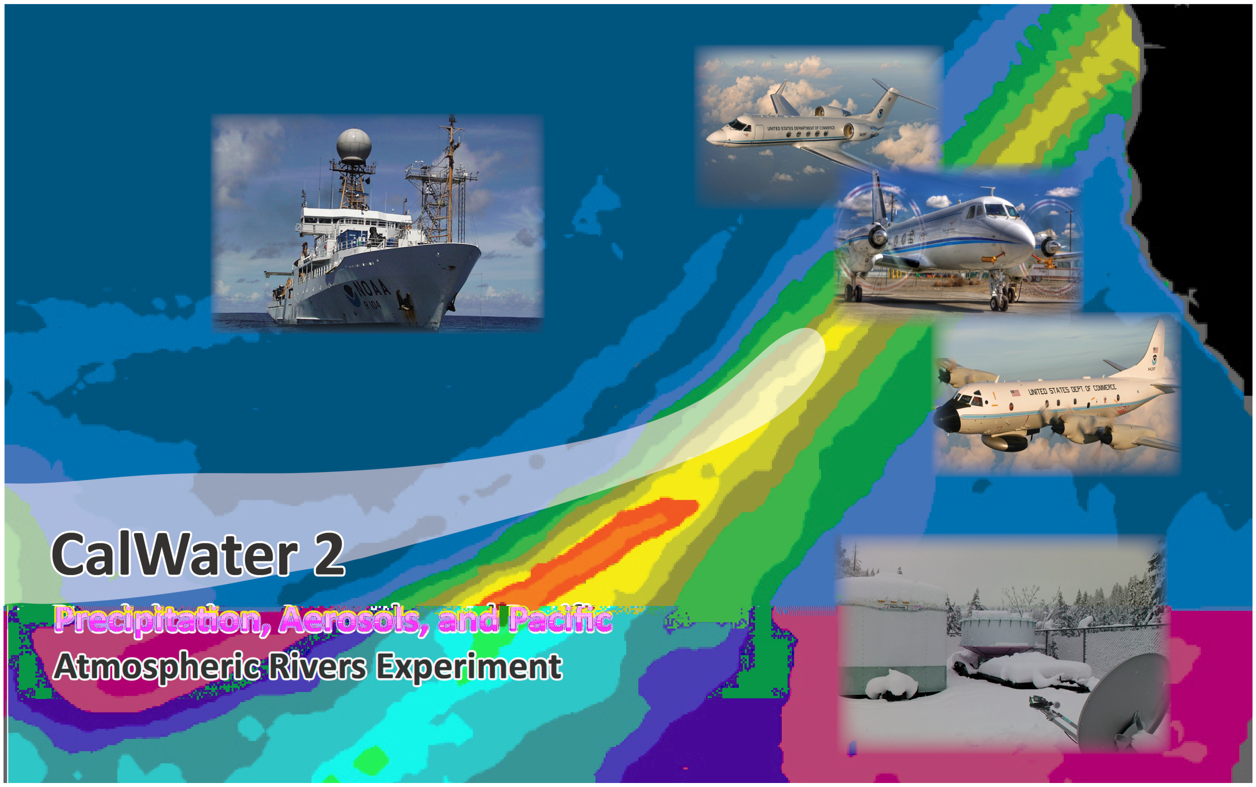


CalWater 2

Precipitation, Aerosols, and Pacific Atmospheric Rivers Experiment

A continuing effort to improve weather and climate prediction systems and
develop better decision support tools for water resources management.

National Oceanic & Atmospheric Administration
U. S. Department of Energy

California Energy Commission
Scripps Institution of Oceanography

Executive Summary

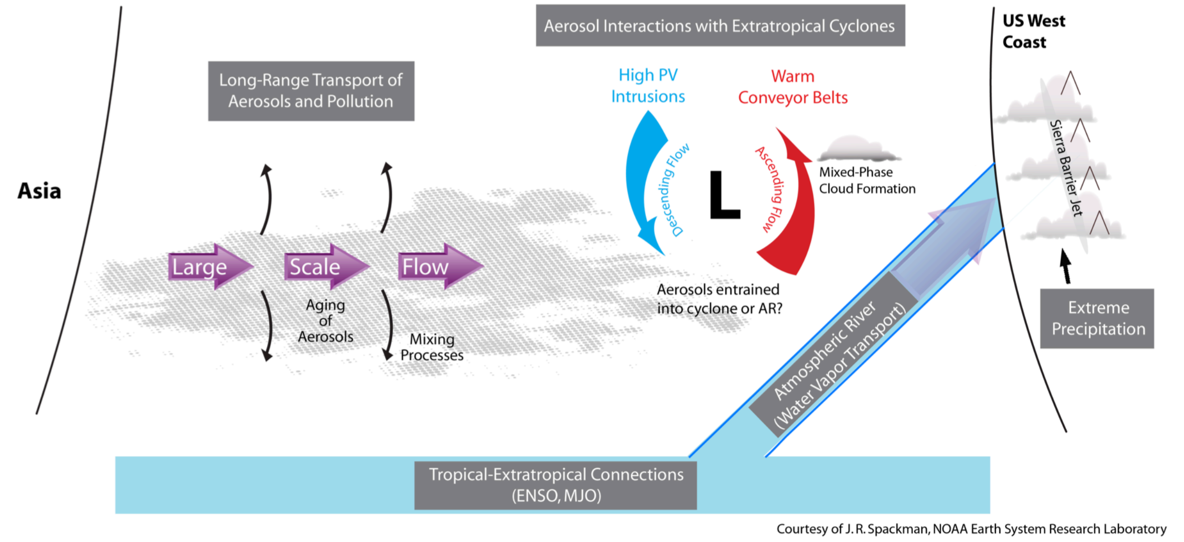
Emerging research has identified two phenomena that play key roles in the variability of the water supply and the incidence of extreme precipitation events along the West Coast of the United States. These phenomena include the role of:

- Atmospheric rivers (ARs) in delivering much of the precipitation associated with major storms along the U.S. West Coast, and
- Aerosols—from local sources as well as those transported from remote continents—and their modulating effects on western U.S. precipitation.

A better understanding of these two processes is needed to reduce uncertainties in weather predictions and climate projections of extreme precipitation and its effects, including the provision of beneficial water supply. In this white paper, we identify science gaps associated with (1) the evolution and structure of ARs including cloud and precipitation processes and air-sea interaction, and (2) aerosol interaction with ARs and the impact on precipitation, including locally-generated aerosol effects on orographic precipitation along the U.S. West Coast. A set of science investigations, called CalWater 2, have been proposed to fill these gaps including a targeted set of aircraft and ship-based measurements and associated evaluation of data over regions offshore of California and in the eastern Pacific for an intensive observing period between January 2015 and March 2015. Recently the DOE Atmospheric Radiation Measurement (ARM) program committed airborne and ship-borne facilities for this same period to a CalWater-related team of investigators in a study called ACAPEX (ARM Cloud Aerosol and Precipitation Experiment), a complementary study to CalWater 2. Observations are also proposed for subsequent winter seasons as part of a 5-year broad interagency vision to address these science gaps. Expected outcomes for CalWater 2 include:

- Improvements in prediction systems for the water cycle at weather and climate timescales,
- Distribution of an unprecedented meteorological, microphysical, and chemical dataset collected in AR environments both onshore and offshore for advancing understanding and prediction of aerosol effects on precipitation, and
- Development of decision support tools for extreme precipitation events, hazard response, and water supply for more effective water resources management.

This assessment has been prepared by an interdisciplinary team of meteorologists, hydrologists, climate scientists, atmospheric chemists, and oceanographers, reflecting the breadth of processes involved and the expertise needed to make new progress. The motivation described herein are largely based upon findings that have emerged in the last few years from airborne and ground-based studies, including CalWater, that have spawned important new questions and promising directions. The proposed observing strategy would build on these advances and employ airborne, ship-, and ground-based assets together with satellite observations to address the scientific objectives. The approach takes advantage of recent investments in new instrumentation, such as the new sophisticated instrumentation developed by UC San Diego to measure the chemical composition of nucleated aerosols, and also in observing systems, including NOAA's Hydrometeorology Testbed, the NASA Global Hawk, and relevant satellite and airborne remote sensing observing systems.



Courtesy of J. R. Spackman, NOAA Earth System Research Laboratory

Figure 1. Conceptual framework for CalWater 2 science goals. The proposed observational strategy includes airborne and ship-based assets over the central and eastern Pacific complemented by ground-based measurements along the U.S. West Coast.

1. Introduction

Variations in the intensity, distribution, and frequency of precipitation events on intraseasonal to interannual timescales lead to uncertainties in water supply and flood risks (*NAS-Climate*, 2010; *NAS-Hydrology*, 2012). The potential impact of climate change on precipitation characteristics poses a challenging new dimension for water resource planning. The management of water resources requires the informed attention of policy makers concerned with future infrastructure needs for disaster mitigation, hydropower generation, agricultural productivity, fisheries and endangered species, consumptive use, and a multitude of other needs. Errors in today's predictions of precipitation and stream flow, as well as in climate projections of extreme precipitation events and water supply, contribute greatly to these uncertainties in water information.

Extreme precipitation events induce major societal impacts and are often difficult to predict accurately. These events pose some of the greatest challenges in weather and climate research. Atmospheric rivers (ARs), a dynamic confluence of atmospheric moisture prevalent in the midlatitudes, can lead to extreme precipitation totals when they make landfall and can both produce hydrological hazards and supply valuable water resources (*Ralph and Dettinger*, 2012; *Leung and Qian*, 2009; *Zhu and Newell*, 1998; *Guan et al.*, 2010; *Dettinger et al.*, 2011). Some of the largest uncertainties in predicting these events propagate from our limited understanding of the water vapor transport in ARs, the flows and meteorology in complex terrain, microphysical processes in the formation of clouds and precipitation, and the impact of aerosols on precipitation efficiency. Improvements in our predictive capability of extreme weather and climate events depend on advances in observational resources, process understanding, and model fidelity. For ARs, high-priority challenges include advancing our knowledge of (1) the sources, transport, and orographic forcing of moisture-laden air masses in ARs, and (2) the interaction between aerosols of different size and composition with water vapor in clouds to promote or suppress precipitation. The impact of aerosols on the intensity, distribution, phase, and frequency of precipitation in a changing climate with increasing emissions from Asia poses major challenges for water resources management and food security. Uncertainties in climate model projections of the storm track and of ARs, as well as the modulating effects of tropical low-frequency variability, such as the Madden-Julian Oscillation (MJO) and ENSO, represent another key challenge (e.g., *Guan et al.*, 2012).

AR water-cycle research requires a cross-cutting approach that builds interaction across the fields of dynamics, chemistry, cloud microphysics, and hydrology. Atmospheric dynamics couples the water vapor content in the tropics and midlatitudes with aerosols through microphysical processes that, along with orography, influence precipitation. The large-scale flow influences where the aerosols and clouds encounter each other and the thermodynamics determines how the aerosol particles nucleate water vapor to form cloud droplets and ice crystals. In this context, many questions remain regarding the role of aerosols in the development of extratropical cyclones and associated ARs.

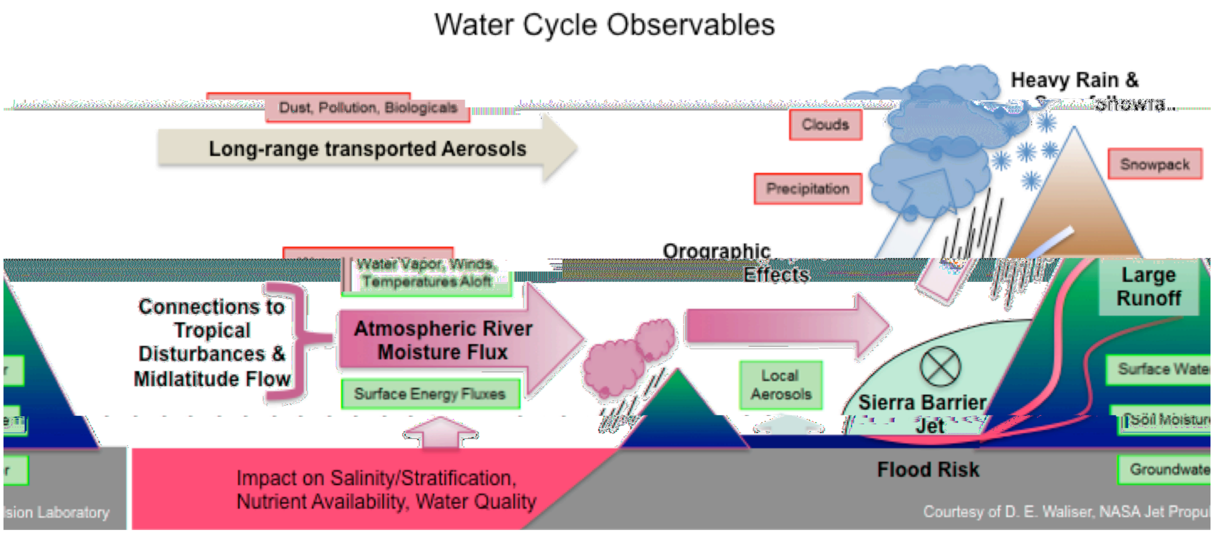


Figure 2. Illustration of the atmospheric and hydrological processes associated with atmospheric rivers (ARs) based on a northward view of an east-west cross section depicting a landfalling AR in a region akin to north/central California. On shore low-level moisture flux over the ocean is shown impinging first on the Coastal range and secondly on the Sierra Nevada mountains, with each orographic barrier producing copious precipitation. Long-range and local transport of aerosols are depicted over the ocean and onshore, respectively, and affect clouds and precipitation. Also shown are the low-level northward barrier jet on the western side of the Sierra Nevada mountains, a depiction of the enhanced river runoffs and flood risks in low lying areas, and the impacts on water quality and other physical characteristics in the coastal ocean. Shown in the pink boxes are those components of the water cycle that are observable with modern measurement technologies, including satellite and airborne remote sensing and in-situ instruments.

ARs are narrow regions of enhanced water vapor transport in the lower troposphere often characterized by strong winds. They are often associated with the warm sector of midlatitude cyclones, in some cases entraining water vapor from the tropics, and can lead to major rain or flooding events upon landfall in the midlatitudes (*Ralph et al.*, 2006, 2011; *Neiman et al.*, 2008a, 2008b, 2009, 2011; *Zhu and Newell*, 1998). Extreme snowfall in the Sierra Nevada and major benefits to California water supply have been linked to landfalling ARs over the past decade (*Dettinger et al.*, 2011; *Guan et al.*, 2010). Passive microwave satellites provide integrated water vapor observations of ARs but they do not provide the wind information necessary to quantify the integrated vapor transport. This gap in information leads to an uncertainty in how much water vapor is transported by ARs. Aerosols carried in the large-scale flow aloft have been shown to play an important role when ARs precipitate upon landfall in California (*Ault et al.*, 2011; *Creamean et al.*, 2013). However, these and other observations of aerosol-cloud-precipitation interactions are based on very limited observations. The size and type of aerosols and their interactions with different types of clouds ultimately determines whether nucleation processes enhance or inhibit precipitation. Research addressing aerosol-precipitation interactions is vital to economic interests in the western US since any one of the physical or chemical processes mentioned above can have a profound effect on precipitation distributions.

The ground is fertile for a large-scale, multi-platform, multi-model study that explicitly addresses the links between precipitation and aerosols. Landfalling ARs are now routinely studied by observational networks but their behavior over the oceans is much less well monitored and the quantitative contributions of evaporation, convergence/divergence, and rainout have not been adequately documented. Aerosol and microphysical measurement techniques have advanced and are capable of providing new information on the role of aerosols in precipitation. Improvements in numerical weather and global aerosol models require the offshore observations to better model and parameterize cloud and precipitation processes, including interactions with aerosols and their removal. And, most importantly, our society needs this key information now to manage and plan for risks, especially in a landscape of increasing pressure on water resources as well as those from a changing climate. The remainder of this white paper describes the new scientific, diagnostic and modeling advances and expanded observational capabilities that have spawned new questions and pave the way for this proposed study. Figure 1 shows the conceptual framework for the CalWater science with and emphasis on the offshore objectives. Figure 2 addresses the impact onshore and the detailed observables of the water cycle that contribute to extreme precipitation events. The observational and modeling strategies proposed to address the scientific questions encapsulated in these schematics are developed in greater detail in this document.

2. New Advances and Capabilities

Several new observational and modeling capabilities that have recently been developed and demonstrated are uniquely capable of addressing relevant new scientific hypotheses and science gaps for CalWater 2:

2.1 NOAA's Hydrometeorology Testbed (HMT)

HMT (http://hmt.noaa.gov) has demonstrated how meteorological observations, including vertically pointing radar and wind profiler measurements, can be used to improve monitoring of key aspects of the water cycle and develop new methods in operational weather forecasting (*Ralph et al.*, 2005a). New decision support tools have emerged from HMT findings that water resource authorities now rely on during heavy rain and flooding events (*Neiman et al.*, 2009; *Wick et al.*, 2012). CalWater 2 will be able to leverage an altogether new set of advanced, land-based observations of the water cycle and ARs that are deployed as part of HMT and its legacy network for Enhanced Flood Response and Emergency Preparedness (EFREP) of 93 ground-based observing sites in California.

2.2 CalWater (2009–2011)

The first CalWater (http://www.esrl.noaa.gov/psd/calwater) study has provided new insight into the structure and evolution of ARs and the impact of aerosols on precipitation in landfalling ARs. Ground-based and supporting airborne measurements and modeling studies suggest that increased ice nuclei (IN) concentrations (e.g., dust) enhance precipitation in the form of snow and increased concentrations of boundary layer cloud condensation nuclei (CCN) suppress precipitation. Additionally, ground-based meteorological radar and wind profiler observations along the west coast and Central Valley of California showed that the Sierra Barrier Jet (SBJ) plays a major role in modulating precipitation during AR events and in transporting aerosols.

2.3 HIAPER Pole-to-Pole Observations (HIPPO) Study (2009–2011)

Recent aerosol and trace gas measurements from the HIAPER Pole-to-Pole Observations study provide insight into the role of synoptic-scale variability on the intercontinental transport of pollutants between Asia and North America. These observations offer relevant upstream context for the CalWater 2 study region. Five HIPPO campaigns with the NSF/NCAR G-V aircraft have been completed over all four seasons and include over 600 vertical profiles from 0.15 to 14 km altitude between 85°N and 67°S latitude in the remote Pacific and Arctic regions (*Wofsy et al.*, 2011). Observations in the northern hemisphere Pacific show aerosols exhibit large variability between and also within each season. Very polluted conditions were encountered over a deep portion of the troposphere in large-scale plumes in the springtime north Pacific midlatitudes and subtropics from anthropogenic and biomass-burning sources in Asia (*Spackman et al.*, 2013). Observations of aerosol mass loadings across the intertropical convergence zone show large interhemispheric gradients in boreal spring. The presence of these large aerosol loadings, comparable to loadings observed in the boundary layers of large U.S. cities, magnifies the concern of possible aerosol modification of clouds and precipitation especially in extreme major precipitation events along the west coast of the US. Satellite data and meteorological analyses provide important context for these in situ measurements. Retrieved aerosol, cloud, and trace gas products from satellite measurements are particularly relevant to examining the broader impact of aerosol-cloud-precipitation interactions.

2.4 Winter Storms and Pacific Atmospheric Rivers (WISPAR)

The NOAA-led WISPAR field campaign demonstrated the research and operational applications of a new dropsonde system, developed for NOAA by NCAR, on the NASA Global Hawk (GH) unmanned aircraft system. The GH flew three research flights for a total of 70 hours in February–March 2011 deploying over 175 dropsondes from near 18 km altitude into ARs, extratropical cyclones, and the remote Arctic atmosphere. The dropsonde system provided high-resolution thermodynamic and wind data between the lower stratosphere and the surface of the ocean. Retrieved radiances from HAMSR, a microwave sounding radiometer operated by the NASA Jet Propulsion Laboratory, provided vertically resolved temperature and water vapor data between the aircraft and the surface over a larger horizontal domain. Together, the data acquired from these instruments have been used to improve the understanding of the structure and evolution of ARs and extratropical cyclones. The observations from 4 different AR transects and a coordinated NOAA G-IV flight during this campaign are providing important new information on how water vapor is transported from the tropics to midlatitudes in ARs and characterizing how well the operational and reanalysis data products represent AR conditions (*Ralph et al.*, 2013).

2.5 Small Unmanned Aircraft System (UAS) Observations

Air-sea flux and aerosol measurements from small UAS in the marine boundary layer have been demonstrated recently. A new method has been developed over the last several years to measure boundary layer turbulent eddy fluxes of heat and momentum as well as aerosol loading and radiation terms from small UAS (*Thomas et al.*, 2012). This capability has the potential to be operated from a ship within AR conditions offshore.

2.6 Long-Lead Prediction Capabilities

Capabilities for skillful modeling and prediction of low-frequency variability in the tropics that have impacts on U.S. west coast extreme events are making important advances (e.g., *Sperber et al.*, 2011, *Mo et al.*, 2011; *Jiang et al.*, 2011, 2012; *Hendon et al.*, 2011). For example, forecast skill of the MJO has advanced considerably over the last 5 or more years with a number of models having useful MJO prediction skill with lead times of around 2-4 weeks. (e.g., *Rashid et al.*, 2010; *Waliser et al.*, 2011). A number of community efforts are taking advantage of these developments in order to develop and disseminate experimental and even operational MJO predictions (*Waliser et al.*, 2006; *Gottschalck et al.*, 2010; *NAS-Climate*, 2010; *Moncrieff et al.*, 2012; *Waliser et al.*, 2012). These capabilities provide an increasingly stable and valuable foundation from which to embark on large-scale field campaign research, allowing timely and robust deployment of airborne assets. A noteworthy effort that will afford substantial research resources for CalWater 2 is the Subseasonal 2 Seasonal (S2S) Prediction Project that is being developed by WWRP/THORPEX and WCRP (*Vitart et al.*, 2012). This activity will provide delayed ensemble prediction output, with 45 day lead times, from a number of participating weather/climate forecast centers in a manner similar to TIGGE for 15-day weather forecasts. The specifications for model output include both basic meteorological variables as well as quantities particularly important to decision support at longer leads. This activity is expected to begin by fall of 2013, and be well underway for supporting, and investigation by, CalWater 2. Utilizing the ensemble predictions from a number of operational centers on the development and evolution of tropical and mid-latitude conditions, and in particular AR events, will provide valuable probabilistic information to the field campaign operations (*Wick et al.*, 2013).

3. Scientific Objectives

3.1 State of the Science

The remote northern hemisphere Pacific troposphere is a dynamically active region of the atmosphere that often fuels the rapid development of extratropical cyclones and, at the same time, conveys some of the most polluted air masses in the atmosphere. As shown schematically in Figure 1, the large-scale flow advects dust and anthropogenic and biomass-burning pollution from Asia into the central Pacific, where it can then be entrained into an extratropical cyclone or its associated AR.

Past studies have shown that ARs are key features of the global water cycle (e.g., *Zhu and Newell*, 1998), are detectable in satellite observations (see example in Fig. 1a of *Ralph et al.*, 2004; *Neiman et al.*, 2008a), are associated with heavy rain and flooding on the U.S. West Coast (*Ralph et al.*, 2005b, 2006, 2011a; *Persson et al.*, 2005; *Neiman et al.*, 2008b, 2011; *Leung and Qian*, 2009; *Smith et al.*, 2010; *Dettinger et al.*, 2011, 2012; *Ralph and Dettinger*, 2012; *White et al.*, 2012), and can be energized by local air sea fluxes from anomalously warm coastal sea surface temperatures (*Persson et al.*, 2005). Studies in Europe (*Stohl et al.*, 2008; *Lavers et al.*, 2011) and South America (*Viale and Nuñez*, 2011) have come to similar conclusions for the west coasts of these other continents as well, and *Moore et al.* (2012) has documented the role of an AR in major flooding in the southeast U.S. *Guan et al.* (2010) and *Dettinger et al.* (2011) documented the major roles that ARs also play in California's water supply, providing from 25 to 50% of the entire water-year's snowpack and precipitation, respectively, in just a few events. *Dettinger* (2011) analyzed Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) climate projections to assess changes in AR characteristics off the California coast, and showed that recent climate-change projections typically include more extreme ARs in the 21st century due largely to greater atmospheric water vapor content. *Guan et al.* (2012) explored the role of MJO's in modulating ARs. Ongoing research from HMT and CalWater is documenting the key roles of the Sierra Barrier Jet in modulating precipitation associated with atmospheric river landfall, while diagnostics of several years of hourly ARO observations at the coast from HMT is revealing the crucial role of the duration of AR conditions in determining hydrologic impacts.

The WISPAR field campaign using the NOAA dropsonde system on the Global Hawk provided unique insight into the performance of current operations reanalysis products on representing the water transport in ARs. Based on 4 flights from WISPAR and two from NOAA's WP-3Ds in earlier experiments, preliminary analyses show that errors in estimated AR water vapor transport range from 0.5-2 million acre-feet/day of equivalent liquid water in individual ARs. To put these results in context, the entire flow of the Colorado River averages about 15 million acre feet per year. This represents a major uncertainty in the representation of the water cycle in state-of-the-art reanalysis (e.g., CFSR, ERA-Interim, MERRA). This error was 3-4 times worse in the NCEP-NCAR reanalysis. Climate models likely have similar, if not more severe, biases with significant implications on their abilities to simulate moisture transport responsible for heavy precipitation and how heavy precipitation events may change in a warmer climate in many regions worldwide. For example, Demory et al. (2013) have shown that the representation of the hydrological cycle and specifically precipitation processes are highly sensitive to model horizontal resolution.

Orographic forcing is a unique and dominant mechanism for converting water vapor into consumable fresh water in the form of precipitation, snowpack, and runoff. How mountains redistribute the fresh water in time and space is an important aspect of the regional and global water cycle. About 60 to 90% of surface water resources originate from mountains worldwide. Aerosols, however, have an important role in determining the precipitation properties in orographic clouds. By modulating the amount and phase of precipitation, aerosols can redistribute precipitation spatially, leading to subsequent changes in snowpack, soil moisture, and runoff with important implications to regions that rely on mountain water resources.

Adding aerosols increases the amount of CCN that nucleate more numerous and smaller cloud drops. This slows the drop coalescence and in turn the conversion of cloud water into rain drops. Aerosols can also enhance the mixed-phase precipitation forming processes by increasing the riming and growth rate of ice hydrometeors. Such effects have been demonstrated by a large number of studies using measurements from field campaigns (e.g., *Rosenfeld*, 2000; *Hudson and Yum*, 2001; *McFarquhar and Heymsfield*, 2001; *Yum and Hudson*, 2002; *Borys et al.*, 2003; *Andreae et al.*, 2004; *Hudson and Mishra*, 2007; *Rosenfeld et al.*, 2008; *Saleeby et al.*, 2008). Slowing the precipitation forming processes in shallow and short lived orographic clouds is expected to cause a net decrease in precipitation amount in the upwind slope of the mountains (*Griffith et al.*, 2005), with some compensation at the downwind slope (*Givati and Rosenfeld*, 2004 and 2005; *Jirak and Cotton*, 2005; *Rosenfeld and Givati*, 2006; *Givati and Rosenfeld*, 2007; *Rosenfeld et al.*, 2007; *Cotton et al.*, 2010). Model simulations supported the hypothesis that adding CCN suppresses orographic precipitation (*Lynn et al.*, 2007). However, adding ice nuclei (IN) to supercooled liquid clouds could increase precipitation. Numerical simulations that show enhancement of mixed-phase precipitation in the presence of aerosols that act as IN support these general trends (*Muhlbauer and Lohmann* 2009; *Lohmann* 2002).

In addition to the above processes, recent field campaigns including SUPRECIP and CalWater 1 in central California where aerosol sources are abundant provided further insights on the role of aerosols on cloud and precipitation, and highlighted the presence of supercooled liquid water down to -21^{o}C and supercooled rain down to -12°C in weak convective cloud band associated with a cyclone over the ocean, and in laminar layer cap clouds over the ridge of the high peaks of the Yosemite section of the Sierra Nevada, at temperatures down to -21°C. Analysis of remote sensing data and modeling by *Choi et al.* (2010) suggests that supercooled liquid droplets can exist at temperatures as low as -40^{o}C and that the variations in the supercooled cloud fraction is negatively correlated with dust loadings. This finding suggests that the seeder-feeder mechanism that greatly enhances precipitation from cold clouds (*Houze*, 1993) can be modulated by IN concentration.

Along with the role of aerosols in the precipitation process, once embedded via deposition onto the snowpack, aerosols and dust have also been identified to play a key role in the melt rate of mountain snowpack (e.g., *Painter et al.*, 2010).

3.2 Science Questions

We propose a coupled modeling-observational strategy to address a set of scientific objectives central to aerosol-precipitation research. A multi-platform observational approach including airborne, ship-, remote sensing-, and ground-based assets would be designed to specifically:

(1) Assess the key physical processes (i.e., rainout, vapor convergence, air-sea interaction, evaporation) that control the water vapor transport budget in ARs over the ocean and at landfall:

  (i) Study the impact of global weather patterns such as ENSO, MJO, and PNA and their tropical-extratropical teleconnections on the frequency, development, and evolution of ARs and the interactions of clouds and aerosols that influence precipitation. [Waliser, Dettinger, Leung, Neiman, Redmond]
  (ii) How much water vapor is entrained directly from the tropics and how much of this makes it to the coast and falls as precipitation? [Ralph, Waliser, Neiman, Wick, Leung, Spackman, Redmond]
  (iii) Evaluate to what extent sea-surface temperatures and the ocean mixed layer influence latent heat release in the vicinity of ARs and hence the evolution of ARs through air-sea flux processes. [Fairall, Rutledge, Wick, Ramanathan, Rudnick]
  (iv) Can mesoscale frontal waves associated with the parent cold front of an AR be detected and if so, can this aid in predictions of AR duration at coastal sites (a critical factor controlling how extreme precipitation will be and where)? [Ralph, Neiman, Dettinger, Wick]
  (v) How does the Sierra Barrier Jet behavior modulate the mesoscale distribution of precipitation, aerosols, and their impacts in the mountains near the north end of the Central Valley (the primary water supply for northern California)? [Hughes, Neiman, Leung, Spackman]
  (vi) Evaluate the kinematic and precipitation structures in off-shore extratropical cyclones and contrast these structures to landfalling cyclones. [Rutledge, Ralph, Neiman]
  (vii) Examine the vertical structure of ARs using a suite of vertical profiling and multi-sensor satellite remote sensing products (e.g., AIRS, CloudSat, CALIPSO, SSMIS). [Waliser, Wick, Spackman]

(2) Investigate to what extent different types of aerosols and their microphysical environment influence precipitation efficiency in ARs:

  (i) Identify the relevant regions of synoptic-scale systems (e.g., in the extratropical cyclone or atmospheric river) where aerosols nucleate water vapor or ice and quantify the enhancement or suppression of precipitation associated with aerosol impacts. [Prather, Leung, Spackman]
  (ii) Identify the properties, sources, and role of aerosols in the precipitation forming processes and enhancement, suppression, and redistribution of precipitation in convectively and orographically forced clouds over the coastal and inland mountain ranges? [Rosenfeld, Prather, Leung]
  (iii) How sensitive is rainout in ARs over the ocean to possible influences of aerosols including remote dust, pollution, and marine biological aerosols? [Spackman, Leung, Prather]

   (iv) Investigate the role of aerosols on the thermodynamic development of extratropical cyclones and the coupled atmospheric rivers associated with these storms. [Leung, Spackman, Cayan]
   (v) To what extent does the large-scale flow influence the interaction of aerosols and precipitation at midlatitudes and influence cyclogenesis? [Ralph, Spackman, Leung]

(3) Determine the role of ARs in providing precipitation that ends drought conditions in key regions. [Dettinger, Ralph]

(4) Study the impact of absorbing aerosols (e.g., dust and black carbon) deposited on snow and how they affect the hydrological cycle in the western U.S. due to early melt associated with the decrease in surface albedo? To what extent do different types of aerosols and varying origins influence this process? [Painter, Prather, Redmond, Leung, Spackman]

We propose a set of modeling and analysis studies to broaden the relevance of the outcomes from the observations and address additional scientific objectives of climate significance:

(1) Assess the key physical processes in weather and climate models that control the water vapor transport budget in ARs. [Dettinger, Leung, Waliser]
(2) Characterize and simulate the dynamical processes (e.g., barrier jets) that modulate the precipitation associated with landfalling ARs using numerical downscaling techniques. [Hughes, Leung, Stephens]
(3) To what extent do climate models represent ARs and the related distribution and frequency of precipitation? [Dettinger, Leung, Stephens, Waliser, Hoerling]
(4) Quantify how well global and regional aerosol models simulate the emission, transport, and removal of aerosols. Assess and refine the representativeness of microphysical parameterizations for the processes associated with nucleation scavenging in different types of clouds (e.g., mixed-phase). [Prather, Leung, Spackman]
(5) Study the impact of aerosols on quantitative precipitation estimates (QPE) and use the observations from the CalWater 2 study to improve quantitative precipitation forecasts (QPF). [Ralph, Leung, Prather, Hughes, Spackman]
(6) Explore medium range-to-seasonal predictability and present-day prediction skill of frequency and intensity of ARs for key geographic regions. [Dettinger, Ralph, Cayan, Waliser]

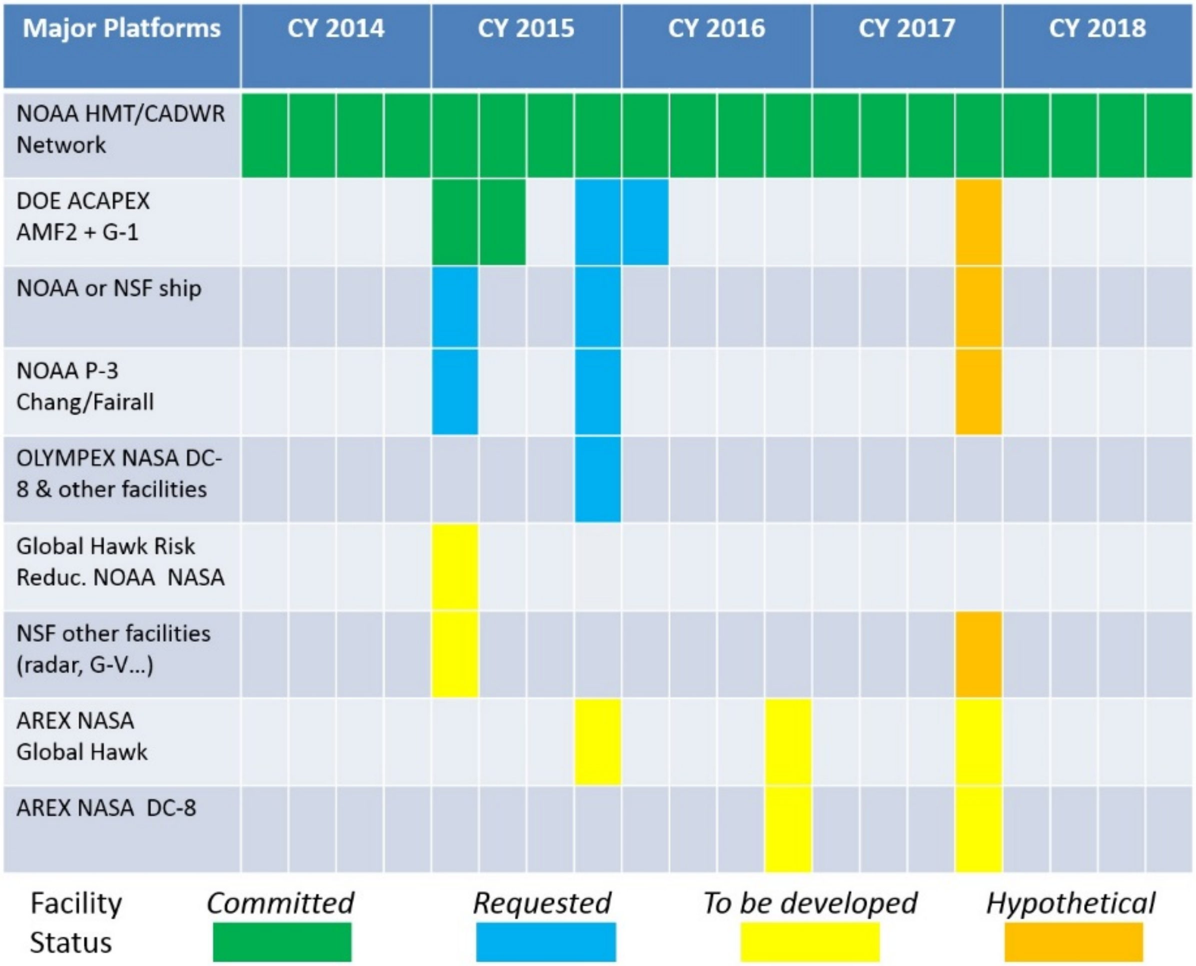
4. Strategies for CalWater 2

4.1 CalWater Five-Year Vision

Following the example of the first CalWater study, which began as an exploratory workshop in 2008 and then carried out increasingly complex field data collection efforts from 2009-2011, CalWater 2 is taking a multi-year approach to addressing major science questions and gaps. The approach envisioned is one in which a series of field campaigns are conducted from 2014-2018 using a variety of platforms and sensors and addressing a range of compelling scientific problems described elsewhere in this document.

The expense and complexity of the data collection offshore requires research aircraft and ship time that involve long-range planning and facility requests, and coordination across agencies whose facilities are needed. This plan takes advantage of the recently developed HMT-West Legacy observing network of roughly 100 sites in a mesonet across California (*White et al.*, 2013) to document key hydrometeorological conditions during cool-season precipitation events in the region. This network was built within the framework of a 5-year agreement, and a second 5-year agreement is nearly in place to operate and maintain this network through 2018. The overarching vision presented here is intended to provide for an observational and modeling framework informed by the science questions described in this white paper by the many experts who have contributed to it. The CalWater 2 vision was briefed to senior leadership in several federal agencies in May 2013, including at NSF and NOAA, with representatives from DOE and ONR. Further briefings to an interagency planning group occurred in July 2013 at the CLIVAR Summit and more briefings are anticipated including for NASA.

Table 1. Strawman 5-year timeline for CalWater 2 field campaigns envisioned over the northeast Pacific and along the US West Coast from 2014-2018. The status of major facilities and associated requests are highlighted schematically. A filled box represents the quarter in which the field campaign would be conducted, not the duration of data collection (each field campaign will likely collect data for 4-6 weeks during that quarter).



Major Platforms	CY 2014				CY 2015				CY 2016				CY 2017				CY 2018			
NOAA HMT/CADWR Network	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
DOE ACAPEX AMF2 + G-1					🟩	🟩		🟦	🟦							🟧				
NOAA or NSF ship					🟦			🟦								🟧				
NOAA P-3 Chang/Fairall					🟦			🟦								🟧				
OLYMPEX NASA DC-8 & other facilities								🟦												
Global Hawk Risk Reduc. NOAA NASA					🟨															
NSF other facilities (radar, G-V…)					🟨											🟧				
AREX NASA Global Hawk								🟨				🟨				🟨				
AREX NASA DC-8												🟨				🟨				

Facility Status: *Committed* 🟩 *Requested* 🟦 *To be developed* 🟨 *Hypothetical* 🟧

During the 5-year period from 2014-2018, a series of "CalWater 2 Intensives" are envisioned including:

- CalWater 2 "Early start" Intensive (early CY 2014; NOAA flight request submitted for 50 hours of NOAA G-IV flight time; prospectus for added land-based sampling)
- CalWater 2 "ACAPEX Intensive 1" (January – March 2015; DOE facilities approved, NOAA facilities requested, NSF proposal submitted for radar upgrade)
- CalWater 2 "ACAPEX Intensive 2" (November – December 2015; DOE request submitted, NOAA WP-3D to be requested)
- CalWater 2 "AREX" (3 field seasons CY 2015-2017; NASA Earth Ventures – Suborbital 2 proposal in development; possible NSF facilities request)

The sequence of Intensives is summarized in Table 1.

4.2 AR Climatology

Field campaign planning requires knowledge of the frequency of occurrence of the phenomena being studied in the regions and seasons of interest. In the case of atmospheric rivers, the following analysis (Fig. 3 and Table 2) uses an automated AR detection tool based on IWV ("ARDT-IWV") developed recently by *Wick et al.* (2012). It uses SSM/I satellite observations of IWV over the northeast Pacific Basin and an automated version of the AR pattern recognition technique created by *Ralph et al.* (2004). The key findings and implications of this analysis are:

- Using the ARDT-IWV tool, the frequency of occurrence of ARs over 12 years of SSM/I IWV data in 6 deg X 6 deg areas offshore is:
  - There are typically 7 to 15 "AR days" for each area per 6-week period
  - There are no 6-week periods in the 12-year sample with less than 1 or 2 AR days.
  - 2 to 4 ARs in a given 6-week period (2.25-4.17)
  - Each AR persists in an area for roughly 3 days on average
- It is most likely that there would be 3 to 4 AR events offshore in a 6-week period.
- It is most likely that each AR would typically last 3 days, making multiple flight-days for a single AR feasible.
- It is most likely that 2 to 3 ARs would hit northern California in a 6-week period.
- AR counts are less for 6-week periods starting after 15 January, on average.

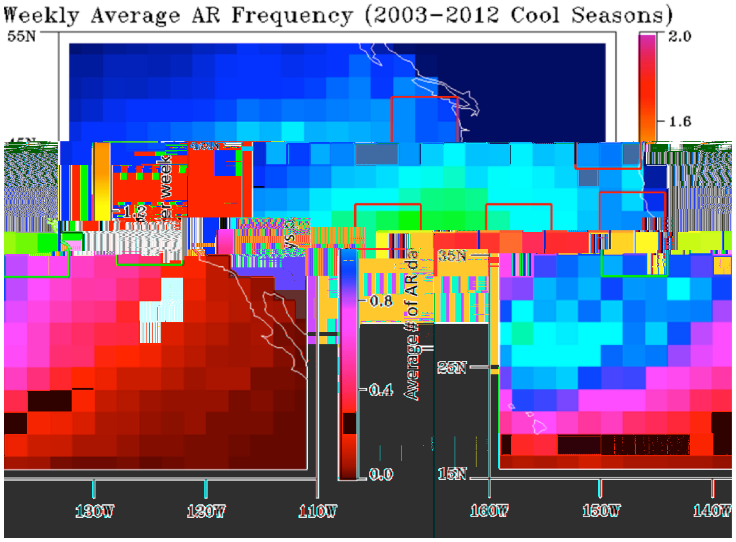


Figure 3. Average number of ARs detected per week in each 2 deg x 2 deg grid cell shown from 1 November to 31 March. Red boxes denote 6 deg x 6 deg areas for which statistics were calculated for several six week periods through the cool season (see Table 2).

Table 2. Average, maximum and minimum number of AR days observed using SSM/I IWV observations in 6 deg X 6 deg boxes (see Fig. 3 for locations). The counts were done for a series of 6-week-long time windows through the cool season starting on 1 November and were determined using the ARDT-IWV tool developed by *Wick et al.* (2013).

Block		**6 Week period starting:**						
		Nov. 1	Nov 15	Nov 29	Dec 13	Jan 1	Jan 15	Jan 29
1 43-49 N 124-130 W	Avg	10.58	8.67	8.17	9.17	9.08	7.00	5.33
	Min	8	6	5	5	5	2	2
	Max	15	12	13	17	14	13	10
2 35-41 N 122-128 W	Avg	9.83	9.00	9.75	9.25	7.83	6.67	6.42
	Min	6	4	2	2	2	2	2
	Max	14	16	18	18	15	14	10
3 33-39 N 132-138 W	Avg	16.67	16.00	15.67	15.50	13.67	11.42	11.00
	Min	12	11	7	8	7	3	3
	Max	21	20	21	22	24	25	20
4 33-39 N 144-150 W	Avg	18.75	17.67	17.42	16.75	16.75	14.33	14.00
	Min	13	8	11	11	11	7	6
	Max	24	25	23	26	25	20	19

4.3 Observational Approach

The proposed measurement strategy consists of land and offshore assets, supplemented by existing satellite observations, to monitor the evolution and structure of ARs and the precipitation that accompanies them from near their regions of development and interaction with aerosol plumes to the U.S. West Coast where ARs make landfall (Figure 4). The onshore impact of aerosols from local sources and long-range transport on precipitation would be similarly investigated, especially in the context of orographic precipitation on the coastal and inland mountain ranges. As shown in Figure 4, the observational strategy requests two aircraft offshore in winter 2014-15. High-altitude observations would include remote sensors and dropsondes over the AR. A profiling aircraft would then provide aerosol and trace gas measurements across the AR and in a region upstream of the ARs to sample the background aerosol before entrainment into the AR. The CalWater 2 observations are designed to complement the airborne and ship-borne assets recently awarded for ACAPEX including the DOE G-1 aircraft and the ARM Mobile Facility (AMF2). They would also take advantage of the proposed dual-polarimetric radar to be installed on the R/V *Ronald H. Brown* (RB). Lastly, the mesoscale observing network that will be available as part of NOAA's HMT-West provides a unique ability to monitor AR conditions at landfall and as they penetrate inland.

Aircraft Observations

The DOE ARM program has committed the G-1 aircraft for the winter 2014-15 intensive observing period and will operate in the near and onshore region of California. Facilities requests are currently under development for the NOAA WP-3D, NOAA G-IV, and NASA Global Hawk to perform airborne observations offshore mostly in a region between California and Hawaii. Flight requests for the NOAA WP-3D and G-IV would simply realign annual airborne observations with these aircraft to a more CalWater-centric focus so the probability of successfully obtaining these assets is very high. Air-sea flux and aerosol measurements from small UAS in the marine boundary layer could also be employed, with the potential to launch them from a ship within AR conditions offshore. Table 3 summarizes the proposed aircraft observations and measurements for the near-term intensive and also includes details of the aircraft observations more generally in the context of the 5-year vision for CalWater 2.

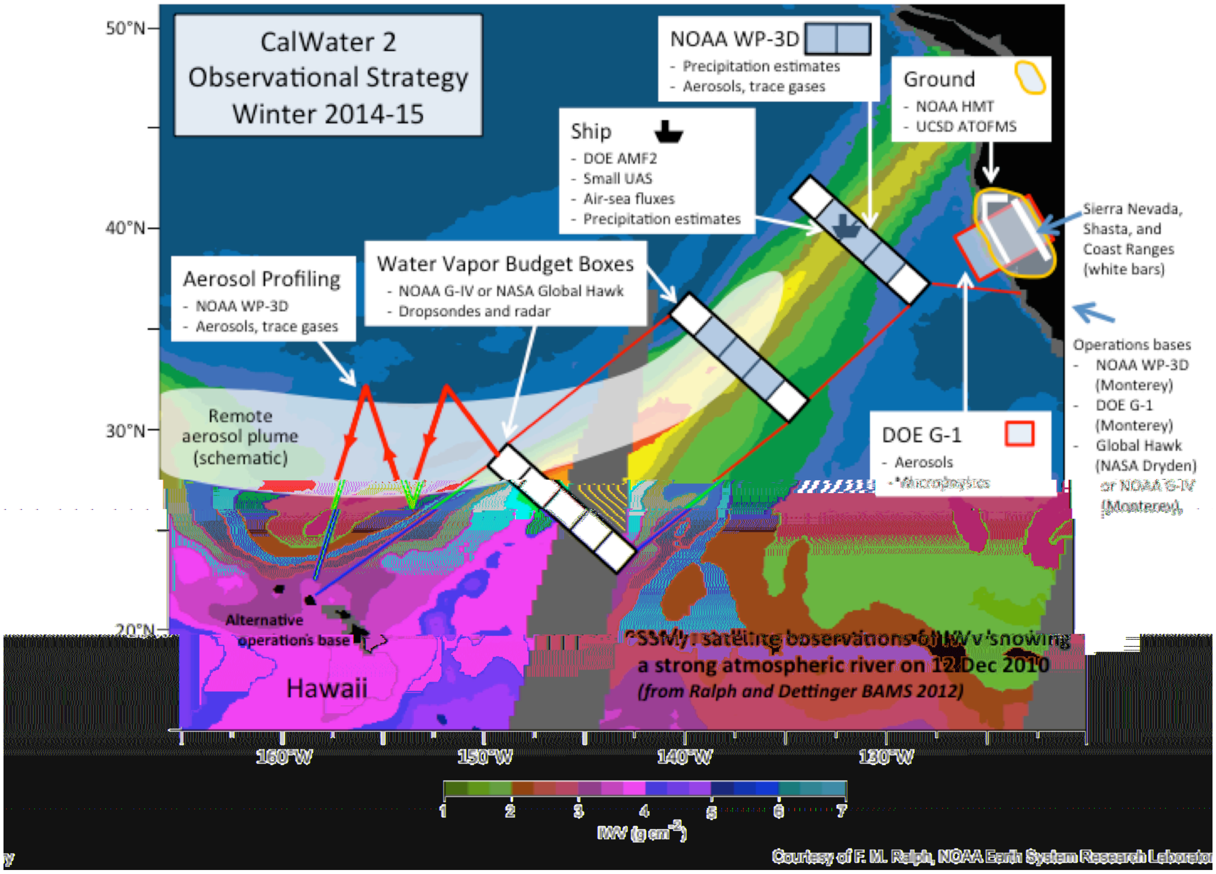


Figure 4. The CalWater 2/ACAPEX observational strategy using high- and low-altitude aircraft platforms, a ship with the AMF2, and a ground-based network including HMT assets. For the winter 2014-15 intensive observing period, the proposed aircraft facilities would include two aircraft offshore (NOAA WP-3D, NOAA G-IV, or/and NASA Global Hawk) and the DOE G-1 in the near and onshore region. The experimental design is superimposed on SSM/I satellite observations from a strong AR event discussed in Ralph and Dettinger (2012). An Asian aerosol plume is shown schematically in the context of the AR to conceptually show the sampling strategy for both the AR (water vapor budget boxes) and aerosol (profiling to the north and west of the AR) objectives. During such an AR event, the ship would be positioned under an aircraft transect to complement the airborne observations. As the parent storm moves to the east, the AR would move to the south and east (toward the G-1 sampling region in the diagram).

Table 3. Proposed Aircraft Observations in 2014-15

Aircraft Platform	Altitude Range (kft)	Proposed Base	Theater of Operations	Measurements
NOAA WP-3D	1–22	Coastal CA	Offshore CA	Aerosols (total aerosol in the accumulation/coarse modes, BC mass loadings and size distributions) Microphysics (CCN, IN, cloud water/ice, precipitation spectra Chemical tracers (CO, CO_2, O_3) Dropsondes (P, T, RH, wind speed/direction) Horizontal convergence observed by tail Doppler radar
NASA Global Hawk	45–65	Edwards, CA	HI to CA	Dropsondes (P, T, RH, wind speed/direction) HAMSR (T, integrated water vapor) Spectropolarimetric observations
NOAA G-IV	1–45	Coastal CA and/or Honolulu, HI	HI to CA	Dropsondes (P, T, RH, wind speed/direction) Tail Doppler radar
DOE G-1	1–23	Coastal/inland CA	On/Offshore CA	Aerosols (total aerosol number and size distributions, BC mass, dust, scattering/absorption, single particle mass spectrometer) and chemical pollution tracers (CO, O3) Microphysics (CCN, IN, cloud drop size distribution, cloud water/ice content) Meteorological Data (T, P, RH, wind, turbulence)
SIO UAS	Up to 10	Coastal CA	Near Offshore CA	Turbulent eddy fluxes of heat and momentum in MBL Total Aerosols (aerosol absorption coefficient, number concentration, size distribution) Cloud drop concentration Broadband and visible fluxes T, water vapor density and water vapor fluxes

Ship-Based Observations

A NOAA ship, the *Ronald H. Brown* (*RB*), will participate in scientific operations associated with the marine aspects of the 2014-15 intensive field operations during CalWater 2 studying Pacific storms and their interactions with aerosols and the ocean mixed layer. There are multiple specific objectives for the project, associated with recovery and re-deployment of surface and profiling floats, CTD casts, and data collection from project-provided and shipboard sensors for atmospheric aerosols, air-sea fluxes, a scanning C-band polarimetric Doppler radar, and several other atmospheric remote sensing systems. The institutions participating directly onboard the RB in the 2014-15 field program include:

- DOE will field an ARM mobile atmospheric facility (AMF2; PI is L.R. Leung) at sea as part of CalWater 2. This facility includes aerosol and bulk meteorological observations, balloon-borne radiosondes, and a variety of radar and lidar.
- An NSF-sponsored component to the cruise will include a dual-polarization upgrade to the RB C-band Doppler radar (Prof. Steve Rutledge, CSU) from the Ronald Brown and ocean

mixed-layer turbulence observations to study air-sea feedback effects during AR events (Profs. Jim Thomson and Tom Sanford, UW/APL).
- A second NSF-sponsored effort will be in aerosol production and ocean bubble observations (PI is Grant Deane, SIO)
- A third NSF-sponsored effort to use fast high-resolution visible and IR systems to measure small-scale wave slopes and thermal signatures of microbreaking (C. Zappa, PI).
- NOAA ESRL/PSD effort to include the PSD seagoing flux observing system (C. Fairall, PI)

Table 4. CalWater 2 Ship-Based Investigator Observing Systems

System	**Type**	**Location**	**Seatainers**
AMF2	Aerosols, meteorology, radars, lidars	02 Forward	3
Air-Sea Fluxes	Fast turbulence systems, solar/IR radiometers	Jackstaff	1
C-Band Polarimetric Radar	Precipitation and microphysics, Doppler velocity, Sea clutter detection	02 Forward	1
SWIFT Spar Buoys	Waves/turbulence	Main aft, deck operations. Deploy and recover buoys.	0
EM-APEX Profilers	Ocean turbulence profiles	Main aft, deck operations. Deploy and recover profilers.	1
SeaSweep	Surface production of aerosols	02 forward. Port side deployment of small tethered buoy.	1
Ocean Video/Acoustics	Bubble population spectra	Main aft, deck operations. Deploy and recover bubble sensing package.	0
IR and Visible Imagers	Whitecaps and thermal surface structure.	03 deck, starboard. Mount video systems.	0
SIO ATOFMS	Size resolved aerosol	02 deck, forward or Chem. Lab.	0

Ground-based Observations (California)

To date, all 915-MHz wind profilers and S-band precipitation profilers (S-PROF) deployed for the HMT and CalWater field campaigns have been located in the central and southern portion of the Sacramento Valley, save for the S-PROF snow-level radar at Shasta Dam. In order to provide crucial observations to directly and continuously monitor the orographic forcing of precipitation in the Lake Shasta region, there are also plans to deploy four new atmospheric river observatories (AROs) as shown in Figure 5, where each new ARO includes a 915-MHz wind profiler, a surface meteorological tower, a GPS receiver, and a surface chemistry sampler. The wind profilers provide hourly averaged vertical profiles of horizontal wind velocity from ~0.1 to 4.0 km above ground with ~100 m vertical resolution and ~1 m s^{-1} accuracy in all-weather conditions (e.g., *Carter et al.*, 1995). In precipitating conditions, the wind profilers can detect the height of the precipitation melting level on an hourly basis using the objective radar brightband detection method of *White et al.* (2002). The meteorological towers provide 2-min observations of surface wind, temperature, moisture, and pressure, and collocated tipping buckets provide 2 min rainfall measurements with 0.01 inch (~0.25 mm) accuracy. Data collected from GPS receivers in tandem with collocated surface temperature and pressure measurements allow for the retrieval of integrated water vapor (IWV) through the full atmospheric column (e.g., *Revercomb et al.*, 2003; *Mattioli et al.*, 2007).

Satellite Observations

Satellite-based observations will be employed to characterize the large-scale environment and supplement the analyses over the oceans where airborne data are unavailable. Polar-orbiting observations from AIRS, CALIPSO and CloudSat (satellite instruments in the A-Train constellation), the soon-to-be launched Global Precipitation Mission (GPM), and MISR (onboard the Terra satellite) will provide important context for the planned field observations on clouds, aerosols, and precipitation in the region of study. Passive microwave observations from the Special Sensor Microwave Imager/Sounder (SSMIS) have been a key component of previous AR studies and will be supplemented by the recently launched Advanced Microwave Scanning Radiometer 2 (AMSR2) on the Japanese GCOM-W satellite. Satellite-derived estimates of the air-sea heat flux will be integrated and evaluated in studies of the influence of air-sea interactions on AR evolution. The proposed airborne and ship-based measurements will also support limited calibration/validation of critical satellite products.

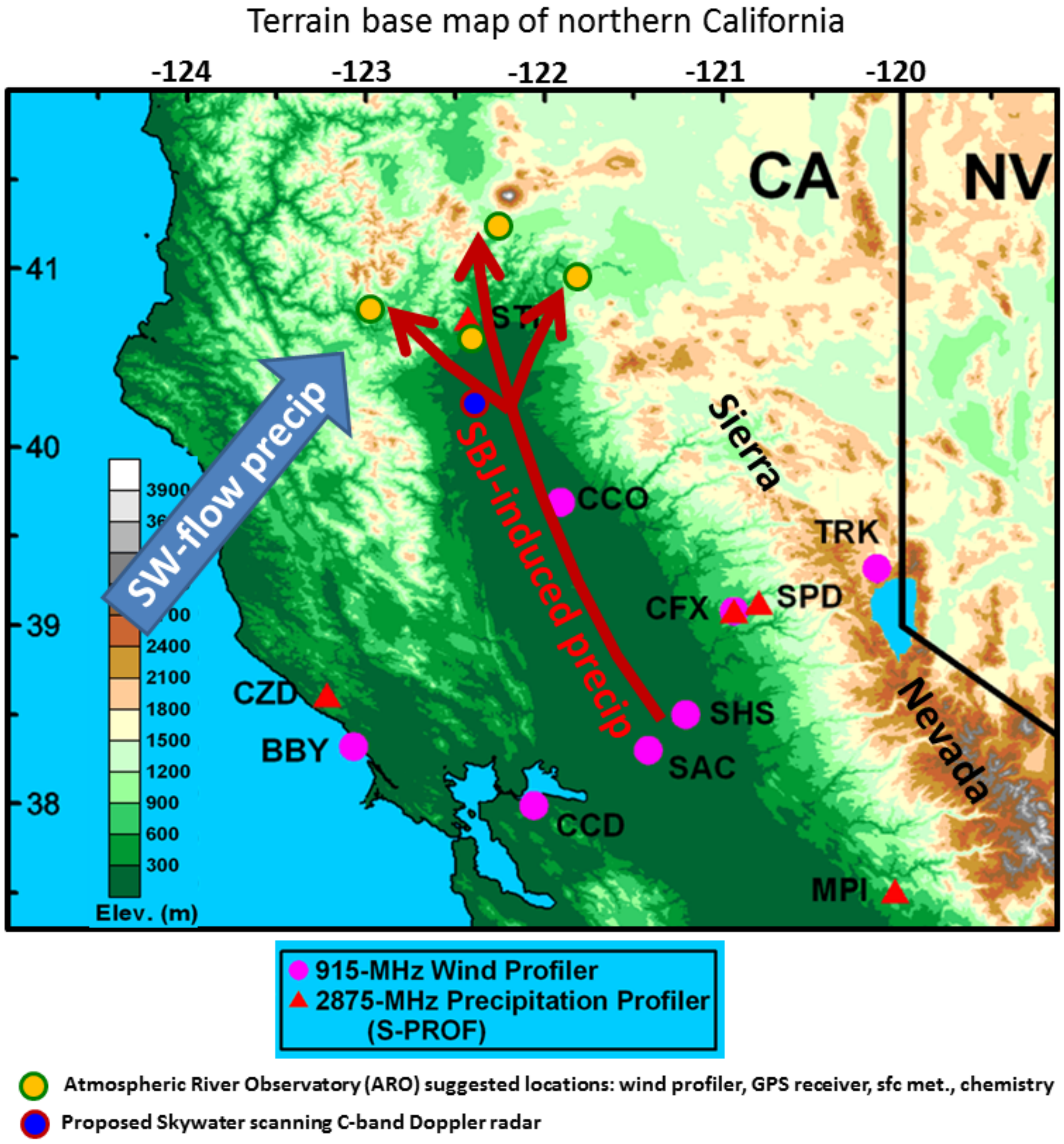


Figure 5. Terrain base map (meters, see color scale) of northern California showing wind profiler sites and S-PROF radars operation during the HMT and CalWater field campaigns (pink circles and red triangles, respectively). The proposed locations of atmospheric river observatories (i.e., wind profiler, GPS receiver, and surface meteorology) are marked with yellow circles, and the location of the proposed Skywater scanning Doppler radar is portrayed with a blue circle. Key air streams are also labeled. (Courtesy of P. J. Neiman, NOAA Earth System Research Laboratory)

4.4 Modeling Approach

Process Modeling of Aerosol-Cloud-Precipitation Interactions

Field campaigns including CalWater in central California have provided insights on the role of aerosols on cloud and precipitation. It has been known for decades that extensive supercooled liquid water (SLW) occurs in the orographic clouds over the Sierra Nevada, especially in the post-frontal clouds (*Reynolds and Dennis*, 1986 and references therein). CalWater documented

SLW in both polluted and pristine air masses down to -21°C, and persistent SLW occurred in clouds that are microphysically highly maritime (i.e., with small concentrations of large cloud drops that coalesce effectively into raindrops), producing highly supercooled rain (down to -21°C). Similar persistent supercooled rain (down to -12°C) was also observed in weak convective cloud band associated with a cyclone over the ocean or in laminar layer cap clouds over the ridge of the high peaks of the Yosemite section of the Sierra Nevada, at temperatures down to -21°C. New measurements from G1 will be used to further document the occurrence of SLW and raindrops in different types of clouds. Analysis will be performed using aerosol and cloud microphysical data to elucidate the role of aerosols on the formation and maintenance of supercooled liquid water and raindrops. Numerical modeling using WRF with a detailed spectral bin microphysics parameterization will be performed in conjunction with the data analysis to test different hypotheses of the role of aerosols in the aforementioned processes.

We will also make use of CalWater 2/ACAPEX data to further investigate the impacts of dust and biological particles on clouds and precipitation. Since G1 will have a similar payload as used in the CalWater 2011 field campaign, but deployed over a longer time period, we will potentially yield more samples to provide more evidence of the impacts of dust and biological particles on clouds and precipitation. Extending the study of *Fan et al.* (2013), the effects of aerosols from long-range transport will also be assessed using WRF with the spectral bin microphysics parameterization for cases where dust or bio particles are detected.

New data will also enable further investigations of the effects of the SBJ on aerosol transport and the subsequent influence on clouds and precipitation. The SBJ occurs frequently in the eastern foothill of the Sierra Nevada during winter. The SBJ can facilitate local transport of aerosols originating from the coastal urban regions and the agricultural central valley regions along the eastern foothill. This low-level aerosol transport of local origins, combined with the low-level water vapor transport during landfalling AR storms, can play a crucial role in determining precipitation distribution over the Sierra Nevada.

Lastly, ice nucleation plays a critical role in converting liquid to ice in the mixed-phase cloud regime (between 0 and -38°C), which in turn has important climate consequences. The role of dust from long-range transport serving as IN and influence precipitation in California has been highlighted in previous discussion. The field experiment will provide excellent data of dust and biological particles as well as cloud microphysical properties to evaluate several newly developed ice nucleation parameterizations. WRF simulations with the various ice nucleation parameterizations will be performed for selected cases to evaluate which parameterization produces results more comparable with the field data for the winter mixed-phase clouds. Sensitivity experiments to assess dust effects cloud properties, precipitation, and radiative forcing will be compared to quantify how uncertainty in ice nucleation parameterizations influences the estimates of dust effects.

Model Intercomparison Experiments

a. Aerosol-cloud-precipitation interactions

CalWater 2 and ACAPEX will provide significant opportunities to study aerosol-cloud-precipitation interactions using synergistic observational analysis and modeling to further our understanding of the role of CCN and IN in precipitation forming processes under different cloud regimes. Because aerosol effects on different types of clouds and precipitation are highly nonlinear, quantifying aerosol direct and indirect effects remain very challenging. To address uncertainty in model representations of aerosol-cloud-precipitation interactions, numerical experiments will be designed for a model intercomparison study. Cases will be selected from the CalWater 2 / ACAPEX field campaign based on analysis of the observation data to include cases associated with precipitation that occurs in post-frontal clouds that are typically quite shallow, with tops just high enough to pass the mountain barrier. Such clouds are inherently quite susceptible to aerosol effects on both warm rain and ice precipitation-forming processes. We will also select cases associated with AR conditions, with and without long range transported dust to investigate the influence of IN on precipitation. Ideally the intercomparison experiments will include models that have different parameterizations of cloud microphysics, including two-moment bulk microphysics with different treatments of autoconversion, ice nucleation, etc, and more detailed spectral bin microphysics. Simulations will also be performed at multiple resolutions to assess the impacts of model resolution in capturing the key features of the cloud system that may influence how aerosols interact with clouds and precipitation. All simulations will follow an experimental protocol to constrain important aspects such as initial and lateral boundary conditions, model resolution, model outputs, for meaningful comparison and evaluation of the simulation results.

b. Modeling of AR and heavy precipitation

Global and regional models are capable of simulating the characteristics of AR to some degrees, but to forecast or simulate the heavy precipitation associated with AR, they must accurately capture the water vapor transport, the atmospheric dynamics, orographic forcing, and cloud microphysical processes when AR makes landfall. We anticipate model resolution and dynamical core to play a significant role in whether models can capture the low level moisture and low level winds, atmospheric stability, Sierra Barrier Jet, and orographically induced moisture convergence. Similarly model physics are also important for capturing air-sea interactions that govern moisture supply from the surface, diabatic heating from radiation and cloud processes, and precipitation processes. We plan to organize and conduct a model intercomparison experiment to systematically evaluate different factors (model resolution, dynamical framework, and model physics) that influence model skill in simulating AR and the associated heavy precipitation. All AR cases encountered during the field campaign will be used. Models with different dynamical frameworks including nesting models (e.g., WRF), global variable resolution model (e.g., Community Atmosphere Model (CAM) spectral element and Model for Prediction Across Scales (MPAS) dynamical cores), and global quasi-uniform resolution model will be included, with each model configured at multiple horizontal grid resolutions ranging from about $1/8^o$ to 1^o. Models with non-hydrostatic dynamics (e.g., WRF, CAM-MPAS) will perform additional simulations at $1/16^o$ and $1/32^o$ for comparison. Simulations will be performed in a weather forecasting mode initialized using global forecast data. Simulations will be intercompared and evaluated using observation data. Analysis will be performed to quantify the errors associated with the water vapor transport, dynamical structures of the AR and boundary layer processes, and cloud micro- and macro-physical properties to gain insights on determining factors of model skill in simulating AR and the associated heavy precipitation. This intercomparison will be extended to include multi-year seasonal simulations of AR by the participating models to evaluate and compare their simulated AR and precipitation statistics.

6. Expected Scientific and Technical Outputs from CalWater 2

Anticipated outcomes for the CalWater 2 study include:

- Improved physical understanding of the relative roles of tropical versus midlatitude water vapor entrainment; horizontal moisture convergence, air-sea moisture fluxes, and rainout in modulating the water vapor transport in atmospheric rivers and the manner orography influences landfalling ARs and the resulting type and amount of precipitation
- Quantification of errors in current reanalysis products, weather and climate models associated with water vapor transport over the Pacific and orographically produced precipitation along the west coast
- Quantification of present-day forecast-skill of AR events and their low-frequency modulations
- Comparison of regional and global model skills in capturing AR and the associated heavy precipitation
- Comparison of how cloud microphysical parameterizations simulate aerosol-cloud-precipitation interactions
- Determination of the roles of aerosol transport from Asia in modulating the water cycle
- Determination of the roles of aerosols from local and remote sources on the precipitation over land, especially over the coastal and inland mountain ranges
- Distribution of an unprecedented meteorological, microphysical, and chemical dataset targeting the dynamics and aerosol-cloud-precipitation interactions in ARs and extratropical cyclones to the broader research community

In the broader context, the advances created by CalWater 2 could lead to a number of outcomes outside the immediate CalWater 2 project:

- Numerical weather and climate model improvement efforts would be able to target key gaps in performance revealed by CalWater 2
- Improvements in predictive models of weather and climate through advances in the knowledge of (i) water vapor transport budget in ARs and (ii) impact of aerosols on precipitation efficiency
- Reduced uncertainty in climate projections of extreme precipitation and water supply in the Western US
- Improved predictability in medium-to-seasonal range forecasts of frequency and intensity of landfalling AR events.
- Improved understanding of the hydrological influences of ARs, namely their impacts on soil moisture, snowpack, streamflow and groundwater
- Understanding the possible impacts of aerosol emissions and their precursors on the availability of water resources
- Development of decision support tools for extreme precipitation events for more effective flood control and water resources management

7. Scientific Steering Group

Core Scientific Steering Group

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