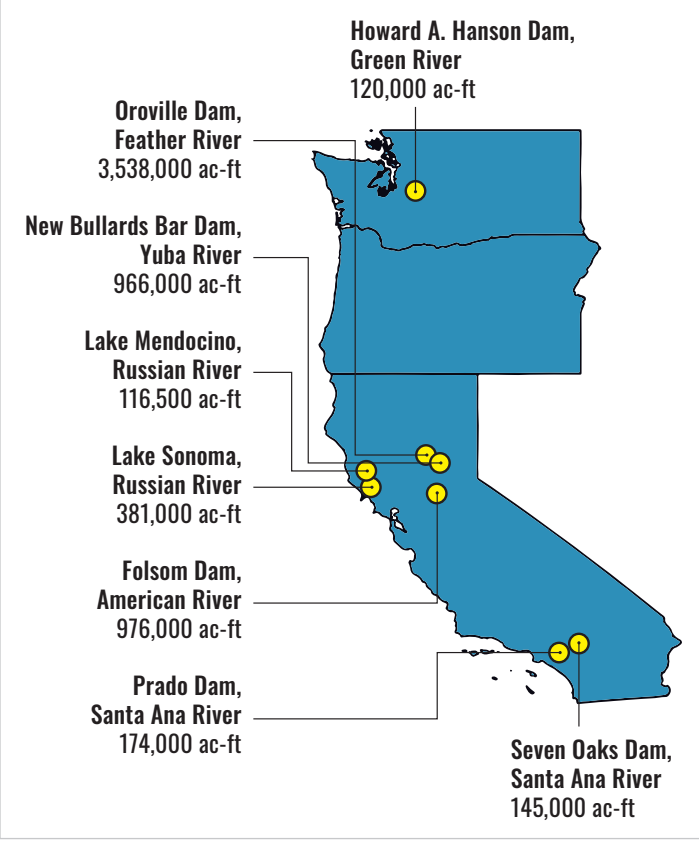
This effort will advance FIRO from six to 24 dams in the western United States and bring national screening for FIRO potential to more than 500 USACE dams nationwide.

Accomplishments

- Demonstrated FIRO viability at two California reservoirs with a variety of physical and operational characteristics. FIRO viability assessments are well underway or nearing completion at five additional reservoirs. These successes have created demand for FIRO as a climate resilience strategy at reservoirs nationwide.
- Achieved results from FIRO, including 19 percent increased storage at Lake Mendocino and 8–11 percent increased recharge at Prado Dam. During a wet year, the Orange County Water District can recharge up to 23,000 acre-feet (ac-ft) of water, worth approximately $23 million, under FIRO operations at Prado Dam.
- Supported a new USACE policy that explicitly allows forecasts to be used in water management operations, thus mainstreaming FIRO.
- Authored a definition of FIRO that has been adopted by the American Meteorological Society.
- Launched FIRO Phase III, the "National Pathfinder," to explore FIRO suitability nationwide, apply FIRO at systems of dams, and develop transferable tools, methods, and skills to deploy FIRO on a national scale.
- Developed a FIRO screening process and methodology with the USACE Engineer Research and Development Center aimed at prioritizing future FIRO assessments among the full portfolio of USACE dams nationwide.
- Developed communication materials on FIRO concepts for partners, stakeholders, and the public, and provided education opportunities for the next generation of scientists and engineers.

Key Objectives

- Adapt FIRO assessments to systems of dams and regions where different storm types influence extreme precipitation and flooding.
- Improve forecasts for ARs throughout the United States and for other storm types in the West to advance FIRO viability nationwide.
- Connect FIRO to managed aquifer recharge (MAR) and other resilience strategies for greater impact, with a focus on California-based FIRO-MAR.
- Advance the FIRO screening process to scale up implementation of FIRO throughout California and nationally.
- Collaborate with USACE, DWR, and other water managers to develop, test, and pursue modern forecasting methods that will facilitate FIRO implementation and achieve maximum FIRO benefits.
- Document FIRO alternatives assessment methodology and identify pathways to meet diverse FIRO needs, including streamlined FIRO assessments for sites identified as having high FIRO suitability by the national screening process.



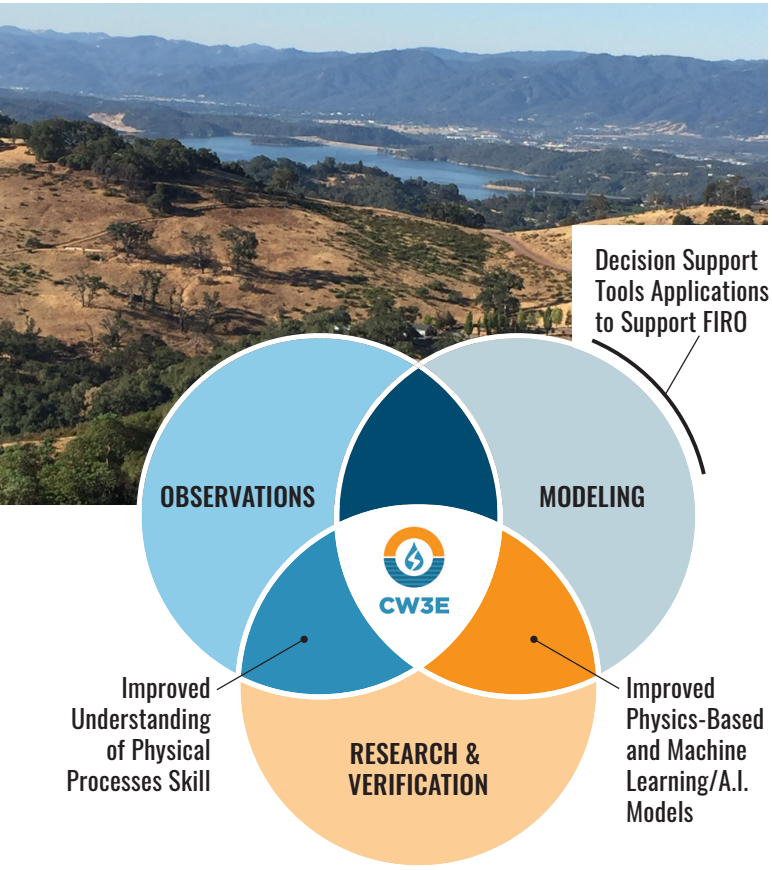
Map of current FIRO projects and their capacities.

Opportunities and Challenges

CW3E's advances in predicting ARs have supported FIRO strategies at reservoirs in the western United States. As FIRO assessments expand from the West to regions where extreme precipitation and flooding are influenced by different storm types, FIRO viability will hinge on the forecast skill for these storms. To help expand FIRO nationally, CW3E will seek to refine its ability to forecast inland-penetrating ARs in other regions impacted by ARs.

Scaling FIRO implementation throughout California and nationally requires the screening process to expand and be transferable to other regions. CW3E will develop a common suite of metrics for assessing basin-scale hydrometeorological forecast skill. When applied to USACE's nationwide portfolio of dams, these metrics will help prioritize future FIRO viability assessments.

Another challenge related to implementing FIRO nationwide will involve scaling FIRO water resource engineering to larger watersheds that feature systems of dams. Reservoir forecast operations, as well as the decision support tools that inform reservoir management, will need to be developed, tested, and implemented at this larger and more complex scale.



A diagram showing the intended outcomes of FIRO through observations, modeling, and research and verification, depicted alongside a photo of Lake Mendocino in California.

> "USACE is committed to leveraging innovation and scientific discovery to improve our operation. Our FIRO partnership with CW3E has already resulted in tangible changes to our operation, resulting in greater benefits for communities in California. USACE looks forward to expanding this collaboration across the region as we 'operationalize' FIRO."
>
> – **Cuong Ly,** Senior H&H and Water Management Engineer, USACE South Pacific Division

Strategies to Achieve Priority Area Objectives

- Develop FIRO process pathways that incorporate efficiencies and lessons learned from FIRO pilot projects and establish "on ramps" that recognize diverse timing, authorized purposes, and other considerations for FIRO implementation.
- Develop a FIRO guidebook that documents the FIRO process, including the alternatives analysis methodology, so future FIRO projects have a "roadmap" for consistently applying FIRO at a range of future sites.
- Develop trainings, documentation, and tools on using ensemble forecast information to help integrate these forecast tools into water management operations.
- Increase engagement with national partners (e.g., USACE districts, NOAA, the U.S. Bureau of Reclamation) to build capacity and accelerate the pace of FIRO implementation.
- Develop RAOPs with NWS by embedding CW3E forecasters and hydrologists in NWS River Forecast Centers as FIRO expands.
- Collaborate with the private sector to support water resource engineering analyses of FIRO alternatives for updating Water Control manuals.
- Explore the application of machine learning and artificial intelligence (A.I.) in FIRO operations with wide-ranging implications.
- Integrate social equity into the FIRO process to ensure FIRO supports the most vulnerable communities.

PRIORITY AREA:

Novel Observations

Goal

Expand oceanic, atmospheric, and hydrologic data collection to improve understanding and prediction of ARs and extreme precipitation.

CW3E will continue to be a leader in transforming hydrometeorological monitoring capabilities by developing high-quality, long-term datasets linking oceanic, atmospheric, and hydrologic processes. One example is AR Recon, an umbrella effort that involves fostering the development and testing of observational systems. It integrates data from buoys, ocean profiling, and airborne and balloon-borne sensors with innovations in data assimilation and forecast verification. Through integrated approaches like AR Recon, CW3E observations more accurately predict and document the location, duration, and impact of ARs and other drivers of extreme precipitation.

Team members work to install the meteorological sensors on the Howe Ranch Station tower in the Upper Yampa River Basin in Colorado with soil from the soil pit laid out in the foreground.

Accomplishments

- Advanced the AR Recon program to an operational requirement in the U.S. National Winter Season Operations Plan, more than doubled the length of the monitoring season and the number of aircraft and flights used to collect observations to improve AR forecasts, and showed that AR Recon improves precipitation forecast skill by up to 20 percent.
- Grew a real-time hydrometeorological monitoring network from 10 stations in northern California to more than 70 stations throughout California, Washington, and Colorado.
- Improved global forecasts through direct data assimilation, model diagnostics, forecast verification, and advances in understanding the physical processes in ARs.
- Collaborated with scientific organizations and educational institutions to expand research; engage local students, faculty, and administrators; identify observational gaps; and prioritize activities to increase resilience to droughts and floods.

Key Objectives

- Explore the impact of ARs on snowpack in the Upper Colorado River Basin and implement the Colorado River Basin soil moisture network to improve streamflow predictions and better manage water resources.
- Triple the spatial coverage of AR Recon by adding observations in ocean basins outside the northeast Pacific Ocean, including in the northwest Pacific Ocean, northwest Atlantic Ocean, and Gulf of Mexico.
- Help lead the implementation of the Atmospheric Rivers Reconnaissance, Observation, and Warning (ARROW) Act, which was signed into law in December 2023, through our RAOP with NOAA and the U.S. Air Force.
- Provide long-term, high-quality observations supporting accurate, high-resolution precipitation estimates throughout the United States for a wide range of operations, including reservoir and water management, emergency operations, and real-time decision support.
- Collaborate with local, national, and global institutions and agencies to build robust, innovative networks that interface with a variety of operational models.

"Partnering with CW3E's AR Recon program to collect atmospheric river data from NOAA's high-altitude Gulfstream IV aircraft has enabled us to expand our understanding of these impactful weather events and close data gaps. Together, we have also proven the value of airborne observations of these events. I am excited that NOAA is bringing on new state-of-the-art aircraft that will greatly enhance our ability to collect vital atmospheric data throughout the year and throughout the northern hemisphere."

– **Vice Admiral Nancy A. Hann,** NOAA Deputy Under Secretary for Operations

Opportunities and Challenges

The diversity and continuity of CW3E's observations will continue to make these data valuable for new uses. For example, CW3E can strengthen existing partnerships with world-class research institutions and operational agencies involved in the AR Recon RAOP, such as the European Centre for Medium-Range Weather Forecasts, the Naval Research Laboratory, and the National Center for Atmospheric Research. There is significant momentum CW3E can leverage from the ARROW Act introduced by California Senator Alex Padilla and signed into law as part of the National Defense Authorization Act in December 2023. CW3E can also lead innovative partnerships between higher education institutions to transform observational capacity and train the next generation of scientists and engineers.

CW3E will need to balance growing demands for long-term hydrometeorological data and storm sampling campaigns with ongoing efforts to develop technologies and document how observations improve forecasts. CW3E will also need to synthesize observations into usable outputs. We will address stakeholder needs in several ways, including tailoring our dashboards for broadcast meteorologists and region-specific users.

Strategies to Achieve Priority Area Objectives

- Lead and actively participate in collaborative efforts with other agencies and institutions operating monitoring networks to extract value from long-term datasets and leverage each other's discoveries.
- Embed novel observations into other priority areas to support water management decisions, advance research, and improve predictions to inform water management.
- Integrate novel observations into the RAOP framework, which has proven successful for advancing FIRO and AR Recon.
- Develop creative ideas for enhancing and expanding CW3E's observational network to monitor the complete water cycle and demonstrate the value of long period-of-record datasets for applications ranging from situational awareness to water management.

Two new aircraft (G550s) will replace NOAA's aging Gulfstream IV aircraft. The new aircraft can fly faster, higher, and longer.

"These new state-of-the-art aircraft will greatly enhance NOAA's ability to gather data critical to hurricane research and forecasting, atmospheric river research and forecasting, climate studies, and other missions. Infrastruture investments like this protect both lives and livelihoods."

– **Rick Spinrad,** Ph.D., NOAA Administrator (NOAA press release 7/15/24)

PRIORITY AREA:

Advanced Precipitation and Streamflow Prediction

Goal

Expand prediction capabilities for ARs and other storm types that cause extreme precipitation.

CW3E will continue to lead the way in predicting ARs, developing physics-based large ensemble predictions, and embracing machine learning innovations to further improve forecast skill. CW3E will also extend its expertise to extremes associated with other meteorological and hydrological processes, such as cutoff lows, narrow cold frontal rainbands, and snow melt.

Accomplishments

- Established the 200-member ensemble West-WRF model as the leading regional predictive model for extreme precipitation associated with ARs.
- Developed integrated water vapor transport and precipitation predictions based on West-WRF and machine learning with up to two additional days of accurate predictions compared with previous methods.
- Established CW3E as a community hub for real-time experimental sub-seasonal and seasonal predictions.
- Established a strong hydrologic modeling and forecasting capability that includes physics-based models and data-driven machine learning algorithms.
- Developed a hydrologic monitoring and seasonal forecasting system based on the WRF-Hydro hydrologic model that operates at near real-time to serve water supply forecast needs.

Key Objectives

- Develop new methods to quantify prediction uncertainty for extreme weather events, including designing large physics-based ensembles and developing probabilistic machine learning models based on West-WRF data.
- Expand modeling capability to other U.S. regions impacted by ARs, and possibly internationally.
- Establish CW3E as a leader of machine learning–based prediction of extreme weather events and stay at the forefront of A.I. advancements for weather at sub-seasonal and seasonal scales, as well as streamflow prediction.
- Lead the discovery of new “forecasts of opportunity” where sub-seasonal prediction skill is relatively high.
- Integrate advanced CW3E meteorological and hydrological predictive capabilities into NWS and DWR operations.

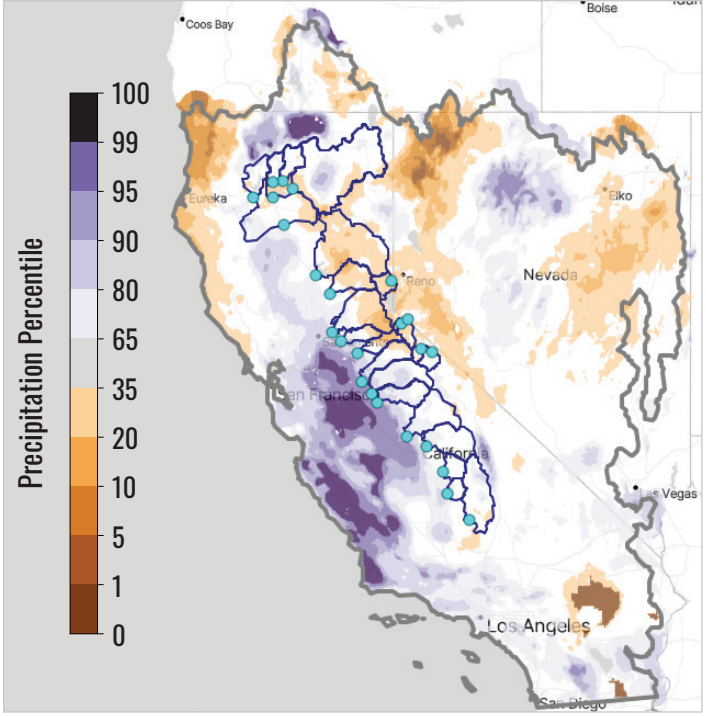
The Expanse supercomputer at the San Diego Supercomputing Center used for CW3E research.

Opportunities and Challenges

CW3E aims to stay at the forefront of physics-based and machine learning models for predicting extreme weather events hours to seven days in advance. With respect to physics-based modeling, CW3E will expand its predictive capabilities to new models, such as the Model for Prediction Across Scales, which covers all regions of interest over the United States with a single computation. We will advance physics packages for predicting ARs and other storm types that impact the West. Additionally, we will continue to leverage community development of the new A.I. weather models and our ability to generate high-resolution reanalysis datasets to train the models, which could change the future of weather prediction. Accomplishing this task will require significant computational resources, including central processing and graphics processing units.

Thanks to research efforts across the field of weather predictions, progress has been made in improving the fidelity of two-week to six-week sub-seasonal predictions of weather extremes. We will build on this progress by implementing postprocessing techniques on sub-seasonal physics-based ensembles, exploring new A.I. weather models at these scales, and investigating how climate variability modulates sub-seasonal forecast skill. Beyond six weeks, current models cannot reliably predict AR storms. Recent studies have shown that ARs may disrupt the signal associated with large-scale teleconnections that otherwise provide some predictive power. CW3E will actively research this area, which could lead to uncovering new physical processes for developing more skillful seasonal predictions.

CW3E's hydrology prediction research will follow a multi-model approach by using WRF-Hydro and the Hydrologic Ensemble Forecasting System, which will leverage improvements from CW3E's weather forecasting systems. Machine learning models can learn the dynamics of land surface hydrology and improve the accuracy of streamflow predictions. CW3E will continue to develop and test these algorithms to improve the operational capabilities of our partners, such as DWR and the River Forecast Centers. Additional streamflow observations in watersheds of interest will further enhance these forecasts.



Climatological percentile of April 2024 precipitation over the California-Nevada River Forecast Center's forecast area. Basins (dark blue outline) and reservoirs (cyan dots) utilized by DWR for seasonal streamflow prediction (i.e. Bulletin 120).

Strategies to Achieve Priority Area Objectives

- Interact regularly with DWR, the River Forecast Centers, and other users of CW3E prediction systems to increase their utilization of these systems.
- Access large computational and storage resources on supercomputers using clusters of the latest generation of graphics processing units hosted by the San Diego Supercomputing Center, the National Center for Atmospheric Research, or other institutions.
- Develop a detailed plan to improve model formulation for West-WRF physics packages.
- Explore dynamical modeling frameworks that enable both global and regional weather modeling.
- Collaborate with the private sector to develop neural weather models.
- Strengthen the distinction between sub-seasonal and seasonal forecasts in all communications and include spring and fall in forecast verification efforts.
- Implement dynamical, statistical, hybrid, and machine learning methods to learn the global climate conditions under which sub-seasonal forecast skill is increased relative to average conditions.
- Build and improve physics-based hydrometeorological modeling systems and supporting data.
- Use machine learning–based data fusion techniques and new observations for better precipitation and streamflow forecasts.

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**Member of Water Affiliates Group*
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East Bay Municipal Utility District*
Irvine Ranch Water District*
Marin County Department of Public Works*
Marin Municipal Water District*
Modesto Irrigation District*
North Marin Water District*
Orange County Water District*
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Salt River Project*
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