CALWATER FIELD STUDIES DESIGNED TO QUANTIFY THE ROLES OF ATMOSPHERIC RIVERS AND AEROSOLS IN MODULATING U.S. WEST COAST PRECIPITATION IN A CHANGING CLIMATE

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A group of meteorologists, hydrologists, climate scientists, atmospheric chemists, and oceanographers have created an interdisciplinary research effort to explore the causes of variability of rainfall, flooding and water supply along the U.S. West Coast.

CalWater is a multiyear program of field campaigns, numerical modeling experiments, and scientific analysis focused on phenomena that are key to the water supply and associated extremes (drought, flood) in the U.S. West Coast region. Table 1 summarizes CalWater's development timeline. The results from CalWater are also relevant in many other regions around the globe. CalWater began as a workshop at Scripps Institution of Oceanography (SIO) in 2008 that brought together scientists in several disciplines, including meteorology, hydrology, air pollution, aerosol chemistry, and climate. The purpose of the CalWater workshop was threefold: 1) to discuss key science gaps and the potential for leveraging long-term Hydrometeorology Testbed (HMT) data collection in California (Ralph et al. 2013), 2) to explore interest in the potential impacts of anthropogenic aerosols on California's water supply, and 3) to build on the Suppression of Precipitation (SUPRECIP) experiment from 2005 to 2007 (Rosenfeld et al. 2008b) and on the development of an aerosol time-of-flight mass spectrometer (ATOFMS; Gard et al.1997) able

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TABLE 1. Major milestones in the development of the CalWater program of field studies and science. EFREP = Enhanced Flood Response and Emergency Preparedness. HMT-AR = Hydrometeorology Testbed site focused on Atmospheric Rivers.

CalWater major planning milestones/calendar year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Initial planning workshop at SIO	X										
Aerosol–precipitation and AR foci chosen		X									
Early start joint Sierra HMT/aerosol site—Sugar Pine		X	X	X	X						
Second field season; more profiler, snow, and Sierra Nevada sites			X	X							
Third field season with G-1 aircraft, scanning radar. . .					X						
Analysis underway		X	X	X	X	X	X				
Decision to pursue CalWater-2					X						
CalWater-2 science steering group formed					X						
CalWater-2 science white paper completed						X					
CalWater-2 interagency briefings in Washington, DC						X					
CA EFREP/HMT-AR mesonetwork > 90% complete							X	X	X	X	X
Early start: NOAA G-IV (AR) + BBY (aerosols)							X				
SIO CalWater-2 planning workshop							X				
CalWater-2015 with ACAPEX (ship, G-1, G-IV, P-3, ER-2)								X			
US Air Force/NOAA/Scripps C-130 AR Recon' Flights									X		
Potential for future CW field campaigns										X	X

(CalWater-1 spans 2008–2014; CalWater-2 planning spans 2012–2014; CalWater-2 spans 2014–2018.)

to discern the sources of aerosol particles seeding the clouds.

The workshop led to a series of increasingly complex field observations over California during 2009–11 (Fig. 1; Table 2) that brought aerosol–cloud/precipitation scientists and hydrometeorologists (including atmospheric dynamics expertise) together for collocated data collection and collaborative analyses. The findings and remaining science gaps led to formation of a CalWater-2 Science Steering Committee (CW SSC) in 2012 that developed a 5-yr vision of how to address these science gaps. This vision is now being realized through aircraft-, ship-, and land-based data collected in 2014 and 2015. Proposals, some already funded, and a modern land-based

extreme precipitation-observing network (White et al. 2013; sponsored by California's Department of Water Resources) are in place to assist in additional field efforts during 2016–18. The goals of this paper

CalWater and Key HMT Observing Sites - Winter 2011
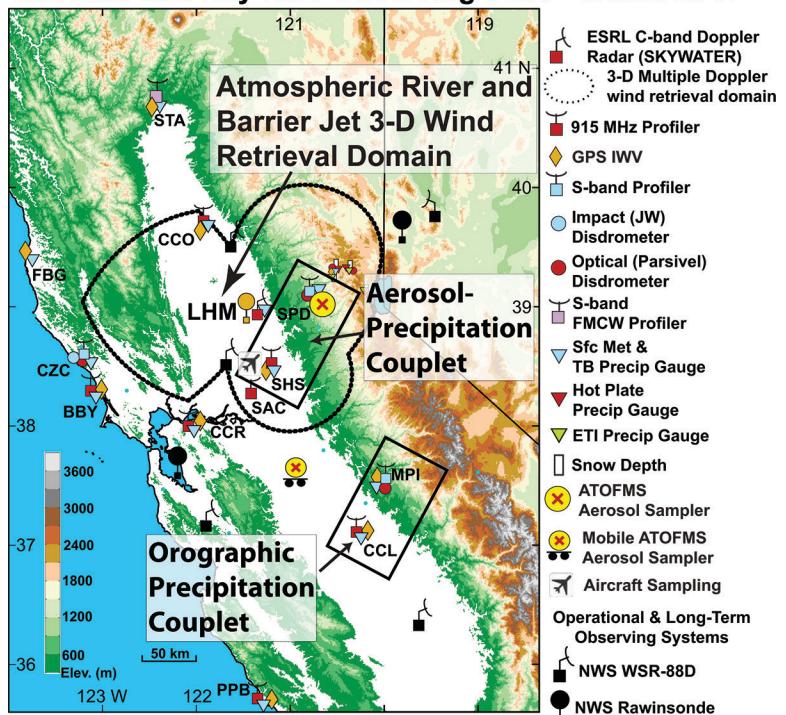
FIG. 1. Base map for CalWater-1 in 2011. Some sites were also in place briefly in Feb 2009 (northern aerosol–precipitation couplet) and in Jan–Mar 2010 (southern aerosol–precipitation couplet).

TABLE 2. Major field sites or observing platforms for CalWater color coded by type (e.g., orange for onshore, blue for aircraft, and green for ship). POCs for each platform or system are listed in the table by their initials: AW [Allen White, NOAA/Office of Oceanic and Atmospheric Research (OAR)/Physical Sciences Division, allen.b.white@noaa.gov], KP (Kimberly Prather, UCSD SIO, kprather@ucsd.edu), DK [David Kingsmill, Cooperative Institute for Research in Environmental Sciences (CIRES) and NOAA, david.kingsmill@colorado.edu], AM (Andrew Martin, UCSD SIO, mc@ucsd.edu), RL (Ruby Leung, DOE Pacific Northwest National Laboratory, ruby.leung@pnnl.gov), RS (Ryan Spackman, Science and Technology Corporation and NOAA, ryan.spackman@noaa.gov), JI (Janet Intrieri, NOAA/OAR/Physical Sciences Division, janet.intrieri@noaa.gov), CF (Chris Fairall, NOAA/OAR/Physical Sciences Division, chris.fairall@noaa.gov), PD (Paul Demott, CSU, pdemott@lamar.colostate.edu), DD (Dave Diner, NASA Jet Propulsion Laboratory, david.j.diner@jpl.nasa.gov), and DW (Duane Waliser, NASA Jet Propulsion Laboratory, duane.e.waliser@jpl.nasa.gov).

Site	Equipment	Lead/POC	2009	2010	2011	2012	2013	2014	2015	2016
Central Sierra—Sugar Pine	Aerosol, meteorological	AW, KP	X	X	X	X				
Southern Sierra—Mariposa	Aerosol, meteorological	AW, KP		X	X					
Central Valley—Sloughhouse	ARO	AW		X	X					
Central Valley—Lincoln	Scanning radar, radiosondes	DK			X					
Carquinez Strait—Concord	ARO	AW		X	X					
HMT network—Many sites	Meteorological—in situ, radar	AW	X	X	X	X	X	X	X	X
BBY	ARO, aerosol	AW, KP, AM						X	X	X
DOE G-1	Aerosol chemistry, microphysics	RL, KP			X				X	
DOE AMF2	Suite	RL							X	
NOAA G-IV	Dropsondes, radar	AW, RS, JI						X	X	
RVB	AMF2, aerosol, air–sea fluxes, expendable bathythermographs, conductivity–temperature–depths	CF, RL, PD							X	
NOAA P-3	Dropsondes, Doppler radar, etc.	RS, DK							X	
NASA ER-2	AirMSPI-2, CPL	DD, RS, DW							X	

are to highlight the key societal drivers across the U.S. West Coast region, to describe the science gaps being addressed by CalWater-2 and how the program of field studies has been organized and conducted, to summarize major results to date, and to discuss ongoing research and programmatic priorities.

Societal drivers. The 2013–2016 drought in California (including up to 95% of the state reaching severe drought status, and 50% exceptional drought) has stressed the vital agriculture sector and is responsible for billions of dollars in economic damages. Key regions are under serious water restrictions, and in the November 2014 election, voters passed a major statewide proposition focused on water issues with landslide support (67% in favor). Conversely, the region is also prone to major flooding, with California ranked in the top three

states nationally for flood damages (Pielke et al. 2002). In many instances droughts end with floods or even landslides, as in the tragic Oso landslide in Washington State that killed 43 people in March 2014 following a record dry early–midwinter across that region (e.g., Henn et al. 2015).

The potential impact of climate change on precipitation characteristics poses an important challenge for water resource planning. Variations in the intensity, distribution, and frequency (i.e., characteristics) of precipitation events on intraseasonal to interannual time scales lead to uncertainties in water supply and flood risks (National Research Council 2010, 2012). 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 (e.g., Ralph et al. 2010; Sukovich et al. 2014) and streamflow, as well as in climate projections of extreme precipitation events and water supply (e.g., Dettinger 2011; Pierce et al. 2013; Warner et al. 2015), contribute greatly to these uncertainties in water information.

In response to these challenges, CalWater is addressing the following key questions:

- How will precipitation characteristics (i.e., extremes, annual totals, location, timing) change in the future, including drought and flood extremes?
- How are water supplies associated with precipitation (rain and snow) likely to change?
- How can better information on extremes enable climate adaptation for drought resilience, flood control, hydropower, ecosystems, and coastal inundation?
- How accurate are atmospheric river (ARs) predictions and how can they be improved?

- What roles do aerosols from long-range transport and local sources play in short-term regional weather or climate predictions?
- What information can be gained from subseasonal-to-seasonal predictions?

KEY PHENOMENA AND SCIENCE GAPS. This section briefly describes the science gaps that have been identified over the last several years, starting with a key workshop in 2008, and codified by the CW SSC in CEC (2012). CalWater uses a coupled modeling–observational strategy to address a set of scientific objectives central to advancing research on the dynamics of extreme precipitation and aerosol–cloud–precipitation interaction along the U.S. West Coast, and these objectives are listed in Tables 3a and 3b. These emphasize the water vapor budget, dynamics, predictions and climate projections of ARs), and studies exploring to what extent different types of aerosols and their microphysical cloud impacts influence precipitation efficiency. A multi-platform observational approach is used, including

TABLE 3A. Specific science questions focused on ARs and their hydrometeorological impacts.
CalWater AR science
1	Study the impact of global weather patterns, such as El Niño–Southern Oscillation (ENSO), Madden–Julian oscillation (MJO), and the Pacific–North American (PNA) pattern, and their tropical–extratropical teleconnections on the frequency, development, and evolution of ARs, and on the interactions of clouds and aerosols that affect precipitation.
2	How does intraseasonal and interannual variability of the large-scale flow over the North Pacific influence the predictability of ARs? Evaluate what variability influences changes in the storm track that increases or decreases the likelihood of landfalling ARs on different time scales.
3	Evaluate to what extent sea surface temperatures, synoptic and mesoscale near-surface wind structures, 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. How much water vapor is entrained directly from the tropics vs the midlatitudes, and what are the pathways for water vapor to the precipitating events at landfall?
4	Can alongfront variability of water vapor transport, such as that associated with 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)?
5	How does terrain-modulated flow impact the mesoscale distribution of precipitation, aerosols, and their impacts in the mountains [e.g., near the north end of the Central Valley due to the Sierra barrier jet (SBJ)]?
6	Examine the vertical structure of precipitation, water vapor, winds, and static stability in ARs using a suite of vertical profiling and multisensor satellite remote sensing products [e.g., Atmospheric Infrared Sounder (AIRS), *CloudSat*, *CALIPSO*, Special Sensor Microwave Imager/Sounder (SSMIS)]. Use HMT vertically pointing radar observations to improve our understanding of coastal orographic precipitation (rain-out) for improving quantitative precipitation estimation (QPE) algorithms and for evaluating the performance of numerical weather prediction microphysics schemes.
7	Evaluate the potential of new soil moisture observations {e.g., from HMT (in situ), or satellite [Soil Moisture Active Passive (SMAP)]} in supporting identification of preconditions for flood potential associated with landfalling ARs.
AR-related modeling studies
8	To what extent do weather and climate models represent ARs, and the related distribution and frequency of precipitation? Assess the key physical processes in weather and climate models that influence the water vapor transport budget in ARs.
9	Characterize and simulate the dynamical processes (e.g., barrier jets, orographic enhancement) that modulate the precipitation associated with landfalling ARs using numerical downscaling techniques.
10	Explore medium-range to seasonal predictability and present-day prediction skill of frequency and intensity of ARs. See Table 3b. Specific science questions focused on aerosols and their influence on clouds and precipitation.

airborne, ship-, remote sensing, and ground-based assets, that covers both onshore and offshore domains (Figs. 1, 2 and 3; Table 2). In addition, a number of numerical modeling studies are involved that use either weather or climate models. While CalWater focuses on atmospheric aspects of water, it is clear that many key impacts are on hydrology. Future interactions are envisioned with hydrology programs, for example, the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI 2010).

Atmospheric rivers: Precipitation and dynamics. ARs (e.g., Zhu and Newell 1998; Ralph et al. 2004; Neiman et al. 2008b; Lavers et al. 2011; Sodemann and Stohl 2013) are narrow regions of enhanced water vapor transport in the lower troposphere that contribute significantly to the global climate and the global hydrological cycle (e.g., Newman et al. 2012). ARs are often located within the warm sector of midlatitude cyclones and can lead to major rain or flooding events upon landfall in the midlatitudes (Ralph et al. 2006, 2013; Neiman et al. 2008a, 2011; Cordeira et al. 2013). ARs are part of the three-dimensional flow within the cyclone, constituting the portion of water vapor transport in the warm sector of the midlatitude cyclone characterized by

the strongest latent heat transport (e.g., Sodemann and Stohl 2013). ARs occur in midlatitude regions across the globe (when they pass over or near Hawaii on their path to the U.S. West Coast, they are locally known as "Pineapple Express" storms). A dynamic confluence of atmospheric moisture prevalent in the midlatitudes can lead to extreme precipitation totals when ARs make landfall, particularly when forced over imposing mountainous terrain, and can both produce hydrologic hazards and supply valuable water resources (e.g., Ralph and Dettinger 2012; Leung and Qian 2009; Zhu and Newell 1998; Guan et al. 2010; Dettinger et al. 2011; Ralph et al. 2013). Some of the largest uncertainties in predicting these events propagate from limitations in quantitative understanding of the water vapor transport in ARs, including accuracy in representing the terms in the water vapor budget equation (i.e., water vapor convergence, evaporation, and precipitation). These terms are sensitive to errors in the representation of air–sea fluxes and microphysics (e.g., Cordeira et al. 2013; Neiman et al. 2014). Another limitation is the representation of how mesoscale features of ARs are affected by complex terrain. A key orographic effect is the generation of coastal and Sierra barrier jets (SBJs) associated with blocking of low-altitude airflow as storms approach the mountains from offshore (e.g.,

	TABLE 3B. Specific science questions focused on aerosols and their influence on clouds and precipitation.
	CalWater aerosol–cloud–precipitation science
1	Quantify the enhancement or suppression of precipitation associated with variations in aerosols in the relevant regions of synoptic-scale systems (e.g., in the extratropical cyclone or AR) where aerosols are nucleating water vapor or ice.
2	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. This includes consideration of the spatiotemporal extent of different sources, as related to the hypothesized modulation of the seeder–feeder mechanism, where boundary layer aerosols can reduce riming efficiency while upper-level long-range transport aerosols seed higher-level (>3 km) clouds forming ice (which leads to riming).
3	How sensitive is the precipitation rate in ARs over the ocean to possible influences of aerosols, including remote dust, pollution, and marine biological aerosols?
4	Investigate the role of aerosols on the thermodynamic development of extratropical cyclones and the coupled ARs associated with these storms.
5	To what extent does the large-scale flow influence the interaction of aerosols and precipitation at midlatitudes in a way that influences cyclogenesis?
6	Improve model treatment regarding the above-mentioned mechanistic processes to improve current predictive capabilities—either in research or operational modes.
7	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 United States 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?
	Aerosol–cloud–precipitation–related modeling studies
8	Quantify how well global and regional aerosol models simulate the emission, transport, and removal of aerosols.
9	Assess and refine the representativeness of microphysical parameterizations for the processes associated with nucleation scavenging in different types of clouds (e.g., mixed phase).
10	Study the impact of aerosols on QPEs and use the observations from the CalWater-2 study to improve QPFs.

Kingsmill et al. 2013; Neiman et al. 2013). The barrier jet can strongly modulate the location of precipitation and can move boundary layer aerosols along the base of a mountain rather than up and over the mountain, yet are not represented well if the model resolution is too coarse (Hughes et al. 2012).

Wick et al. (2013b) used three winters of forecasts from the world's leading forecast centers [European Centre for Medium-Range Weather Forecasts (ECMWF), National Centers for Environmental Prediction (NCEP), Met Office, Japan Meteorological Agency, Canadian Meteorological Centre] to quantify that on average there is ±500-km uncertainty in the landfall position of ARs striking the U.S. West Coast at 5-day lead time. Also, the existence of mesoscale frontal waves has been shown to be key to causing an AR to stall at the coast (e.g., Ralph et al. 2011), and yet these frontal waves are notoriously difficult to accurately predict. The National Weather Service's (NWS) precipitation forecasts systematically have had a 50% low bias in the extreme events in the West Coast area, 90% of which were landfalling ARs (Ralph et al. 2010). Very recently Doyle et al. (2014) concluded that the largest source of errors in initial conditions for a numerical prediction of a landfalling extratropical cyclone (named "Xynthia") in Europe was the uncertainty in the position of water vapor associated with an AR offshore 2 days before landfall. "The moisture sensitivity indicates that only a relatively small filament of moisture within an atmospheric river present at the initial time was critically important for the development of Xynthia" (Doyle et al. 2014, p. 338).

Moving to the global scale, GCMs project an increase in zonally averaged horizontal water vapor transport at nearly all latitudes; for example, for 40°N in winter, 22 GCMs project that integrated water vapor (IWV) transport (IVT) will increase between 10% and 40% by the end of the twenty-first century under emission scenario representative concentration pathway 4.5 (RCP4.5; Lavers et al. 2015). Although the global water budget has long been a subject of research, the means to quantify (observationally) how well models portray the meridional transport of moisture over the globe within ARs and related phenomena (e.g., tropical moisture exports and warm conveyor belts) has been absent. Nonetheless, recent evaluations of global climate model representations of precipitation, evaporation, and moisture transport against observed river discharges into oceans (Trenberth et al. 2011, p. 4907) concluded: "Their differences reveal outstanding issues with atmospheric models and their biases." One reason for this is that horizontal water vapor transport in climate models is sensitive to grid spacing (Hughes et al. 2012; Demory et al. 2013). It should be noted that convection is also sensitive to model resolution, which could also contribute to these errors. These uncertainties raise the question of how much water vapor transport is correct, which squarely points to a gap in our quantitative understanding of ARs and a *lack of observations against which to evaluate this sensitivity*. Demory et al. (2013, p. 2202) note that "although observational studies of the global energy and water budgets are an essential aspect of assessing GCMs, their incompleteness and lack of independence and physical consistency prevent an accurate component-level evaluation of the global hydrologic cycle in GCMs."

Aerosols: Impact on clouds and precipitation. Improvements in our predictive capability of extreme weather and climate events involves understanding the interaction between aerosols of different sizes and compositions with water vapor, liquid, and ice in clouds to promote or suppress precipitation. Aerosols from multiple sources, including local pollution and biomass burning, sea salt, and long-range transported dust and biological particles acting as cloud condensation nuclei or ice nuclei, have been shown to influence clouds and precipitation in California. For example, anthropogenic aerosols that are incorporated from the surface and boundary layer in orographic clouds can efficiently slow down cloud-drop coalescence and riming on ice precipitation (Rosenfeld et al. 2008b, 2013a). The delayed conversion of cloud water into rain can reduce precipitation in the upwind slopes of mountains with small compensation on the lee side, resulting in a net loss of precipitation and mountain snowpack (Givati and Rosenfeld 2004; Rosenfeld and Givati 2006). On the contrary, long-range transported dust and biological particles may serve as efficient ice nuclei to enhance precipitation and increase the ratio of snowfall to total precipitation (Ault et al. 2011; Creamean et al. 2013; Fan et al. 2014). Aircraft measurements in CalWater-1 showed that clouds in pristine air masses with dearth of ice nuclei were devoid of ice and snow and had persistent supercooled cloud and rainwater down to −21°C (Rosenfeld et al. 2013b). Aerosols may also affect ARs through enhancing the North Pacific cyclones by the mechanism of convective invigoration (Rosenfeld et al. 2008a), as found by Wang et al. (2014a,b). Aerosol influences are also affected by meteorological and kinematic considerations, such as an SBJ limiting where boundary layer aerosols reach clouds, and decoupling of boundary layer and elevated marine layers that may

determine the microphysical properties of modestly supercooled cloud regions (Rosenfeld et al. 2013a,b).

Understanding the different sources of aerosols and how they affect clouds and in turn precipitation has important implications to forecasting of precipitation, floods, and water resources at weather to seasonal time scales. Given the notable impacts of aerosols on precipitation intensity, phase, and spatial distribution, there is a need to evaluate the potential for improving quantitative precipitation forecasts (QPFs) by incorporating aerosol effects, including the assimilation of aerosol and cloud observations, into operational models. On interannual to longer time scales, it is plausible that precipitation may respond to variations and changes in dust emissions, biomass burning, anthropogenic emissions, marine aerosol sources, and terrestrial biological sources. Creamean et al. (2015) and White et al. (2015) diagnosed interannual and regional variations, respectively, in aerosol content of precipitation and the character of precipitation and described meteorological and microphysical mechanisms that were in play. Dettinger and Cayan (2014) found that 85% of the variance in annual precipitation in northern California results from variations in the top 5% wettest days each year, which are associated with ARs. Thus, the combined degree to which the number and strength of ARs change and their precipitation efficiency change can have significant impact on water resources management and hydropower potential. Observations can fill gaps in understanding and modeling aerosol effects on regional precipitation for advancing predictions of water cycle changes in the future.

ACCOMPLISHMENTS TO DATE. *Field deployments.* "CalWater-1" increased the number of precipitation, aerosol, and kinematic (wind) observing sites, platforms, and sensors across
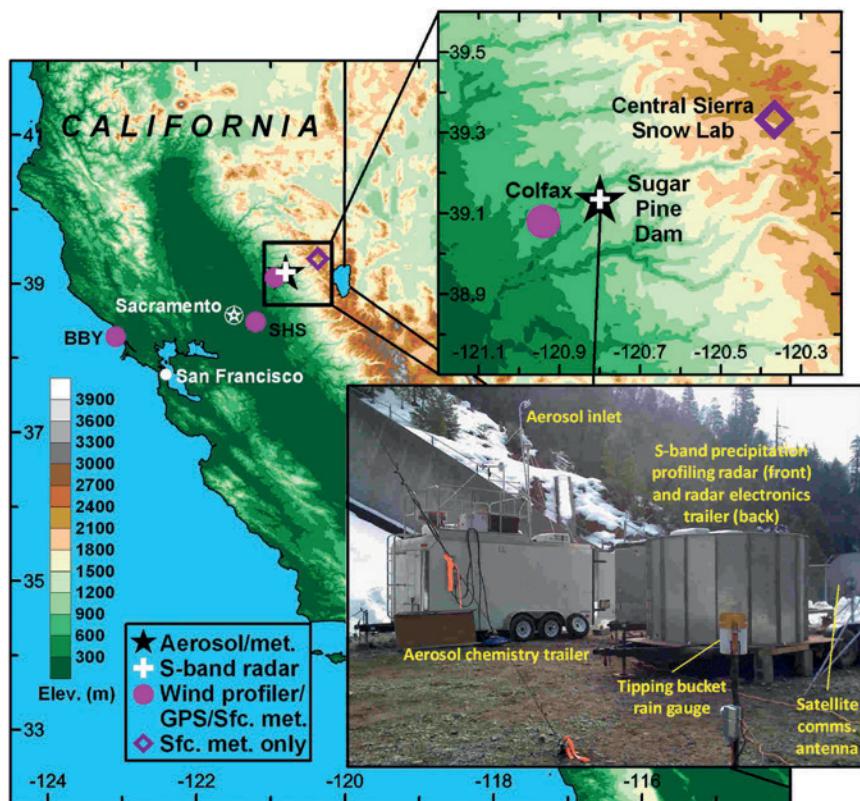
Fig. 2. Integrated aerosol–cloud–precipitation–hydrometeorology field site at Sugar Pine Dam in Feb 2009 (from Ault et al. 2011).

California, and collected data, from 2009 to 2011. The effort focused on data collection in the Sierra Nevada, the Central Valley, and along the coast near Bodega Bay, California (Fig. 1). The first CalWater field deployment occurred during two weeks in late February 2009 at one observing site (Sugar Pine; Fig. 2). This short "early start" field deployment observed two ARs, 30% of the water-year precipitation, and evidence of Asian dust. The 2011 field season confirmed several previous science postulates. These included the role of long-range transported aerosols on triggering snow precipitation (Ault et al. 2011; Creamean et al., 2013), as well as the role of highly supercooled layers and convective clouds of possible marine origin commonly acting as sources of drizzle and rain and as "feeder" clouds. Also, the interaction between landfalling ARs and the SBJ was documented (Kingsmill et al. 2013; Neiman et al. 2013).

"CalWater-2" started collecting data in February 2014 and emphasized coastal and offshore observations. The initial deployment was intended to be a brief and small early start campaign with three to four flights of the National Oceanic and Atmospheric Administration (NOAA) G-IV aircraft, but it expanded to include 12 flights and aerosol/

microphysics observations at Bodega Bay on the coast. The CalWater-2015 field deployment (Fig. 3) included NOAA's flagship Research Vessel *Ronald H. Brown (RVB),* as well as a P-3 and G-IV aircraft. The DOE-sponsored Atmospheric Radiation Measurement (ARM) Cloud Aerosol Precipitation Experiment (ACAPEX) campaign provided the DOE ARM Mobile Facility 2 (AMF2) observing system, mounted on the NOAA vessel, as well as the DOE G-1 aircraft and support for aerosol and microphysics sensors at the coast. The NASA ER-2 aircraft flew several missions as well with remote sensors tailored partly for validation of a prototype space-based sensor being tested on the International Space Station. The California Department of Water Resources (DWR)-sponsored statewide extreme precipitation network, tailored to observe landfalling ARs, was a foundation of the experiment. Table 2 provides a concise list of major sites, equipment, principal investigators (PI) or points of contact (POCs) and data collection from 2009 to the present. See the caption for Table 2 for the full names, affiliations, and e-mail contact information for the POCs.

Targeted phenomena observed thus far. The meteorological emphasis of CalWater-1 was on observing landfalling ARs and SBJs, as well as their interaction. The aerosol emphasis of CalWater-2 was on collecting precipitation in a range of atmospheric conditions that included ARs, shallow orographic rain, post-frontal convection, snow, and under various aerosol conditions.

ATMOSPHERIC RIVERS AND SIERRA BARRIER JETS. During the three CalWater-1 field seasons, 13 SBJ events and 10 ARs were observed during intensive observing periods (IOPs). Of the SBJs, four were strong (>25 m s⁻¹ maximum wind), seven were moderate (15–25 m s⁻¹), and two were weak (<15 m s⁻¹) using the criteria of Neiman et al. (2009). Of the ARs, one was strong (i.e., offshore IWV > 3 cm), seven were moderate, and two were weak (i.e., offshore IWV marginally reached 2 cm). During the 2010/11 CalWater-1 field season (December–March), the total precipitation at key Sierra Nevada sites during IOPs was 480–660 mm (19–26 in.; including over 300 cm, or 120 in., of snow; see Guan et al. 2013). This precipitation was 60% of the total precipitation during the 3.2-month field season. The scanning radar collected 295 h of data, and 87 radiosondes were launched to capture the interaction between ARs penetrating inland to the Sierra Nevada and SBJs. In addition, the NOAA G-IV flew 12 missions in February 2014 as part of the CalWater-2 Early Start campaign. The first week of the early start campaign was extremely active with a series of landfalling ARs across northern California (Fig. 4), Oregon, and Washington. Landfalling ARs during the period of 7–9 February 2014 brought 250–375 mm (10–15 in.) of rain to parts of northern California, providing some drought relief. Although the roughly 190 mm observed by the northern Sierra eight-station index was about 25% of its total for the water year, the year overall received only 62% of normal, and the region's drought continued. Later landfalling AR events in February and March 2014 produced more rain in Oregon and Washington, eventually eliminating their drought conditions and preconditioning soils for a massive, and fatal, landslide in Washington (Henn et al. 2015). CalWater-2015
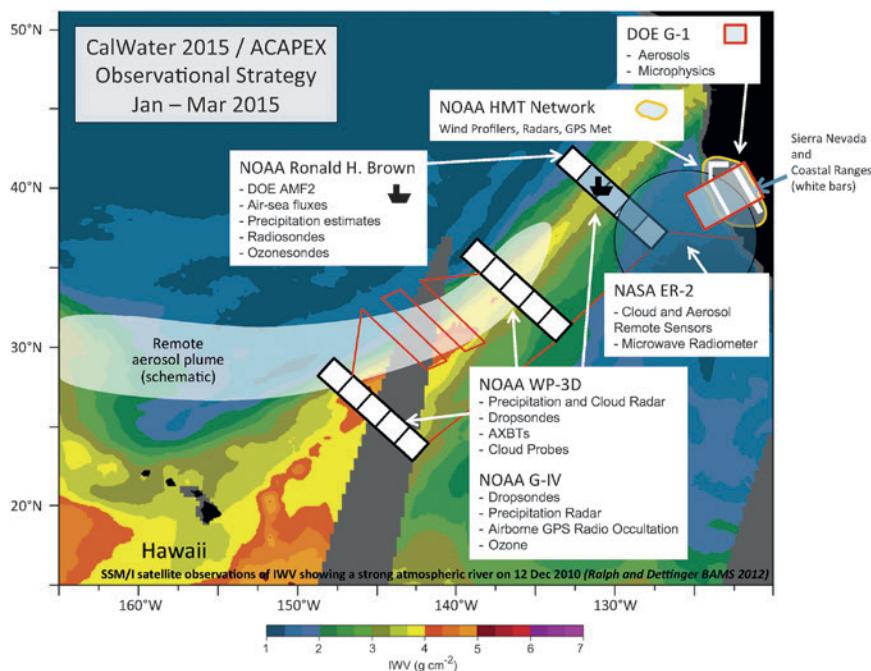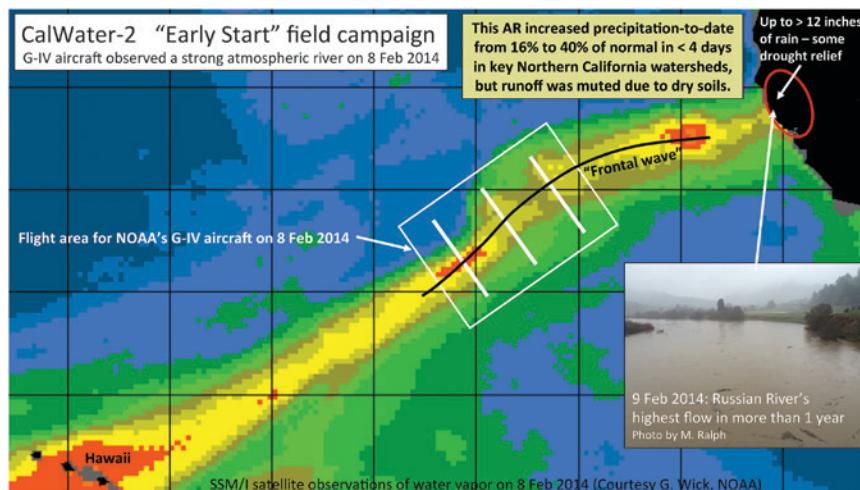

FIG. 3. Conceptual design of a major field experiment developed for the CalWater-2 science white paper in 2012, which formed the foundation for proposals to DOE, NOAA, NASA, NSF, ONR, and the California Energy Commission (CEC).

captured many more AR events, especially offshore (see the CalWater-2015 section).

AEROSOLS AND MICROPHYSICS. In 2009, the Scripps Institution of Oceanography (SIO) mobile laboratory of the University of California, San Diego (UCSD); precipitation sampling [U.S. Geological Survey (USGS)]; and surface meteorology and radar {HMT West [NOAA/Earth System Research Laboratory (ESRL)]} operated at

FIG. 4. Satellite image (SSM/I water vapor) and associated flight track of the NOAA G-IV aircraft on 8 Feb 2014.

Sugar Pine Dam for two weeks in late February 2009 (Fig. 2). In 2010, the same suite as in 2009 at Sugar Pine Dam was also operated at the Mariposa airport in the southern Sierra Nevada in February and March. The 2011 field campaign included 25 flights of the DOE G-1 aircraft from McClellan Air Base (Sacramento, California) between 2 February and 6 March 2011. The aircraft collected aerosol size distributions, cloud condensation nuclei (CCN), ice nuclei [Colorado State University's continuous flow diffusion chamber (CSU CFDC)], aerosol and cloud residual particle chemistry (ATOFMS), and cloud microphysical data over a region extending from just off the Pacific coast to the Nevada border, and along the Central Valley. Also, the UCSD SIO mobile laboratory, precipitation sampling (USGS), and surface meteorology and radar [HMT West (NOAA/ESRL)] operated again at Sugar Pine Dam, for the third consecutive winter. During the CalWater-2 Early Start campaign in 2014, the UCSD SIO mobile laboratory, precipitation sampling (USGS), surface meteorology and radar [HMT West (NOAA/ESRL)], and ice nucleation measurements were collected at the Bodega Marine Laboratory from 13 February to 10 March 2014. During this time the nearby coastal mountains received up to 200 mm (8 in.) of rain. CalWater-2015 captured even greater amounts of data on aerosol–cloud–precipitation processes, including a major field site at the coast (see the CalWater-2015 section).

Select findings. DUST FROM LONG-RANGE TRANSPORT IS FOUND TO INFLUENCE SIERRA NEVADA PRECIPITATION. In spite of the brevity (two weeks) and its logistical shakedown focus, the CalWater Early Start

campaign in February 2009 produced two well-defined ARs and significant precipitation. It also provided the first observation of long-range transport of dust in the precipitation at the ground, with supporting meteorological evidence that the dust had originated from over Asia and entered the tops of orographic clouds over the field site in the Sierra Nevada (Ault et al. 2011). Two 2009 events each had AR conditions with nearly identical orographic forcing (storm-total water vapor flux and AR orientation). However, the latter event produced 40% greater precipitation, and, unlike the first event, dust was detected in the precipitation collected (Ault et al. 2011). This result was reinforced by the collection of aerosol and cloud microphysics data by aircraft in the clouds in 2011, as well as surface precipitation sampling and meteorological data, which included evidence that dust at higher altitudes (3–6 km) was acting as ice nuclei (Creamean et al. 2013; Fig. 5). This role of dust aloft was found to be especially important in the postfrontal conditions (Fig. 5b; and after passage of the upper clouds above the AR). Through data analysis (Creamean et al. 2013) and numerical modeling (Fan et al. 2014), the 2011 field experiment provided further important evidence of the impact long-range transported dust has on snowfall in the Sierra Nevada, suggesting that precipitation from clouds seeded by dust and biological particles enhanced riming in the lower-level orographic clouds through the seeder–feeder mechanism, leading to enhanced precipitation from the Central Valley to the mountains. Modeling results (Fan et al. 2014) suggest that seeding by long-range transported aerosols increased precipitation by 10%–20% due to a ~40% increase in snow

formation in two case studies. The existence of lower-elevation cloud layers supercooled to as low as −20°C and apparently deficient in ice nuclei, perhaps due to marine air overrunning (see next subsection) or stable stratification that leads to a decoupling of the surface boundary layer from clouds at times, enhances the role of aerosols transported at higher levels. In short, the two 2009 events each had AR conditions with nearly identical orographic forcing (storm-total water vapor flux and AR orientation), but the latter one that included dust aloft produced 40% greater precipitation (Ault et al. 2011).

ATMOSPHERIC RIVERS OVERRUN THE SIERRA BARRIER JET. Until the CalWater-1 field deployments, it was uncertain how an inland-penetrating AR was affected by the presence of an SBJ. Hypotheses included that 1) the AR swept out the SBJ, 2) the AR turned due to blocking and became the SBJ, and 3) the AR rode up and over the SBJ, or some combination of these. The importance of this process arises from the key roles of the AR and SBJ in determining the location of orographic precipitation (Neiman et al. 2013; Kingsmill et al. 2013), as well as the nature of the aerosols in those airstreams. These questions were addressed through observations collected in 2011 by a network of wind-profiling radars, a balloon sounding system, and a scanning C-band Doppler radar ("SkyWater radar") (Fig. 6). Observations showed that as an AR penetrates inland from the coast to the Central Valley, it often rides up and over the SBJ (Kingsmill et al. 2013; Neiman et al. 2013), although there is some evidence of merging with the western edge of the SBJ (Kingsmill et al. 2013). Kingsmill et al. (2013) also showed that the nearly orthogonal airstreams caused orographic precipitation in differing regions; the Mount Shasta area precipitation is dominated by the SBJ and the northern Sierra area precipitation is dominated by the overrunning AR. Finally, a dynamical downscaling method, validated against CalWater-1 observations, determined that models require fine resolution (i.e., <10-km grid spacing) to accurately capture the northward transport of water vapor by the SBJ, without which there are errors of roughly 25%–35% in the models' meridional versus zonal water vapor fluxes, thereby contributing to serious errors in downwind water budgets (Hughes et al. 2012).

PROJECTED TRENDS IN ATMOSPHERIC RIVERS IN CLIMATE MODELS. As context and motivations for CalWater, the presence of, and future changes in, ARs making landfall on the central California coastline in coupled ocean–atmosphere climate models used in the
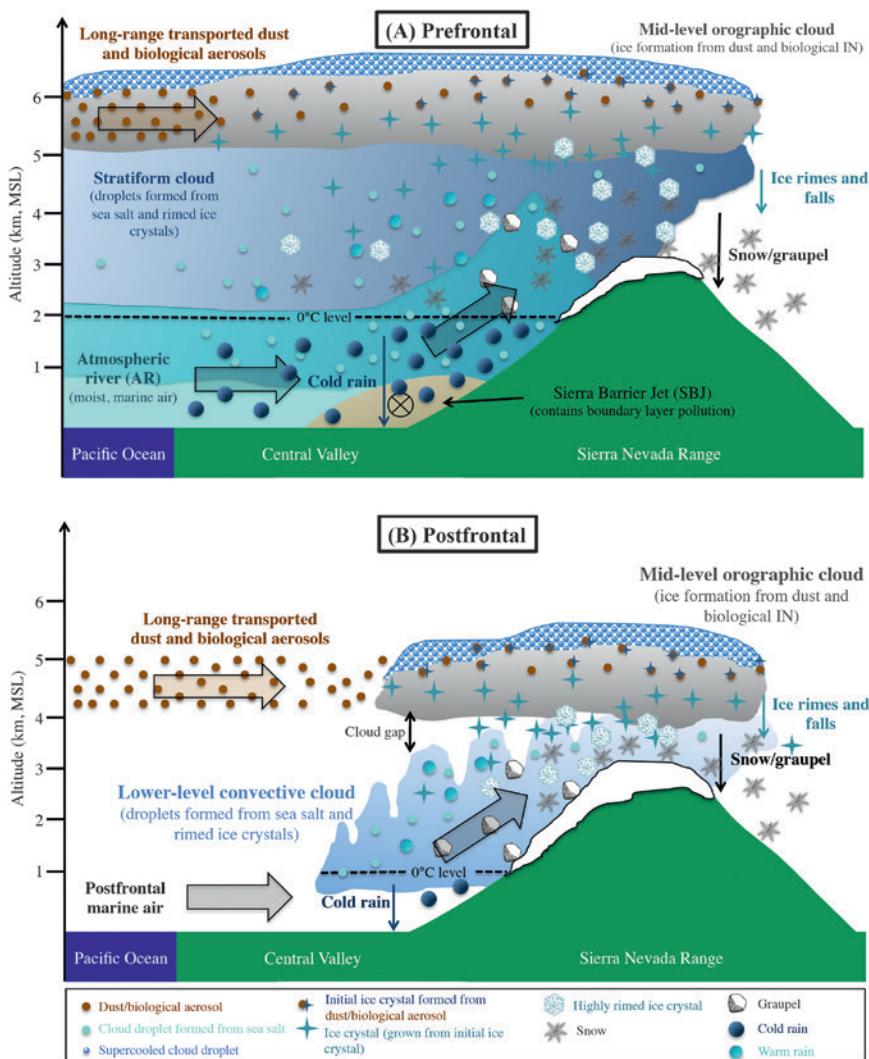
FIG. 5. Schematic synopsis of aerosol–AR–SBJ interactions, and their impacts on clouds and precipitation (from Creamean et al. 2013).
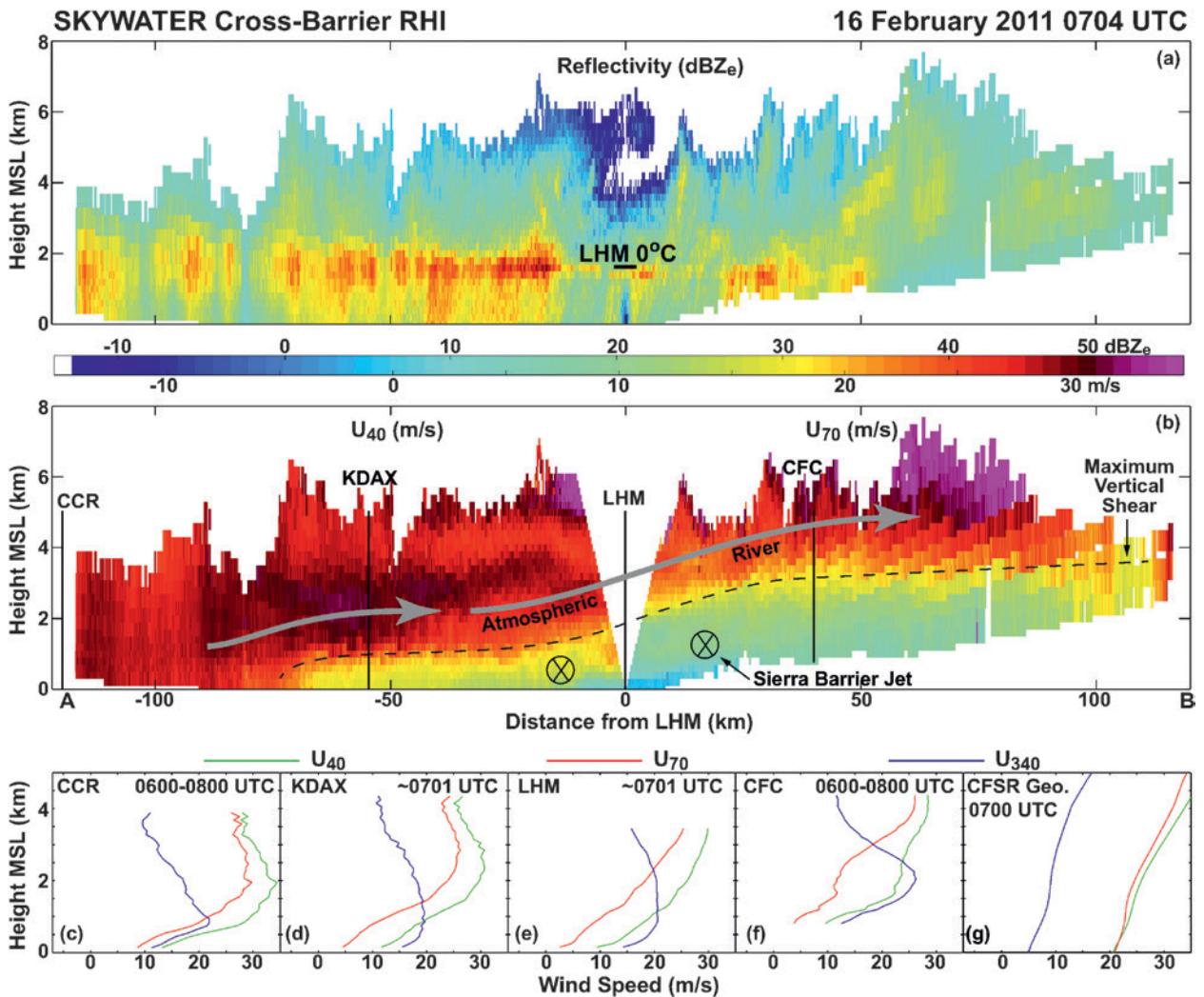
Fig. 6. SkyWater radar observation of an AR riding up and over an SBJ seen in a cross section from west to east crossing the radar site in the Central Valley (from Fig. 12 in Kingsmill et al. 2013).

Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007) were explored. ARs are present in modern weather (Zhu and Newell 1998) and climate models (e.g., Fig. 7). Using IVT thresholds patterned upon those used in operations and recent studies (Rutz et al. 2014), all ARs were identified in projections of future climates, under continuously accelerating (A2) greenhouse gas emissions by seven climate models; then, the future ARs were compared to those in historical climate simulations by the same models. Although westerly winds across the central California coast generally weakened in the projections (see Fig. 6 in Dettinger 2011), the amount of vapor in the atmosphere increased as the atmosphere warmed (Fig. 5 in Dettinger 2011), so that the number of meteorological occasions that rise to atmospheric river status increases significantly in five of the seven models. Average IVT rates in the future ARs

increased in five of the seven models (but a different five), with average AR IVTs in the remaining models more or less remaining unchanged. Notably though, in all seven models, the largest IVTs simulated in the late twenty-first-century ARs were substantially greater than any in the twentieth century (Dettinger 2011). Similar results have been reported for ARs in other parts of the world (e.g., Lavers 2015). More recently, using model outputs from the Coupled Model Intercomparison Project, phase 5 (CMIP5), for the IPCC's Fifth Assessment Report, Warner et al. (2015) found increases in the 99th percentile IWV and IVT corresponding to more extreme AR events along the west coast of North America. Enhanced IWV is the main contributor to the increase in IVT, suggesting negligible change in winds. Thus, ARs are expected to be increasingly important and hazardous in California and, probably also, along the west coasts

of midlatitude landmasses worldwide. Our knowledge of, and ability to anticipate (in terms of both weather and climate), the frequency, timing, intensities, and the precipitation efficiencies of AR storms will only become more important in terms of water resources, droughts, and floods, as the century's climate changes unfold (Dettinger et al. 2011; Das et al. 2013; Dettinger and Cayan 2014). It should be noted that the dominant cause of interannual variability in precipitation in northern California's key watershed is due to interannual variation in the top 5% wettest days each year, which are primarily associated with landfalling ARs (Dettinger and Cayan 2014).

AUTOMATED AR DETECTION METHOD DEVELOPMENT AND ASSESSMENT OF FORECAST SKILL. A key approach in assessing ARs in satellite observations, reanalyses, climate models or weather models, or in assessing their impacts is to examine as many AR events as possible. The most observationally oriented method has used IWV (Ralph et al. 2004, Neiman et al. 2008b), but it has depended on human pattern recognition. Although simpler methods have been developed for some applications, such as described above, there was a need to develop a fully automated method. CalWater-1 efforts included development of an IWV-based automated AR detection tool [Atmospheric River Detection Tool (ARDT) for IWV (ARDT-IWV); Wick et al. 2013a] based on modern pattern recognition software and methods, and was validated against the human-pattern recognition method, with a 92% critical success index across many events. Because the ARDT-IWV can be applied to both satellite- and model-generated spatial grids of IWV, it was now possible to evaluate many forecasts of ARs against the Special Sensor Microwave Imager (SSM/I) satellite–observed AR conditions at landfall. This included evaluations of five leading global models, over three winters and for lead times out to 10 days, in terms of AR landfall on the U.S. West Coast. It revealed for the first time key systematic aspects of current AR prediction performance (Wick et al. 2013b), including the following: in many cases ARs were seen in the forecasts as much as 10 days before landfall, values of maximum IWV were relatively well predicted out several days, and landfall location error increased from ±200 km at 1-day lead time to ±900 km at 10-days' lead time (Fig. 8). Analysis also showed up to 1°–2° latitude southward bias in landfall location at several days lead time. This evaluation provides a baseline against which to measure future forecast performance.

FUTURE DIRECTIONS—A VISION AND EARLY START FOR CALWATER-2. *CalWater-2 planning and early start field activities from 2012 to 2014.* In late 2011, during the analysis phase of CalWater-1, it was recognized that major gaps in our understanding of key physical processes remained, and that many of these related to conditions offshore over the eastern North Pacific Ocean. Filling these gaps would require a larger scope of planning and field activity, and of funding. To further develop these goals and plans, a CalWater-2 Science Steering Committee SSC was formed, co-chaired by Ralph, Prather, and Cayan. The CalWater-2 SSC developed a science white paper (CEC 2012) that captured the
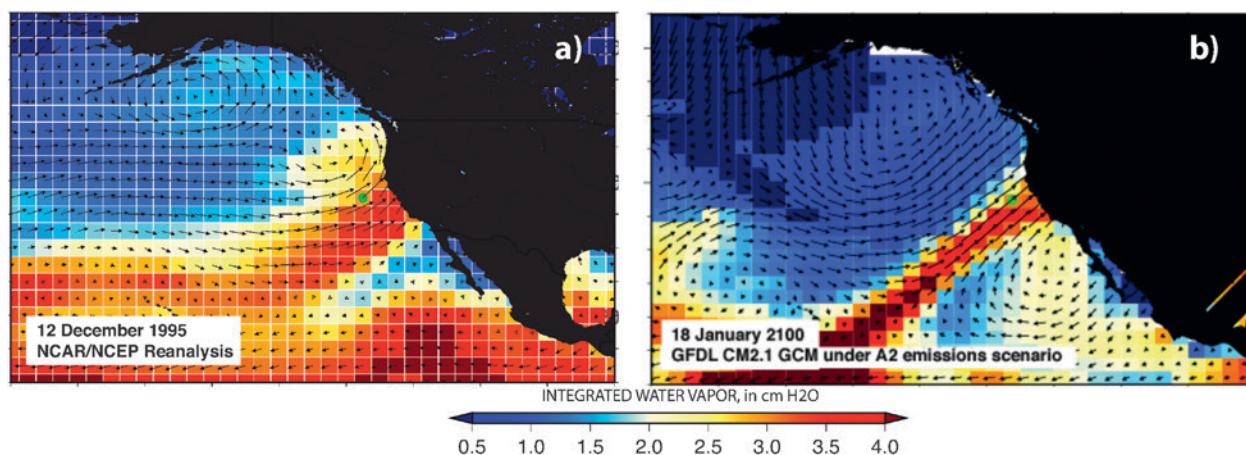

FIG. 7. Maps of 925-mb winds (vectors) and IWV (shading) over oceans from (a) National Center for Atmospheric Research (NCAR)–NCEP Reanalysis-1 fields (updates to Kalnay et al. 1996) on 12 Dec 1995, and from (b) the Geophysical Fluid Dynamics Laboratory Climate Model, version 2.1 (GFDL CM2.1), under an A2 emissions scenario on 18 Jan 2100 (modified from Dettinger 2011).

science gaps, hypotheses, and methods to address them. Key planning milestones are shown in Table 1.

The CalWater-2 SSC white paper became the foundation for several proposals. The first was submitted in 2012 to DOE for use of its G-1 aircraft and AMF2, as well as the UCSD SIO's ATOFMS, the CSU CFDC ice nucleation instrument, and other sensors, to pursue CalWater objectives. The proposed study was named ACAPEX, and it placed a heavy emphasis on the aerosol–cloud–precipitation aspects of CalWater-2. Subsequently, filter collections for ice nuclei concentration and (chemical and biological) composition measurements were added to the AMF2 suite of remote sensing and aerosols measurements via the DOE ARM program support. A later proposal to the National Science Foundation (NSF) provided support of ground-based aerosol measurements at the coast to coincide with ACAPEX and CalWater-2 more generally (including multiyear data collection).

In addition, by this time the installation of a unique major network of sensors (100 sites) was nearly complete in California, focused on landfalling ARs and associated hydrometeorological conditions (White et al. 2013). Thus, the SSC agreed it was time to present the white paper to federal agency programs that had expressed some interest in potentially engaging in some way. This turned into a pair of meetings in Washington, D.C., in May 2013 at NOAA and then at NSF. The meetings also included DOE and NOAA/Office of Naval Research (ONR) representatives. One outcome of the presentations was exploration by NOAA of deploying the NOAA G-IV research aircraft in early 2014 as a CalWater-2 Early Start effort. As the record-breaking California drought deepened and as awareness increased of the key role of ARs (in fact, the absence of ARs) in the drought [including a result by Dettinger (2013) that showed ARs were key in ending droughts in the region], NOAA committed to a major deployment. Twelve flights of the G-IV were carried out in February 2014, just as the first (and only) significant ARs of the winter hit northern California. The campaign was based near San Francisco, but then operated also out of Hawaii and Alaska, thereby demonstrating the feasibility of a major G-IV campaign focused on ARs. This campaign helped motivate the development of new AR-focused forecast tools that were used daily in flight planning. They were
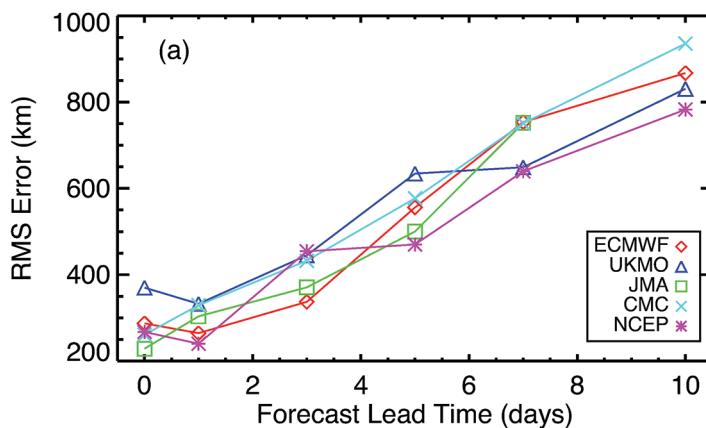
Fig. 8. Estimates of error in forecast AR landfall location as a function of lead time based on the evaluation of five leading global numerical weather prediction models using the ARDT-IWV method. Validation of forecasts was made using SSM/I satellite–based observations of AR landfall position (from Wick et al. 2013b).

developed through a partnership between the Center for Western Weather and Water Extremes (CW3E) at SIO (Ralph), Plymouth State University (Cordeira), and NOAA (White), and are now available as part of the new "atmospheric river portal" (http://arportal.ucsd.edu/).

Also in early 2014, a study led by Kim Prather (SIO) and Paul DeMott (CSU) carried out a ground-based early start campaign at Bodega Bay (BBY) using existing NSF support. Bodega Bay was chosen to capture marine, urban, and long-range transport aerosol properties and impacts on cloud active particle properties at a well-established coastal field site with existing infrastructure provided by Bodega Marine Laboratory of the University of California, Davis. The field site was installed on the coast and included an extensive suite of aerosol and cloud microphysics sensors, collocated with an atmospheric river observatory (ARO; White et al. 2013). The same aerosol suite (aerosol size distribution, aerosol mass, aerosol composition, CCN) and precipitation sampling systems used in previous CalWater 1 efforts were used in the early start campaign Additionally, aerosol filter collections were made for biological and ice nucleating particle analyses extending across the entire mixed-phase cloud temperature regime, and the first field linkage of the CFDC with an ATOFMS to measure the compositions of aerodynamically separated ice crystals [activated ice nucleus (IN)] from the CFDC [using a pumped counterflow virtual impactor (PCVI)]. Preconcentration of aerosols (e.g., Tobo et al. 2013) was also used successfully to improve statistical

sampling of IN concentrations at modest supercooling (to as warm as −10°C) using the CFDC.

CalWater-2015. CalWater-2015 field operations occurred during January–March 2015 over California and offshore (following roughly the concept in Fig. 3), and involved a wide array of sensors and platforms (Fig. 9). The science leadership team members and their roles in the CalWater-2015 field campaign are summarized in Table 4. Observing platforms for CalWater-2015 included the DOE facilities allocated as part of the aerosol-focused ACAPEX campaign, as well as *RVB*, which carried DOE's AMF2 equipment suite, plus the NOAA seagoing air–sea flux (www.esrl.noaa.gov/psd/spotlight/2011/flux-system.html) and other oceanographic sensors. The DOE G-1 came as part of ACAPEX, along with ice nucleating particle measurements online by CFDC

and offline using filter collections, ATOFMS, and a major suite of cloud microphysics sensors. NSF sponsored a ground-based site for air chemistry, aerosols, and cloud microphysics at Bodega Bay. NOAA also allocated its G-IV aircraft again, building on experience from the CalWater-2 Early Start in 2014, and one of its P-3 aircraft, both carrying dropsondes and tail Doppler radars, and emphasizing observations of water vapor transport and its structure in ARs. The P-3 also carried a downward-looking ocean wave radar, a downward-looking W-band Doppler cloud radar, and airborne expendable bathythermographs (AXBTs) from the navy to measure the ocean mixed layer. The G-IV also carried an ozone sensor and a GPS radio occultation (RO) sensor [the Global Navigation Satellite Systems Instrument System for Multistatic and Occultation Sensing (GISMO), an airborne version of the Constellation Observing
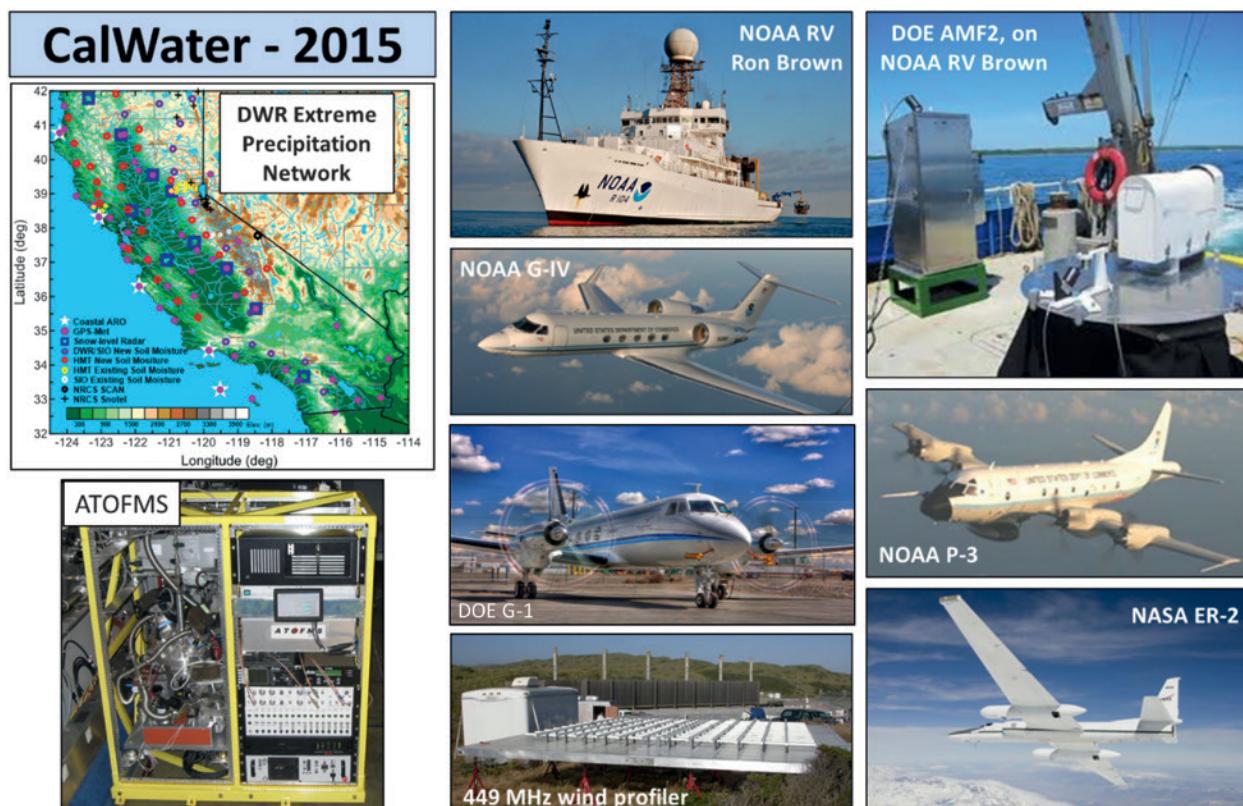
Fig. 9. Major observing facilities and mobile platforms for CalWater-2015 (12 Jan–8 Mar 2015). DOE G-1 aircraft: measuring cloud, rain, and snow particles, as well as aerosols, such as dust and smoke from sources near and far. NOAA G-IV aircraft: measuring AR strength and structure offshore using dropsondes and precipitation radar. NOAA P-3 aircraft: measuring ocean and atmosphere with radars for precipitation, clouds, ocean waves, and dropsondes (atmosphere) and AXBTs (ocean). NOAA Research Vessel *RVB*: measuring aerosols, clouds, ARs, ocean surface and subsurface conditions and air–sea fluxes. DOE AMF2: many sensors mounted on the NOAA ship, measuring aerosols, precipitation, clouds, and winds aloft and at the surface. California DWR extreme precipitation network: measuring ARs, snow level and soil moisture across California. NSF-sponsored aerosol and rain measurements at the coast. NASA ER-2 aircraft: measuring aerosols, clouds, and water vapor with radar, lidar and radiometer, and radiosondes.

System for Meteorology, Ionosphere and Climate (COSMIC) satellite RO method]. Table 2 provides a list of the platforms, equipment, the primary sponsor, and the instrument lead.

The final major facility came into this deployment from the National Aeronautics and Space Administration (NASA). The ER-2 aircraft with the second-generation Airborne Multiangle Spectropolarimeter Imager (AirMSPI-2) and cloud physics lidar (CPL) sensors to measure clouds and aerosols in support of ground validation of a new prototype sensor [Cloud–Aerosol Transport System (CATS)] that was placed on the International Space Station (ISS) in 2014 as a complement to the *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (*CALIPSO*) mission in sun-synchronous polar orbit. The Rapid Scatterometer (RapidScat), another ISS sensor, was installed in August 2014 to measure ocean surface winds and is also available for calibration–validation by sensors involved in CalWater-2015.

The 2015 deployment occurred during an extreme drought in California, but nonetheless the mobility of the aircraft and ship allowed for a very successful campaign. Major AR activity occurred offshore for much of the experiment, diverse aerosol conditions occurred at the coastal aerosol field site and over California, and the largest AR and heaviest precipitation of the experiment struck in early February 2015. This event occurred exactly when the field equipment, forecast team, and field team were all in place and functioning fully. It was sampled offshore simultaneously by all four aircraft, the ship, and AMF2. When it hit shore the next day, all land-based facilities and aircraft were successfully deployed and coordinated. Table 5 summarizes the 2015 campaign, which included 56 research flights, consisting of 264 flight hours, and the release of 443 dropsondes and 148 AXBTs. The ship was at sea for 30 days and encountered at least 10 days with AR conditions. Extensive collection of in situ aerosol and microphysics measurements were made for nearly 60 days at the Bodega Bay coastal field site. NOAA, DOE, NSF, NASA, ONR, and DWR invested a combined total of more than $11 million, split about equally for atmospheric river objectives and aerosol–cloud–precipitation objectives.

Gaps, goals, and activities envisioned for 2016–18 and beyond.

- Atmospheric river water vapor budgets, including precipitation (*P*), evaporation (*E*), convergence and IWV tendency, water vapor transport, and key effects of orography on landfalling ARs (Fig. 10). A key element of this would be to obtain upstream accurate rainfall estimates over the ocean (beneath ARs) with a future polarimetric ship-based radar.
- Measurements of the snow level, rain shadows, and the dividing streamline associated with orographic precipitation (Fig. 11).
- Quantifying the extraction of long-range transported aerosols through interactions with clouds and precipitation over the Pacific, including associated with ARs.
- Satellite calibration–validation opportunities.
- Observation-based diagnostics and performance metrics for weather and climate models.
- Prediction skill and predictability assessments building on the foundation laid by Wick et al.

TABLE 4. CalWater-2015 field program science leadership team.

Mission scientists	Affiliation (emphasis)
F. Martin Ralph	SIO (ARs)
Kim Prather	SIO (aerosol–cloud/precipitation)
Ruby Leung	DOE (aerosol–cloud/precipitation)
Allen White	NOAA (ARs)

Platform scientists	Facility
Ruby Leung	DOE AMF2 and G-I
Chirs Fairall	NOAA *RVB*
Janet Intrieri	NOAA G-IV
Ryan Spackman	NOAA P-3
Allen White	HMT
Kim Prather	BBY
David Diner	NASA ER-2

Working group leads	Working group
Ryan Speckman	2015 Operations Implementation
Andrew Martin	Modeling and Analysis
John Helly	Data Management
Jason Cordeira	Forecasting

TABLE 5. Overview of the CalWater-2015 airborne field deployment from Jan to Mar 2015.

	G-I (through end—7 Mar)		G-IV (through end—24 Feb)			ER-2 (thru end—24 Feb)		P-3 (through end—12 Feb)		
	Science (h)	Field days	Science	Drops	Field days	Science	Field days	Science	Drops	Field days
Starting amount		54	93* h	372* drops	40	52 h	40	60 h	150 drops	20
Used	102 h		80 h	365 drops	40	41 h	37	41 h	78 drops	17
Remaining			13-h Hawaii ferry	7 drops		11 h		20* h	72* drops	
Remaining (%)			86	2		21		33	48	
Last possible science flight	8 Mar									
Science flights to date	28 flights		12 flights			9 flights		7 flights		
Avg per flight	3.6 h		6.7 h/flight	30 drops/flight		4.5 h/flight		6 h/flight	11 drops/flight	

Total flights	56
Total flight (h)	264
Total dropsondes	443
Total AXBTs	148

* P-3 departed before using all its hours and dropsondes. The 20 P-3 hours were transferred to the G-IV (as a 19-h increase) and 72 P-3 drops were added to G-IV.

(2013a,b) in terms of AR detection and predictability.

OVERARCHING IMPACTS AND DESIRED FUTURE OUTCOMES FOR WEATHER, WATER, AND CLIMATE. CalWater addresses fundamental gaps in the understanding of key physical processes underlying the global water cycle. This focus has brought together a diverse and cross-disciplinary group of scientists. The collaborations have involved data collection, numerical simulation (weather and climate), diagnoses, and tool development. Many results have been published and more are in process. One key result is the determination that roughly 40%–50% of annual precipitation in northern California is associated with landfalling ARs, revealing that they are critical to the water supply in the region (Dettinger et al. 2011; Guan et al. 2012; Ralph et al. 2013). The studies also revealed the key role of long-range transport of dust at high altitudes from Asia, the Middle East, and Africa (Ault et al. 2011; Creamean et al. 2013) in affecting precipitation processes under AR conditions and in systems responsible for the balance of winter precipitation.

The CalWater program of studies has helped to better quantify the risks associated with climate change, including the first analysis of ARs in climate models (Dettinger 2011). The results also inform potential climate change adaptation strategies associated with the use of new forecast information related to AR precipitation through the potential use in forecast-informed reservoir operations. The enhanced understanding of ARs has enabled serious consideration of new strategies for retaining extra water behind dams in California during the flood season to support the water supply in the dry season, based on the potential ability to accurately predict AR events.

CalWater's findings have relevancy to regions beyond the U.S. West Coast, especially in the west coasts of midlatitude continents, and the program has created career opportunities for cross-disciplinary scientists.
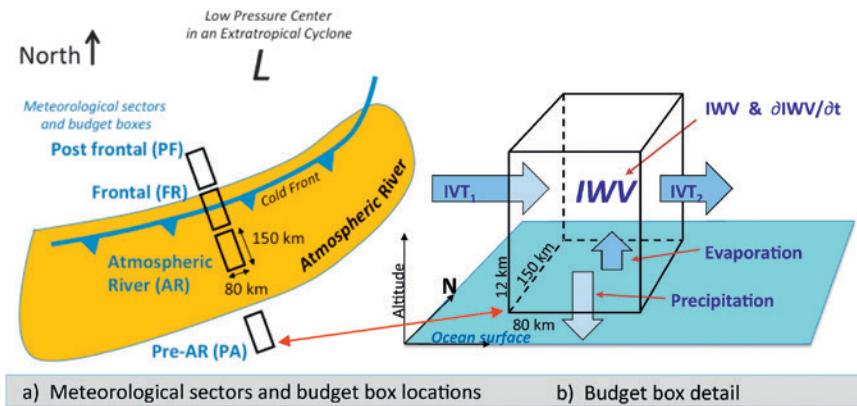
The ground is fertile for a large-scale, multiplatform, multimodel study that explicitly addresses the links between precipitation and aerosols. Landfalling ARs are now routinely studied by observational networks but their behavior over the oceans is much less well monitored and the quantitative contributions of evaporation, convergence/divergence, and rain-out, as well as entrainment of tropical water vapor in ARs have not been

adequately documented. Aerosol and microphysical measurement techniques have advanced and can provide new information on the role of aerosols in precipitation. Improvements in numerical weather and global aerosol models require offshore observations to better model and parameterize cloud and precipitation processes, including interactions with aerosols and their removal. The potential of aerosol-modulated rain-out over the ocean to influence total water vapor transport in ARs, and thus precipitation

in the western United States, is a remaining question. 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.

Fig. 10. Schematic summary of the physical process controlling the water vapor budget in and near an AR, and the range of meteorological sectors across which the magnitudes and relative importance of each physical process governing the time tendency of IWV in an AR is expected to vary. Excerpted from an experimental design by F.M. Ralph et al.
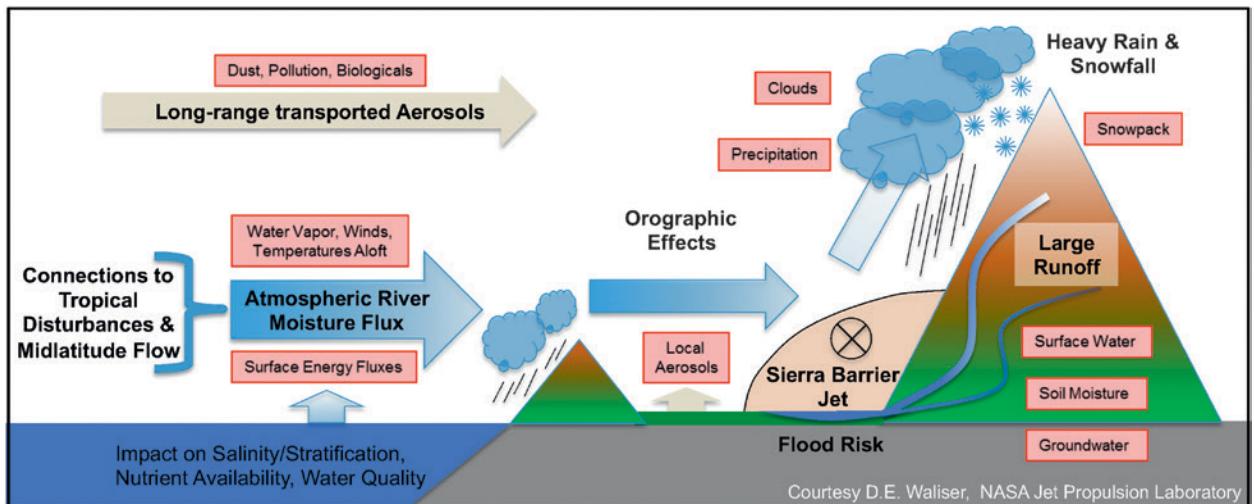
Fig. 11. Illustration of the atmospheric and hydrological processes associated with ARs based on a northward view of a west-to-east cross section depicting a landfalling AR in a region akin to north/central California. Onshore low-level moisture flux over the ocean is shown impinging first on the coastal range and second on the Sierra Nevada, with each orographic barrier producing copious precipitation. Long-range and local aerosols are depicted over the ocean and onshore, respectively, and affect clouds and precipitation. Also shown are the northward barrier jet along the western base of the Sierra Nevada, 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.

by the Center for Western Weather and Water Extremes, as well as Science and Technology Corporation. The knowledge and major effort of innumerable engineering, aircraft, ship, and technical support staff were vital to the development and execution of CalWater over the last several years.

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