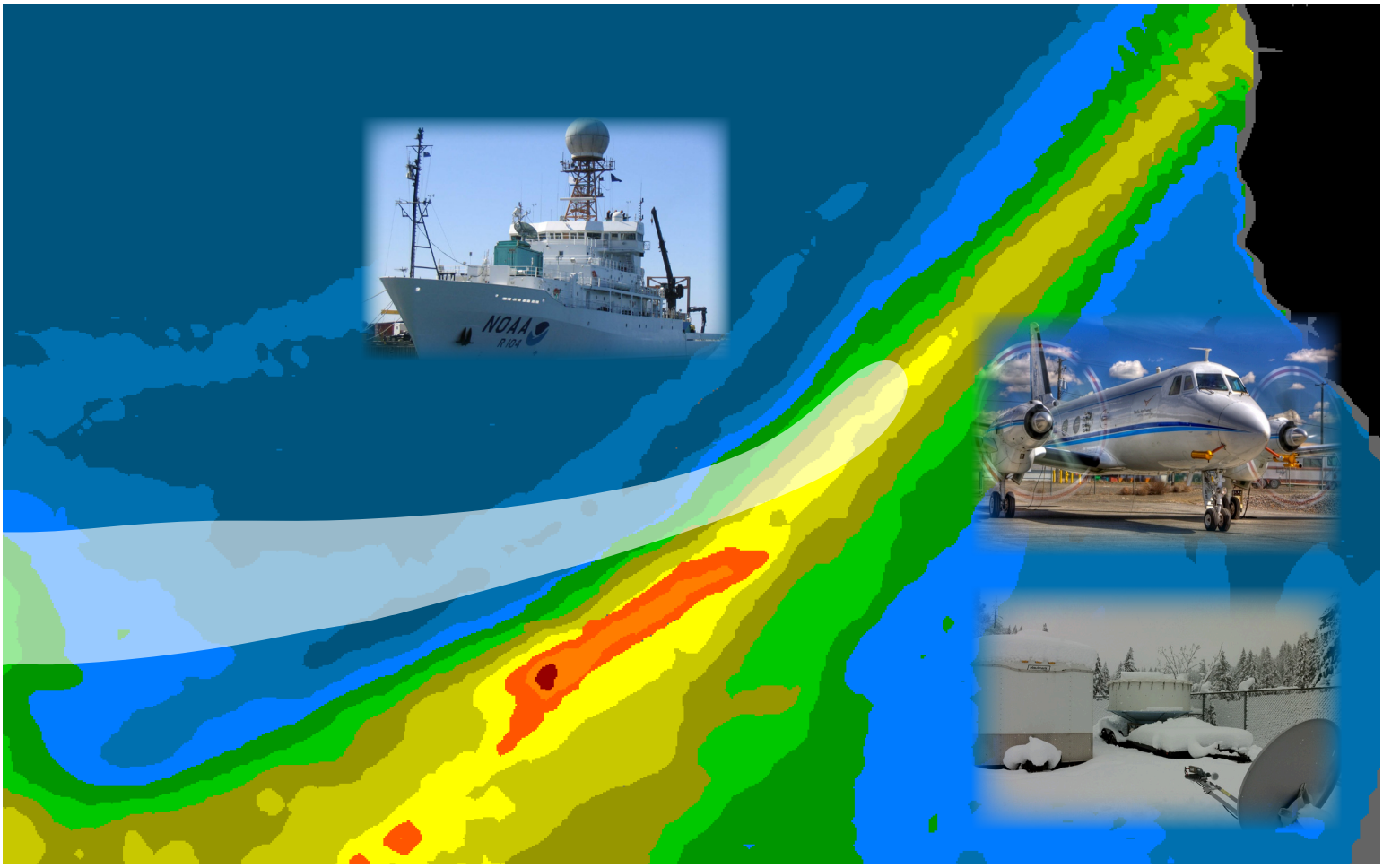

CalWater 2

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

CalWater 2: Precipitation, Aerosols, and Pacific Atmospheric Rivers Experiment

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 water vapor 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 phenomena 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, (2) the prediction of aerosol burdens and properties during intercontinental transport from remote source regions to the U.S. West Coast, and (3) aerosol interactions with ARs and the impact on precipitation, including locally generated aerosol effects on orographic precipitation along the U.S. West Coast. We propose a set of science investigations, called CalWater 2, to fill these gaps with a targeted set of aircraft and ship-based measurements and associated evaluation of data over regions offshore of California and in the central and eastern Pacific for an intensive observing period, proposed for December 2014 through March 2015. Expected outcomes for CalWater 2 include:

- Improvements in prediction systems for weather and climate,
- Distribution of an unprecedented meteorological and chemical dataset collected in AR environments both onshore and offshore, and
- Development of decision support tools for extreme precipitation events and water supply for more effective water resources management.

This assessment has been prepared by an interdisciplinary team of meteorologists, hydrologists, atmospheric chemists, and oceanographers, reflecting the breadth of processes involved and the expertise needed to make new progress. The findings described herein are largely based upon results that have emerged in the last few years from novel airborne and ground-based studies and 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 observing systems.

30 Nov 2012

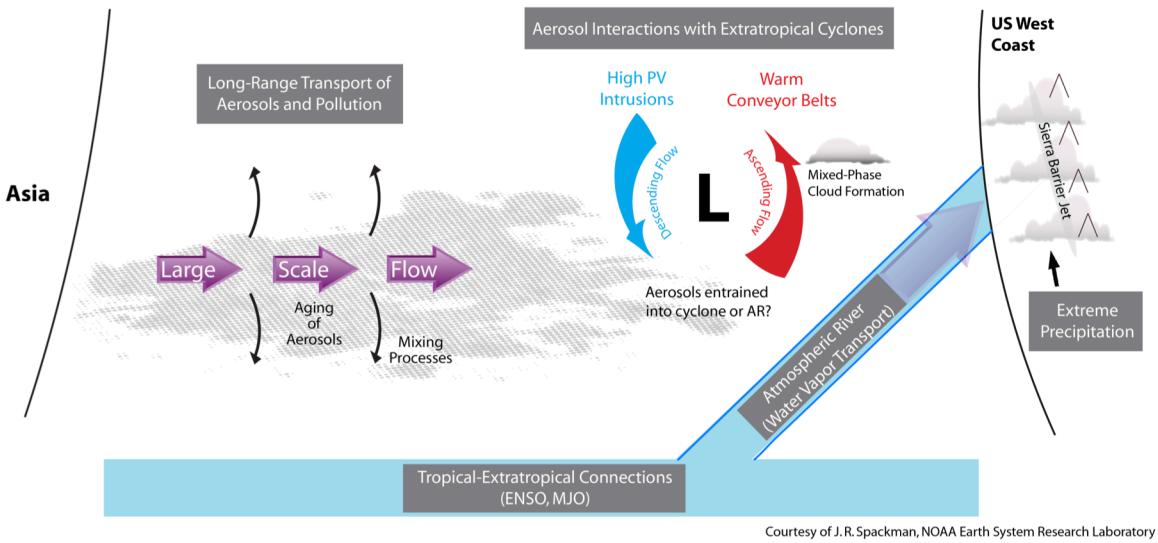

Figure 1. Conceptual framework for CalWater 2 science goals. The proposed observational strategy includes airborne and ship-based assets over the central and eastern Pacific complemented by ground-based measurements along the U.S. West Coast.

1. Introduction

Changes 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*, 2011; *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, 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 transport of 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, and frequency of precipitation in a changing climate with increasing emissions from Asia poses major challenges for water resources management and food security (*Ault et al.*, 2011). 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 an interdisciplinary approach that builds interaction across the fields of dynamics, chemistry, and cloud microphysics. Atmospheric dynamics couples the water vapor content in the tropics and midlatitudes with aerosols through microphysical processes that 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.

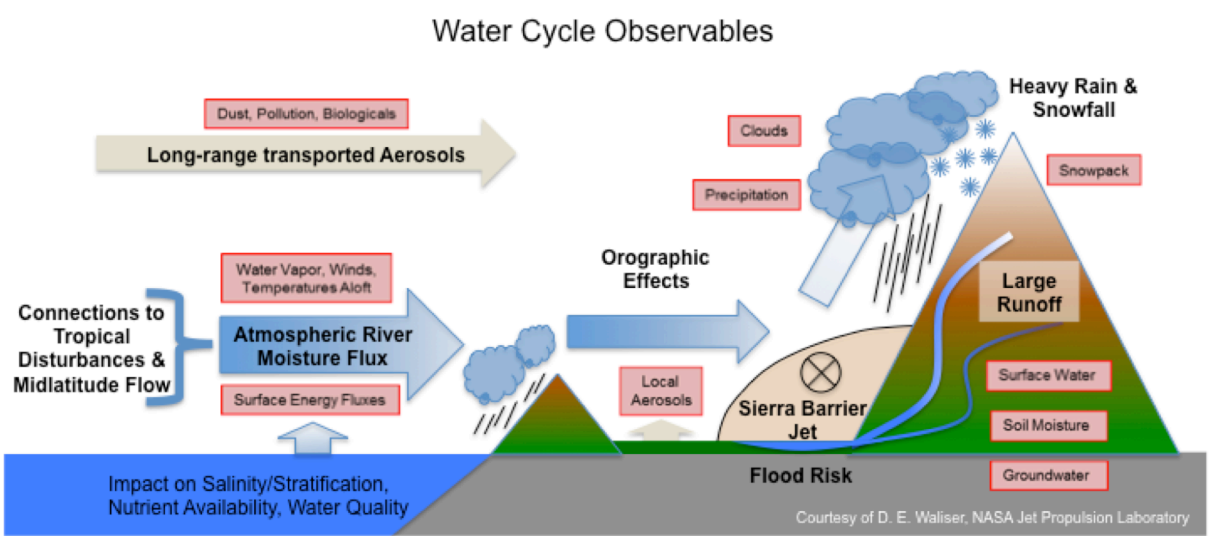

Figure 2. Illustration of the atmospheric and hydrological processes associated with atmospheric rivers (ARs) based on a northward view of an east-west cross section depicting a landfalling AR in a region akin to north/central California. On shore low-level moisture flux over the ocean is shown impinging 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 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). However, these and other observations of aerosol scavenging phenomena 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 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. The conceptual framework for the proposed study is presented in Figure 1 with an emphasis on the offshore science while 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 explained in detail later 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)

CalWater (http://www.esrl.noaa.gov/psd/calwater) 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.*, 2012). 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 the A-Train 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 NASA GH flew three research flights for a total of almost 70

hours in February–March 2011 deploying a total of 177 dropsondes from near 18 km altitude into atmospheric rivers (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 albeit at a coarser resolution than from the dropsondes but over a larger spatial 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.

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; *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; see also TIGGE effort at http://tparc.mri-jma.go.jp/TIGGE/tigge_MJO.html). 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 particularly noteworthy effort that will afford substantial forecast resources for CalWater 2 is the Subseasonal 2 Seasonal (S2S) Prediction Projection that is being developed by WWRP/THORPEX and WCRP (*Vitart et al.*, 2012). This activity will provide 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 by the time of 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.

3. Scientific Objectives

3.1 State of the Science

The remote northern hemisphere Pacific troposphere is a dynamic part of the atmosphere that fosters the rapid development of extratropical cyclones and also is the conveyor of some of the most polluted air masses globally. As shown schematically in Figure 1, the large-scale flow advects anthropogenic and biomass-burning pollution from Asia into the central Pacific, a region favorable for the development of storms especially during the cool season.

Past studies have shown that ARs (which are regions of the lower atmosphere characterized by strong winds and large water vapor contents usually associated with a surface cold front in the midlatitudes and related to the warm conveyor belt) are key features of the global water cycle (e.g., *Zhu and Newell*, 1998), are detectable in satellite observations (see example in Fig. 1a; *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 et al.*, 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 warn 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 precipitation 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 NASA Global Hawk provided unique insight into the performance of current operations reanalysis products on representing the water transport in ARs. Based on 4 flights on WISPAR and two from NOAA's P-3 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. Multiply this error by the several ARs present normally on the globe at any one time and then by the number days per year, and it is apparent that this represents a major uncertainty in the representation of the water cycle in state-of-the-art reanalysis (e.g., CFS-R, 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.

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°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°C and that the variations in the supercooled cloud fraction is negatively correlated with the frequency of dust aerosols. This finding suggests that the seeder-feeder mechanism that greatly enhances precipitation from cold clouds (*Houze*, 1993) can be modulated by IN concentration.

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 and ship-, satellite-, and ground-based assets would be designed to specifically:

(1) Assess the key physical processes that control the water vapor transport budget in ARs:

(i) Study the impact of global weather patterns such as ENSO and tropical-extratropical connections associated with the MJO on the frequency, development, and evolution of ARs and the interactions of clouds and aerosols than influence precipitation. [Waliser, Dettinger, 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, Redmond, Spackman]
(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]

(2) Investigate how aerosols influence precipitation efficiency:

(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]
(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]

(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, 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, 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, Stephens, Waliser]
(3) To what extent do global climate models represent the precipitation from ARs? Perform a series of simulations to evaluate what they suggest for the distribution and frequency of precipitation in the future. [Dettinger, Stephens, Hoerling]
(4) Quantify how well global 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 Observational Approach

The proposed measurement strategy would consist of land and offshore assets, supplemented by existing satellite observations, to monitor the evolution and structure of ARs from near their regions of development and interaction with aerosol plumes to the U.S. West Coast where ARs make landfall (Figure 3). Similarly, the impact of aerosols from local sources and long-range transport on precipitation inland will be investigated, especially in the context of orographic precipitation on the coastal and inland mountain ranges. The CalWater 2 observations are designed to complement the assets proposed for the ARM Cloud Aerosol Precipitation Experiment (ACAPEX) in winter 2014-15 including the ARM Mobile Facility (AMF2) and DOE G-1 research aircraft. 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.

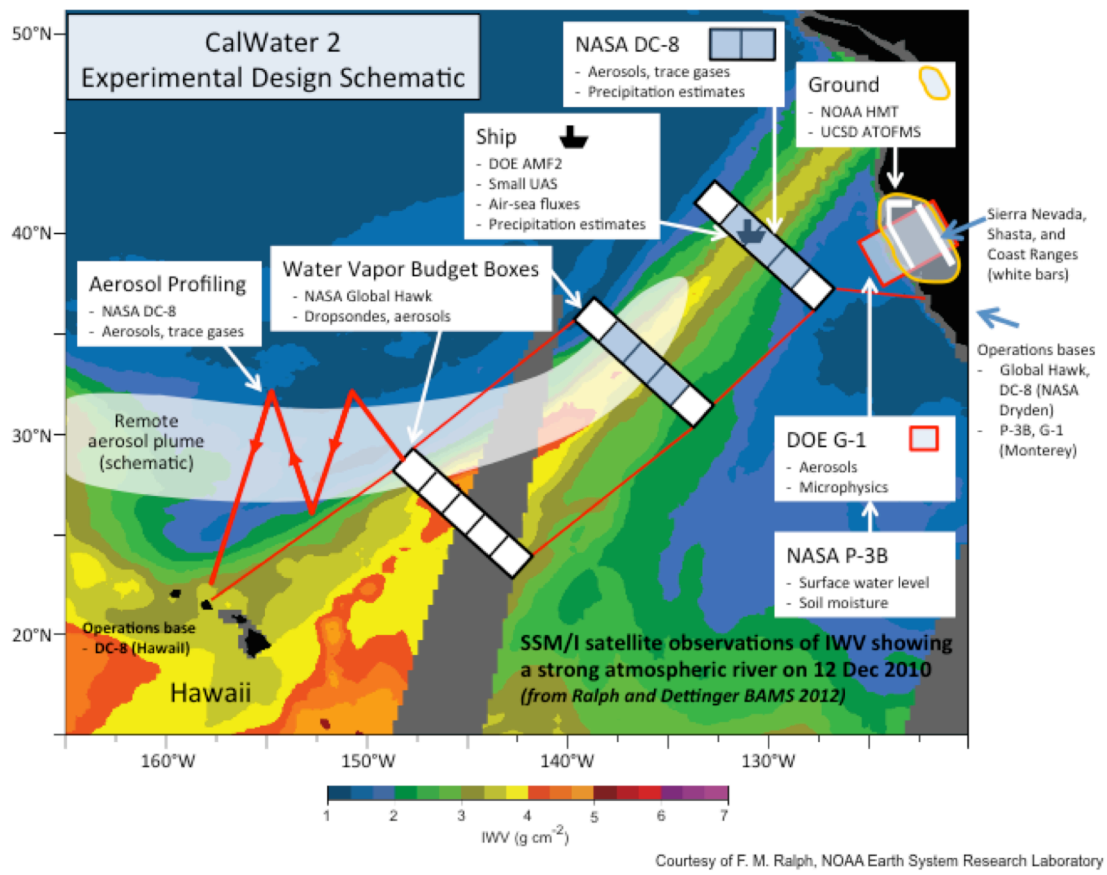

Figure 3. The CalWater 2/ACAPEX observational strategy using high- and low-altitude aircraft platforms, a ship with the AMF2, and a ground-based network including HMT assets and the UCSD/SIO ATOFMS. The aircraft assets include one or two aircraft offshore (NOAA WP-3D, NOAA G-IV, NSF/NCAR G-V, NASA Global Hawk) and the DOE G-1 onshore. 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 (transects and water vapor flux boxes) and aerosol (profiling to the north and west of the AR) objectives. During such an AR event, the ship would be vectored along an aircraft transect of an AR to coordinate the 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).

Aircraft Observations

One to two facilities requests will be made for both high- and low-altitude observations for CalWater 2. Candidate platforms and accompanying payloads for CalWater 2 and ACAPEX are described in Table 1.

Table 1. Proposed Aircraft Observations

Aircraft Platform	Altitude Range (kft)	Location	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
NSF/NCAR G-V	0.5–45	Coastal CA and/or Honolulu, HI	HI to 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)
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
C-band polarimetric precipitation radar
W-band cloud radar
Wind profiler
Radiosonde observations (including tethered)
Eddy correlation turbulent fluxes and radiative fluxes
Near-surface meteorology
Ocean mixed-layer structure, currents, turbulence and surface waves
Complementary DOE AMF2 measurements from ACAPEX

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, we also recommend deploying four new atmospheric river observatories (AROs) as shown in Figure 4 in addition to the existing network, 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 (A-Train satellite instruments) 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.

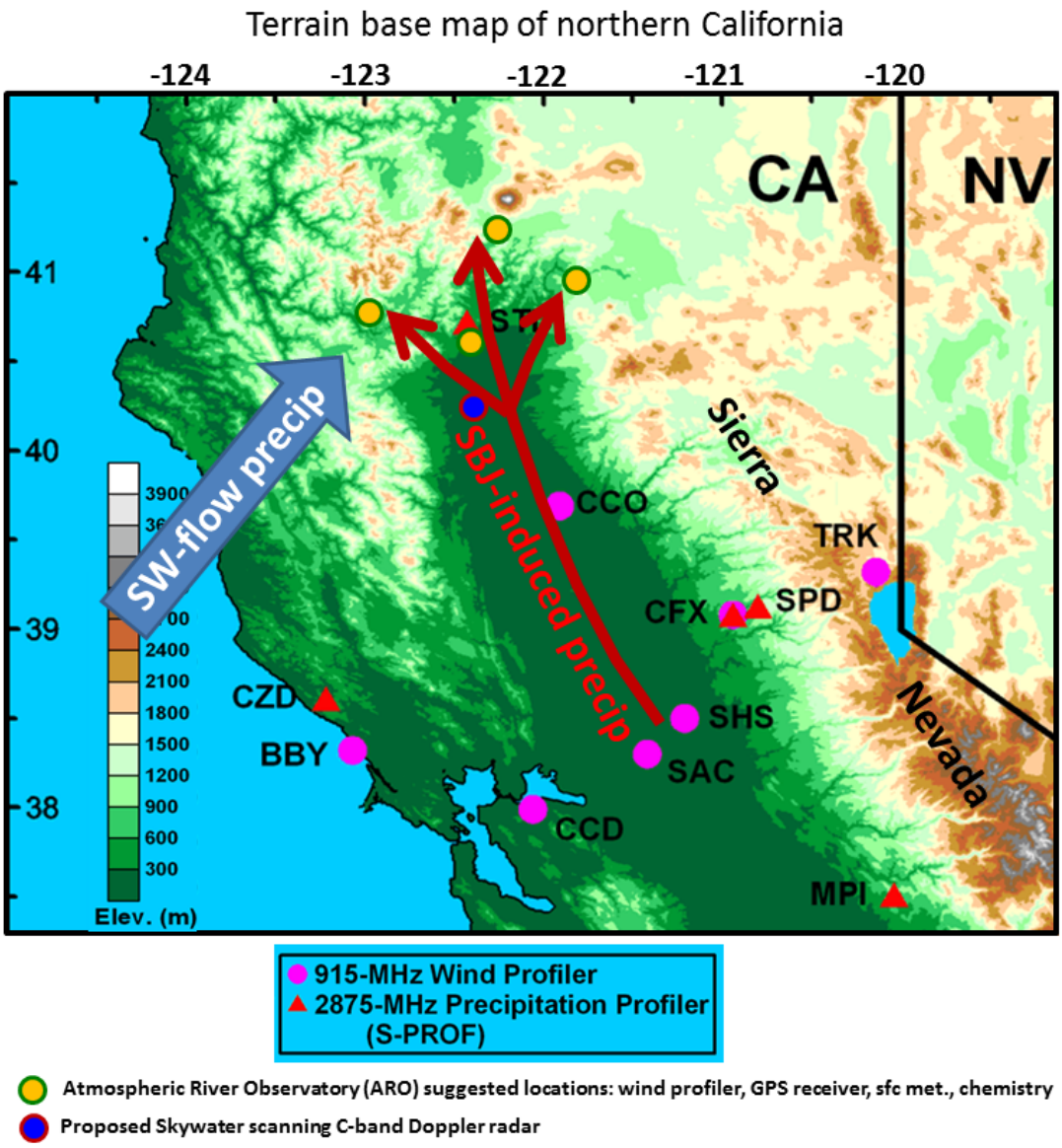

Figure 4. Terrain base map (meters, see color scale) of northern California showing wind profiler sites and S-PROF radars operation during the HMT and CalWater field campaigns (pink circles and red triangles, respectively). The proposed locations of atmospheric river observatories (i.e., wind profiler, 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)

4.2 Modeling Approach

Process Modeling

L. R. Leung – aerosol-cloud-precipitation interactions, spectral bin microphysics
M. Hughes – AR modeling, WRF downscaling
R. B. Pierce – aerosol and chemistry transport modeling

Weather and Climate Modeling
M. Dettinger – ARs, hydrology perspective
D. Waliser – ARS phenomena/processes, tropical connections, prediction and predictability
G. Stephens – high-capability, high-performance modeling of extreme precipitation events
M. Hoerling – ARs, extreme precipitation events, pattern perspective

5. Synergies with DOE ARM Resources

The CalWater 2 experiment would complement proposed DOE ARM resources as part of ACAPEX, to provide observations at the surface and aloft over both the central/eastern Pacific Ocean and the west coast of the U.S. to:

- Study the impacts of tropical-extratropical interactions and Asian aerosols on heavy precipitation
- Address outstanding issues related to aerosol-cloud-precipitation interactions in clouds transitioning from the maritime regime to the orographic regime in central California, and
- Examine how effects may differ for aerosols from long-range transport versus local sources.

The data to be collected by the DOE AMF2 and G-1 as part of ACAPEX, in conjunction with the CalWater 2 aircrafts, UAS, and ship- and ground- based measurements with data analysis and modeling will enable improved understanding and modeling of the targeted processes that play key roles in the water cycle of the western U.S. and regions influenced by similar processes.

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 water vapor entrainment, horizontal moisture convergence, air-sea moisture fluxes, and rainout in modulating the water vapor transport in atmospheric rivers
- Quantification of errors in current reanalysis products, weather and climate models associated with water vapor transport over the Pacific
- Quantification of present-day forecast-skill of AR events and their low-frequency modulations
- 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 and chemical dataset targeting the dynamics and aerosol-cloud-precipitation interactions in ARs and extratropical cyclones to the broader research community

7. Expected Outcomes outside CalWater 2 that would be enabled by the scientific and technical advances created in CalWater 2

- 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.
- 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

8. Scientific Steering Group

Core Scientific Steering Group

Investigator	Affiliation
F. M. Ralph (Co-Lead)	NOAA Earth System Research Laboratory
K. A. Prather (Co-Lead)	Scripps Institution of Oceanography, University of California San Diego
D. Cayan (Co-Lead)	Scripps Institution of Oceanography, University of California San Diego US Geological Survey
M. Dettinger	Scripps Institution of Oceanography, University of California San Diego US Geological Survey
C. Fairall	NOAA Earth System Research Laboratory
L. R. Leung	Pacific Northwest National Laboratory
D. Rosenfeld	The Hebrew University of Jerusalem
S. Rutledge	Colorado State University
J. R. Spackman	NOAA Earth System Research Laboratory Science and Technology Corporation
D. E. Waliser	NASA Jet Propulsion Laboratory

Contributors

Contributor	Affiliation
D. Diner	NASA Jet Propulsion Laboratory
J. Fernando	University of Notre Dame
M. Hoerling	NOAA Earth System Research Laboratory
M. Hughes	NOAA Earth System Research Laboratory
G. Mace	University of Utah
P. J. Neiman	NOAA Earth System Research Laboratory
T. Painter	NASA Jet Propulsion Laboratory
V. Ramanathan	Scripps Institution of Oceanography, University of California San Diego
K. Redmond	Desert Research Institute
D. Rudnick	Scripps Institution of Oceanography, University of California San Diego
G. Stephens	NASA Jet Propulsion Laboratory
G. A. Wick	NOAA Earth System Research Laboratory

9. References

Ault, A. P., C. R. Williams, A. B. White, P. J. Neiman, J. M. Creamean, C. J. Gaston, F. M. Ralph, and K. A. Prather (2011), Detection of Asian dust in California orographic precipitation, *J. Geophys. Res.*, *116*, D16205, doi:10.1029/2010JD015351.

Bao, J.-W., S. A. Michelson, P. J. Neiman, F. M. Ralph, and J. M. Wilczak, Interpretation of enhanced integrated water vapor bands associated with extratropical cyclones: Their formation and connection to tropical moisture, *Mon. Wea. Rev.*, *134*, 1063-1080.

Carter, D.A., K.S. Gage, W.L. Ecklund, W.M. Angevine, P.E. Johnston, A.C. Riddle, J. Wilson, and C.R. Williams (1995), Developments in UHF lower tropospheric wind profiling at NOAA's Aeronomy Laboratory, *Radio Sci.*, *30*, 977-1001.

Choi, Y.-S., R. S. Lindzen, C.-H. Ho, and J. Kim (2010), Space observations of cold-cloud phase change, *Proc. Natl. Acad. Sci.*, *107*, 11211-11216.

Dettinger, M. D. (2011), Climate change, atmospheric rivers, and floods in California – A multimodel analysis of storm frequency and magnitude changes, *Journal of the American Water Resources Association*, *47*, 514-523.

_____, Ralph, F.M., Das, T., Neiman, P.J., and Cayan, D., 2011: Atmospheric rivers, floods, and the water resources of California. *Water*, *3* (Special Issue on Managing Water Resources and Development in a Changing Climate), 455-478.

Fu, R., Y. Hu, J. S. Wright, J. H. Jiang, R. E. Dickinson, M. Chen, M. Filipiak, W. G. Read, J. W. Waters, and D. L. Wu (2006), Short circuit of water vapor and polluted air to the global stratosphere by convective transport over the Tibetan Plateau, *Proc. Natl. Acad. Sci.*, *103*, 5664-5669, doi:10.1073/pnas.0601584103.

Gottschalck, J., M. Wheeler, K. Weickmann, F. Vitart, N. Savage, H. Lin, H. Hendon, D. Waliser, K. Sperber, M. Nakagawa, C. Prestrelo, M. Flatau, and W. Higgins (2010), A Framework for Assessing Operational Madden-Julian Oscillation Forecasts: A CLIVAR MJO Working Group Project, *Bull. Amer. Meteor. Soc.*, *91*(9), 1247-1258.

Guan, B., N. P. Molotch, D. E. Waliser, E. J. Fetzer, and P. J. Neiman (2010), Extreme snowfall events linked to atmospheric rivers and surface air temperature via satellite measurements, *Geophys. Res. Lett.*, *37*, L20401, doi:10.1029/2010GL044696.

_____, D. E. Waliser, N. P. Molotch, E. J. Fetzer, P. J. Neiman (2012), Does the Madden-Julian oscillation influence wintertime atmospheric rivers and snowpack in the Sierra Nevada?, *Mon. Wea. Rev.*, *140*, 325-342.

Hendon, H., K. Sperber, D. Waliser, and M. Wheeler (2011), Modelling Monsoon Intraseasonal Variability: From Theory to Operational Forecasting, Workshop on Modelling Monsoon Intraseasonal Variability, 15-18 June 2010, APEC Climate Center, Busan, Korea, *Bull. Amer. Meteor. Soc.*, doi:10.1175/2011BAMS3164.1.

Houze, R. A., Jr. (1993), *Cloud Dynamics*, Academic Press, 573 pp.

Intergovernmental Panel on Climate Change (IPCC) (2007), Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.)], 996 pp., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jiang, X., D. E. Waliser, D. Kim, M. Zhao, M. Khairoutdinov, W. Stern, S. D. Schubert, K. R. Sperber, G. J. Zhang, W. Wang, R. Neale, and M.-I. Lee (2011), Simulation of the

Intraseasonal Variability over the Eastern Pacific ITCZ in Climate Models, *Climate Dynamics,*, doi:10.1007/s00382-011-1098-x.

Koch, D., et al. (2009), Evaluation of black carbon estimations in global aerosol models, *Atmos. Chem. Phys.*, *9*, 9001-9026, doi:10.5194/acp-9-9001-2009.

Koren, I., O. Altaratz, L. A. Remer, G. Feingold, J. V. Martins, and R. H. Heiblum (2012), Aerosol-induced intensification of rain from the tropics to the mid-latitudes, *Nat. Geosci.*, *5*, doi:10.1038/NGEO1364.

Lavers, D. A., R. P. Allan, E. F. Wood, G. Villarini, D. J. Brayshaw, and A. J. Wade, Winter floods in Britain are connected to atmospheric rivers, 2011. *Geophys. Res. Lett.*, *38*, L23803, doi:10.1029/2011GL049783.

Leung L. R, and Y. Qian, 2009. Atmospheric rivers induced heavy precipitation and flooding in the Western U.S. simulated by the WRF regional climate model. *Geophys. Res. Lett.*, *36*, L03820, doi:10.1029/2008GL036445.

Li, Z. F. Niu, J. Fan, Y. Liu, D. Rosenfeld, and Y. Ding (2011), Long-term impacts of aerosols on the vertical development of clouds and precipitation, *Nat. Geosci.*, doi:10.1038/NGEO1313.

Lohmann, U., 2002: A glaciation indirect aerosol effect caused by soot aerosols, *Geophys. Res. Lett.*, *29*, 1052, doi:10.1029/2001GL014357.

Matrosov, S. (2012), Observations of wintertime U.S. West Coast precipitating systems with W-Band satellite radar and other spaceborne instruments, *J. Hydrometeor.*, *13*, 223-238.

Mattioli, V., E. R. Westwater, D. Cimini, J. C. Liljegren, B. M. Lesht, S. I. Gutman, and F. J. Schmidlin (2007), Analysis of Radiosonde and Ground-Based Remotely Sensed PWV Data from the 2004 North Slope of Alaska Arctic Winter Radiometric Experiment, *J. Atmos. Oceanic Technol.*, *24*, 415-431.

McFarquhar, G. M., and A. J. Heymsfield (2001), Parameterizations of INDOEX microphysical measurements and calculations of cloud susceptibility: Applications for climate studies, *J. Geophys. Res., 106***,** 28,675–28,698.

Mo, K., C. Jones, and J. Paegle (2011), Pan America, in *Intraseasonal Variability of the Atmosphere-Ocean Climate System, 2nd Edition*, edited by W. K. M. Lau and D. E. Waliser, Springer, Heidelberg, Germany.

Moncrieff, M. W., D. E. Waliser, M. J. Miller, M. A. Shapiro, G. R. Asrar, and J. Caughey (2012), Multiscale convective organization and the YOTC virtual global field campaign, *Bull. Amer. Meteor. Soc.*, *93*, 1171-1187, doi:10.1175/BAMS-D-11-00233.1.

Muhlbauer, A., T. Hashino, L. Xue, A. Teller, U. Lohmann, R. M. Rasmussn, I. Geresdi, and Z. Pan (2010), Intercomparison of aerosol-cloud-precipitation interactions in stratiform orographic mixed-phase clouds, *Atmos. Chem. Phys.*, *10*, 8173-8196.

_____, and U. Lohmann (2009), Sensitivity Studies of Aerosol-Cloud Interactions in Mixed-Phase Orographic Precipitation, *J. Atmos. Sci., 66***,** 2517-2538.

NAS-Climate (2010), Assessment of Intraseasonal to Interannual Climate Prediction and Predictability, *Board on Atmospheric Sciences and Climate,* The National Academies Press, Washington, D.C., http://www.nap.edu/catalog.php?record_id=12878.

NAS-Hydrology (2012), *Challenges and Opportunities in the Hydrologic Sciences*, 150 pp., The National Academies Press, http://www.nap.edu/catalog.php?record_id=13293.

Neiman, P. J., F. M. Ralph, G. A. Wick, J. D. Lundquist, and M. D. Dettinger (2008a), Meteorological characteristics and overland precipitation impacts of atmospheric rivers

affecting the west coast of North America based on eight years of SSM/I satellite observations, *J. Hydrometeor.*, *9*, 22-47.

_____, _____, _____, Y.-H. Kuo, T.-K. Wee, Z. Ma, G. H. Taylor, and M. D. Dettinger (2008b), Diagnosis of an intense atmospheric river impacting the Pacific Northwest: Storm summary and offshore vertical structure observed with COSMIC satellite retrievals, *Mon. Wea. Rev.*, *136*, 4398-4420.

_____, A. B. White, F. M. Ralph, D. J. Gottas, and S. I. Gutman (2009), A water vapour flux tool for precipitation forecasting, *Water Management*, *162*, 83-94.

_____, L. J. Schick, F. M. Ralph, M. Hughes, G. A. Wick (2011), Flooding in western Washington: The connection to atmospheric rivers, *J. Hydrometeor.*, *12*, 1337-1358.

Penner, J. E., L. Xu, and M. Wang (2011), Satellite methods underestimate indirect climate forcing by aerosols, *Proc. Natl. Acad. Sci.*, *108*, 13404-13408, doi:10.1073/pnas.1018526108.

Persson, P.O.G., P.J. Neiman, B. Walter, J.-W. Bao and F.M. Ralph, 2005: Contributions from California coastal-zone surface fluxes to heavy coastal precipitation: A CALJET case study During the Strong El Niño of 1998. *Mon. Wea. Rev.*, *133*, 1175-1198.

Pratt, K. A., P. J. DeMott, J. R. French, Z. Wang, D. L. Westphal, A. J. Heymsfield, C. H. Twohy, A. J. Prenni, and K. A. Prather (2009), In situ detection of biological particles in cloud ice-crystals, *Nat. Geosci.*, *2*, doi:10.1038/NGE0521.

Ralph, F.M., P.J. Neiman, and G.A. Wick, 2004: Satellite and CALJET aircraft observations of atmospheric rivers over the eastern North-Pacific Ocean during the El Niño winter of 1997/98. *Mon. Wea. Rev.*, *132*, 1721-1745.

_____, R. M. Rauber, B. F. Jewett, D. E. Kingsmill, P. Pisano, P. Pugner, R. M. Rassmussen, D. W. Reynolds, T. W. Schlatter, R. E. Stewart and J. S. Waldstreicher (2005a), Improving short-term (0-48 hour) Cool-season quantitative precipitation forecasting: Recommendations from a USWRP Workshop. *Bull. Amer. Meteor. Soc.*, *86*, 1619-1632.

_____, P. J., Neiman, and R. Rotunno (2005b), Dropsonde observations in low-level jets over the Northeastern Pacific Ocean from CALJET-1998 and PACJET-2001: Mean vertical-profile and atmospheric-river characteristics. *Mon. Wea. Rev., 133*, 889-910.

_____, _____, G. A. Wick, S. I. Gutman, M. D. Dettinger, D. R. Cayan, and A. B. White (2006), Flooding on California's Russian River: Role of atmospheric rivers, *Geophys. Res. Lett.*, *33*, L13801, doi:10.1029/2006GL026689.

_____, _____, G. N. Kiladis, K. Weickmann, and D. W. Reynolds (2011a), A multiscale observational case study of a Pacific atmospheric river exhibiting tropical-extropical connections and a mesoscale frontal wave, *Mon. Wea. Rev.*, *139*, 1169-1189.

_____, and M.D. Dettinger (2011b), Storms, Floods and the Science of Atmospheric Rivers. *EOS, Transactions, Amer. Geophys. Union.*, *92*, 265-266.

_____, and _____ (2012), Historical and national perspectives on extreme west-coast precipitation associated with atmospheric rivers during December 2010, *Bull. Amer. Meteor. Soc.*, *93*, 783-790, doi:10.1175/BAMS-D-11-00188.1.

Randel, W. J., M. Park, L. Emmons, D. Kinnison, P. Bernath, K. A. Walker, C. Boone, and H. Pumphrey (2010), Asian monsoon transport of pollution to the stratosphere, *Science*, *328*, 611, doi:10.1126/science.1182274.

Rashid, H. A., H. H. Hendon, M. C. Wheeler, and O. Alves (2010), Prediction of the Madden-Julian Oscillation with the POAMA dynamical prediction system. , *Clim. Dyn.*, doi:10.1007/s00382-010-0754-x.

Revercomb, H. E., et al. (2003), The ARM program's water vapor intensive observation periods, *Bull. Amer. Meteorol. Soc*., doi:10.1175/BAMS-84-2-217.

Rosenfeld, D., U. Lohmann, G. B. Raga, C. D. O'Dowd, M. Kulmala, S. Fuzzi, A. Reissell, and M. O. Andreae (2008), Flood or drought: How do aerosols affect precipitation, *Science*, *321*, 1309, doi:10.1126/science.1160606.

Smith, B.L., S.E. Yuter, P.J. Neiman, and D.E. Kingsmill, 2010: Water vapor fluxes and orographic precipitation over northern California associated with a land-falling atmospheric river. *Mon. Wea. Rev.*, *138*, 74-100, doi:10.1175/2009MWR2939.1.

Spackman, J. R., J. P. Schwarz, R. S. Gao, L. A. Watts, D. W. Fahey, and S. C. Wofsy, Black carbon burden in the remote Northern Hemisphere springtime Pacific, *Geophys. Res. Lett.*, in preparation.

Sperber, K., J. Slingo, and P. Inness (2011), Modeling Intraseasonal Variability, in *Intraseasonal Variability of the Atmosphere-Ocean Climate System, 2nd Edition*, edited by W. K. M. Lau and D. E. Waliser, p. 613, Springer, Heidelberg, Germany.

Stohl, A., C. Forster, and H. Sodemann, 2008: Remote sources of water vapor forming precipitation on the Norwegian west coast at 60° N - a tale of hurricanes and an atmospheric river. J. *Geophys. Res.*, **113**, D05102, doi:10.1029/2007JD009006.

Su, H., J. H. Jiang, X. Liu, J. E. Penner, W. G. Read, S. Massie, M. R. Schoeberl, P. Colarco, N. J. Livesey, and M. L. Santee (2010), Observed increase of TTL temperature and water vapor in polluted clouds over Asia, *J. Clim.*, *24*, 2728-2736, doi:10.1175/2010JCLI3749.1.

Thomas, R. M., K. Lehman, H, Nguyen, D. L. Jackson, D. Wolfe, and V. Ramanathan, 2012: Measurement of turbulent water vapor fluxes using a lightweight unmanned aerial vehicle system. *Atmos. Meas. Tech.*, *5*, 243-257.

Viale, M., and M. N. Nuñez, 2011: Climatology of Winter Orographic Precipitation over the Subtropical Central Andes and Associated Synoptic and Regional Characteristics. *J. Hydrometeor*, *12*, 481-507, doi:10.1175/2010JHM1284.1.

Vitart, F., A. W. Robertson, and D. T. Anderson (2012), Subseasonal to Seasonal Prediction Project: bridging the gap between weather and climate, *WMO Bulletin*, *61*, 23-28.

Waliser, D. E., K. Weickmann, R. Dole, S. Schubert, O. Alves, C. Jones, M. Newman, H. L. Pan, A. Roubicek, S. Saha, C. Smith, H. van den Dool, F. Vitart, M. Wheeler, and J. Whitaker (2006), The experimental MJO prediction project, *Bull. Amer. Meteor. Soc.*, *87*(4), 425-431.

_____. (2011), Predictability and Forecasting, in Intraseasonal Variability of the Atmosphere-Ocean Climate System, 2nd Edition, edited by W. K. M. Lau and D. E. Waliser, p. 613, Springer, Heidelberg, Germany.

_____, et al. (2012), The "Year" of Tropical Convection (May 2008 to April 2010): Climate variability and weather highlights, *Bull. Amer. Meteor. Soc.*, *93*, 1189-1218, doi:10.1175/2011BAMS3095.1.

White, A. B., D. J. Gottas, E. T. Strem, F. M. Ralph, and P. J. Neiman (2002), An automated brightband height detection algorithm for use with Doppler radar spectral moments, *Atmos. Oceanic Technol.*, *19*, 687-697.

_____, B. Colman, G. M. Carter, F. M. Ralph, R. S. Webb, D. G. Brandon, C. W. King, P. J. Neiman, D. J. Gottas, I. Jankov, K. F. Brill, Y. Zhu, K. Cook, H. E. Buehner, H. Opitz, D. W. Reynolds, L. J. Schick, 2012: NOAA's Rapid Response to the Howard A. Hanson

Dam Flood Risk Management Crisis. *Bull. Amer. Meteorol. Soc., 93*, 189-207, doi: 10.1175/BAMS-D-11-00103.1.

Wick, G. A., et al. (2012), Automated AR detection tool, IEEE Transactions on Geoscience and Remote Sensing, in press.

Wofsy, S. C., et al. (2011), HIAPER Pole-to-Pole Observations: fine-grained, global-scale measurements of climatically important atmospheric gases and aerosols, *Philosophical Transactions of the Royal Society A*, *369*, 2073-2086.

Zhang, R., G. Li, J. Fan, D. L. Wu, and M. J. Molina (2007), Intensification of Pacific storm track linked to Asian pollution, *Proc. Natl. Acad. Sci.*, *104*, 5295-5299, doi:10.1073/pnas.0700618104.

Zhu, Y., and R. E. Newell (1998), A proposed algorithm for moisture fluxes from atmospheric rivers, *Mon. Wea. Rev.*, *126*, 725-735.