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ARM Cloud Aerosol Precipitation Experiment (ACAPEX) Science Plan

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ARM
CLIMATE RESEARCH FACILITY

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Summary

The western U.S. receives precipitation predominantly during the cold season when storms approach from the Pacific Ocean. The snowpack that accumulates during winter storms provides about 70-90% of water supply for the region. Understanding and modeling the fundamental processes that govern the large precipitation variability and extremes in the western U.S. is a critical test for the ability of climate models to predict the regional water cycle, including floods and droughts. Two elements of significant importance in predicting precipitation variability in the western U.S. are atmospheric rivers and aerosols. Atmospheric rivers (ARs) are narrow bands of enhanced water vapor associated with the warm sector of extratropical cyclones over the Pacific and Atlantic oceans. Because of the large lower-tropospheric water vapor content, strong atmospheric winds and neutral moist static stability, some ARs can produce heavy precipitation by orographic enhancement during landfall on the U.S. West Coast. While ARs are responsible for a large fraction of heavy precipitation in that region during winter, much of the rest of the orographic precipitation occurs in post-frontal clouds, which are typically quite shallow, with tops just high enough to pass the mountain barrier. Such clouds are inherently quite susceptible to aerosol effects on both warm rain and ice precipitation-forming processes.

The **A**tmospheric Radiation Measurement (ARM) **C**loud **A**erosol **P**recipitation **Ex**periment (ACAPEX) will deploy the DOE ARM Mobile Facility 2 (AMF2) and the ARM Aircraft Facility (AAF) G1 in January – March 2015 in conjunction with CalWater 2 – a NOAA field campaign. The joint field campaign aims to improve understanding and modeling of large-scale dynamics and cloud and precipitation processes associated with ARs and aerosol-cloud interactions that influence precipitation variability and extremes in the western U.S. Our observational strategy consists of the use of land and offshore assets to monitor (1) the evolution and structure of ARs and their moisture sources from near their regions of development, (2) long-range transport of aerosols in eastern North Pacific and potential interactions with ARs, and (3) how aerosols from long-range transport and local sources influence cloud and precipitation in the U.S. West Coast where ARs make landfall and post-frontal clouds are frequent.

Deployed onboard the NOAA R/V Ron Brown, AMF2 will provide critical measurements to quantify the moisture budget and cloud and precipitation processes associated with ARs, and to characterize aerosols and aerosol-cloud-precipitation interactions associated with aerosols from long-range transport in the Pacific Ocean. The G1 aircraft will probe the clouds that form over the ocean and their transformations upon landfall as well as the orographic effects over the coastal range and the Sierra Nevada. The G1 flights will provide critical information needed for comparing the simulated and observed processes of the vertical profiles of cloud microstructure, and the resultant precipitation initiation and glaciation. This will allow the development and validation of more realistic simulations that will replicate the aircraft measurements and thus quantify more reliably the entities that cannot be obtained directly by the aircraft measurements to improve understanding and modeling of aerosol-cloud-precipitation interactions.

Acronyms and Abbreviations

ACAPEX	ARM Cloud Aerosol Precipitation Experiment
AR	Atmospheric Rivers
ARM	Atmospheric Radiation Measurement
BC	Black Carbon
CALIPSO	Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation
CAS	Cloud Aerosol Spectrometer
CCN	Cloud Condensation Nuclei
CIP	Cloud Imaging Probe
CPC	Condensation Particle Counter
CSPHOT	Cimel sunphotometer
CVI	Counter-flow Virtual Impactor
DOE	U.S. Department of Energy
EFREP	Enhanced Flood Response and Emergency Preparedness
FRSR	Fast Rotating Shadow Band Radiometer
HIAPER	High-performance Instrumented Airborne Platform for Environmental Research
HIPPO	HIAPER Pole-to-Pole Observations
HMT	Hydrometeorological Testbed
IN	Ice Nuclei
INS	Inertial Navigation System
MAERI	Marine Atmospheric Emitted Radiance Interferometer
MET	Marine Meteorological Instruments
MFRSR	Multi-filter Rotating Shadowband Radiometer
MISR	Multi-angle Imaging Spectro Radiometer
MJO	Madden-Julian Oscillation
MPL	Micropulse Lidar
NOAA	National Oceanic and Atmospheric Administration
PIR	Precision Infrared Radiometer
PNNL	Pacific Northwest National Laboratory
PRP	Portable Radiation Package
PSD	Particle Size Distributions
PSP	Precision Spectral Pyranometer
RASS	Radio Acoustic Sounding System
RPH	Roll, Pitch and Heave
SBJ	Sierra Barrier Jet

SEANAV	Sea-borne Navigation System
SWE	Snow Water Equivalent
TDR	Tail Doppler Radar
WISPAR	Winter Storms and Pacific Atmospheric Rivers
WV	Water Vapor

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1.0 Introduction

The western U.S. receives precipitation predominantly during the cold season when storms approach from the Pacific Ocean. The snowpack that accumulates during winter storms provides about 70-90% of water supply for hydropower generation, irrigation, and other uses. Understanding and modeling the fundamental processes that govern the large variability of precipitation in the western U.S. is a critical test for the ability of climate models to simulate clouds and precipitation and to predict the regional water cycle and extremes from intraseasonal to century time scales. Two elements of significant importance in predicting precipitation variability in the western U.S. are atmospheric rivers (AR) and aerosols. ARs are narrow bands of enhanced water vapor associated with the warm sector of extratropical cyclones over the Pacific and Atlantic oceans (Zhu and Newell 1998; Ralph et al. 2004; Bao et al. 2006). Because of the large lower-tropospheric water vapor content, strong atmospheric winds and neutral moist static stability (Figure 1), some ARs can produce heavy precipitation by orographic enhancement during landfall on the U.S. West Coast (Ralph et al. 2005, 2006; Neiman et al. 2008).

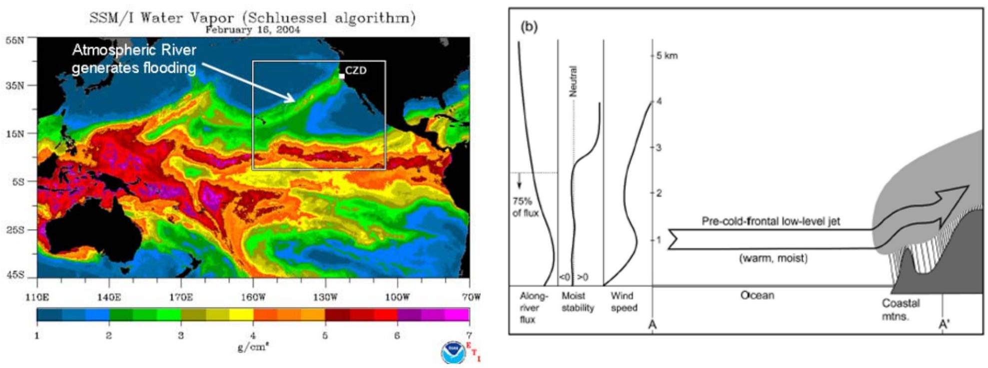

Figure 1. Left: Special Sensor Microwave Imager (SSM/I) retrieved vertically integrated water vapor on February 16, 2004 in which an AR was detected. Right: A schematic showing the vertical profiles of atmospheric moisture flux, moist stability, and wind speed associated with an AR and heavy precipitation as the AR makes landfall on the mountainous west coast (Source: Ralph et al. 2005).

While ARs are responsible for a large fraction of heavy precipitation in the western U.S. during winter, much of the rest of the orographic precipitation occurs in post-frontal clouds, which are typically quite shallow, with tops just high enough to pass the mountain barrier. In such conditions supercooled cloud water was documented to occur quite regularly in the western side of the orographic clouds over the topographic barrier when the cloud tops were >-15°C to -20°C (Heggli et al. 1983, Reynolds and Dennis 1986). Such clouds are inherently quite susceptible to aerosol effects on both warm rain and ice precipitation-forming processes. Measurements from the Suppression of Precipitation (SUPRECIP) field campaigns (Rosenfeld et al. 2008) suggest that aerosols that are incorporated in orographic clouds can efficiently slow down cloud-drop coalescence and riming on ice precipitation and delay the conversion of cloud water into precipitation. As a result, precipitation is redistributed with significant reductions on the upwind slopes and small compensation on the lee side, resulting in a net loss of precipitation and winter snowpack in the mountains.

In an effort to advance scientific understanding, numerical modeling, and measurements of critical physical processes underlying future changes in water supply and flood risks, a multi-year field experiment CalWater has been formulated to study the AR and aerosol effects on precipitation (http://www.esrl.noaa.gov/psd/CalWater/). Field experiments were carried out in Jan – Feb 2009 and Jan – Mar 2010 at Sierra Nevada sites that include ground-based aerosol and hydrometeorological measurements. In the Dec 2010 – Mar 2011 experiment, the Pacific Northwest National Laboratory (PNNL) G1 research aircraft flew between 2 February and 7 March 2011 and documented meteorology, cloud microphysics, and aerosol size and sources/composition in the Sierra Nevada and Central Valley.

The CalWater field experiments have documented important cloud and precipitation processes associated with the ARs and the significant role of the Sierra Barrier Jet (SBJ) in orographic enhancement of precipitation (Neiman et al. 2010; Lundquist et al. 2010). However, much remains unanswered as to the development of ARs and the amount and origin of moisture that is transported by the AR to feed the heavy precipitation in the west coast of the U.S. Previous studies by Mo (1999) and Bond and Vecchi (2003) have linked tropical variability including the Madden-Julian Oscillation (MJO) to precipitation in the western U.S. Based on a detailed case study, Ralph et al. (2011) found that the phasing of several major planetary-scale phenomena including the MJO and extratropical wave activities led to the direct entrainment of tropical water vapor into the AR that subsequently produced heavy precipitation over the coastal mountain ranges. Guan et al. (2011) showed that AR timing and frequency and snow water equivalent (SWE) in the Sierra Nevada are significantly augmented when MJO is active over the far western tropical Pacific. However, to what extent tropical-extratropical interactions involving the MJO play a role in ARs and the importance of the tropical and other moisture sources to heavy precipitation as ARs make landfall on the west coast is not known.

During the 2009 and 2010 CalWater field experiments, comprehensive aerosol chemistry and meteorological measurements documented the potential role of long-range (Asian) dust transport to precipitation in the Sierra Nevada. Comparing two storms with enhanced water vapor associated with AR conditions, Ault et al. (2011) hypothesized that Asian dust transported across the Pacific and incorporated into the upper altitudes of precipitation-producing clouds of a storm increased snowpack compared to the other storm with similar meteorological conditions but lower dust content in precipitation. Augmented by data collected on the G1 aircraft, the 2011 CalWater field experiment further provided important evidence of Asian dust on snowfall in the Sierra Nevada. In addition, the High-performance Instrumented Airborne Platform for Environmental Research (HIAPER) Pole-to-Pole Observations (HIPPO) field campaigns measured a comprehensive suite of tracers of the carbon cycle and related species using the NSF/NCAR G-V aircraft during 2009-2011. From several meridional cross sections over the mid-Pacific, the HIPPO data showed episodes of high concentrations of black carbon (BC) from Asian sources. How Asian aerosols including dust and BC influence precipitation in the western U.S. depends on their composition and concentrations as well as their ability to serve as ice nuclei (IN) and cloud condensation nuclei (CCN) as they are transported across the Pacific.

To fill the above gaps in our understanding and ability to simulate and predict AR and aerosol effects that influence cloud and precipitation, the **A**tmospheric Radiation Measurement (ARM) **C**loud **A**erosol **P**recipitation **Ex**periment (ACAPEX) will deploy the DOE ARM Mobile Facility 2 (AMF2) and the ARM Aircraft Facility (AAF) G1 in January – March 2015 in conjunction with the NOAA CalWater 2 observational assets to improve understanding and modeling of large-scale dynamics and cloud and precipitation processes associated with AR and aerosol-cloud interactions that influence precipitation variability and extremes in the western U.S. AMF2 will be deployed on NOAA R/V Ron Brown, together with the NOAA G-IV and P-3 aircrafts to quantify the atmospheric water budget in ARs and characterize aerosols from long-range transport over the Pacific Ocean, while the G1 aircraft will document the precipitation-forming processes and their interactions with aerosols upon landfall of the moist air masses and their impinging on the orographic barriers.

2.0 Objectives and Science Questions

The overarching objectives of ACAPEX and CalWater 2 are to provide measurements to:

- Document and quantify the structure and evolution of ARs and their moisture budgets
- Improve understanding and modeling of the influence of the tropics, including tropical convection and the various intraseasonal modes of variability associated with tropical convection, on extratropical storms and ARs
- Characterize aerosols and their microphysical properties over the Pacific Ocean
- Improve understanding and modeling of aerosol-cloud-precipitation interactions in clouds transitioning from the maritime regime to the orographic regime

ACAPEX, in conjunction with CalWater 2, will address two broad sets of science questions:

- What influences the evolution and structure of AR and its associated cloud and precipitation?
  - To what extent does water vapor in ARs originate from the tropics? What role does tropical convection play in this?
  - What are the roles of air-sea fluxes and ocean mixed-layer processes in AR evolution?
  - What are the key dynamical processes that modulate cloud and precipitation from landfalling ARs?
- How do aerosols affect the amount and phase of precipitation?
  - How frequent are aerosols transported across the Pacific and what characteristics make them effective CCN and/or IN?
  - How do aerosols from long-range transport and local sources influence cloud and precipitation over California, in both AR and non-AR conditions?
  - How do aerosols influence cyclogenesis and the thermodynamic development of extratropical cyclones and the coupled ARs associated with these storms?

The above scientific questions are encapsulated by the schematic presented in Figure 2. The figure shows how the remote northern hemisphere Pacific troposphere is a dynamic part of the atmosphere that fosters the rapid development of extratropical cyclones. It also serves as the conveyor of some of the most polluted air masses globally. As shown in Figure 2, the large-scale flow advects anthropogenic and biomass-burning pollution as well as dust from Asia into the central Pacific, a region favorable for the development of storms especially during the cool season. Coastal mountains have important effects on mesoscale circulation and on how aerosols influence clouds and precipitation.

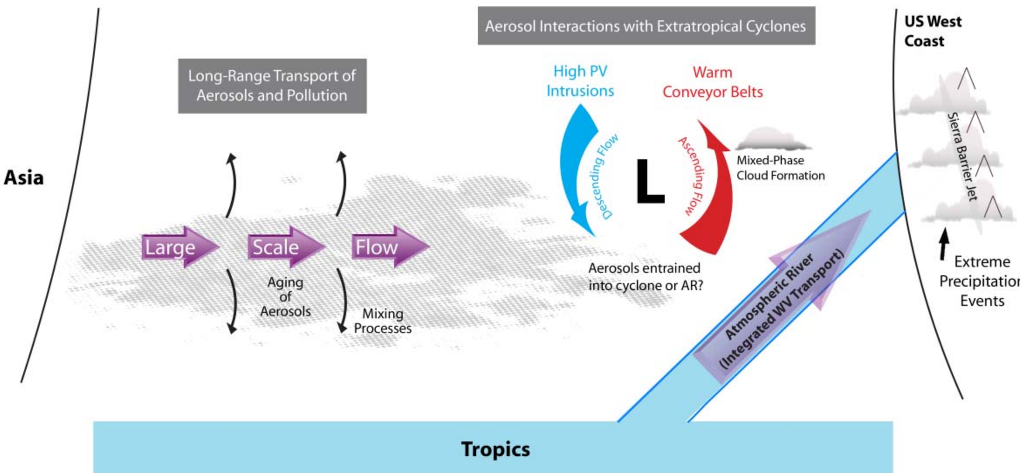

Figure 2. Conceptual framework for CalWater 2 / ACAPEX science objectives. The observational strategy requests airborne and ship-based assets over the central and eastern Pacific complemented by ground-based and aircraft measurements along the U.S. West Coast.

Through data analysis and modeling, measurements collected from ACAPEX and CalWater 2 will be used to improve parameterizations of aerosol-cloud-precipitation interactions and to advance understanding and modeling of extratropical storms that produce heavy precipitation in the western U.S. Advances in these areas will lead to improvements in the predictions of global and regional hydrologic cycle, including droughts and extreme precipitation, and potential changes in the future climate, as well as improve weather forecasts of heavy precipitation distribution, including floods and droughts, in the western U.S.

3.0 Observations

3.1 Overarching Strategy for the Joint CalWater 2/ACAPEX

CalWater 2/ACAPEX will use an observational strategy consisting of the use of land and offshore assets to monitor the evolution and structure of ARs from near their regions of development and long-range transport of aerosols in eastern North Pacific and potential interactions between the two, as well as to investigate the interactions between aerosols and cloud/precipitation in the U.S. West Coast where ARs make landfall and post-frontal clouds are frequent. The ACAPEX observations are designed to complement the assets for CalWater 2. More specifically, ACAPEX will deploy the DOE ARM Mobile Facility 2 (AMF2) and the ARM Aircraft Facility (AAF) G1, in conjunction with instruments provided by NOAA for CalWater 2, to study moisture transport by AR and the role of tropical convection and tropical-extratropical interactions on AR development and aerosol effects on cloud and precipitation, respectively. Figure 3 shows a schematic of the overall CalWater 2/ACAPEX observational strategy.

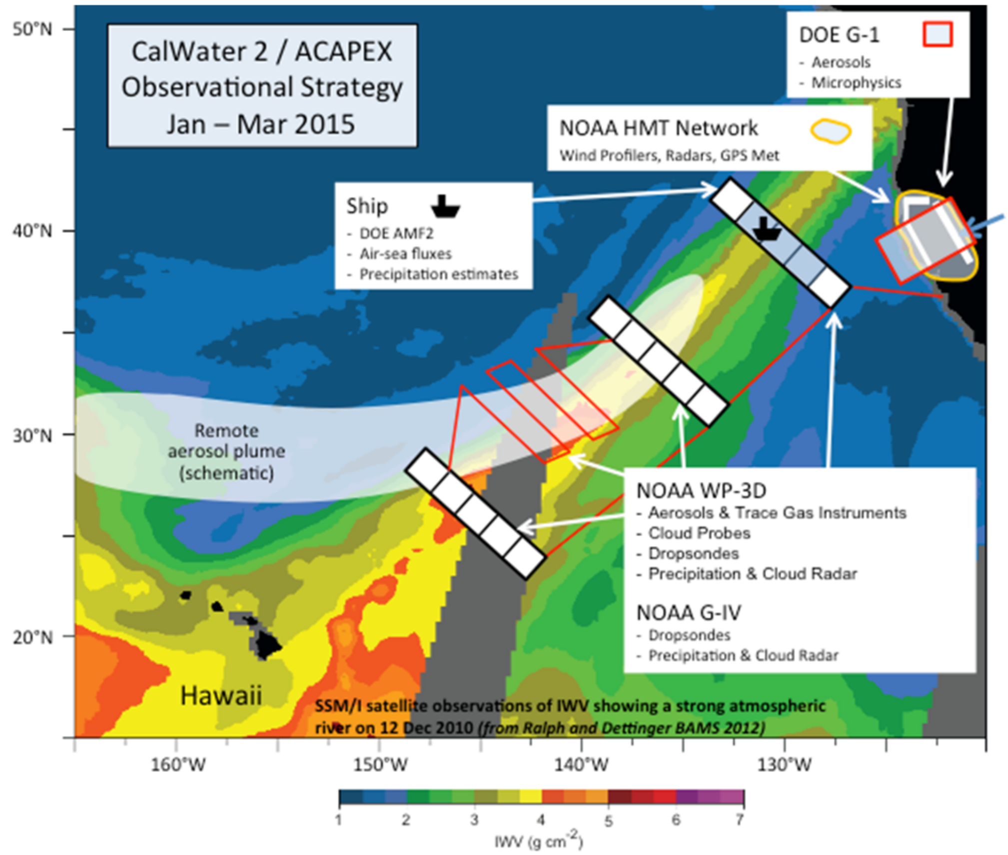

Figure 3. The CalWater 2/ACAPEX observational strategy using high- and low-altitude aircraft platforms, a ship (NOAA R/V Ron Brown) with the AMF2, and a ground-based network including Hydrometeorology Testbed (HMT) assets and the UCSD /SIO ATOFMS.

The aircraft assets include two aircrafts offshore (NOAA WP-3D and NOAA G-IV) and the DOE G1 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 G1 sampling region in the diagram).

Both CalWater 2 and ACAPEX will also be able to leverage major land-based observations of the water cycle and ARs that are deployed as part of NOAA's Hydrometeorology Testbed (HMT; hmt.noaa.gov) and its legacy network for Enhanced Flood Response and Emergency Preparedness (EFREP) of 93 ground-based observing sites in California (Figure 4). We will also make use of polarimetric radars of the national network that can provide information on hydrometeor types and sizes. Data from six locations (San Francisco, Eureka, Beale Air Force Base, Sacramento, San Joaquin Valley, Reno) in the vicinity of our study region in central California will be particularly useful.

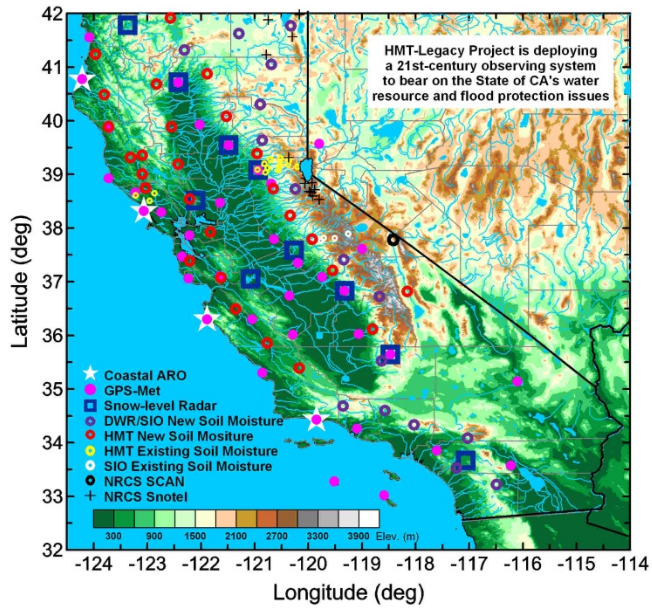

Figure 4. A combined >100-site network of state-of-the-art hydrometeorological observations from NOAA's HMT and EFREP.

CalWater 2/ACAPEX will include aircrafts and measurement systems, including AMF2, on board Ron Brown to measure all the water budget components of the AR including air-sea fluxes, atmospheric transport, and cloud and precipitation. The mid-altitude aircraft NOAA WP-3D will measure thermodynamic and wind profiles using dropsonde observations and provide aerosol and microphysical measurements to support the meteorological measurements. With its Tail Doppler Radar (TDR), the NOAA P-3 will be used to measure horizontal divergence fields on the scales that drive precipitation and will use the high-spatial resolution reflectivity information to provide spatially extensive precipitation estimates. The WP-3D will also house the particle size distribution(PSD) W-band Doppler radar (clouds, sea spray) and the PSD Scanning Surface Radar Altimeter (surface wave spectra, surface mean square slope, and rain rate). The NOAA G-IV aircraft will provide the larger context for the offshore observations including dropsondes and TDR. The G1 aircraft will be deployed in the coastal and inland region of central California to provide measurements of clouds and aerosols. In addition, polar-orbiting observations from Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and CloudSat (A-Train satellite instruments) and Multi-angle Imaging Spectro Radiometer (MISR) (onboard the Terra satellite) will provide important context for the planned field observations on clouds, aerosols, and precipitation in the region of study. The overall suite of measurement platforms and instruments for CalWater 2 and ACAPEX is described below.

Aircraft Observations (NOAA, DOE)

The platforms and accompanying payloads for CalWater 2 and ACAPEX are described in Table 1.

Table 1. Aircraft observations.

Aircraft Platform	Altitude Range (kft)	Location	Theater of Operations	Measurements
NOAA WP-3D	1–22	Coastal California	On/Offshore California	Vertical profiles of P, T, RH, and wind speed/direction (dropsondes) Ocean mixed-layer thermodynamic structure (AXBTs) Aerosols (total aerosol in the accumulation/coarse modes) Microphysics (CCN, IN, cloud water/ice, precipitation spectra) Horizontal convergence observed by TDR PSD W-band radar (clouds) PSD WSRA (ocean waves, roughness)
NOAA G-IV	1–45	Coastal California and/or Honolulu, HI	HI to California	Vertical profiles of P, T, RH, and wind speed/direction (dropsondes) Precipitation and surface winds from TDR Tracer of pollution (O_3) and strat-trop exchange
DOE G-1	1–23	Coastal/inland California	On/Offshore California	Aerosols (total aerosol number and size distributions, BC mass, dust, scattering/absorption, single-particle mass spectrometer) and chemical pollution tracers (CO, O_3) Microphysics (CCN, IN, cloud-drop size distribution, cloud water/ice content) Atmospheric state (T, P, RH, wind, turbulence)

Ship-based Observations (NOAA, DOE)

NOAA instruments:

- Eddy correlation fluxes
- Near-surface meteorology
- Ocean mixed-layer structure, currents, turbulence and surface waves
- Balloon-borne vertical profiles of temperature, relative humidity, and wind speed/direction and ozone mixing ratio

DOE AMF2 (more detailed provided in Section 3.2):

- Aerosol Observing System (AOS)
- Radar Wind Profiler (RWP)
- Cloud radars
- Ceilometer, micropulse lidar (MPL), and high spectral resolution lidar (HSRL)
- 3-channel microwave radiometer (MWR3C)
- Portable Radiation Measurement Package (PRP2) and sun pyranometer (SPN)
- Marine meteorological instruments (MET) including balloon-borne vertical profiles of temperature, relative humidity, and wind speed/direction

Ground-based Observations (NOAA, UCSD)

NOAA Hydrometeorological Testbed (HMT) and EFREP networks (Coastal and Central California, Figure 4):

- Wind profilers/Atmospheric river observatories (1-2 coastal sites, 2 inland sites)
- S-band precipitation profilers (4 sites in and near the Sonoma valley)
- Snow-level radars (10 sites)
- National polarimetric radar network (San Francisco, Eureka, Beale Air Force Base, Sacramento, San Joaquin Valley, Reno. See http://radar.weather.gov/)
- Meteorological tower observations
- IWV from GPS-met sites (>40 sites)
- Soil moisture at 10 cm depth (>30 sites)

UCSD/NOAA-HMT: Bodega Bay:

- Surface meteorology and rain gauge
- 449 MHz wind profiling radar w/ radio acoustic sounding system (RASS) (profile of horizontal wind and virtual temperature in the lowest few kilometers; reflectivity echoes to estimate cloud base and cloud top height)
- Aerosol time-of-flight mass spectrometer for source apportionment of ground-based aerosols to complement G1 measurements
- Aerosol size distributions (10 nm – 10 micron)
- CCN measurements
- Gas phase measurements (O3, CO, SO2)
- Aethalometer BC measurements
- Meteorology measurements
- 35 km south of Cazadero, California (CZC), with NOAA-HMT that with surface meteorology, rain gauge, soil moisture, and S-band profiling precipitation radar

3.2 Objectives and Strategies for ACAPEX

3.2.1 AMF2 Deployment

The overarching goals of deploying AMF2 in the joint CalWater 2/ACAPEX campaign are twofold: (1) To quantify the moisture budget and cloud and precipitation processes associated with ARs, and (2) to characterize aerosols and aerosol-cloud-precipitation interactions associated with aerosols from long-range transport in the Pacific Ocean.

AMF2 will be deployed on the NOAA R/V Ron Brown, in conjunction with other instruments on board the ship. AMF2 will provide profile information, in conjunction with the dropsondes from the NOAA G-IV, to quantify the AR moisture budget. AMF2 will also provide surface flux measurements, which will be used in conjunction with other surface flux measurements from the ship. Combining these data with satellite measurements of clouds and moisture will provide information to quantify the role of tropical convection and the associated tropical waves on the development of ARs and quantify the evolution of moisture, cloud, and precipitation associated with ARs.

AMF2 will also provide measurements of clouds and aerosols that will be used in conjunction with cloud/aerosol measurements from NOAA P-3 to characterize aerosols from long-range transport. Table 2 lists the AMF2 instruments and measurements that will be used in ACAPEX.

Table 2. AMF2 instruments and measurements.

Instrument	Measurement
Aerosol Observing System	
Cloud Condensation Nuclei Counter (CCN100)	Concentrations of CCNs as a function of supersaturation
Condensation Particle Counter (CPC model 3772)	Concentration of aerosol particles down to an aerodynamic diameter of 10 nm
Hygroscopic Tandem Differential Mobility Analyzer (HTDMA)	Aerosol (size, mass or number) distribution as a function of relative humidity
Ambient Nephelometer	Light scattering coefficient of aerosols at ambient relative humidity
Wet Nephelometer/f(RH) (humidigraph)	Light scattering coefficient of aerosols over a range of relative humidities
Particle Soot Absorption Photometer (PSAP), 3 wavelength	Optical transmittance of particles deposited on a filter and three wavelengths
Ozone	Concentration (range) by absorption
Cloud Radars	
Ka/X-band Scanning ARM Cloud Radar (Ka/X-SACR)	Primary measurements are cloud particle size distribution, hydrometeor fall velocity, radar polarization, radar reflectivity
Marine W-band ARM Cloud Radar (MWACR)	The primary measurements are radar Doppler (the power spectrum and moments of the radar signal expressed as a function of Doppler frequency or Doppler velocity) and radar reflectivity
Ka-Band Zenith Pointing Radar (KAZR)	Determines the first three Doppler moments (reflectivity, vertical velocity, and spectral width) at a range resolution of ~30m from near-ground to ~20km
Roll, Pitch and Heave (RPH) stable platform	Hydraulic controlled platform using data provided by the Sea-borne Navigation System (SEANAV) system – compensates for ship's motion for the vertically pointing w-band radar
Cloud Macrophysics and AOD	
Micropulse Lidar (MPL)	Detect the altitude of clouds
Microwave Radiometer (MWR)	Column integrated amounts of water vapor and liquid water at 23.8 and 31.4 GHz
Microwave Radiometer, 3-channel (MWR3C)	Brightness temperature from three channels centered at 23.834, 30 and 89 GHz
High Spectral Resolution Lidar (HSRL)	Aerosol optical depth, volume backscatter coefficient, cross section and depolarization
Total Sky Imager (TSI)	Hemispheric sky images during daylight hours and retrievals of fractional sky cover when solar elevation > 10 degrees
Vaisala Ceilometer (VCEIL)	Cloud base height, vertical visibility and potential backscatter signals by aerosols - maximum vertical range is 7700m

Table 2. (cont.)

Instrument	Measurement
Winds, Temperature, Emissivity	
Beam Steerable Radar Wind Profiler (BSRWP)	Backscattered radiation, horizontal winds, radar Doppler, radar reflectivity, virtual temperature
Marine Atmospheric Emitted Radiance Interferometer (M-AERI)	Absolute thermal infrared spectral radiance emitted by the atmosphere down to the instruments. The Marine Atmospheric Emitted Radiance Interferometer (MAERI) has additional functionality to observe off-zenith scenes and measures surface temperature and emissivity (ocean skin temp)
Inertial Navigation System (SEANAV)	Laser ring gyro GPS aided Inertial Navigation System (INS) provides high accuracy motion data in three translational frames and three rotational frames of reference: surge, sway, and heave; roll, pitch and yaw
Meteorology and Radiation	
Radiosondes	Measure profiles of pressure, temperature, humidity, and geopotential height; launch four times per day
Portable Radiation Package (PRP) and Sun Pyranometer (SPN)	The PRP consists of an unshaded Precision Spectral Pyranometer (PSP) and Precision Infrared Radiometer (PIR) and a Fast Rotating Shadow Band Radiometer (FRSR). The FRSR uses the same detector as a Multi-filter Rotating Shadowband Radiometer (MFRSR). A Sun Pyranometer is available to be deployed alongside the PRP
CIMEL Sunphotometer (CSPHOT)	For ocean deployments the CSPHOT sensor is put in a zenith-only mode. No scanning of other sectors of the sky is provided

3.2.2 AAF G1 Deployment

The G1 aircraft will probe the clouds that form over the ocean and their transformations upon landfall as well as the orographic effects over the coastal range and the Sierra Nevada. This will include both thermodynamic and aerosol effects. Single-particle measurements by ATOFMS (UCSD/SIO) will probe how the sources of aerosols seeding the clouds play a role in impacting cloud microphysics. Thermodynamic effects include the added solar surface heating or radiative surface cooling over land. The daytime solar heating can lead to enhanced convection and mixing with locally emitted aerosols and their precursors. The nighttime surface cooling can lead to decoupling of the surface from the marine air that invades the land, all the way to the Sierra Nevada, keeping the marine microstructure of the clouds undisturbed. Another important thermodynamic feature is the barrier jet, both ahead of the coastal range and the Sierra Nevada. Table 3 lists the instruments that will be used in G1.

The G1 flights will focus on the initiation processes of precipitation and glaciation, as the evolution in both time and height provides key information for simulating the processes for the full lifetime of the clouds. Little information can be gained by flying through mature and glaciated cloud systems, because this state of the cloud could have been reached by a large variety of microphysical and thermodynamic processes. Documenting the way by which the cloud reaches this state is critically important, as it determines the precipitation distribution in time and space, as well as the vertical diabatic heating profiles, which couples the cloud and circulation systems.

Table 3. G1 instruments and measurements.

Instrument	Measurement
Platform Pos/Vel/Attitude	
Trimble GPS DSM 232	Position/velocity @ ~10Hz
Trimble TANS 10Hz	Position, velocity, altitude
Systron Donner C-MIGITS III	Position, velocity, altitude
Atmospheric State	
Rosemount 102 probe	Temperature
Rosemount 1201F1	Static pressure
Rosemount 1221F2 (3x)	5-Port air motion sensing: true airspeed, angle-of-attack, side-slip
GE-1011B chilled-mirror hygrometer	Dew-point temperature
Tunable Diode Laser Hygrometer (TDL-H)	Absolute humidity
AIMMS-20	Wind and turbulence
Video Camera P1347	Downward video images from fuselage bottom
Video Camera P1344	Forward video images behind cockpit window
Liquid and Total Water Content	
SEA WCM-2000	Liquid water content, total water content, and ice water content (derived)
CAPS-hotwire	Liquid water content
DMT Cloud Spectrometer and Impactor (CSI)	Total condensed cloud water content
Particle Volume Monitor-100A (PVM-100A)	Cloud liquid water content
Cloud Microphysics	
High Volume Precipitation Spectrometer (HVPS-3)	Cloud droplets size distribution (150-19,600 μm)
2-Dimensional Stereo Probe (2D-S)	Cloud droplets size distribution (10 – 3,000 μm)
Cloud Imaging Probe (CIP) of the Cloud Aerosol and Precipitation Spectrometer (CAPS)	Cloud-droplet size distribution (25-1550 μm)
Fast-Cloud-Droplet Probe (F-CDP)	Cloud particle size distribution (2-50 μm)
Cloud-Droplet Probe (CDP-2)	Large aerosol and cloud droplets (2-50 μm)
Cloud Aerosol Spectrometer (CAS) (part of CAPS)	Large aerosol and cloud droplets (0.5-50 μm)
Aerosol	
UCPC TSI 3025	Total particle concentration (> 3 nm)
CPC TSI 3010	Total particle concentration (> 10 nm)
CPC TSI 2010	Total particle concentration (> 10 nm) behind CVI
PCASP-100X	Aerosol size distribution (100-3000 nm)
UHSAS-A	Aerosol size distribution (60-1000 nm)
CAS of CAPS	Aerosol size distribution (500-50,000 nm)
CCN counter (dual SS)	CCN concentration at two super-saturations

Table 3. (cont.)

Instrument	Measurement
Aircraft ATOFMS	Aerosol single-particle composition, mixing state and size
Radiance Particle/Soot Absorption Photometer (PSAP)	Aerosol absorption, 3 wavelengths
Single-Particle Soot Photometer (SP2)	Soot spectrometer
Nephelometer (TSI 3563)	Aerosol scattering, 3 wavelengths
CFDC	IN concentration
Sample Collection	
Optical Particle Counter (OPC) 0 Model CI-3100	Aerosol size distribution (0.7 to 15 μm) to monitor isokinetic inlet performance
Optical Particle Counter (OPC) 0 Model CI-3100	Aerosol size distribution (0.7 to 15 μm) to monitor CVI inlet performance
Pumps for aerosol flow	Maintains flow through aerosol inlet and internal plumbing
Counter-flow Virtual Impactor (CVI)	Sample stream of cloud-droplet residuals
TDL-H closed path	Absolute humidity behind CVI
Gases	
N2O/CO -23r	Concentration of CO, N2O, and H2O
Thermo Electron 49i	Ozone

The flights will provide the critical information needed to address the objective of comparing the simulated and observed processes of the vertical profiles of cloud microstructure, and the resultant precipitation initiation and glaciation. This will allow the development and validation of more realistic simulations that will replicate the aircraft measurements and thus quantify more reliably the entities that cannot be obtained directly by the aircraft measurements.

The G1 aircraft was deployed in the CalWater campaign during February–March 2011 to collect measurements for investigating aerosol-cloud interactions and their role in precipitation in central California. The instrument package for ACAPEX is similar to that used in CalWater, including atmospheric states, liquid and total water content, cloud microphysics, aerosols, and gases, but with the benefit of the operational experience that will make instruments including CCN/IN counter and CVI fully operational in their optimal settings.

CalWater used flight plans with pre-determined trajectory, as shown in Figure 5. We will extend the flight plans to about 100 km into the ocean and adding more pre-determined trajectories in areas where clouds of interest occurred in CalWater, including:

- At the foothills and western slope of the Sierra Nevada to the east of Sacramento
- Over the crest to the east of Sacramento
- Over the high terrain of the Yosemite for best cap clouds
- Over the coastal mountains
- Over the ocean near the coast

The flight plans will be prioritized for areas with good coverage of polarimetric radars of the national network for a better determination of the hydrometeor types. Similar to CalWater in spring of 2011, numerical weather forecasts in support of the field campaign will be provided by NOAA and tracer forecasts will be provided by PNNL for planning of the G1 deployment.

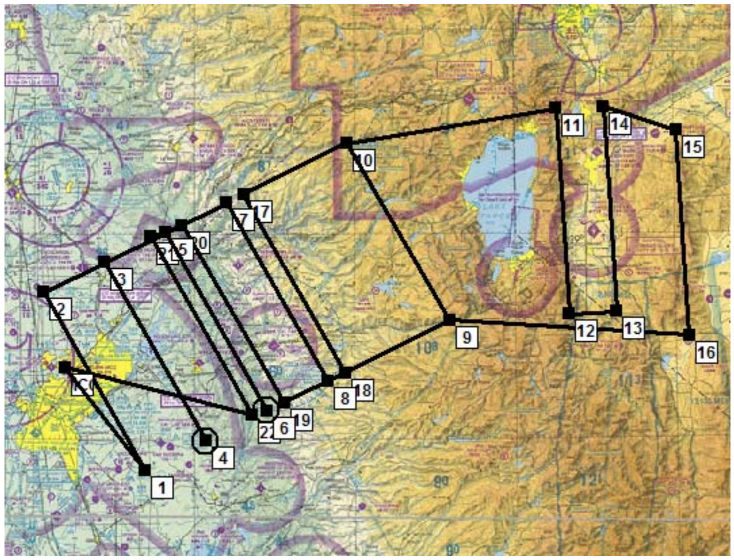

Figure 5. The main orographic flight plan for CalWater in the coastal and foothill areas of central California. The order of the flight plan was along the following points: 1-2-3-4-3-5-6-5-7-8-9-10-11-12-13-14-15-16-9-10-17-18-19-20-21-22-30.

4.0 Science

This section highlights some key findings from CalWater that motivate the CalWater 2/ACAPEX field campaign, and provides more detailed science questions that will be addressed using data collected from the joint CalWater 2/ACAPEX. The deployment of AMF2 will contribute primarily to science questions related to the ARs and the deployment of AAF G1 will contribute primarily to science questions related to aerosol-cloud-precipitation interactions, but some science questions such as long-range transport of aerosols and potential influence on AR development and cloud and precipitation over land can take advantage of both platforms.

4.1 Evolution and Structure of Atmospheric Rivers

The Winter Storms and Pacific Atmospheric Rivers (WISPAR) field campaign using the NOAA dropsondes 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 four flights on WISPAR and two from NOAA's P-3 in earlier experiments, preliminary analyses show that errors in AR water vapor transport range from 0.5-2 million acre-feet/day of equivalent liquid water in individual ARs (Figure 6). To put these results in context, the entire annual 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.

The unique observations including critical instruments from AMF2 such as the cloud radar, wind/humidity profiler, and microwave radiometer would enable the following analyses to fill gaps in current understanding of AR structure and evolution, especially regarding the water vapor transport budget and the associated cloud and precipitation processes:

- How much water vapor is entrained directly from the tropics and how much of this makes it to the coast and falls as precipitation? What role does tropical convection play in the development of AR and its moisture budget?
- What fraction of rainfall in landfalling ARs results from air-sea fluxes of moisture from the ocean's surface and how much is from horizontal convergence of pre-existing atmospheric water vapor?
- How much rainout occurs in ARs over the ocean, and are the cloud and precipitation processes sensitive to possible influences of Asian aerosols?
- Does "recycling" of atmospheric water via evaporation in virga play a significant role in the AR water vapor transport budget?
- 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)?
- How does the SBJ 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)?
- What global weather patterns (e.g., MJO, ENSO, Western Pacific decaying typhoons) affected by tropical convection most influence AR evolution, structure and impacts on the U.S. West Coast?
- Do ARs transport other key atmospheric gases or aerosols besides moisture?

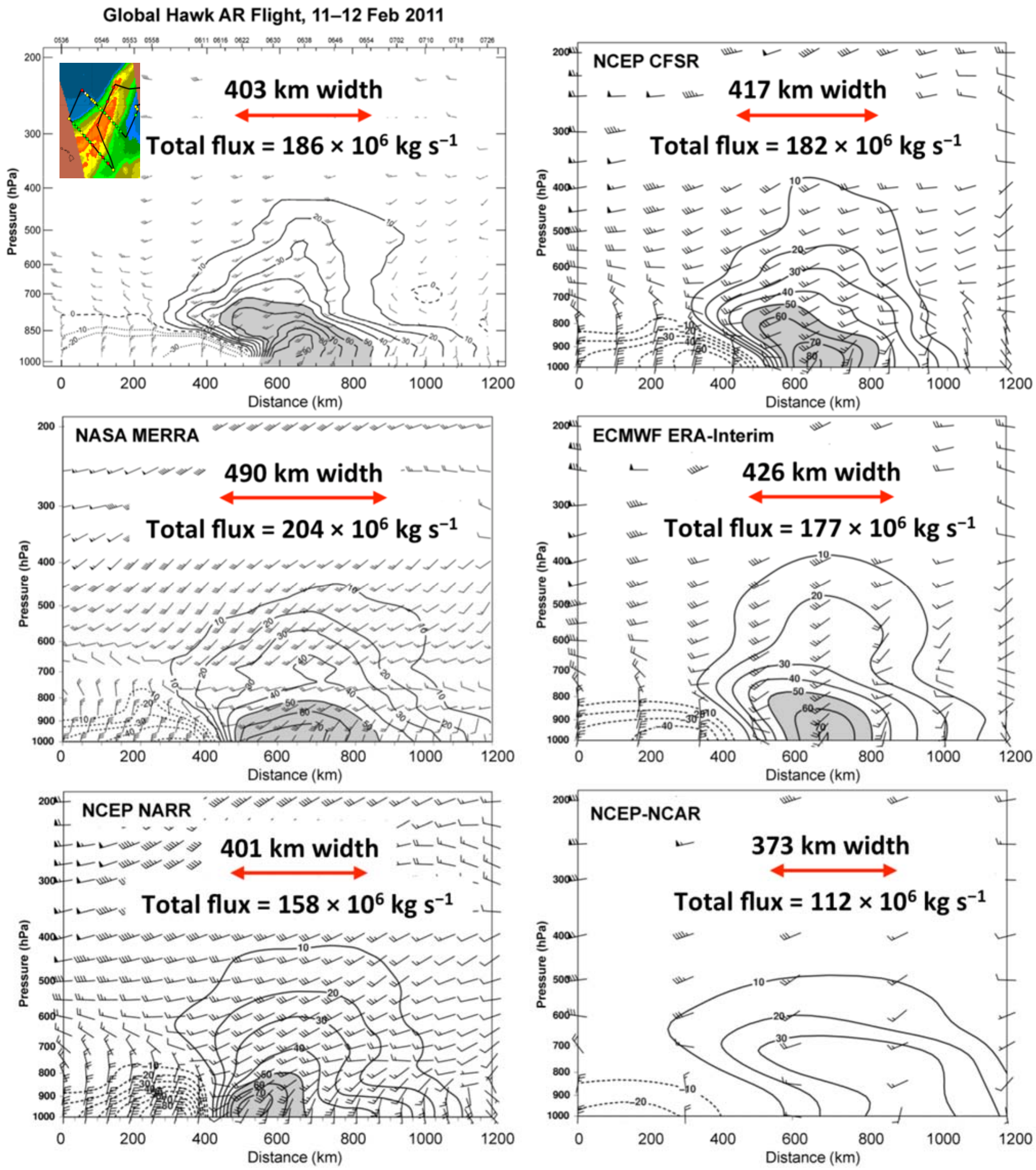

Figure 6. Cross section showing the dropsonde data through the AR in the inset figure (top left panel) for the first Global Hawk science flight. The contours are along-front water vapor (WV) flux in units of kg m^{-1} s^{-1}. The AR, with a width of about 403 km, provides vertically integrated vapor transport equivalent to 11 times the water flow of the Mississippi River.

4.2 Aerosol Effects on Cloud and Precipitation

Orographic forcing is a unique and dominant mechanism for harnessing WV 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 – 90% of 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 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 slow the mixed-phase precipitation-forming processes by decreasing 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 IN to supercooled liquid clouds would 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 in central California where aerosol sources are abundant provided further insights on the role of aerosols on cloud and precipitation, and highlighted the presence of supercooled liquid water down to -21^{o}C and supercooled rain down to -12°C in weak convective cloud band associated with a cyclone over the ocean, and in laminar layer cap clouds over the ridge of the high peaks of the Yosemite section of the Sierra Nevada, at temperatures down to -21°C. Analysis of remote sensing data and modeling by Choi et al. (2010) suggests that supercooled liquid droplets can exist at temperatures as low as -40^{o}C and that the variations in the supercooled cloud fraction is negatively correlated with 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 the IN concentration.

Indeed long-range transport of Asian dust has been shown to have an impact on air quality in western North American (VanCuren and Cahill 2002). Observational studies have also speculated the impacts of Asian dust through its role as IN on clouds and precipitation that impact snow production (Pratt et al. 2009; Sassen 2002). Using data from the CalWater Early Start campaign (22 February to 11 March 2009), Ault et al. (2011) showed that the presence of Asian dust may have increased precipitation by 1.4 times in an AR event compared to another AR event with similar WV transport, but without the presence of dust.

As a follow-on to the measurements in 2009 reported by Ault et al. (2011), one goal of G1 flights in CalWater 2011 was to assess the role of dust and biological particles that had been detected in ground-based precipitation samples. Indeed, in the 2011 G1 flights, single-particle measurements showed the repeated importance of long-range transported dust and biological particles from Asia and perhaps even further west impacting upper layer high altitude clouds. Importantly, days when long-range transported dust and biological particles were present in the high altitude clouds corresponded with the largest amounts of snowfall on the ground. Such impacts of dust and biological particles were shown to impact a broad range of the mountains through precipitation measurements over a several hundred-mile north-south transect along the Sierras. In general, as shown in 2009 through precipitation measurements, a strong correlation (almost linear) was found between larger snowstorms and high amounts of dust in precipitation sample at ground level. From these measurements we hypothesized that days with extensive precipitation occurred when IN formed in high level clouds by dust/bio particles acted in the seeder-feeder mechanism with enhanced riming occurring as IN fell through the lower level orographic marine clouds with large droplets, leading to extensive amounts of precipitation at the ground.

Previous research as well as specific findings described above has answered some old questions, while opening more new ones. Scientific questions that will be addressed using data from CalWater 2/ACAPEX include:

- How frequent is supercooled rain a main precipitation-forming process in the CalWater area of interest in the various cloud types? Why was supercooled rain so abundant during CalWater while it was rarely reported earlier?
- How does dust and biological particles influence the occurrence of supercooled rain?
- How can highly marine clouds exist with sustained supercooled water and rain? This directly contradicts extensive reports that clouds glaciate naturally very fast in clouds that form in pristine air with large cloud drops (e.g., Rangno and Hobbs 1988 and 1991).
- How do different added aerosol types change the cloud and precipitation-forming processes in maritime, weak convective cloud band over the ocean, and laminar layer cap clouds over the mountain ridges?
- How well do current cloud microphysical parameterizations capture aerosol-cloud interactions in mixed-phase clouds?
- What are the implications for more accurate simulations of precipitation and modeling of aerosol impacts on precipitation?
- How do aerosols from local sources versus long-range transport affect precipitation phase and spatial distribution?
- What is the role of the SBJ in aerosol transport and how does this influence cloud and precipitation?

Data to be collected from G1 in the ACAPEX experiment will provide important information to elucidate different mechanisms of how aerosols influence cloud microphysical and precipitation-forming processes.

5.0 Relevance to DOE Mission

The mission of the ARM Climate Research Facility is to deliver improved climate data and models for policy makers. A major weakness in global climate models is their limitations in simulating the regional hydrological cycle, particularly extremes such as floods and droughts. The west coast of North America presents a specific challenge because of the large precipitation variability and significant implications to water resource management coupled with the growing demand. Although local mountains have a large influence on precipitation, accurately predicting precipitation variability and potential changes in the future requires improved understanding and modeling of atmospheric processes across a wide range of scales. On the intraseasonal time scales, tropical-extratropical interactions involving processes such as the MJO and extratropical wave activities may play an important role in the entrainment of tropical or near-surface moisture by ARs that is a key component of heavy precipitation along the west coast. The IPCC AR4 models show varying degrees of fidelity in simulating AR frequency (Dettinger et al. 2011) and the

MJO (Lin et al. 2006), but their ability to correctly simulate the development of ARs and their link to tropical processes including the MJO and the AR moisture transport is not clear because current understanding of these various aspects have not been well quantified by measurements. An additional complicating factor is how aerosols from long-range transport across the Pacific Ocean and local sources may influence clouds and precipitation, leading to changes in frequency and intensity of heavy precipitation, spatial distribution of precipitation, and partitioning between snowfall to rainfall, all with important implications in the western U.S.

ACAPEX, in conjunction with CalWater 2, will provide the much-needed data over the central/eastern Pacific Ocean to study AR evolution and AR moisture budget and sources, and long-range transport of Asian aerosols, and the potential for interactions between the two and effects on heavy precipitation. The field campaign will also address leading-edge issues related to aerosol-cloud-precipitation interactions in clouds transitioning from the maritime regime to the orographic regime in central California, and how the effects of aerosols may vary for aerosols from long-range transport versus local sources. The data to be collected by AMF2 and G1 as part of ACAPEX, in conjunction with the CalWater 2 aircrafts 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.

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