# CalWater Science Plan

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## Executive Summary

# 1.0 Introduction

## 1.1 CalWater's Science Drivers

### 1.1.1 Atmospheric Rivers and the CalWater Project

Atmospheric rivers (ARs) - constantly moving, narrow bands of intense water vapor transport through the lower atmosphere - play a critical role in the global hydrologic cycle. When ARs impinge on California coast and Sierra Mountains during the winter storm season they contribute major portions of the state's annual water budget, supply renewable hydropower energy generation and often prompt extreme flood events. Figure 1 illustrates an example of a strong AR seen in SSM/I satellite data stretching across Pacific to Central California; the event resulted in greater than 15 inches rainfall in one day.

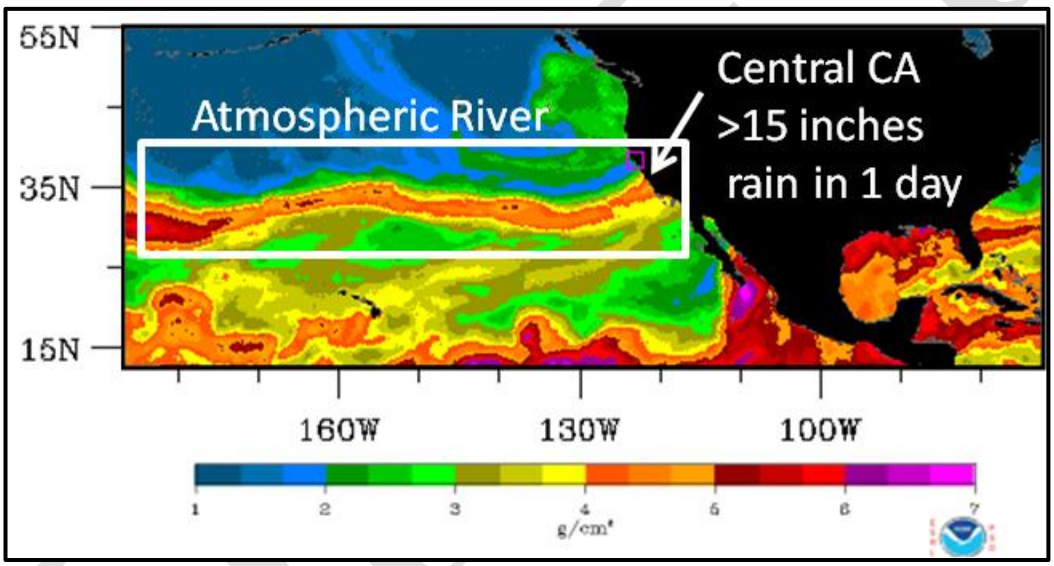


Figure 1 Example of a strong AR seen in SSM/I satellite data stretching across Pacific to Central California

Understanding AR characteristics and impacts are critical for water management policy decisions. Figure 2 illustrates the contributions of AR days to total precipitation for water years 1998 to 2006; 25-50% of total annual rainfall was associated with AR days in much of California.

In addition to the AR precipitation phenomenon, there is a need to understand the influence of changing aerosol contents on AR precipitation amounts and distribution. In particular, identifying any potential changes in event frequency and severity in a changing climate is essential because of the implications to water supply, flood control, and extreme storms.

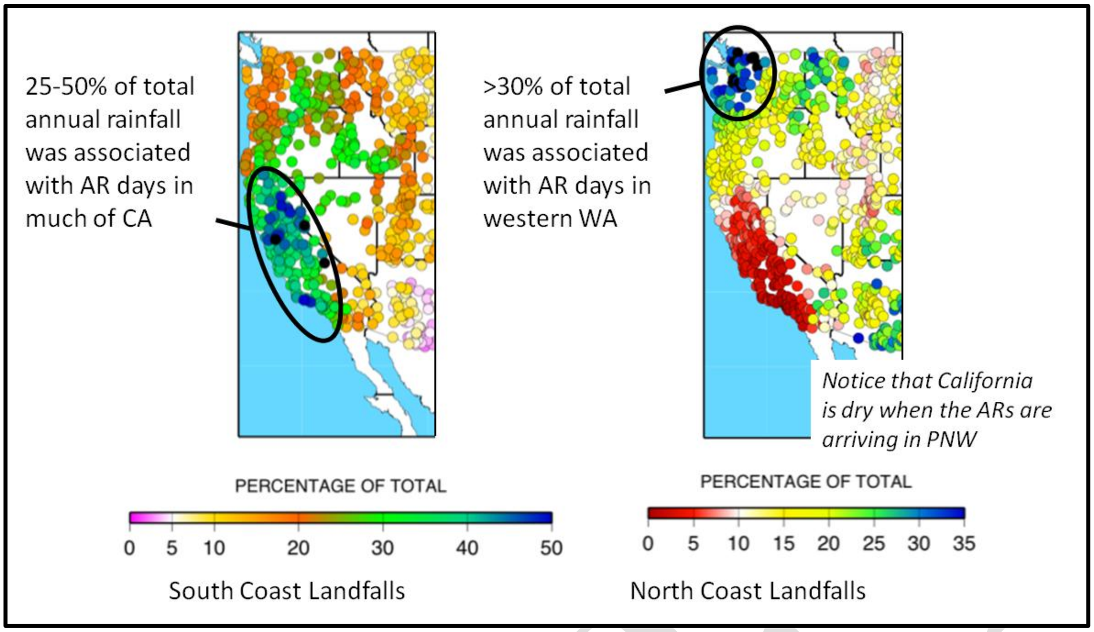


Figure 2 AR events contribute major portions of total annual rainfall to regions along the US Pacific Coast

This CalWater Science Plan documents a collaborative research effort to define the contribution of atmospheric rivers to the total precipitation and its distribution, the impact of aerosols on atmospheric rivers, uncertainties in the total water vapor budget of atmospheric rivers, relationships between atmospheric rivers and climate indices and climate change, and the contribution of atmospheric rivers to black carbon transport and deposition.

### 1.1.2 Challenges of Changing Climate

Climate change poses additional challenges for California water management due to the potential changes in the annual water budget and for increased severity and frequency of extreme precipitation events. Most climate projections fall within a fairly narrow range of precipitation changes in much of the US. In Northern California; "small change" is the most common projection (Dettinger 2005; Figure 3). However, as with Arctic Pack Ice projections from IPCC (Figure 4) it is unclear that the current models capture the full range of uncertainty in annual precipitation.

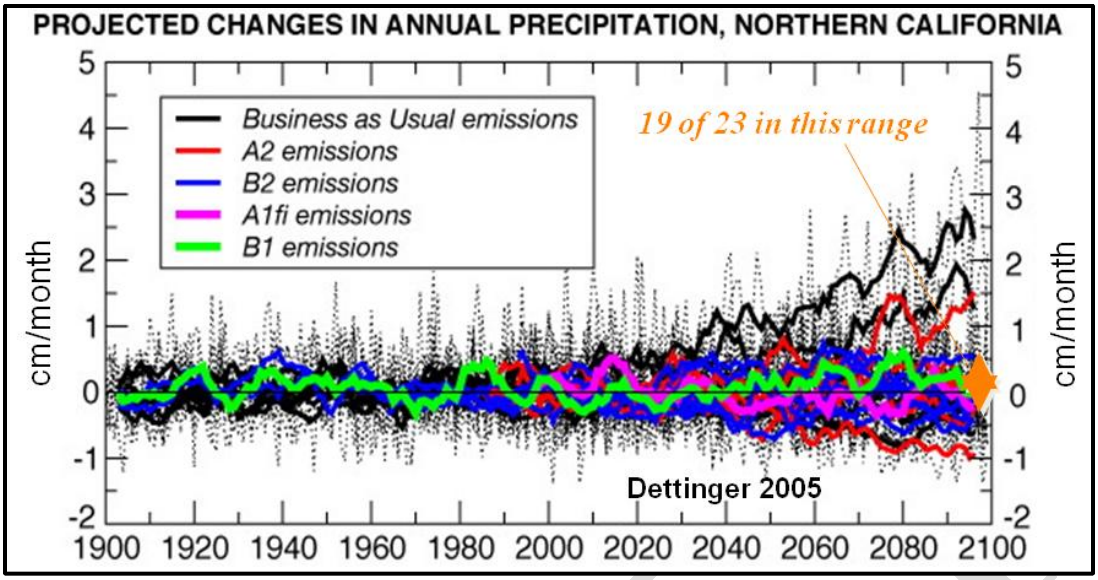


Figure 3 Projected trends in annual precipitation by an ensemble of climate change models indicate a small change in annual precipitation in northern California.

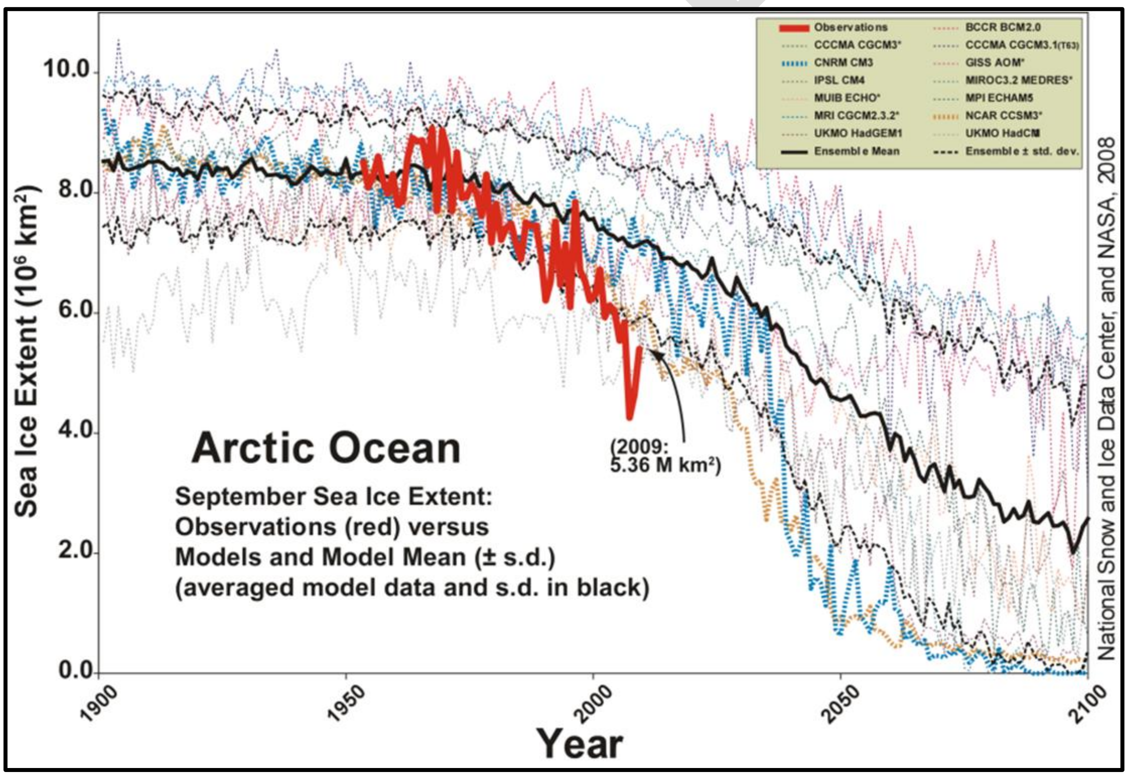


Figure 4 Uncertainty of climate model projections is illustrated for Arctic Sea ice extent which is observed to be decreasing at a faster rate than predicted. Courtesy J. Stroeve - personal communication

And even with no change in annual totals, the extreme events (storms/droughts) are expected to increase. A statistical summary of climate change models' projections of extreme precipitation events indicates a trend towards increasing frequency of flood worthy storms during the winter season (Dec-Jan-Feb). Currently there are about 6 extreme precipitation days and the climate change projections indicate perhaps 9 extreme events per year in 2100, a 50 percent increase by the year 2100 (Figure 5).

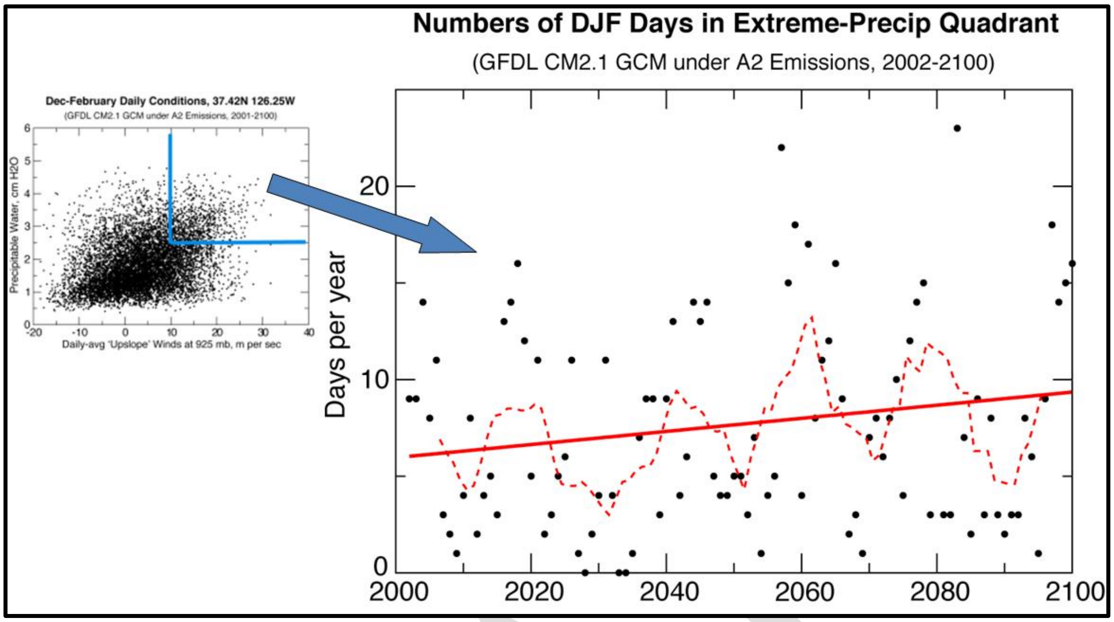


Figure 5 Climate change models project an increased frequency of extreme precipitation events during the winter storm season in California. (Courtesy Mike Dettinger, Scripps Institute of Oceanography)

Regardless of the climate change models there are indications that the flood frequency characteristics of California's rivers are changing. As an example, tabulation of the annual maximum daily flows for the American River basin for the period 1905 – 2005 show that the top 8 daily maximum flows have occurred since 1950 and the largest of record occurred in 1997 (Figure 6).

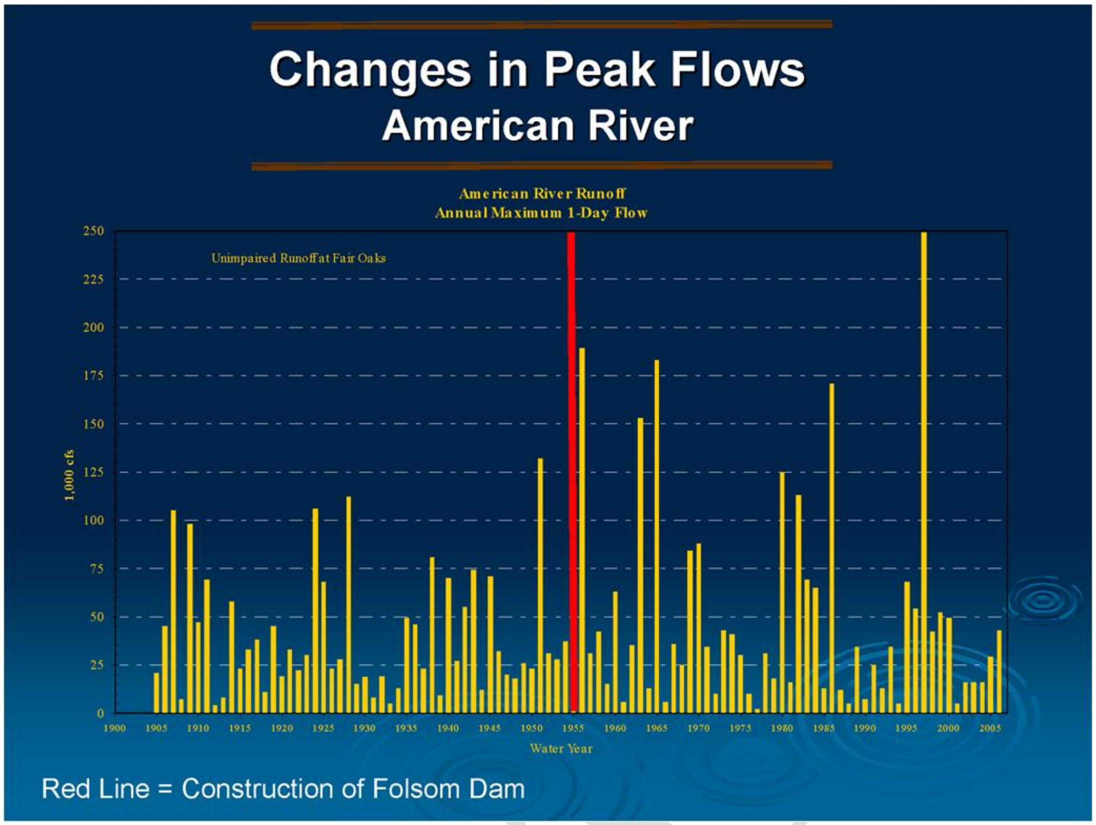


Figure 6 Tabulation of annual maximum daily flows for the American River above the Folsom Dam site indicate an increased frequency of extreme floods since the 1950's. (Courtesy Lester Snow, CA-DWR)

### 1.1.3 California's Water Resources Management Goals

As noted in the California Water Plan (CDWR 2009) the State is facing one of the most significant water crises in its history—one that is hitting hard because it has so many aspects. Growing population and reduced water supplies are worsening the effects of a multi-year drought. Climate change is reducing snowpack storage and increasing floods. There is a need to act proactively to provide integrated, reliable, and secure water resources and management systems for our health, economy, and ecosystems. California's Climate Adaptation Strategy is being developed in response to Gov. Schwarzenegger's November 2008 Executive Order S-13-08 that specifically asked how state agencies can respond to rising temperatures, changing precipitation patterns, sea level rise, and extreme natural events.

### 1.1.4 NOAA's Strategic Goals and Mission Requirements

NOAA's mission is "to understand and predict changes in Earth's environment and conserve and manage coastal and marine resources to meet our nation's economic, social, and environmental needs." Forecasting water is central to NOAA's mission. NOAA emphasizes that managing this key natural resource requires advanced monitoring and predictive capabilities to reduce conflict between many competing demands. To accomplish this NOAA has expanded its sources of observational data, advanced numerical models, and sought improved the accuracy of its forecasts and warnings.

Further, to provide enhanced information on climate change NOAA is proposing a new line office – the NOAA Climate Service – that would be dedicated to bringing together the agency's strong climate science and service delivery capabilities. The NCS will encompass a core set of longstanding NOAA capabilities for climate research, observations, modeling, predictions and assessments. The CalWater project is an excellent example of the type of research and development responsive to NOAA's mission requirements.

## 1.2 CalWater History

The CalWater project is an outgrowth of NOAA's CALJET and PACJET projects from 1997-2003 on the West Coast. Then the highly instrumented HMT-West project, which targeted California's flood-vulnerable American River Basin, was deployed during the period from 2005 through 2010. Regional extensions of HMT-West involved deployment of various hydrometeorological instrumentations along the Pacific Coast in order to better track and model the incidence of land falling atmospheric rivers and the resultant precipitation patterns.

A planning meeting in 2008 identified CalWater as a major field program jointly sponsored by NOAA and the California Energy Commission with two main scientific thrusts to determine the role of atmospheric rivers in water supply and flooding, and the impact of aerosols on precipitation. Both of these are focused on quantifying their respective roles in creating uncertainty in climate projections of precipitation in California in the future. The CalWater Atmospheric Rivers Working Group met on June 9-10, 2009 at the Scripps Seaside Forum at Scripps Institution of Oceanography in La Jolla, CA to coordinate research activities for the winter 2009-2010 CalWater experiment and begin planning for possible activities in a follow-on CalWater 2 project in the 2012 timeframe. More recently, a meeting was held June 17 at Scripps to advance definition of the CalWater research priorities and agenda.

## 1.3 Overview of CalWater Science Plan

This CalWater Science Plan is intended to document the project goals and objectives, and to lay out the various research activities to be conducted by the interdisciplinary teams. Summary descriptions of the scientific research approaches are provided along with anticipated outcomes, timelines and milestones and resources.

# 2.0 CalWater Science Plan

## 2.1 Goals and Objectives

The CalWater project is a collaborative activity between the California Energy Commission, NOAA Earth System Research Laboratory, Scripps Institute of Oceanography and other research partners seeking to develop new information on the precipitation influence of atmospheric rivers on California water supply and floods, and the associated impact of aerosols.

Specific objectives of the CalWater project are derived from the major activity (or application) areas and include the following:

- Examine the structure and kinematics of AR storms as they approach the coastline and ascend the coastal mountains, and determine the role of low-level wind jets in precipitation formation and location.
- Study the microphysical features and orographic precipitation mechanisms in storm clouds over the coastal mountains.
- Characterize the uncertainty of IPCC projections of annual total and extreme precipitation events resulting from inadequate representation of ARs.
- Evaluate how well the IPCC models represent non-brightband, shallow rainfall processes, and "cut-off lows" and associated large scale circulations, which may or may not involve ARs.
- Develop and validate techniques for downscaling global and regional models that represent the key water vapor transport and precipitation processes.
- Assess the potential relative influence that aerosols can have on orographic precipitation.

## 2.2 Implementation Strategy

### 2.2.1 CalWater Participating Agencies and Organizations

CalWater is formed as a coalition between the California Energy Commission (CEC), NOAA Earth System Research Laboratory (ESRL), Scripps Institute of Oceanography (SIO), the Pacific Northwest National Laboratory (PNNL) and a number of other academic research partners. It is only through such an interdisciplinary collaboration that advancement of our understanding of atmospheric rivers and aerosols can be realized, thus providing a scientific foundation for water management and potential climate change impacts.

The California Energy Commission (http://www.energy.ca.gov/) is the state's primary energy policy and planning agency. The Commission responsibilities include: a) forecasting future energy needs; b) licensing thermal power plants, c) promoting energy efficiency; d) supporting public interest energy research that advances energy science and technology through research, development, and demonstration programs; e) supporting renewable energy and implementing the state's Alternative and Renewable Fuel and Vehicle Technology Program; and f) planning for and directing state response to energy emergencies. The CEC's interests in the CalWater project relate to the fundamental contributions that better information on ARs and aerosols can provide to renewable energy generation as hydropower, the influence of power and other anthropogenic emissions have on precipitation, and the potential impacts of climate change on the state's water resources.

NOAA-ESRL's Physical Sciences Division (PSD; http://www.esrl.noaa.gov/psd/about/) conducts the physical process research necessary to help provide the nation with a seamless suite of information and forecast products ranging from short-term weather forecasts to longer-term climate forecasts and assessments. During the past decade the PSD has led the CALJET, PACJET and HMT-West projects in California which have led to fundamental advances of understanding the role of ARs on the state's water budget and flood threats. The PSD has also entered into a partnership with the California Department of Water Resources on the Enhanced Flood Response and Emergency Preparedness (EFREP) project which is implementing key results from HMT-West and extending the observational network. Leveraging of ESRL-PSD's HMT-West and EFREP observational and AR modeling capabilities will contribute greatly to the CalWater project.

Scientific investigations at Scripps Institution of Oceanography (http://scripps.ucsd.edu/) span the realms of sea, air, land, and life in efforts to determine how Earth systems work and interact. Scripps researchers have been conducting basic research on the hydroclimatology of western North America as it pertains to medium- to long-range hydrologic forecasting. They are strong collaborators with ERSL-PSD on the HMT-West, EFREP and other projects.

Pacific Northwest National Laboratory (PNNL; http://www.pnl.gov/) is one of the U.S. Department of Energy's (DOE's) ten national laboratories, managed by DOE's Office of Science. It is located in Richmond, WA. PNNL researchers work in partnership with academia, other national laboratories, government agencies and industry to deliver science and technology to help the nation and the world solve their most complex energy and environmental challenges. PNNL has particular capabilities for regional climate modeling, subgrid cloud parameterizations, and coupling land and atmosphere models. Regional and global climate models and hydrology models have been developed and applied to understand the impacts of climate variability and change on water resources.

The Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado at Boulder explores all aspects of the earth system and search for ways to better understand how natural and human-made disturbances impact our dynamic planet. CIRES researchers imbedded at the ESRL-PSD facilities have special capabilities for the atmospheric sciences including advanced observational systems involving radars and GPS, and numerical modeling of mesoscale weather phenomenon.

The NOAA Western Regional Climate Center (WRCC; http://www.wrcc.dri.edu/) delivers climate services at national, regional and state levels working with NOAA partners in the National Climatic Data Center, National Weather Service, the American Association of State Climatologists, and NOAA Research Institutes.

### 2.2.2 CalWater Management Council

A CalWater Management Council has been formed to provide overall guidance and funds management for the project. The project leads include Joe O'Hagan from the California Energy Commission and Marty Ralph from ESRL-PSD.

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### 2.2.3 CalWater Science Team

The following team consists of experts who will participate in CalWater based on a combination of support directly from CEC and on closely related efforts they will leverage.

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## 2.3 Operating Plan

### 2.3.1 Communication

Interactions amongst the CalWater community take on a number of forms, depending upon whether or not field operations are occurring. Science team planning meetings involving all participants are held once per year at a location in California. At these meeting results of field season data collections and analysis results are presented, and next season plans are formulated. The CalWater web page (http://CalWater.noaa.gov/) is a primary source of information for posting of project activities. News stories are added as frequently as possible to keep the pages current and to convey happenings to the community. The web page also serves as a portal to much of the CalWater data, and as an archive of key documents. Communications for field operations are described below.

2.3.2 General Timeline and Milestones

CalWater Early Start

CalWater Phase I (focus on Sierra Nevada)

CalWater Phase II (offshore water vapor budget in ARs; Aerosols Transport)

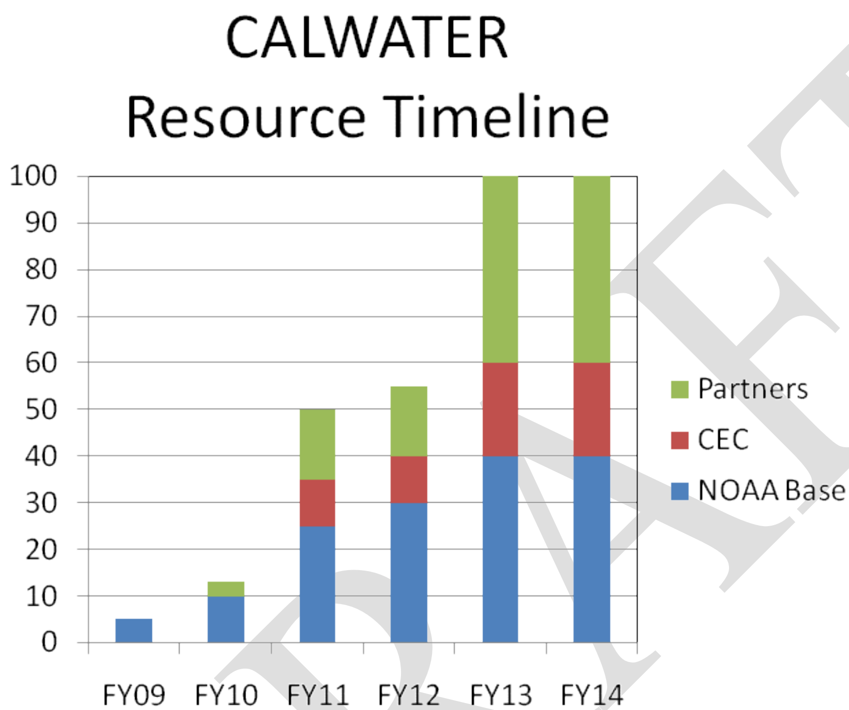


Figure X Generalized timeline for CalWater resource commitment. Ordinate in % of maximum annual resource commitment.

# 3.0 CalWater Cross-Cutting Strategies

## 3.1 Overview

Several cross-cutting strategies are involved with the CalWater project, including a) advanced observational systems, b) numerical modeling, c) intensive observing periods, and coordination with other programs.

## 3.2 Observation Systems

Observation systems comprised of a wide variety of remote and in-situ sensors are required to be deployed to obtain relevant and accurate data characterizing atmospheric conditions. Figure X shows the locations of instruments deployed for the HMT-West effort; leveraging the currently in-place observational systems of HMT-West and EFREP is a major advantage to the CalWater project. Remote sensing instrumentation includes a scanning polarimetric radar, several wind profiling and precipitation profiling radars and a network of GPS receivers for measuring precipitable water vapor. Precipitation gauges and disdrometers, surface meteorological stations, soil moisture/temperature probes, snow depth sensors and stream level loggers are among the in situ sensors that will be deployed. In addition, rawinsondes will be released serially immediately upwind of the area during storm episodes.

These special, highly detailed observations will be collected within the wider scale context of the operational observing networks of the National Weather Service (NWS) and other agencies (Figure XX). In addition to their regular rawinsonde releases, the NWS will release supplemental rawinsondes near the coast and in the lee of the Sierra Nevada during selected storm episodes. Ongoing observations in the Russian River watershed of California's Coast Range for NOAA's Weather-Climate Connection project will complement the CalWater measurements. Similar or expanded CalWater deployments are expected in the same area for each of the following few winters. A listing of the instrument types and their location coordinates is presented at http://www.esrl.noaa.gov/psd/programs/2009/hmt/instruments.html.

Additional new remote and in-situ sensors will be deployed to address specific needs of the CalWater project. …

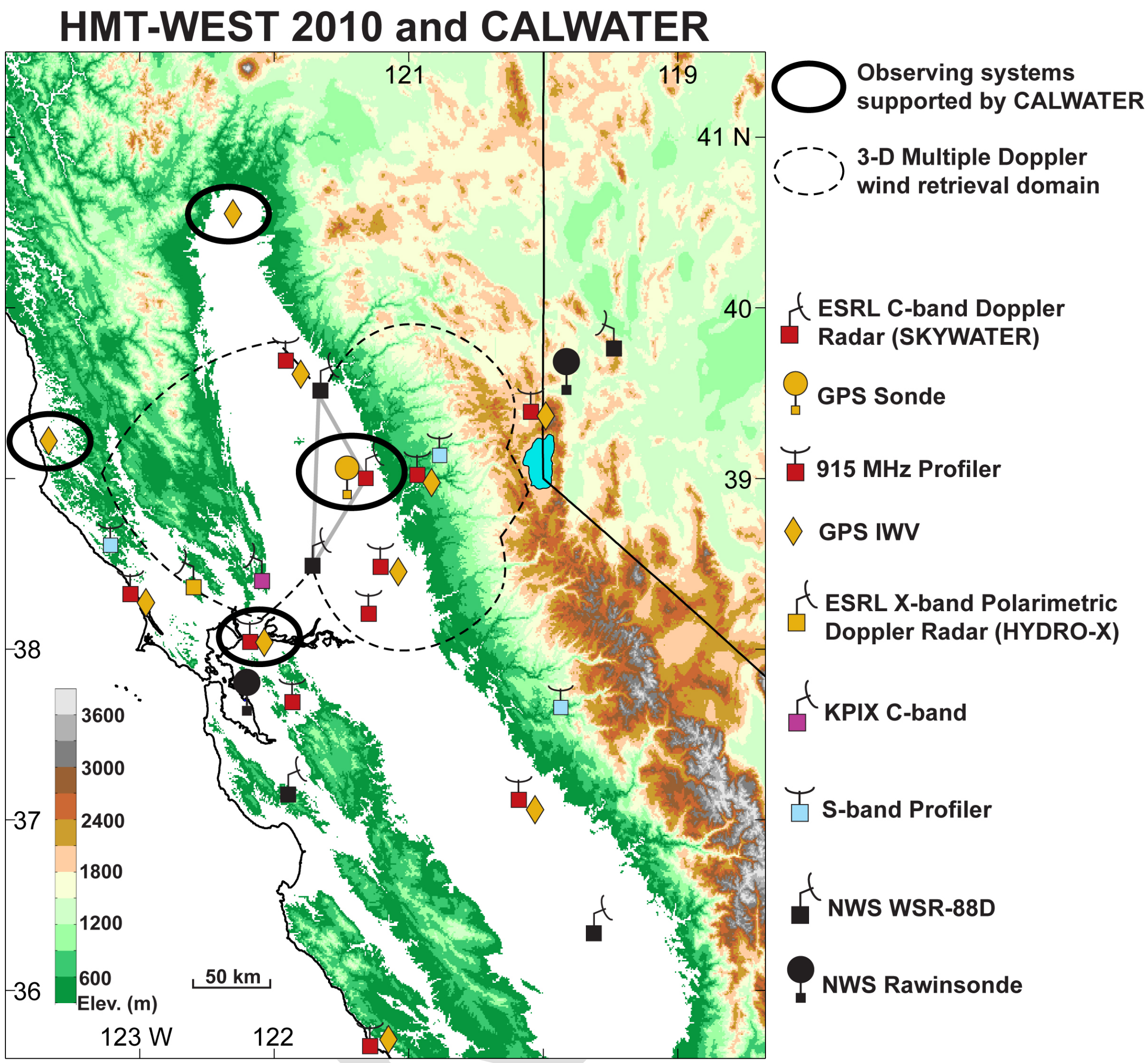


Figure X. Basemap of proposed observing system deployments for HMT-West and CalWater during winter 2009-2010. Observing systems enclosed by the solid ellipses are partially supported from CalWater resources. The domain enclosed by the dashed curve is where 3-D winds can be derived from the Doppler radars at the vertices of the gray triangle.

### 3.3 Numerical Modeling

The basic dimensions of numerical weather prediction (NWP) modeling include:

- Observations
- Data assimilation methods
- Parameterizations and numerics in the forecast models
- Ensemble prediction techniques
- Statistical postprocessing to mitigate forecast model bias

To date, research and development in NWP on behalf of HMT has been conducted primarily by the ESRL Global Systems Division. Virtually all of the new profilers, surface observations, and GPS vapor measurements that were deployed for HMT were assimilated with only minor accommodations into the Local Analysis and Prediction System (LAPS), which is the platform for all of the HMT supplemental NWP, so there has been essentially no additional investment in data assimilation. The models being used for the HMT ensemble are mostly configurations of the WRF model that were used in earlier GSD field programs, so model development was not a large investment either. Instead, GSD's investment has been approximately equally divided into designing, implementing, maintaining, and evaluating the ensemble modeling system (Jankov et al. 2007, Jankov et al. 2008), and new statistical post-processing techniques, mainly for probabilistic quantitative precipitation forecasts (PQPF, Yuan et al. 2008).

The HMT-West project has implemented an ensemble of four different mesoscale forecast models that cover the entire CNRFC domain of responsibility with 9 km grid spacing. The models are reinitialized and integrated out to 120 hours, every three hours. A 3-h forecast cycle is appropriate for the type of meteorological phenomenon of interest to the RFC, which are synoptic-scale systems that may take a day or more to traverse the domain. The goal of this forecast system is to make best-possible forecasts of 6-h precipitation accumulation. Forecasts will be verified against several gridded quantitative precipitation estimates (QPE). The ensemble outputs are provided to the CNRFC in real time via the ALPS workstation.

For the WFO problem ESRL has implemented a single-model approach with a grid of 5-km increment that reinitializes every hour and runs forward out to 12 hours. This update frequency is appropriate to the kind of event that causes most flash floods in the HMT area, which is 6-10 hour bursts associated with an atmospheric river. The goal of this forecast system is to make best-possible forecasts of 1-h precipitation accumulation. Forecasts are to be verified against a new NEXRAD product that uses real-time minimum-latency rain gages to bias-correct radar-estimated QPE in real time, providing 5-minute updates to hourly QPE. For now this capability is available uniquely at the Monterey WFO, so we focus our initial attention on this office. For the current winter, model outputs are provided to forecasters only via the Web, which limits their utility.

It is important to note that this modeling strategy represents a balance of interests in using the available resources. Decisions on how to invest GSD's supercomputer resources among these two solutions were based on the relative maturity of the solutions, and the urgency to prepare for the evolution of HMT research and testbed activities into the project planning of the Emergency Forecast Response Enhancement Program (EFREP) sponsored by the California Department of Water Resources. The goals of EFREP are essentially identical to those of the RFC-oriented components of HMT. This balance is reassessed annually and adjusted as needed.

### 3.4 Intensive Observing Period Planning and Execution

Intense operating periods (IOPs) are time periods within the field season when all available resources are directed to capturing as much data as possible that could be used to best characterize the hydrometeorological event of interest. Identification of an IOP triggers project staff and observational systems to the highest state of readiness so that data sets of the highest quality and resolution can be obtained. Deployment of field staff for manned instruments is initiated when an IOP is called.

During field operations (in the west this is typically from the beginning of December into mid-March), Operations Directors and Team Leaders are identified and each serves on one or more two-week shifts. It is the Operations Director's responsibility to make decisions regarding when to conduct intensive operations periods (IOPs; when to begin an IOP and when to terminate it), how to utilize available resources (sondes; field personnel, etc), and to write an IOP summary in a timely fashion. Forecast event threshold precipitation amounts of at least 1" are generally required. Lesser amounts may of interest to test equipment and/or little rainfall has occurred. Larger amounts may not be of interest if there have been many IOP during the field season; ~10 IOP is a typical target. The Operations Director works closely with the team leaders to keep abreast of developing weather. A number of blogs (e.g., Status, Forecast and Operations Summary) will also maintained on the web page on a daily basis (or more frequently as needed) during the field season.

A most important form of communication during the field season is a daily conference call. It is important to keep these calls as brief as possible. During a period's relative calm weather it is common for these calls to last approximately 5 minutes. When a storm is imminent the calls are more involved, and run somewhat longer. Approximately on a bi-weekly schedule, long-range weather discussions are held as well, these typically last on the order of one-half hour. Also, after important IOPs (a significant event) a longer debrief call may be scheduled.

### 3.5 Coordination with Other Programs

The CalWater project is anticipated to benefit greatly from coordination of observational, numerical modeling and associated staffing with a number of on-going projects. A primary coordination effort is with the HMT-West observational and numerical modeling activities (described above). Coordination with the EFREP will also result in deployment of observations and modeling resources directly usable by CalWater.

Unmanned aircraft systems, such as the Manta (Scripps/NOAA) and Global Hawk (NASA/NOAA), have the potential to take measurements in areas that are currently unmonitored due to airplane and pilot limitations and could provide research and operational activities in these hard-to-reach environments more accurately, more economically, and with less risk involved. UAS could fly further out over the ocean, dropping sensors into storms at regular intervals. These sensors, or sondes, could then detect changes in AR storm tracks and intensity.

# 4.0 CalWater Major Activity Areas and Projects

## 4.1 Overview

CalWater is a major field program jointly sponsored by NOAA and the California Energy Commission with two main scientific thrusts to determine the role of atmospheric rivers in water supply and flooding, and the impact of aerosols on precipitation. Both of these are focused on quantifying their respective roles in creating uncertainty in climate projections of precipitation in California in the future.

## 4.2 Atmospheric Rivers

### 4.2.1 Background Science

The phenomenon of so-called atmospheric rivers (AR) is the major hydrometeorological forcing for California and may apply as well to any coastal region, Pacific or Atlantic, and even the continental United States. Since the global characterization of ARs by Zhu and Newell (1998), HMT scientists have contributed to a fundamental understanding of the role that ARs play in precipitation events on the West Coast, and in particular their role in producing extreme precipitation events. Figure Y is a close up illustration of a land-falling atmospheric river in the eastern Pacific, leading to flooding on the north coast of California.

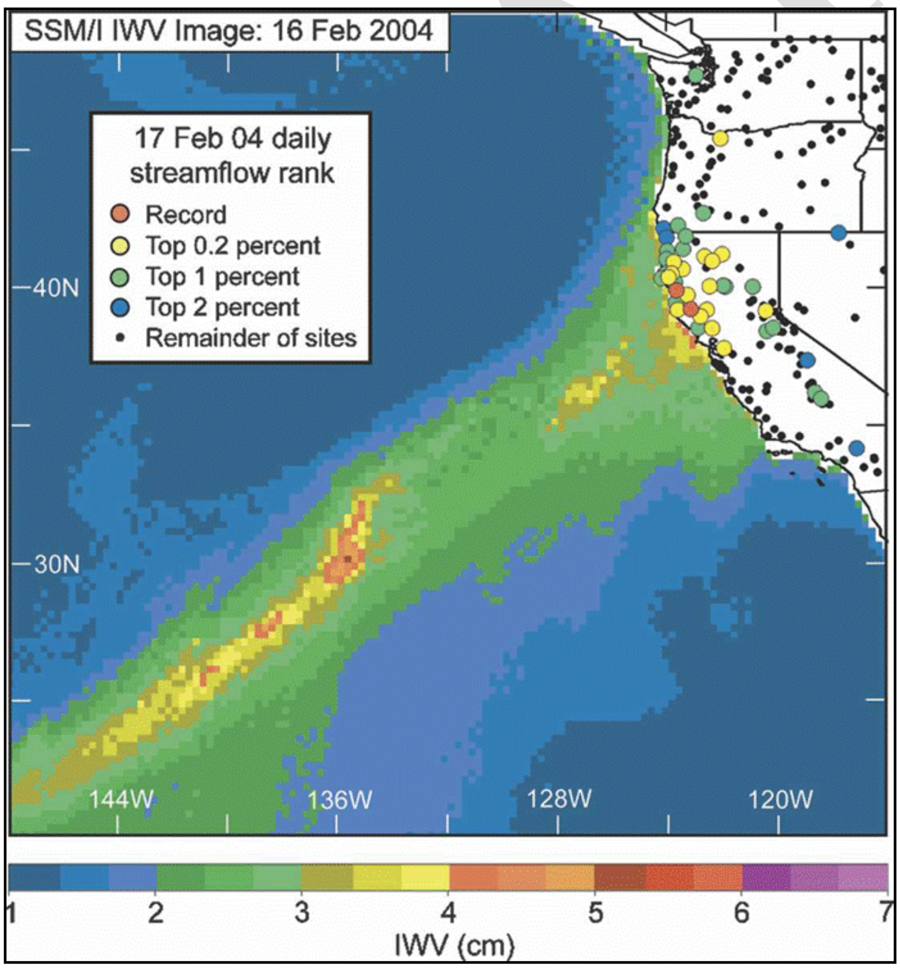

Figure Y Composite SSM/I satellite image of IWV (cm; color bar at bottom) constructed from polar-orbiting swaths between 1400 and 1830 UTC 16 Feb 2004 and ranking of daily streamflows (percent; see inset key) on 17 Feb 2004 for those gauges that have recorded data for >=30 yr. The streamflow data are based on local time; add 8 h to convert to UTC (from Ralph et al. 2006).

Zhu and Newell (1998) showed that the majority of the middle-latitude moisture flux occurs in atmospheric rivers, which occur in both hemispheres and all seasons, but the fraction of the globe that they cover at any given time is 10% or less. The quantitative impacts of land falling atmospheric rivers on precipitation and flooding across western North America have only begun to be assessed. For example, Ralph et al. (2004) showed the connection between a land falling atmospheric river and a narrow swath of heavy rainfall in northern California. More recently, Ralph et al. (2006) linked heavy orographic precipitation and severe flooding in northern California's Russian River basin to another land falling atmospheric river. This latter study also established that all seven flood events on the Russian River between October 1997 and February 2006 coincided with atmospheric river conditions. That study was extended by Neiman, et al (2008a) to cover adjacent north- and south-coast regions of western North America. Composite SSM/I IWV analyses showed land falling wintertime ARs extending northeastward from the tropical eastern Pacific, whereas the summertime composites were zonally oriented and, thus, did not originate from this region of the tropics. Companion SSM/I composites of daily rainfall showed significant orographic enhancement during the landfall of winter (but not summer) ARs. It is becoming increasingly clear that our ability to improve predictions of many of the largest storms and floods impacting western North America, and our ability to track their progress as they propagate down the coastal margin, will depend on advancing our understanding and observations of atmospheric rivers beyond what has been presented in the studies cited above.

### 4.2.2 Hypotheses

Several hypotheses will be addressed by the CalWater Atmospheric Rivers topic.

1. Uncertainty in IPCC projections of annual precipitation and extreme precipitation events in California results partly from uncertainty in the representation of ARs offshore in the IPCC models.
2. Significant errors in projections of precipitation and associated flood risks exist in IPCC Global models and attendant regional models because they do not adequately represent the effects of the coast range and Sierras on land-falling atmospheric rivers.
3. Other sources of uncertainty in California precipitation projections are related to how the IPCC models represent non-brightband, shallow rainfall processes, and "cut-off lows" and associated large scale circulations, which may or may not involve ARs.
4. Downscaling of global models and regional models is needed to properly represent the key water vapor transport and precipitation processes, and yet it remains unclear what models, resolutions or other model parameters are needed to do so.
5. If a model does not represent the coastal barrier jet or the Sierra barrier jet, it is unable to represent the potential impacts of aerosols on orographic precipitation.

### 4.2.3 Experimental Design - Approach and Activities

For the atmospheric river theme there are six activities anticipated including: 1) Field Study, 2) AR Structure, 3) Downscaling Approaches for ARs, 4) Uncertainty in Reanalysis and IPCC Models, 5) AR Precipitation Subprocesses, and 6) Tropical-Extratropical Interactions.

#### 4.2.3.1 Field Study

- Objective: Conduct a field study in northern California that heavily leverages existing observations, but fills key gaps with augmented samplers and specialized equipment. The field studies will be leveraged off the HMT-West field program.
- Background: The field phase of CalWater will provide the opportunity to examine key interactions between ARs, their associated frontal systems, and the Sierra barrier jet as well as the resulting orographically modulated distribution of precipitation. Those observing systems requiring dedicated deployments and deemed critical to this endeavor include (for additional details see concept paper by Neiman et al 2008 (Appendix F):
    - Satellite data can help identify the presence of ARs over the open ocean upstream of the topography.
    - Aircraft data are required to measure the three-dimensional AR structures (including the trailing polar cold front) and associated moisture fluxes in this offshore domain.
    - A suite of surface based remote and in-situ sensors tied to NOAA's HMT-West effort (e.g., wind profilers, vertically-pointing S-band precipitation radars, scanning gap-filler radars, GPS receivers, disdrometers, rain gauges, etc.), including a number of AR observatories will represent a key part of the ground-based complement of instruments for monitoring ARs once they make landfall.
    - The field study can be complemented with analysis of available historical data and model fields. Long duration surface observations of precipitation and streamflow coupled with satellite observations and surface-based remote sensors (primarily via integrated water vapor and vapor-flux products) will enable further evaluation of the contribution of ARs to the water budgets of the Sierra Nevada and Coastal Range watersheds.
- Major hypotheses addressed: 1, 2, 3 and 4
- Team:
    - David Kingsmill (CIRES/Univ. of Colorado)
    - Allen White (NOAA/ESRL/PSD)
    - Gary Wick (NOAA/ESRL/PSD)
    - …
- Leading organization: NOAA/ESRL/Physical Sciences Division/Water Cycle Branch
- Strategies and tasks:
    - Observe 3-D winds using scanning radars at Sheridan and Sonoma Mountain.

  - Observe bulk water vapor transport in the Central Valley by implementing Atmospheric River Observatory (ARO) software for an existing wind profiler at Chico, CA and deploying a profiler/GPS-met system with ARO software near the Carquinez Strait to measure water vapor flux into the Central Valley.
  - Observe vertical thermodynamic structure using balloon sounding.
  - Observe integrated water vapor time series at Point Arena and Redding/Shasta.
  - Observe precipitation, including snowfall, along southern Sierra mountain transect, along with stream stage height throughout the AR observing period and also retrospectively during previous AR cases.
- Deliverables:
  - Observations data:  Skywater radar data, Carquinez Strait profiler, balloon soundings from Sheridan, GPS-met data from Pt arena and Redding (or Shasta) for collaborative use by the full CalWater science team
  - Formal publication
- Schedule

- Resources

4.2.3.2 AR Structure

- Objective: Observe and interpret the structure and transformation of AR conditions at the coast to those affecting the Sierra Nevada.
- Background: The existing record of AR observations is insufficient to evaluate the potential impact of climate change on AR activity. NWP reanalyses represent a potential tool but their suitability for representing ARs requires further evaluations. Activities related to validating characteristics of ARs such as their frequency and width within existing NWP models are underway within NOAA and can be leveraged for this work. Diagnostic studies exploring the behavior of different ensemble predictions with varying aerosol parameters could be an effective tool in addressing past aerosol impacts. Specific evaluation of the representation of precipitation-related physical processes in the IPCC models is needed to determine their ability to capture climatological variability. Modeling studies can further help evaluate the largely unknown role of ARs in long-range aerosol transport as well as pollutant deposition in the Sierra Nevadas. Enhanced modeling is also required to assess the contribution of entrainment of tropical water vapor to the total water vapor budget of AR events.
- Major hypotheses addressed: 1, 2, 3 and 4
- Team:
    - Paul Neiman (NOAA/ESRL/PSD)
    - David Kingsmill (Univ. of Colorado)
    - Mimi Hughes (NRC Post doc)
    - Sandra Yuter (North Carolina State Univ.)
    - Gary Wick (NOAA/ESRL/PSD)
    - Marty Ralph (NOAA/ESRL/PSD)
    - Dan Cayan, Mike Dettinger (Scripps/USGS)
- Leading organization: NOAA/ESRL/Physical Sciences Division/Water Cycle Branch
- Strategies and tasks:
    - Synthesize scanning radar, wind profiler, water vapor, balloon soundings, satellite, ACARS and rainfall data in all AR events during the field study
    - Collaborate with modeling team to use the observations to evaluate IPCC models, hi-res models and downscaled reanalyses.
    - Diagnose the frequency of occurrence and composite characteristics of the Sierra Barrier jet using the Chico wind profiler data, including last 7 years.
    - Investigate contribution to CA precipitation by NBB rain, and associated circulations and connection to ARs and non-AR's, as well as the coherence of NBB rain events between the coast and the Sierras.
    - Document the spatio-temporal distribution of precipitation along and adjacent to the northern California Sierra Nevada during atmospheric river events using both radar and precipitation gauge observations over a ~10 year period to assess their climatological distributions.
    - Characterize the spatio-temporal kinematic structure of the Sierra Nevada barrier jet using data from a combination of three scanning Doppler radars (SkyWater, KDAX, KBBX) and a network of wind profilers to derive 3-D

  - winds over the Sierra Nevada windward slope and adjacent Central Valley.
  - Identify landfalling atmospheric rivers using satellite, profiler, balloon sounding and GPS IWV observations and document how they modulate barrier jet kinematic structure and the distribution of precipitation.
  - Validate numerical model and regional reanalysis precipitation and wind fields using the aforementioned observations.
- Deliverables:
  - Observations data: Contribute to a joint formal publication (with the CalWater aerosol-precip team) on the overall CalWater experimental design and field study
  - Better physical understanding of how the coast range and Sierras affect ARs and resultant precipitation form and amount
  - Recommendations regarding modeling strategies, resolutions to capture ARs
  - Formal publication
- Schedule

- Resources

4.2.3.3 Uncertainty in Reanalysis and IPCC Models

- Objective: Document, using ground based and satellite data, the uncertainty in Reanalysis and IPCC climate change model representation of ARs offshore and as they make land-fall, including impacts on precipitation.
- Background: …
- Major hypotheses addressed: 1, 2, 3 and 5
- Team: :
  - Mike Dettinger (Scripps/USGS)
  - Dan Cayan (Scripps/USGS)
  - George Kiladis (NOAA/ESRL/PSD)
  - Masao Kanamitsu (Scripps)
  - Kei Yoshimura (Scripps)
- Leading organization: Scripps/USGS
- Strategies and tasks:
  - Apply recently developed methods to identify ARs in Reanalysis (global and regional RSM CaRD10 10km reanalysis from Kanamitsu and Yoshimura) for regional and IPCC runs and compare with statistical behaviors seen in reanalysis data and Neiman et al. 2008 AR climatology and Ralph et al. 2004 AR composite satellite and airborne observations.
  - Assess Reanalysis and downscaled model structure from cases studies of AR's selected from satellite, radar and profiler observation era, using the regional and local observations to evaluate model performance.
  - Using RSM, develop short term forecasts and diagnostics of AR events that occur during 2009-2010 field observation period, and together with the Leung, Hughes, Dettinger, compare results with WRF results.
  - Examine snow and rain amounts, proportionate snow/rain amounts, and Tuolumne and Merced River watershed stream stage during AR events identified from satellite and radar observations.
  - Apply methods to emerging next generation IPCC simulations
  - Develop diagnostics that measure the impacts of coast range & Sierras on ARs .
  - Assess NBB rain at Yosemite using a disdrometer.
- Deliverables:
  - Quantification of the role of uncertainty in IPCC representation of ARs in uncertainty in overall California precipitation projections (annual total and extreme events), and description of AR structure in Reanalysis in comparison to nature.
  - Purchase and deployment of a disdrometer to supplement Yosemite field site
  - Formal publication
- Schedule
- Resources

#### 4.2.3.4 Downscaling Approaches for ARs

- Objective: Explore high-resolution models and downscaled reanalyses to determine what modeling approaches, resolutions and physics are needed to represent water vapor and aerosol transports in ARs as they traverse the coastal mountains and Sierra Nevada Mountains.
- Background: A dynamical downscaling technique has been demonstrated (Kanamaru and Kanamitsu 2006) based on the concept that small scale detail can be attained by laterally forcing the high resolution regional model with large scale analysis. The essential difference between the dynamical downscaling method and data assimilation, which is used in NARR and in all the global reanalyses, is that the former does not utilize station observations to correct model forecast error. In this context, the dynamical downscaling can be referred to as "regional data assimilation without observation" (von Storch et al, 2000). Using the results from extensive validation of the downscaled analysis with dense surface observations, it has been demonstrated that the downscaling with higher resolution regional model outperforms lower resolution regional data assimilation analysis.
- Major hypotheses addressed: 4
- Team:
  - Ruby Leung (PNNL)
  - Yun Qian (PNNL)
  - Mimi Hughes (NRC postdoc)
  - Mike Dettinger (Scripps/USGS)
- Leading organization: DOE/PNNL
- Strategies and tasks:
  - Perform WRF continuous simulations initialized on October 1, 2009 through the end of the CalWater period at different model resolutions and using different physics parameterizations.
  - Evaluate WRF simulations using CalWater data.
  - Diagnose model skill for AR vs non-AR days, and ARs days with and without barrier effects to derive optimal model configurations for downscaling in California.
  - Diagnose the influence of atmospheric vs land surface conditions on precipitation and flooding in California based on the WRF simulations and observations of AR cases.
- Deliverables:
  - Assessment of WRF performance against observations in ARs observed during CalWater
  - Quantify the role of atmospheric vs land surface conditions on precipitation and flooding in California
  - Formal publication
- Schedule

- Resources

4.2.3.5 AR Precipitation Subprocesses

- Objective: Use reanalysis data and satellite and rain gauge observations to assess the role of shallow rainfall, non-brightband rain and "cut-off lows" in AR and non-AR precipitation events.
- Major hypotheses addressed: 2, 3 and 5
- PIs:
    - Kelly Redmond (WRCC)
    - Dan Cayan (Scripps/USGS)
    - Marty Ralph (NOAA/ESRL)
- Leading organization: WRCC
- Strategies and tasks:
    - Quantify contributions of cut-off lows to CA precipitation, including connection to ARs and tropical taps using reanalysis data.
    - Spatial, temporal, and rain/snow characteristics of precipitation
    - Develop method to assess frequency and nature of cut-off lows in IPCC runs.
    - Investigate contribution to CA precipitation by NBB rain, and associated circulations and connection to ARs and non-AR's, as well as the coherence of NBB rain events between the coast and the Sierras.
- Deliverables
    - Catalogue of cutoff lows during last 5-6 decades of Reanalysis, association of cutoff lows to ARs from better resolved satellite era and lesser-resolved Reanalysis era, and contribution of cut-off lows to precipitation (rain and snow).
    - Description of representation of NBB rain in global or regional model simulations.
    - Formal publication.
- Schedule
- Resources

4.2.3.6 Tropical-Extratropical Interactions

- Objective: Diagnose the role of tropical-extratropical interactions and the Madden-Julian Oscillation in modulating ARs and extreme precipitation.
- Background: The poleward extrusion of water vapor from the tropics during the cool season is often initiated by the penetration of extratropical disturbances into the tropics (e.g., Kiladis 1998; Knippertz 2007). However, the details by which these extrusions take place and contribute to the formation and intensification of ARs are not well known. Previous results (Matthews and Kiladis 1999a; Matthews and Kiladis 1999b) demonstrate strong evidence of modulation of Rossby waves by both the MJO and El Niño-Southern Oscillation (ENSO), and Jones (2000) and Weickmann and Berry (2007) observed an impact of the MJO on extreme events along the west coast. Understanding these interactions will contribute to understanding of the potential limits of predictability of AR events and resulting precipitation. Studying such potential correlations will also be important to serve as prerequisite or preliminary tests for identifying other impacts on ARs related to climate change.
- Major hypotheses addressed: 5
- PIs:
  - Kelly Redmond (WRCC)
  - Dan Cayan (Scripps/USGS)
  - Marty Ralph (NOAA/ESRL)
- Leading organization: WRCC
- Strategies and tasks:
  - Quantify contributions of cut-off lows to CA precipitation, including connection to ARs and tropical taps using reanalysis data.
  - Spatial, temporal, and rain/snow characteristics of precipitation
  - Develop method to assess frequency and nature of cut-off lows in IPCC runs.
  - Investigate contribution to CA precipitation by NBB rain, and associated circulations and connection to ARs and non-AR's, as well as the coherence of NBB rain events between the coast and the Sierras.
- Deliverables
  - Catalogue of cutoff lows during last 5-6 decades of Reanalysis, association of cutoff lows to ARs from better resolved satellite era and lesser-resolved Reanalysis era, and contribution of cut-off lows to precipitation (rain and snow).
  - Description of representation of NBB rain in global or regional model simulations.
  - Formal publication.
- Schedule

- Resources

## 4.3 Aerosols Impact on Precipitation

### 4.3.1 Background Science

Aerosols have profound impacts on the precipitation forming processes in clouds, and as a result on the cloud dynamics, cloud cover and precipitation amounts (Rosenfeld et al., Science, 2008). This has implications to the climate system at all scales and to the water resources. The implications for water resources in California are of particular importance, due to the magnitude of this effect and the scarcity of water in that part of the world. The role of anthropogenic aerosols in these impacts is becoming increasingly clear. Improving the understanding of these aerosol effects will allow us to:

- Develop methods to mitigate their negative impacts on water resources and hydroelectric power generation
- Improve quantitative precipitation prediction
- Improve the accuracy of numerical weather forecasting
- Improve the prediction of future climate scenarios

The potential impact of aerosols on AR precipitation is likely to be dependent on the storm conditions and synoptic environment. Even within AR river events, different modes of precipitation such as associated with bright-band and non-bright-band rainfall [e.g. White et al. 2003; Neiman et al. 2005; Kingsmill et al. 2006; see also the companion CalWater discussion paper titled "Naturally occurring shallow (non-bright-band) rain processes versus anthropogenic aerosol impacts on precipitation raindrop size distributions and intensities"] are potentially influenced differently by aerosols. It is speculated that while aerosols might not have a significant impact on events with deep vertical structure, they may have a greater effect on shallow events or the shallow portions of events with both components. This hypothesis, however, is unproven and needs significant investigation. Isolating a small impact of aerosols within measurement uncertainties could prove to be extremely challenging. The ability to explore this within models and ensemble runs could be very important to obtaining any answer.

There are also interactions between ARs and local air pollutants. Landfalling ARs in California are typically preceded by stably stratified high-pressure conditions, which allow for the trapping and build-up of locally generated cold air and pollutants in the Central Valley. As storm systems approach land, the trapped air containing these pollutants begin to extrude westward through the Petaluma Gap to the coastal zone via an isallobaric wind response (Neiman et al. 2006). It is believed that the stagnant, shallow Central Valley airmass erodes further through vertical mixing with the approach of LLJ conditions tied to approaching ARs. It is also during this period that precipitation usually intensifies (e.g., Ralph et al. 2006; Neiman et al. 2008b). Following the passage of the AR with its heavy precipitation and following the polar cold frontal passage, the atmospheric stability typically weakens considerably, as cold air aloft migrates over land while the Pacific-modified cold sector at low levels yields less cooling. Consequently, the Sierra Nevada often experiences lingering convective precipitation in this sector of the cyclone (after the passage of the AR). However, given the deep vertical mixing that often occurs then, locally generated pollutants would likely be quickly dispersed and much of the local pollution is likely to have been washed from the lower atmosphere by the preceding parts of the storm. Based on this sequence of events during the landfall of a Pacific storm, the AR may represent a key transition from strong trapping and concentration of pollutants in the Central Valley to a highly dispersive environment. The impacts of ARs on transport of locally generated aerosols are highly uncertain, as are their roles in deposition of locally generated black carbon (see also the pair of companion CalWater discussion papers on black carbon) and the opportunities for pollutants to most influence precipitation formation and rates.

On a more fundamental level, very little is known to date regarding the role of ARs in black carbon transport and aerosol entrainment. It is entirely unclear whether the AR represents a region of enhanced long range aerosol, dust, and black carbon transport across the Pacific due to the strong wind speeds and the concentration of these traceables through frontal convergence, or if the AR rains out these pollutants over the open ocean. The most hydrologically influential ARs transport air from the southwest or west, and thus may not be well placed to be the largest conduits for transport from Asian sources. Other ARs however follow more circuitous paths and may bear on these long-range transports. If ARs do carry significant contributions of black carbon, it is unclear whether the ARs act to focus or dilute the distribution of the deposition of the black carbon. The potential influence of ARs on the rainfall type (i.e., rainfall with or without a radar brightband) and the subsequent impact of the carbon once on the surface is also largely unknown.

### 4.3.2 Hypotheses

Several hypotheses will be addressed by the CalWater aerosols topic.

1. Aerosols will have little impact on AR events with deep vertical structure but potentially greater impact on shallow events or shallow portions of mixed events.
2. Anthropogenic aerosols suppress orographic precipitation by slowing the autoconversion rate, and hence decrease the amount of precipitation from the shallow and short living orographic clouds.
3. Uncertainty regarding the magnitude of potential anthropogenic impacts of aerosols on precipitation in California results from a lack of understanding of the fundamental physics of precipitation generation in ARs.
4. Advancements of numerical model representations of precipitation founded on observations are needed to properly represent key precipitation mechanisms associated with aerosols and black carbon.
5. Collaboration between CalWater meteorologists and aerosol experts are required to ensure that interpretations of aerosol impacts on precipitation do not overlook alternative hypotheses that equally explain the observed behavior without invoking aerosol impacts.

### 4.3.3 Experimental Design - Approach and Activities

For the aerosols theme there are three activities anticipated including: 1) Field Study, 2) Aerosol Precipitation Mechanisms, 3) Numerical Modeling Integration and 4) Effect of Black Carbon on Mountain Snow Packs.

4.3.3.1 Field Study

- Objective: Conduct supplementary field studies in northern California that address specific aspects of aerosol precipitation processes. The field studies will be leveraged off the HMT-West field program.
- Background: Supplemental ground-based observations and airborne aerosol measurements above selected surface sites are needed to assess the relative influence on precipitation within ARs as well as the contribution of ARs to aerosol transport and any influence of geographic orientation of the ARs. These observations could also help assess any focusing of black carbon deposition. Ultimately, to address these issues related to aerosols and black carbon, a long-term dataset must be gathered. This experiment would represent a starting point for gathering such a dataset.
- Major hypotheses addressed: 1
- Team:
  - Christopher R. Williams (CIRES/Univ. of Colorado)
  - Allen White (NOAA/ESRL/PSD)
  - V. Ramanathan and K Prather (SIO/UCSD)
  - S. Menon (Lawrence Berkeley National Laboratory)
  - L.R. Leung (PNNL)
- Leading organization: NOAA/ESRL/Physical Sciences Division/Water Cycle Branch
- Strategies and tasks:
  - Deploy CalWater met sites at Sugar Pine in the central Sierra and at Yosemite in southern Sierra. Equipment at each site includes S-Prof radar, disdrometer, surface met data and wind profiler. It is important to measure with time at fixed ground stations the following parameters: a) condensation nuclei (CN), b) cloud condensation nuclei (CCN), c) trace gases, d) black carbon, e) aerosol particle size distribution (optical, electronic), f) cloud drop size distribution, g) rain drop size distribution, h) snow density, i) wind speed and direction, j) temperature, k) dew point, l) ice nuclei, if possible.
  - Derived information from observations (precipitation type, NBB rain, BB rain, snow level, precipitating cloud depth, drop-size distributions, rain rate and orographic rainfall ratio all with at least 30 min time resolution, plus wind profiler-derived airflow trajectories from Central Valley profiler sites and designations of time periods with and without barrier jet conditions).
  - Single particle analyses of BC mixing state for various regions of California both from surface based measurements and from aircraft campaigns during CALMEX.
  - Vertical profiles of black carbon and Ozone on aircraft or balloons used in CALNEX campaigns; Profiles over central and N California, especially when Asian plumes arrive to evaluate the role of long range transport.
  - Vertical profiles of black carbon heating rates are critical since this determines the trigger for convection due to changes in the CAPE.

  - Aircraft measurements, similar to those made in SUPRECIP-2, will be done during the winter field campaign. Stacked aircraft measurements are critical. Aerosol aircraft would measure: a) CN, b) CCN, c) nephelometer for black carbon, d) trace gases, e) temperature and dew point, f) navigation and aviation. cloud physics aircraft would measure: a) cloud drop size distribution, b) hydrometeors imaging and size distribution, c) cloud liquid water content, d) CN, e) temperature and dew point, f) navigation and aviation.
  - Air-sea exchange of water vapor and aerosol fluxes.
  - Create a regional data set for 3-dimensional BC (and aerosol) distribution, their radiative properties and the forcing and atmospheric heating rates.
- Deliverables:
  - Observations data: Radar, distrometer surface met and wind profiler data for collaborative use by the full CalWater science team.
  - Formal publication
- Schedule
- Resources

4.3.3.2 Aerosol Precipitation Mechanisms

- Objective: Conduct field data assimilation and laboratory analyses of sampled air to determine the characteristics of aerosols pertinent to precipitation mechanisms.
- Major hypotheses addressed: 2
- Team:
  - Daniel Rosenfeld (Institute of Earth Sciences, Hebrew University of Jerusalem)
  - ~~V. Ramanathan and K Prather (SIO/UCSD)~~
  - ~~S. Menon (Lawrence Berkeley National Laboratory)~~
  - ~~L.R. Leung (PNNL)~~
- ~~Leading organization: NOAA/ESRL/Physical Sciences Division/Water Cycle Branch~~
- ~~Strategies and tasks:~~
  - ~~Deploy CalWater met sites at Sugar Pine in the central Sierra and at Yosemite in southern Sierra. Equipment at each site includes S-Prof radar, disdrometer, surface met data and wind profiler.~~
  - ~~Derived information from observations (precipitation type, NBB rain, BB rain, snow level, precipitating cloud depth, drop-size distributions, rain rate and orographic rainfall ratio all with at least 30 min time resolution, plus wind profiler-derived airflow trajectories from Central Valley profiler sites and designations of time periods with and without barrier jet conditions).~~
  - ~~Single particle analyses of BC mixing state for various regions of California both from surface based measurements and from aircraft campaigns during CALMEX.~~
  - ~~Vertical profiles of black carbon and Ozone on aircraft or balloons used in CALNEX campaigns; Profiles over central and N California, especially when Asian plumes arrive to evaluate the role of long range transport.~~
  - ~~Vertical profiles of black carbon heating rates are critical since this determines the trigger for convection due to changes in the CAPE. Stacked aircraft measurements are critical.~~
  - ~~Air-sea exchange of water vapor and aerosol fluxes.~~
- ~~Deliverables:~~

  ~~OBS: Radar, distrometer surface met and wind profiler data for collaborative use by the full CalWater science team.~~

  ~~DIAGNOSTICS: a formal publication~~

- ~~Schedule~~
- ~~Resources~~

4.3.3.3 Numerical Modeling Integration

- Objective: Integrate identified precipitation mechanisms into numerical models.
- Background: Jacobson (2008) noted that in order to address these issues with a numerical model, it is necessary for the model to treat aerosol and precipitation particles with size and composition resolution and the feedbacks of aerosol particles to meteorology, clouds, and precipitation. The model must treat clouds explicitly and the incorporation of aerosol particles within cloud drops. This is particularly important for simulating the effects of black carbon inclusions on clouds and precipitation and the effects of precipitation changes on aerosol removal. Further, the model should treat ice nucleation from a physical point of view, particularly accounting for delayed activation until the relative humidity over ice reaches a supersaturation threshold. Since the model must be run for a long time, it is also necessary for the model to incorporate large-scale meteorological effects at and local effects at high resolution. Simulations needed include multiseasonal baseline and sensitivity simulations covering the State of California and at least Nevada. The simulations would treat and exclude, respectively, emissions of aerosol particles (or soot aerosol particles in one case) from anthropogenic sources. Baseline simulations (with aerosol particles) should be compared with climatological and paired in- time-and-space data. Differences between the simulations should reveal answers to the questions raised concerning the effects of aerosol particles on precipitation and air pollution. See concept paper by Jacobson for details (Appendix F).
- Major hypotheses addressed: 3, 4
- Team:
    - Mark Z. Jacobson (Stanford University)
    - Daniel Rosenfeld (Institute of Earth Sciences, Hebrew University of Jerusalem)
- Leading organization: NOAA/ESRL/Physical Sciences Division/Water Cycle Branch
- Strategies and tasks:
    - Deploy CalWater met sites at Sugar Pine in the central Sierra and at Yosemite in southern Sierra. Equipment at each site includes S-Prof radar, disdrometer, surface met data and wind profiler.
    - Derived information from observations (precipitation type, NBB rain, BB rain, snow level, precipitating cloud depth, drop-size distributions, rain rate and orographic rainfall ratio all with at least 30 min time resolution, plus wind profiler-derived airflow trajectories from Central Valley profiler sites and designations of time periods with and without barrier jet conditions).
    - Single particle analyses of BC mixing state for various regions of California both from surface based measurements and from aircraft campaigns during CALMEX.
    - Vertical profiles of black carbon and Ozone on aircraft or balloons used in CALNEX campaigns; Profiles over central and N California, especially when Asian plumes arrive to evaluate the role of long range transport.

    - Vertical profiles of black carbon heating rates are critical since this determines the trigger for convection due to changes in the CAPE. Stacked aircraft measurements are critical.
    - Air-sea exchange of water vapor and aerosol fluxes.
- Deliverables:
    - Observations data: Radar, distrometer surface met and wind profiler data for collaborative use by the full CalWater science team.
    - Formal publication
- Schedule
    - Data gathering for model simulations, repeated simulations themselves, and the post-simulation analysis require 2-3 years. Data gathering should require a few months, simulations for multiple periods requires 1-2 years, and analysis/writing requiring the remaining time.
- Resources

4.3.3.4 Effect of Black Carbon on Mountain Snow Packs in California

- Objective: Conduct field data assimilation and modeling activities to determine the impact that black carbon particles have on mountain snow packs.
- Background: The current assessment of BC effect on snow surface albedo and subsequent melt rates are based on model parameterizations and hypothesis. For example, snow crystal size and BC mixing state in the snow must be assumed in order to estimate the albedo change due to BC concentration in snow. Furthermore, the estimated albedo change, if snow crystal size and mixing state were known, is still inferred from model results. Direct measurements linking albedo and BC concentration are rare and associated with high uncertainties. Both measurements of snow crystal size and albedo, along with BC concentration are needed to verify the connection. Also the sensitivity of melt rate to albedo changes has not been observationally quantified. Sensitivity studies of snow melt to albedo reduction should be conducted. Once the connection between albedo and melt rate is established, hypothesized feedbacks should also be evaluated. Measurements of the vertical distribution of BC throughout the melt season would help to solve some of these questions. See concept paper by Hadley and Corrigan for details (Appendix F).
- Major hypotheses addressed: 4
- Team:
    - Odelle L. Hadley (Lawrence Berkeley National Laboratory)
    - C. Corrigan (Scripps Institute of Oceanography)
- Leading organization: Scripps Institute of Oceanography
- Strategies and tasks:
    - Collect and analyze snow samples for BC concentrations at the beginning, middle and end of snow and rain events. Develop an analysis method that only requires 5 ml of sample.
    - Compare BC concentration at the beginning of a precipitation event with that at the end; this will provide information on BC scavenged below the cloud.
    - Develop model parameterizations on wet removal of BC from the atmosphere.
- Deliverables:
    - Observations data: BC concentrations and particle type characterizations, in association with precipitation event data.
    - Formal publication
- Schedule:
- Resources:

## 5.0 CalWater Schedule

This section would have an overall schedule as a GANNT chart with identification of start-stop timing for specific tasks; field seasons, …

## 6.0Resources

This section would have a summary tabulation of resources (time and effort) as a matrix for all tasks.

## References


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## Appendix A: Acronyms

| | |
|---|---|
| AHPS | Advanced Hydrologic Prediction System |
| ALPS | Advanced Linux Prototype System |
| AMS | American Meteorological Society |
| API | Application Programming Interface |
| AR | Atmospheric River |
| ARB | American River Basin |
| AWIPS | Advanced Weather Interactive Processing System |
| ARO | Atmospheric River Observatory |
| BAMS | Bulletin of the American Meteorological Society |
| CARB | California Air Resources Board |
| CDEC | California Data Exchange Center |
| CEC | California Energy Commission |
| CFS | Climate Forecast System |
| CHPS | Community Hydrologic Prediction System |
| CIRES | Cooperative Inst. for Research in Environmental Sciences |
| CSC | Coastal Services Center |
| CU | University of Colorado at Boulder |
| CUAHSI | Consortium of Universities for the Advancement of Hydrologic Science, Inc. |
| DA | Data Assimilation |
| DMIP | Distributed Model Intercomparison Project |
| DOH | Development and Operations Hydrologist (RFC position) |
| DTC | Developmental Testbed Center |
| DWR | California Department of Water Resources |
| EFREP | Enhanced Flood Response and Emergency Preparedness |
| EnsPost | Ensemble Post-Processor |
| EPG | Ensemble Product Generation System |
| EPP | Ensemble Pre-Processor |
| EPP3 | Next Generation EPP that combines best features of EPP2 and GFS Subsystems |
| ESP | Ensemble Streamflow Prediction |
| ESP2 | Next Generation ESP Technique |
| ESPADP | ESP Analysis and Display Program |
| ESRL | Earth System Research Laboratory |
| EVS | Ensemble Verification System |
| FCST | Forecast executable (component of NWSRFS) |
| FEMA | Federal Emergency Management Agency |
| FEWS | Flood Early Warning System (Delft; The Netherlands) |
| FFMP | Flash Flood Monitoring and Prediction |
| FM-CW | Frequency modulated-continuous wave (radar) |
| FOC | Flood Operations Center (Sacramento); also Field Operations Coordinator |
| GFE | Gridded Forecast Editor |

| | |
|---|---|
| GFS | Global Forecast System |
| GIS | Geographic Information System |
| GOES-R | Geostationary Operational Environmental Satellite R-Series |
| GSD | Global Systems Division (NOAA/ESRL) |
| GUI | Graphical User Interface |
| GWO | Global Wind Oscillation |
| HEC-HMS | Hydrologic Engineering Center Hydrologic Modeling System (USACE) |
| HEC-RAS | Hydrologic Engineering Center River Analysis System (USACE) |
| HEC-ResSim | Hydrologic Engineering Center Reservoir Simulation System (USACE) |
| HL-RDHM | Hydrology Laboratory Research Distributed Hydrologic Model (NWS) |
| HMOS | Hydrologic Model Output Statistics Ensemble Processor |
| HMT | Hydrometeorology Testbed |
| HPC | Hydrometeorological Prediction Center (NCEP) |
| HRAP | Hydrologic Rainfall Analysis Project |
| HSD | Hydrologic Services Division |
| HSEB | Hydrologic Software Engineering Branch |
| HSMB | Hydrologic Science and Modeling Branch |
| IFP | Interactive Forecast Program (component of NWSRFS) |
| IOOS | Integrated Ocean Observing System |
| IOP | Intense Operations Period |
| IT | Information Technology |
| IWF | Integrated Water Forecasting |
| IWRM | Integrated Water Resource Management |
| IWRS-PATT | Integrated Water Resource Services-Priority Area Task Team |
| IWRSS | Integrated Water Resource Science and Services |
| IWV | Integrated Water Vapor |
| LAPS | Local Analysis and Prediction System |
| LIDAR | Light Detection and Ranging |
| LIS | Land Information System (NASA) |
| MAP | Mean Areal Precipitation |
| MAT | Mean Areal (air) Temperature |
| MADIS | Meteorological Assimilation Data Ingest System |
| MDL | Meteorological Development Lab |
| MET | Meteorological Evaluation Tool |
| MJO | Madden-Julian Oscillation |
| MODIS | Moderate Resolution Imaging Spectrometer (NASA) |
| MOS | Model Output Statistics |
| NAM | North American Mesoscale Model |
| NAP | National Advisory Panel |
| NARR | North American Regional Reanalysis (NWS) |
| NASA | National Aeronautics and Space Administration |

| | |
|---|---|
| NCAR | National Center for Atmospheric Research |
| NCEP | NOAA NWS National Center for Environmental Prediction |
| NDFD | National Digital Forecast Database (NWS) |
| NED | National Elevation Dataset |
| NESDIS | National Environmental Satellite, Data, and Information Service |
| NFARB | North Fork of the American River Basin |
| NHD | National Hydrography Dataset (USGS) |
| NMQ | National Mosaic and QPE (NMQ) |
| NOAA | National Oceanic and Atmospheric Administration |
| Noah | Community Noah Land Surface Model (NOAA) |
| NOHRSC | National Operational Hydrologic Remote Sensing Center |
| NOS | National Ocean Service |
| NPVU | National Precipitation Verification Unit |
| NRC | National Research Council |
| NSA | National Snow Analyses |
| NSSL | National Severe Storms Laboratory |
| NWS | National Weather Service |
| NWSRFS | National Weather Service River Forecast System |
| OAR | Oceanic and Atmospheric Research |
| OCWWS | Office of Climate, Weather and Water Services |
| OFS | Operational Forecasting System (component of NWSRFS) |
| OHD | Office of Hydrologic Development |
| OMB | Office of Management and Budget |
| OST | Office of Science and Technology |
| O-to-R (O2R) | Operations to Research |
| PE | Potential Evaporation |
| PET | Potential Evapotranspiration |
| PoP | Probability of Precipitation |
| PPBES | Planning, Programming, Budgeting, and Execution System |
| PNNL | Pacific Northwest National Laboratory |
| PQPF | Probabilistic Quantitative Precipitation Forecast |
| PRISM | Parameter-elevation Regressions on Independent Slopes Model |
| PSD | NOAA/ESRL Physical Systems Division |
| PW | Precipitable Water |
| Q2 | Next-generation QPE |
| QPE | Quantitative Precipitation Estimate |
| QPF | Quantitative Precipitation Forecast |
| R&D | Research and Development |
| RFC | River Forecast Center |
| R-to-O (R2O) | Research to Operations |
| RUC | Rapid Update Cycle model (NOAA) |
| RWRS | Regional Water Resources Services |
| SAC-SMA | Sacramento Soil Moisture Accounting Model |
| SECART | Southeast and Caribbean Regional Team |

| | |
|---|---|
| SIO | Scripps Institution of Oceanography |
| SL | Snow Level |
| SMART-R | Shared Mobile Atmospheric Research and Teaching Radar |
| SOA | Service Oriented Architecture |
| S-PROF | Vertically pointing S-band precipitation profiler |
| SR | SMART Radar |
| SREF | Short-Range Ensemble Forecast |
| STI (ST&I) | Science Technology and Infusion |
| STIP | Science and Technology Infusion Plan (NWS, 2002) |
| SWE | Snow Water Equivalent |
| TOR | Terms of reference |
| USACE | U.S. Army Corps of Engineers |
| USDA | U.S. Department of Agriculture |
| USFS | U.S. Forest Service |
| USGS | U.S. Geological Survey |
| USWRP | United States Weather Research Program |
| VPR | Vertical Profile of Reflectivity |
| WFO | Weather Forecast Office |
| WRCC | Western Regional Climate Center (NOAA) |
| WRF | Weather Research and Forecasting modeling system |
| WRMS | Water Resources Management Services |
| WRSS | Water Resources Science Services |
| XEFS | Experimental Ensemble Forecast System (NWS) |
| XEFS | Experimental Ensemble Forecast System |
| XML | Extensible Markup Language |

## Appendix B: CalWater Bibliography

## Appendix C: Observing Systems Descriptions

Aircraft

Airborne platforms for meteorological research in NOAA have been in use since the late 1970s. They provide access to the lower and middle troposphere with large payload, large fuselage volume, long duration, and long range. Aircraft instrumentation includes fight-level data sensors, airborne radars with Doppler wind finding, cloud physics instrumentation (including electric field measurements), remote sensors for surface wind and rainfall estimation, expendables (e.g.; dropsondes, AXBTs, AXCPs, and drifting buoys), and an aircraft-satellite data link (ASDL) to transmit data back to the ground. Some equipment, such as that for remote sensing of sea-surface conditions or for atmospheric electricity measurements, is unique to one airframe or the other. In addition to the hurricane research mission, for which they were originally procured, these aircraft support diverse programs throughout NOAA, outside the agency, and internationally. Unmanned aircraft systems (UAS) are operated by remote pilots and ranging in wingspan from less than six feet to more than 115 feet. UAS can also collect data from dangerous or remote areas and bridge an observational gap between ground and satellite observations. Additional information can be found at: http://uas.noaa.gov/.

Aerosol Time of Flight Mass Spectrometer (ATOFMS)

ATOFMS instruments perform real-time measurements of ambient particles and have been used in a wide variety of environments, including on aircrafts (ICE-L) and research vessel platforms during international field campaigns (INDOEX, ACE-Asia, CalCOFI). Measurements of particle composition and size made by ATOFMS provide valuable insights into aerosol transformation processes in both field studies and laboratory studies. Improvements to existing instruments and development of new instrumentation and data analysis methods are ongoing. Procedures for quantification of data and scaling detected ATOFMS particle types to atmospheric concentrations have been published. Comparison of source emission measurements to ambient data has permitted source apportionment of particle loadings. ATOFMS data has also been used as inputs to atmospheric chemistry models. Recently ATOFMS has seen increased use for the detection of bioaerosols. The ATOFMS has also been applied in characterizations of particles and particle concentrators used in aerosol health effects studies. Additional information can be found at: http://atofms.ucsd.edu/ATOFMS.

Distrometer

A disdrometer is an instrument used to measure the drop size distribution and velocity of falling hydrometeors (http://en.wikipedia.org/wiki/Disdrometer). The Distromet LTD Model RD-80 disdrometer uses the momentum of falling raindrops to measure the size distribution of rain. The amplitude of the pulse generated as a drop hits the disdrometer's electromechanical transducer is roughly proportional to the drop's momentum and, ultimately, the drop's diameter. The size range of drops that can be measured spans from 0.3 mm to 5 mm. Drops larger than 5 mm are rare because they tend to be unstable and breakup into smaller drops. By comparing disdrometer measurements from coastal and inland mountain sites, we will learn more about the microphysical processes associated with orographic precipitation, one of the underlying goals of PACJET. The disdrometer measurements will also shed light on the microphysical information derived from the X-band polarimetric scanning radar and the S-band vertically pointing radars deployed for PACJET-2003. The integrated size distribution measured by the disdrometer is a direct measurement of the rainfall intensity, which will be compared to the rainfall intensities measured by a variety of other rain gauges and estimated by the radars. These comparisons will be used to diagnose the strengths and limitations of various in situ and remote sensing measurement techniques used to provide rainfall intensity.

Radiosonde

A radiosonde (Sonde is French for probe) is a unit for use in weather balloons that measures various atmospheric parameters and transmits them to a fixed receiver (http://en.wikipedia.org/wiki/Radiosonde). Radiosondes may operate at a radio frequency of 403 MHz or 1680 MHz and both types may be adjusted slightly higher or lower as required. A rawinsonde is a radiosonde that is designed to also measure wind speed and direction. Colloquially, rawinsondes are usually referred to as radiosondes. Modern radiosondes measure or calculate pressure, altitude, geographical position (Latitude/Longitude), temperature, relative humidity, wind speed and direction, and cosmic ray readings at high altitude

Satellite Information

Satellite remote sensing is used to gather information on sea surface temperature, air-sea interaction, winds, water vapor, clouds and radiation. The satellite group uses a suite of geostationary and polar orbiting satellite data from NOAA, DMSP, and NASA environmental satellites to gain a fundamental understanding of the atmosphere and air-sea interface. Enhanced sea surface temperature products are obtained through optimal blending of infrared and microwave satellite observations. Current satellite sensors are unable to directly retrieve the air temperature and specific humidity just above the ocean surface. Sounders retrieve information corresponding to broad layers while radiometers like SSM/I retrieve information on the total atmospheric column water content. Sounders retrieve information corresponding to broad layers while radiometers like SSM/I retrieve information on the total atmospheric column water content. Initial methods relied on data from SSM/I and empirical relationships between the total precipitable water and surface specific humidity. Improved methods for instantaneous retrievals have developed using a combination of data from SSM/I and AMSU-A. The improved accuracy results from inclusion of the sounder data which helps distinguish variations near the surface from those at higher levels of the atmosphere. A variety of real-time satellite imagery and archived images from a suite of geostationary and polar-orbiting satellites are available. Additional information can be found at: http://www.esrl.noaa.gov/psd/psd2/coastal/satres/.

SkyWater Scanning Radar

C-band represents a compromise between more heavily attenuated higher radar frequencies, such as X-band, and the larger size and weight requirements of lower frequency S-band weather radars, such those used for the land-based WSR-88D (NEXRAD) systems. In many respects, this radar is the equivalent of an oceangoing NEXRAD that can provide research-quality observations, in addition to routine storm surveillance. Rain statistics at sea derived from its data are well suited for evaluating assumptions used in satellite precipitation algorithms. Additional information can be found at: http://hmt.noaa.gov/pubs.html.

SPROF Radar with Profiler

Operational precipitation surveillance has long been the province of centimeter-wavelength radars in the United States. Recently, the National Oceanic and Atmospheric Administration (NOAA) Aeronomy Laboratory combined wind profiler technology with S-band (lambda = 10 cm) radar hardware to create a new precipitation profiler (Ecklund et al. 1999). The S-band vertical profiler is based on existing S-band and UHF profiler technology which has been modified for research. It's dynamic range has been extended to study moderate to heavy precipitation which would not be otherwise possible. The S-band has been calibrated through a side-by-side comparison with the Ka-band radar. In a typical cloud profiling mode of operation, the sensitivity is -14 dBZ at 10 km. Examples taken from a recent field campaign illustrate the profiler's ability to measure vertical velocity and radar reflectivity profiles in clouds and precipitation. Additional information can be found at:
http://www.esrl.noaa.gov/psd/data/obs/instruments/SbandDescription.html.

Surface Meteorology

Surface-meteorology instruments measure a variety of quantities near the earth's surface. The most standardized and commonly deployed instruments monitor meteorological state variables, such as mean pressure, temperature, moisture, wind, and radiation. For hydrological applications, instruments are also deployed to measure the amount, type, and size distribution of rain and snow, as well as the heat and water content of the soil. Also, the latest advancements in GPS technology have allowed for estimates of vertically-integrated atmospheric water vapor to be derived from a single surface-based reciever. Lastly, instruments that measure atmospheric turbulence are occasionally used to monitor the flux of heat, momentum, and moisture between the atmosphere and the earth's surface. Instruments include:

- Meteorology
  - Wind speed, gust, and direction
  - Pressure
  - Temperature
  - Relative Humidity
  - GPS Integrated Water Vapor
- Precipitation
  - Tipping Bucket Gauge
  - Precipitation Weighing Gauge
  - Impact Disdrometer
  - Optical Disdrometer
  - Hot Plate Total Precipitation
  - Snow Depth
- Radiation
  - Pyranometer
  - Net Radiometer
  - Solar Tracker

- Soil
  - Temperature
  - Water Content
- Turbulence
  - Sonic Anemometer
  - Gas Analyzer

Additional information can be found at:
http://www.esrl.noaa.gov/psd/data/obs/instruments/SurfaceMetDescription.html.

Wind Profilers
Wind profilers are Doppler radars that most often operate in the VHF (30-300 MHz) or UHF (300-1000 MHz) frequency bands. There are three primary types of radar wind profilers in operation in the U.S. today. The NOAA Profiler Network (NPN) profiler operates at a frequency of 404 MHz. The second type of profiler that is used by NOAA research and outside agencies is the 915-MHz boundary-layer profiler. The 404-MHz profilers are more expensive to build and operate, but they provide the deepest coverage of the atmosphere. The 915-MHz profilers are smaller and cheaper to build and operate, but they lack height coverage much above the boundary layer. A third type of profiler that operates at 449 MHz (the so-called 1/4-scale 449-MHz profilers) combines the best sampling attributes of the other two systems. Additonal information can be found at:
http://www.esrl.noaa.gov/psd/data/obs/instruments/WindProfilerDescription.html.

## Appendix D: Numerical Models Descriptions

## Appendix E: Synopsis of CalWater Major Activities for 2009

## Appendix F: White Papers

## Appendix G: Previous meeting reports