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DOE/SC-ARM-16-012

ARM Cloud-Aerosol-Precipitation Experiment (ACAPEX) Field Campaign Report

LR Leung

March 2016

ARM CLIMATE RESEARCH FACILITY

DISCLAIMER

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March 2016

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Office of Science, Office of Biological and Environmental Research

Executive Summary

The U.S. Department of Energy (DOE)'s Atmospheric Radiation Measurement (ARM) Climate Research Facility's ARM Cloud Aerosol Precipitation Experiment (ACAPEX) field campaign contributes to CalWater 2015, a multi-agency field campaign that aims to improve understanding of atmospheric rivers and aerosol sources and transport that influence cloud and precipitation processes. The ultimate goal is to reduce uncertainties in weather predictions and climate projections of droughts and floods in California. With the DOE G-1 aircraft and second ARM Mobile Facility (AMF2) well equipped for making aerosol and cloud measurements, ACAPEX focuses specifically on understanding how aerosols from local pollution and long-range transport affect the amount and phase of precipitation associated with atmospheric rivers. ACAPEX took place between January 12, 2015, and March 8, 2015, as part of CalWater 2015, which included four aircraft (DOE G-1, National Oceanic and Atmospheric Administration [NOAA] G-IV and P-3, and National Aeronautics and Space Administration [NASA] ER-2), the NOAA research ship *Ron Brown*, carrying onboard the AMF2, National Science Foundation (NSF)-sponsored aerosol and precipitation measurements at Bodega Bay, and the California Department of Water Resources extreme precipitation network.

During the field campaign, The DOE G-1 flew a total of 28 flights, including 8 flights in AR conditions (ocean, coastal, valley/mountain), 6 flights in coastal stratus, 4 flights in orographic clouds not influenced by AR, and 10 flights to characterize aerosols, cloud condensation nuclei (CCN), and ice nucleating particles (INP) in clear sky conditions. *Ron Brown*, with AMF2, departed Honolulu, HI, on 14 January, 2015 and traveled across the Pacific Ocean to sample conditions under two ARs It completed its mission on 9 February, 2015 at the Port of San Diego, CA. During the most notable AR event in early February, four aircraft flew coordinated flights on 5 February through the AR in the Pacific Ocean and rendezvoused with *Ron Brown*. On 6 February, the AR made landfall in the morning near Bodega Bay. The four aircraft flew another coordinated flight and rendezvoused along the coast. G-1 flew three other missions in the Central Valley and through orographic clouds in the Sierra Nevada in postfrontal conditions. Combined with measurements from other platforms and satellites, ACAPEX provided unique opportunities to study aerosol-cloud interactions and precipitation processes in the most observed AR to date.

Acronyms and Abbreviations

2DS	Two Dimensional Stereo (2DS) Particle Imaging Probe
ACAPEX	ARM Cloud Aerosol Precipitation Experiment
AMF	ARM Mobile Facility
AR	atmospheric river
ARM	Atmospheric Radiation Measurement Climate Research Facility
CA	California
CDP	Cloud droplet probe
CNN	cloud condensation nuclei
DOE	U.S. Department of Energy
ESRL	Earth System Research Laboratory
FCDP	Fast cloud droplet probe
IN	ice nuclei
INP	ice nucleating particles
KAZR	Ka-band ARM zenith radar
NSF	National Science Foundation
NASA	National Aeronautic and Space Administration
NOAA	National Oceanic and Atmospheric Administration
PNNL	Pacific Northwest National Laboratory
SBJ	Sierra barrier jet
WCM	Multi-Element Water Content System (WCM-2000)
UCSD	University of California at San Diego

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1.0 Background

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 (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, 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; Leung and Qian 2009). 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 (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 (Rosenfeld et al. 2008). While anthropogenic aerosols may suppress orographic precipitation (Givati and Rosenfeld 2004), dust from long-range transport incorporated into precipitation-producing clouds from aloft may increase precipitation, particularly in the form of snowfall (Ault et al. 2011; Creamean et al. 2013; Fan et al. 2014).

The DOE ARM Cloud-Aerosol-Precipitation Experiment (ACAPEX) field campaign contributes to CalWater 2015, which is by far the largest in a series of field campaigns that started in 2009. The field campaigns aim to improve understanding of atmospheric rivers and aerosol sources and transport that influence cloud and precipitation processes, with the ultimate goal of reducing uncertainties in weather predictions and climate projections of droughts and floods in California. The overarching objectives of CalWater 2015 are to provide measurements to:

- Document and quantify the structure and evolution of atmospheric rivers (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 microphysical properties and examine aerosol removal processes over the Pacific Ocean, and
- Improve understanding and modeling of aerosol-cloud-precipitation interactions in clouds transitioning from the maritime regime to the orographic regime.

With the DOE G-1 aircraft and AMF2 well equipped for making aerosol and cloud measurements, ACAPEX focused more specifically on achieving the third and fourth objectives to address the following science questions:

- How do aerosols affect the amount and phase of precipitation?
- How frequent are aerosols transported across the Pacific and what characteristics make them effective cloud condensation nuclei (CCN) and/or ice nuclei (IN)? How does cloud processing of aerosols influence the aerosol properties and cloud-forming ability?

- 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 atmospheric rivers associated with these storms?
- How are the aged and new aerosols from local California sources such as those in the Bay Area, Central Valley, and Sacramento eventually removed in the different precipitation systems?

The planning of CalWater 2015 began in 2011, after the completion of CalWater-1, which collected data from 2009-2011 in northern CA. The CalWater-2 "Early Start" campaign in 2014 provided spin-up for the major campaign in 2015. Major facilities and staff from partners, including NOAA, DOE, California Department of Water Resources, NSF, NASA, UCSD/Scripps, Colorado State University, Hebrew University of Jerusalem, Plymouth State University, North Carolina State University, and the Naval Research Laboratory, formed an interagency steering committee co-led by scientists from UCSD/Scripps.

Platforms and Measurements in CalWater 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 atmospheric river strength and structure offshore using dropsondes and precipitation radar
- **NOAA P-3 aircraft**: measuring ocean and atmosphere with radars for precipitation, cloud and ocean waves, and air and ocean sondes
- **NOAA *Ron Brown* ship**: measuring aerosols, clouds, atmospheric rivers, and ocean surface and subsurface conditions
- **DOE AMF2**: many sensors mounted on the NOAA ship; measuring aerosols, precipitation, clouds and winds aloft and at the surface
- **CA Dept. of Water Resources extreme precipitation network**: measuring atmospheric rivers, snow level, and soil 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

Figure 1. Top: Three research aircraft at McClellan Airfield, Sacramento, CA on 25 January 2015. Bottom: List of the platforms and measurements in CalWater 2015 sponsored by different agencies.

As the PI of ACAPEX, L. Ruby Leung coordinated with collaborating agencies on the planning that culminated in the execution of the field campaign between January 12, 2015 and March 8, 2015. CalWater 2015 included four aircraft (DOE G-1, NOAA G-IV and P-3, and NASA ER-2), the NOAA research ship *Ron Brown* carrying onboard the AMF2, NSF-sponsored aerosol and precipitation measurements at Bodega Bay, and the California Department of Water Resources extreme precipitation network. The command center was operated at McClellan Airfield in Sacramento, CA, where G-1, G-IV, and P-3 were stationed (except G-IV was stationed in Honolulu from mid-to-late February). NASA-ER2 was stationed in Palmdale, CA. Daily weather briefings including forecasts of AR, aerosol, and cloud took place each day from 8-9AM PT (http://mead.ucsd.edu/?page_id=533).

The DOE G-1 flew a total of 28 flights including:

- 8 flights in AR conditions (ocean, coastal, valley/mountain)
- 6 flights in coastal stratus
- 4 flights in orographic clouds not influenced by AR
- 10 flights to characterize aerosols, cloud condensation nuclei (CCN), and ice nucleating particles (INP) in clear sky

Ron Brown, with AMF2, departed Honolulu, HI, on 14 January, 2015 and traveled across the Pacific Ocean to sample conditions under two ARs, completing its mission on 9 February 2015 at the Port of San Diego, CA. Some coordinated flights were flown and rendezvoused with *Ron Brown* to provide measurements for the study of AR water vapor budget, cloud macrophysical and microphysical structures, and aerosol distribution to address the science questions.

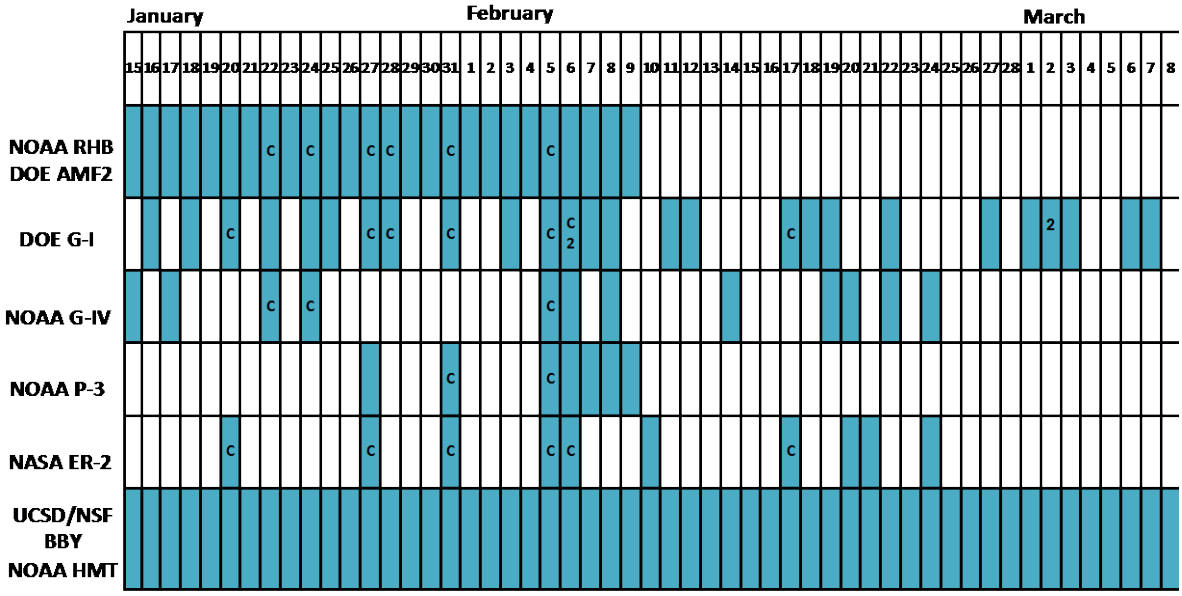

Figure 2. CalWater 2015 facilities activities. Blue boxes indicate deployment of facilities, C stands for coordinated activities, and 2 stands for 2 flights/day.

Team members of ACAPEX include:

PI: L. Ruby Leung, PNNL

Co-PI: Kim Prather, UCSD; Marty Ralph, UCSD; Daniel Rosenfeld, Hebrew University of Jerusalem; Ryan Spackman, NOAA ESRL and Science & Technology Corporation

Co-investigators: Chris Fairall, NOAA ESRL; Jiwen Fan, PNNL; Samson Hagos, PNNL; Mimi Hughes, NOAA ESRL; Steven Rutledge, CSU; Duane Waliser, NASA JPL; Hailong Wang, PNNL.

2.0 Notable Events or Highlights

The weather in California was generally dry during CalWater 2015 with a persistent high-pressure center in the northeastern Pacific, reducing the chances for AR making landfall in western North America. Atmospheric rivers were, however, active over the ocean and G-IV made dropsonde measurements across multiple transects for about eight ARs for moisture budget analysis. Among them, only three ARs that made landfall in northern CA were sampled by the DOE G-1 during ACAPEX. On 15 January, 2015, a dissipating AR made landfall in northern California. A research flight was made to sample the aerosols and clouds in coastal CA. A dust layer was detected in the Central Valley shortly after takeoff and on return. G-1 flew several legs at multiple altitudes in the coastal area over ocean and land in parallel with the coastline and over Bodega Bay for co-located measurements of meteorology (NOAA wind profiler), ambient aerosols and aerosols in precipitation, and cloud-active aerosols (CCN and IN). Another dissipating AR made landfall in northern CA in early March. G-1 flew multiple flights in postfrontal conditions in the valley and Sierra Nevada to collect aerosols and cloud microphysical data.

The most notable AR event was sampled between 5 February and 8 February in 2015. On 5 February, four aircraft flew coordinated flights through the AR in the Pacific Ocean and rendezvous with *Ron Brown*. Figure 3 (left panel) shows the flight paths and the location of *Ron Brown*, together with the overpass of NASA's *Terra* satellite that jointly provided measurements of water vapor, temperature, winds, cloud macrophysical and microphysical properties, aerosols, surface fluxes, precipitation, surface radiation, and ocean subsurface conditions in the AR environment over the ocean before landfall. G-1 flew at 15,000 ft on ferry and captured the sharp rise in temperature and humidity when it encountered the AR in the ocean. It descended to 1,000 ft above *Ron Brown* and spiraled up to 5,500 ft for cloud measurements at multiple levels.

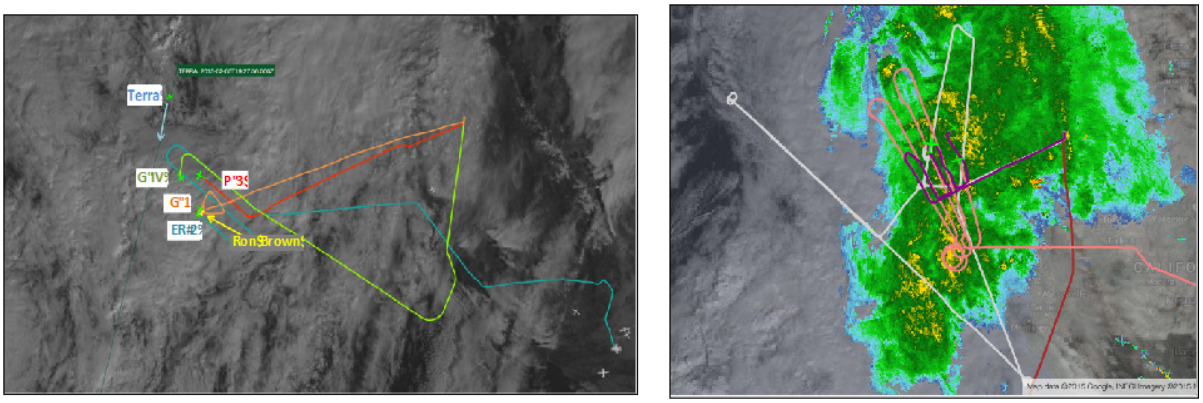

Figure 3. Left: Four aircraft flew over *Ron Brown* on February 5, 2015 in an AR over the North Pacific while the NASA Terra satellite made an overpass. Right: The four aircraft made coordinated measurements again on February 6, 2015 when the AR made landfall near Bodega Bay in central California.

On 6 February 2015, the AR made landfall in the morning near Bodega Bay. The four aircraft flew another coordinated flight and rendezvoused along the coast (right panel of Figure 3). G-1 flew another mission in the afternoon as the AR associated front reached the Central Valley and Sierra Nevada, producing heavy precipitation along the way. During the afternoon flight, the cloud base was at about 4,000 ft, with ice falling from above. G-1 flew multiple legs along the Central Valley and Sierra Nevada for measurements in orographic clouds. The airmass was clean with very low CCN concentration of 50 cm^{-3}. Back trajectory from the mountain flight locations traced the airmass to lower-level tropical sources near the Hawaiian Islands. On 7 and 8 February, G-1 flew two more flights to sample the postfrontal conditions in the Central Valley and Sierra Nevada.

Overall, the five G-1 flights flown between 5 and 8 February, 2015 delivered comprehensive measurements of aerosols and clouds before, during, and after an AR made landfall in northern California. Data from G-1 in the ocean, coast, valley, and mountains captured varied environments related to the AR. Combined with measurements from other platforms and satellites, ACAPEX provided unique opportunities to study aerosol-cloud interactions and precipitation processes in the most observed AR to date.

3.0 Lessons Learned

As part of the inter-agency CalWater 2015 field campaign, ACAPEX was highly successful due to a number of factors:

- The experience gained through the CalWater field campaigns in 2009 and 2011 as well as the NOAA Early Start in 2014 was instrumental to planning the more complex CalWater 2015 field campaign.
- The pre-campaign planning that began in 2012 with annual workshops and meetings was important to defining and prioritizing science objectives and coordinating deployment plans across different teams responsible for multiple platforms.
- The campaign was well supported by the dedicated scientists and technicians from all agencies and organizations involved.
- The resources contributed from different agencies were highly complementary, and the PIs and mission scientists for the different campaigns or platforms shared common interests and objectives.

The main challenge encountered during the field campaign was the weather conditions, with few ARs making landfall in northern California, and the frequent clear days that reduced the chance for making observations to study aerosol-cloud-precipitation interactions. This challenge was, however, not unforeseen, so the ACAPEX team had developed many flight plans to study different clouds such as coastal stratus, in addition to the orographic clouds associated with ARs and postfrontal conditions, and to characterize the spatial distribution of aerosols in the study area as context for aerosol influence on clouds and precipitation during storms. In addition, ACAPEX addressed several issues:

- Coordinating measurements from aircraft and *Ron Brown* was difficult initially because of limited Wi-Fi access on the ship to communicate the weather forecast information and the desired location of the ship for collocated measurements.

- The AMF instruments needed extra protection from the strong winds and high waves while *Ron Brown* was under AR conditions. Occasionally, *Ron Brown* had to move outside the AR pathway to avoid damage to the instruments.
- Flying through heavy precipitation in the postfrontal orographic clouds, ice accumulation on G-1 and water accumulation in the cloud probes presented challenges for making accurate measurements.

4.0 Results

Data collected for ACAPEX including measurements collected by G-1 and AMF2 have been post-processed and quality controlled. The data can be accessed from the ARM Data Archive. As examples, Figure 4 shows the cloud drop size distribution from CDP on G-1, KAZR cloud reflectivity from AMF2 on *Ron Brown*, and the altitude and temperature along the G-1 flight path on 5 February, 2015. Highlighted in the blue box are data collected during the time period of 19Z and 19.5Z when G-1 was close to *Ron Brown* in the Pacific Ocean. The cloud reflectivity data indicate a phase change of the hydrometeors at the freezing level near 3 km, and the clouds extend to about 7 km at the location of *Ron Brown*. Above *Ron Brown*, the CDP data from G-1 show warm liquid clouds, with cloud drops peaking around 10 μm, and concentrations of about 10-50 per cc per μm at 15^{o}C.

On 7 February, G-1 flew between the Central Valley and Sierra Nevada during postfrontal conditions. There were low-level clouds scattered in the Central Valley, and a solid cloud deck with a base at about 14,000 ft. On the west slope of the Sierra Nevada, G-1 detected supercooled cloud drops at temperatures as low as -38^{o}C near the convective cloud top, mixed with ice crystals (Figure 5). The atmosphere was very clean, though some soot and dust particles were detected east of the ridge, consistent with light absorption measurement, suggesting the presence of aerosols with low hygroscopicity. Back-trajectory analysis indicates that the sources of airmass along the flight paths in the Sierra Nevada to be arriving from the upper troposphere in East Asia.

On 8 February, a Sierra Barrier Jet (SBJ) was detected at low altitude in the valley, with wind direction changes from 155^{o} near the surface to 180^{o} at about 4,000 ft. G-1 flew along the valley to study aerosol transport by the SBJ along the valley and how it may influence clouds and precipitation. The atmosphere was relatively clean in the valley with low particle counts. At the northern end of the valley, there was strong turbulence due to the complex terrain. Sampling along the Sierra Nevada mountain ridge parallel to the Central Valley, G-1 flew mostly in cloudy conditions with precipitation falling from above. Both cloud ice and supercooled cloud drops were found along the ridge with convective clouds. Closer to Lake Tahoe and along the western slope, clouds became even more convective with strong turbulence. CCN concentration was even lower on this day, possibly due to rain-out, but dust and organic carbon particles were detected, with East Asia as the likely source, based once again on back-trajectory analysis.

In summary, aerosol and cloud microphysical data collected before, during, and after a landfalling AR between 5-8 February 5-8, 2015 indicate generally low CCN of 10-100 per cc, low INP ~ 0.1-1 per L, with cloud drop concentrations ~ 10-50 per cc per mm, and cloud drop size < 10-50 mm. Despite the low concentrations, aerosols have absorbing properties with chemical composition of organics and dust. Based on back-trajectory analysis, these aerosols are likely transported over long range across the Pacific Ocean. Because of low CCN hygroscopicity and low concentration of INP, tiny supercooled cloud drops exist at

low temperature, so the clouds have a large mixed-phase zone. The data set collected during ACAPEX provides important opportunities for studying the impacts of CCN and IN on supercooled liquid and cloud phase, ice nucleation mechanisms, and precipitation-forming mechanisms for stratiform clouds over the ocean and orographic clouds in the postfrontal environment of an AR.

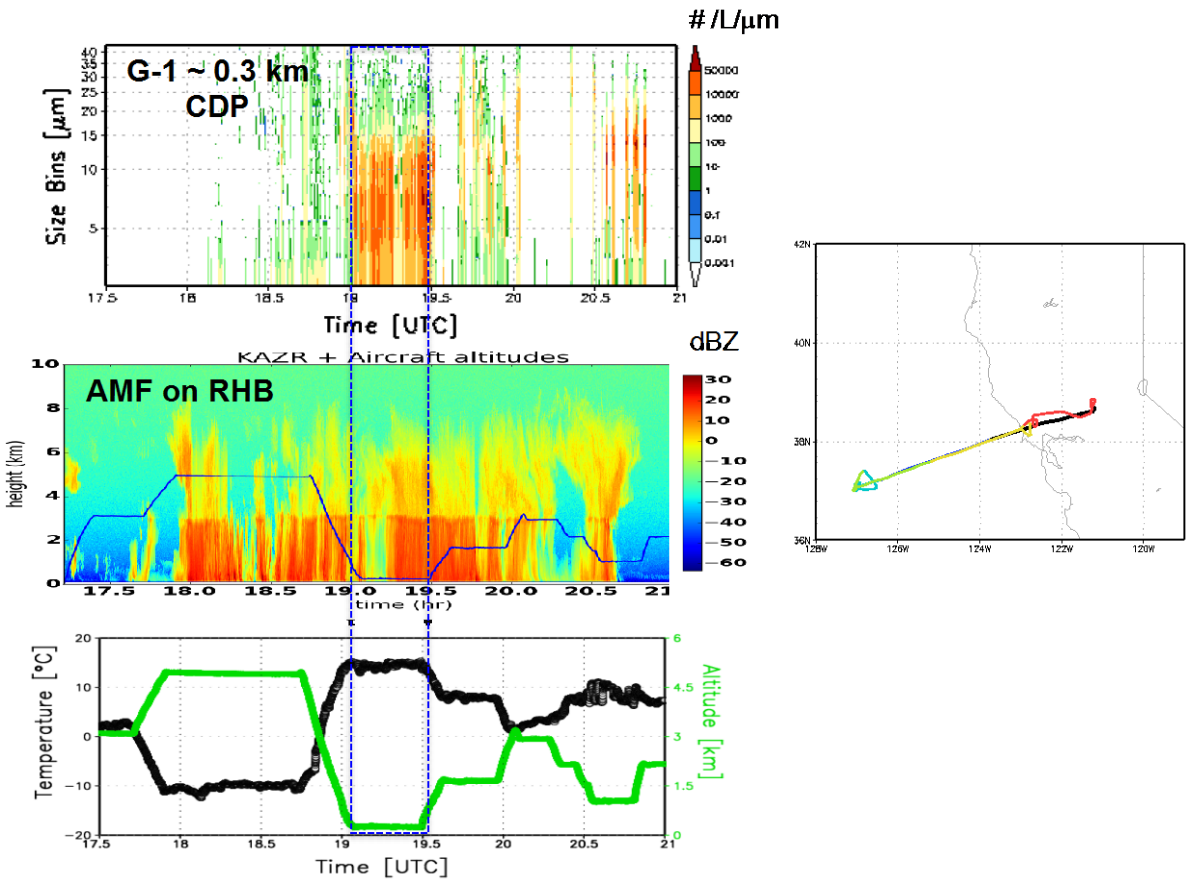

Figure 4. Data from G-1 and AMF2 during the rendezvous on 5 February, 2015. Top left: Cloud drop size distribution in #/L/ µm from CDP on G-1 at an altitude of about 0.3 km above *Ron Brown*. Middle left: KAZR cloud radar reflectivity in dBZ on AMF2 located on *Ron Brown*. Bottom left: Altitude (green) (in km) and temperature (in ºC) along the G-1 flight path. Right: the G-1 flight path for the coordinated flight, with a triangular path above *Ron Brown*.

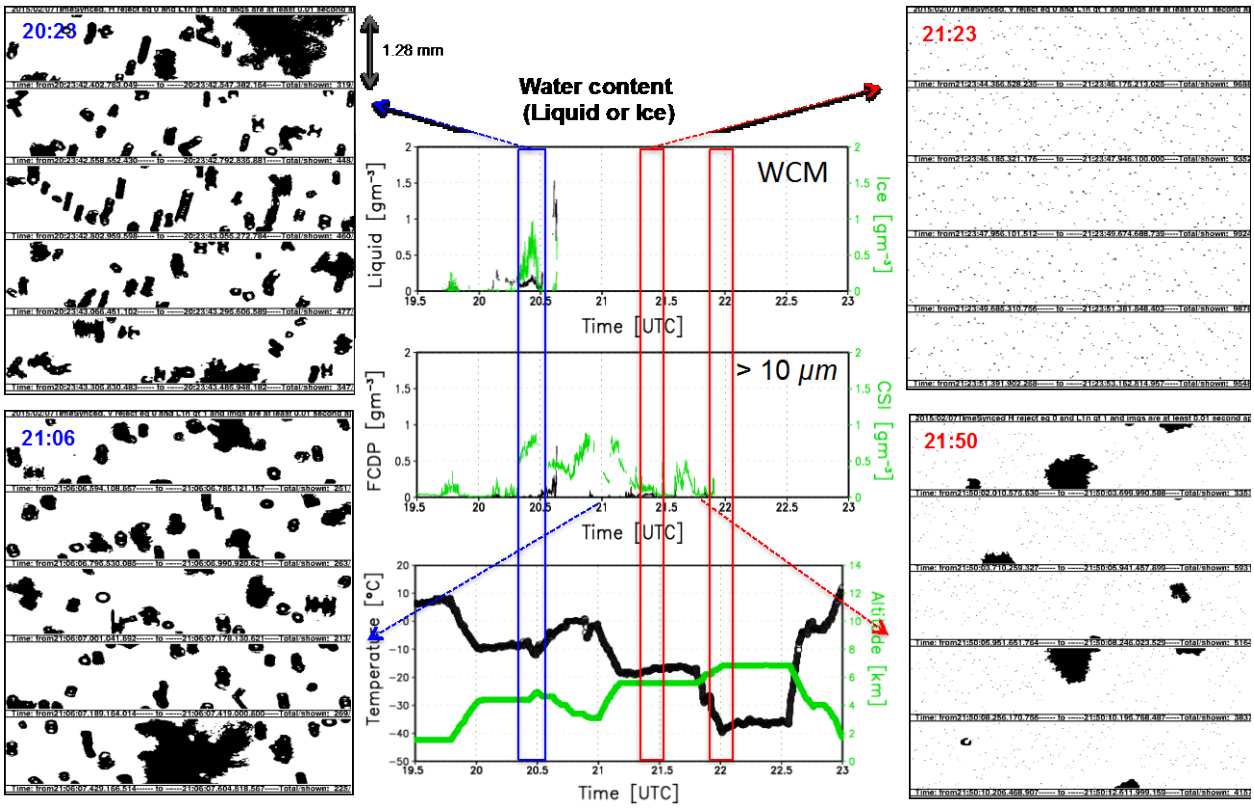

Figure 5. Images of cloud hydrometeors from 2DS onboard G-1 during the 7 February flight. Larger cloud drops were detected in clouds over the Central Valley (images on left) and small supercooled cloud drops were detected in clouds on the west slope of the Sierra Nevada (images on right). The middle panels show the liquid and ice concentrations measured by WCM and FCDP in g/m^3 along the flight path with altitude and temperature shown in the bottom panel.

5.0 Public Outreach

Information about ACAPEX can be found on the following ARM websites:
ARM campaign:
Campaign: ARM Cloud Aerosol Precipitation Experiment (ACAPEX)
ACAPEX News and Press
ARM feature story:
Land, Sea, and Air: ACAPEX Targets Atmospheric Rivers

Information about the interagency CalWater 2015 field campaign, including the daily weather forecasts, can be found on:
CalWater 2015 – ACAPEX
CalWater2

Public outreach

The CalWater – ACAPEX team organized a media workshop titled "Refilling California's Reservoirs—The Roles of Aerosols and Atmospheric Rivers" at the 2014 American Geophysical Union Fall Meeting in San Francisco, CA. The workshop took place at 10:30 am on 18 December, 2014 at the Fall Meeting Press Conference Room. CalWater/ACAPEX mission scientists Marty Ralph and Kim Prather from UC San Diego, Ruby Leung from PNNL, and Ryan Spackman from NOAA's Earth Systems Research Laboratory discussed the campaign and accomplishments to date.

During CalWater 2015, the team organized a media day at the McClellan Airfield on 3 February to share information about the field campaign, its science drivers, and its societal relevance. Mission scientists Marty Ralph and Kim Prather from UC San Diego, Ruby Leung from PNNL, and Chris Fairall and Allen White from NOAA's Earth Systems Research Laboratory met with reporters and gave a tour of the aircraft. The media day was widely reported in news media, journals, and magazines as listed below.

Media Coverage

- *CBS This Morning*
  "Relentless Calif. storms caused by 'atmospheric river'"
  February 9, 2015
- *KCRA, CNN Affiliate*
  "Scientists dissect approaching 'atmospheric river'"
  February 3, 2015
- *KPIX, CBS Affiliate*
  "Team Of Scientists Sailing Into Massive Pacific Storm To Study 'Atmospheric River' Effects On California Drought"
  February 3, 2015
- *Capital Public Radio*
  "Research of Atmospheric Rivers Key To Understanding California's Water Supply"
  February 3, 2015
- *Fox 40*
  "NOAA Goes Airborne To Study Storm"
  February 3, 2015
- *89.3 KPCC*
  "Rivers of water in the air provide much of California's rain"
  December 11, 2014

Features

- *Chemical and Engineering News*
  "Dissecting California Precipitation"
  March 16, 2015
- *LA Times*
  "Scientists go high and low for data on drought-fighting 'sky rivers'"
  February 14, 2015

- *The Wide World of Sport*
  "Dusty Atmospheric River Strikes California"
  February 10, 2015
- *CBS Sacramento*
  "Flying Into A Storm To Figure Out The Drought"
  February 7, 2015
- *San Francisco Gate*
  "Researchers fly into heart of California storm to gather key data"
  February 6, 2015
- *Climate Central*
  "How Warming May Alter Critical 'Atmospheric Rivers'"
  February 6, 2015
- *Breitbart*
  "*Atmospheric river storm approaches: "We think this will be a big one"*"
  February 6, 2015
- *USA Today*
  "Scientists to eye sky 'rivers' during California storm"
  February 5, 2015
- *Wired*
  "Infoporn: Forecasting a river of water"
  February 5, 2015
- *The Sacramento Bee*
  "Scientists ride the Pineapple Express"
  February 5, 2015
- *Gizmodo*
  "We're Going to Fly Four Planes Straight into the Pineapple Express"
  February 4, 2015
- *LiveScience*
  "Sky River to Bust Northern California Drought This Week"
  February 4, 2015
- *Weather Underground*
  "Atmospheric River Heads for California as a Massive Field Study Gears Up"
  February 3, 2015
- *The San Diego Union-Tribune*
  "Scientists fly into storms for research"
  February 3, 2015
- *The Sacramento Bee*
  "Atmospheric river poised to soak Sacramento"
  February 3, 2015
- *The Washington Post*
  "Sky me a river: Scientists say flood threat linked to atmospheric rivers"
  January 26, 2015
- *Reporting Climate Science*
  "Field Research To Get Data On California Drought"
  January 20, 2015

- *Nature*
  "CalWater 2015 targets atmospheric rivers off California"
  January 20, 2015
- *Los Angeles Times*
  "California drought could end with storms known as atmospheric rivers"
  January 18, 2015
- *Scripps Institution of Oceanography at University of California – San Diego*
  "Refilling California's Reservoirs—The Roles of Aerosols and Atmospheric Rivers"
  December 16, 2014
- *Greenwire*
  "Scientist probes weather risk that's like 'fire hose aimed at the coast'"
  April 30, 2014

Blog and Twitter

- Aaron Naeger, *Dusty Atmospheric River Strikes California*
- https://twitter.com/NWSSacramento/status/563447645142650881

ACAPEX Publications

5.1 Journal Articles/Manuscripts

Gao, Y, J Lu, and LR Leung. 2015. "Uncertainties in Projecting Future Changes in Atmospheric Rivers and their Impacts on Heavy Precipitation over Europe." *Journal of Climate*, in review.

Ralph, F.M., K. Prather, D. Cayan, J.R. Spackman, P. DeMott, M. Dettinger, C. Fairall, R. Leung, D. Rosenfeld, S. Rutledge, D. Waliser, A. White, G. Franco, J.O'Hagan, J. Cordeira, A. Martin, and J. Helly. 2015. "CalWater Field Studies Designed to Quantify the Roles of Atmospheric Rivers and Aerosols in Modulating U.S. West Coast Precipitation in a Changing Climate." *Bulletin of the American Meteorological Society*, doi:10.1175/BAMS-D-14-00043.1.

Gao, Y., J. Lu, L.R. Leung, Q. Yang, S. Hagos, and Y. Qian. 2015. "Dynamical and Thermodynamical Modulations on Future Changes of Landfalling Atmospheric Rivers over Western North America." *Geophysical Research Lett*ers 42: 7179–7186, doi:10.1002/2015GL065435.

Hagos, S., L.R. Leung, Q. Yang, C. Zhao, and J. Lu. 2015. "Resolution and Dynamical Core Dependence of Atmospheric River Frequency in Global Model Simulations." *Journal of Climate* 28: 2764-2776, doi: 10.1175/JCLI-D-14-00567.1.

5.2 Meeting Abstracts/Presentations/Posters

Invited presentations and seminars:

Leung, L.R., 2015. "Atmospheric Rivers and Heavy Precipitation from a Hierarchy of Climate Simulations." American Geophysical Union Fall Meeting, December 14-18, 2015, San Francisco, CA.

Leung, L.R., 2015. "Modeling Aerosol Effects on Clouds and Precipitation: Insights From CalWater 2015." American Geophysical Union Fall Meeting, December 14-18, 2015, San Francisco, CA.

Leung, L.R., 2015. "Long-range Transport of Dust and Impacts on Clouds and Precipitation." International Conference on Hydro-Biogeochemical Processes: Mechanisms, Coupling and Impacts, October 27-31, 2015, Wuhan, China.

Leung, L.R., 2015. "A Tale of Two Rivers." Seminar at University of New South Wales, October 23, 2015, Sydney, Australia.

Leung, L.R., 2015."A Tale of Two Rivers." Keynote presentation at the 2015 Atmospheric and Interdisciplinary Research (AIR) Conference, April 8-9, 2015, Tucson, AZ.

Leung, L.R., 2014. "CalWater 2 – ARM Cloud-Aerosol-Precipitation Experiment (ACAPEX)." Invited presentation at the 2014 American Geophysical Union Fall Meeting, December 15-19, 2014, San Francisco, CA.

Spackman, R., M. Ralph, K. Prather, D. Cayan, P. DeMott, M. Dettinger, C. Fairall, R. Leung, D. Rosenfeld, S. Rutledge, D. Waliser, A. White, 2014. "CalWater 2 – Precipitation, Aerosols, and Pacific Atmospheric Rivers Experiments." Invited presentation at the 2014 American Geophysical Union Fall Meeting, December 15-19, 2014, San Francisco, CA.

Oral presentations:

Leung, L.R., 2016. "Atmospheric Rivers and Heavy Precipitation from a Hierarchy of Climate Simulations." 96th American Meteorological Society Annual Meeting, January 10-14, 2016, New Orleans, LA.

Leung, L.R., 2015. "Atmospheric Rivers and Heavy Precipitation from a Hierarchy of Climate Simulations." 16th AMS Conference on Mesoscale Processes, August 3-5, 2015, Boston, MA.

Leung, L.R., 2015. "Atmospheric Rivers and Heavy Precipitation from a Hierarchy of Climate Simulations." 26th IUGG General Assembly, June 22-July 2, 2015, Prague, CZ.

Poster presentations:

Leung, L.R., 2015. "Atmospheric Rivers and Heavy Precipitation from a Hierarchy of Climate Simulations." Translating Process Understanding to Improve Climate Models, October 15-16, 2015, Princeton, NJ.

Leung, L.R., 2015. "The CalWater 2 – ARM Cloud-Aerosol-Precipitation Experiment (ACAPEX)." ARM/ASR Science Team Meeting, March 16-19, 2015, Vienna, VA.

In addition, research using CalWater 2015 data was prominently featured at the 2015 American Geophysical Union Fall meeting on 14-18 December, 2015 in San Francisco, CA. A list of oral and poster presentations is given below.

A44C: Precipitation, Weather, and Climate: Atmospheric Rivers and Aerosol-Cloud Interaction Studies I (Oral)

☐ 16:00 A44C-01 CalWater 2015 — Atmospheric Rivers and Aerosol Impacts on Precipitation J. Ryan Spackman1, F Martin Ralph2, Kimberly A Prather3, Dan Cayan4, Paul J DeMott5, Michael D Dettinger4, James D Doyle6, Chris W Fairall7, L. Ruby Leung8, Daniel Rosenfeld9, Steven A Rutledge5, Duane E Waliser10 and Allen B White7, (1)Science and Technology Corporation, Boulder, CO, United States, (2)Scripps Institution of Oceanography, La Jolla, CA, United States, (3)University of California San Diego, La Jolla, CA, United States, (4)Scripps Institute of Oceanography, La Jolla, CA, United States, (5)Colorado State University, Fort Collins, CO, United States, (6)NRL, Monterey, CA, United States, (7)NOAA Boulder, Boulder, CO, United States, (8)Pacific Northwest National Laboratory, Richland, WA, United States, (9)Hebrew University of Jerusalem, Jerusalem, Israel, (10)NASA Jet Propulsion Laboratory, Pasadena, CA, United States

☐ 16:15 A44C-02 Modeling Aerosol Effects on Clouds and Precipitation: Insights from CalWater 2015 L. Ruby Leung1, Kyo-Sun Sunny Lim1, Jiwen Fan1, Kimberly A Prather2, Paul J DeMott3, J. Ryan Spackman4 and F Martin Ralph5, (1)Pacific Northwest National Laboratory, Richland, WA, United States, (2)University of California San Diego, La Jolla, CA, United States, (3)Colorado State University, Fort Collins, CO, United States, (4)Science and Technology Corporation, Boulder, CO, United States, (5)Scripps Institution of Oceanography, La Jolla, CA, United States

☐ 16:30 A44C-03 Impact of Local Pollution Versus Long Range Transported Aerosols on Clouds and Precipitation over California Kimberly A Prather, University of California San Diego, La Jolla, CA, United States

☐ 16:45 A44C-04 Aerosol and Cloud-Nucleating Particle Observations during an Atmospheric River Event Paul J DeMott1, Christina S. McCluskey1, Markus Petters2, Kaitlyn J Suski3, Ezra JT Levin3, Thomas Christopher James Hill3, Sam A Atwood4, Gregory P Schill3, Katherine Rocci5, Yvonne Boose6, Andrew Martin7, Gavin Cornwell8, Hashim Al-Mashat8, Kathryn Moore8, Kimberly A Prather8, Nicholas Rothfuss2, Hans Taylor2, L. Ruby Leung9, Jason M Tomlinson9, Fan Mei10, John M Hubbe9, Daniel Rosenfeld11, J. Ryan Spackman12, Chris W Fairall13, Jessie Creamean14, Allen B White13 and Sonia M Kreidenweis1, (1)Colorado State University, Fort Collins, CO, United States, (2)North Carolina State University at Raleigh, Raleigh, NC, United States, (3)Colorado State University, Department of Atmospheric Science, Fort Collins, CO, United States, (4)Colorado State University, Atmospheric Science, Fort Collins, CO, United States, (5)University of New Hampshire Main Campus, Durham, NH, United States, (6)ETH Swiss Federal Institute of Technology Zurich, Institute for Atmospheric and Climate Science, Zurich, Switzerland, (7)Scripps Institution of Oceanography, La Jolla, CA, United States, (8)University of California San Diego, La Jolla, CA, United States, (9)Pacific Northwest National Laboratory, Richland, WA, United States, (10)Joint Global Change Research Institute, College Park, MD, United States, (11)Hebrew University of Jerusalem, Jerusalem, Israel, (12)Science and Technology Corporation, Boulder, CO, United States, (13)NOAA Boulder, Boulder, CO, United States, (14)University of California, SD, Boulder, CO, United States

☐ 17:00 A44C-05 Atmospheric River Forecasting: Current Capabilities, Needs and New Directions F Martin Ralph1, Robert Hartman2, Jason M Cordeira3, Jay Jasperse4, John Rutz5, Paul J Neiman6, Andrew Martin1 and David Anthony Lavers1, (1)Scripps Institution of Oceanography, La Jolla, CA, United States, (2)NOAA/NWS California-Nevada River Forecast Center, Sacramento, CA, United States, (3)Plymouth State University, Plymouth, NH, United States, (4)Sonoma County Water, Santa Rosa, CA, United States, (5)NOAA, Salt Lake City, UT, United States, (6)NOAA Camp Springs, Camp Springs, MD, United States

☐ 17:15 A44C-06 An Airborne and Ground-based Study of a Long-lived and Intense Atmospheric River Impacting California during the CalWater-2014 Early-Start Field Campaign Paul J Neiman1, Moore Benjamin2, Allen B White3, Gary A Wick3, Joshua Aikins4, Darren L Jackson5, J. Ryan Spackman6 and F Martin Ralph7, (1)NOAA, Boulder, CO, United States, (2)SUNY Albany, Albany, NY, United States, (3)NOAA Boulder, Boulder, CO, United States, (4)NOAA/CIRES, Boulder, CO, United States, (5)Cooperative Institute for Research in Environmental Sciences, Boulder, CO, United States, (6)STC/NOAA, Boulder, CO, United States, (7)Scripps Institution of Oceanography, La Jolla, CA, United States

☐ 17:30 A44C-07 Atmospheric River Observations with the HAMSR Aircraft Microwave Sounder Bjorn Lambrigtsen1, Shannon Thomas Brown1, Mathias M Schreier2, Hong Van T Dang1 and Ali Behrangi1, (1)NASA Jet Propulsion Laboratory, Pasadena, CA, United States, (2)Jet Propulsion Laboratory, Pasadena, CA, United States

☐ 17:45 A44C-08 Computation of Air-sea fluxes in Atmospheric Rivers over the Northeast Pacific using Dropsonde Observations Chris W Fairall1, Byron Blomquist2, Chelle L Gentemann3, F Martin Ralph4, J. Ryan Spackman5, Janet M Intrieri1 and Allen B White1, (1)NOAA Boulder, Boulder, CO, United States, (2)University of Colorado at Boulder, Boulder, CO, United States, (3)Remote Sensing Systems, Santa Rosa, CA, United States, (4)Scripps Institution of Oceanography, La Jolla, CA, United States, (5)Science and Technology Corporation, Boulder, CO, United States

A51L: Precipitation, Weather, and Climate: Atmospheric Rivers and Aerosol-Cloud Interaction Studies II (Poster)

☐ A51L-0231 A New U.S. West Coast Network of Atmospheric River Observatories Allen B White1, James M Wilczak2, Thomas E Ayers2, Clark W King2, James R Jordan3, William J Shaw4, Julia E Flaherty4 and Victor R Morris4, (1)NOAA Boulder, Boulder, CO, United States, (2)NOAA Boulder, Earth Systems Research Laboratory, Boulder, CO, United States, (3)Cooperative Institute for Research in Environmental Sciences, Boulder, CO, United States, (4)Pacific Northwest National Laboratory, Richland, WA, United States

☐ A51L-0232 Evaluating Modeled Variables Included in the NOAA Water Vapor Flux Tool Lisa S Darby1, Allen B White1 and Timothy Coleman2, (1)NOAA Boulder, Boulder, CO, United States, (2)NOAA, Boulder, CO, United States

☐ A51L-0233 Atmospheric River impacts in British Columbia and the Pacific Northwest on 22-24 January 2015 during the CalWater 2015 field campaign Natalie G Gaggini1, J. Ryan Spackman1, Paul J Neiman2, Allen B White3, Chris W Fairall3, Chris Barnet1, Antonia Gambacorta4 and Mimi Hughes5, (1)Science and Technology Corporation, Boulder, CO, United States, (2)NOAA, Boulder, CO, United

States, (3)NOAA Boulder, Boulder, CO, United States, (4)Science and Technology Corporation, Columbia, MD, United States, (5)University of Colorado at Boulder, Boulder, CO, United States

☐ A51L-0234 Ship-based Surface Flux Observations Under Atmospheric Rivers During the CALWATER 2015 Field Campaign Byron Blomquist1, Chris W Fairall2, Janet M Intrieri2, Daniel E Wolfe3 and Sergio Pezoa3, (1)University of Colorado at Boulder, Boulder, CO, United States, (2)NOAA Boulder, Boulder, CO, United States, (3)NOAA, Boulder, CO, United States

☐ A51L-0235 Investigating Atmospheric Rivers using GPS TPW during CalWater 2015 ABSTRACT WITHDRAWN

☐ A51L-0236 Sampling the Vertical Moisture Structure of an Atmospheric River Event Using Airborne GPS Radio Occultation Profiling Jennifer Susan Haase1, Kelsey Malloy2, Brian Murphy3, Jeffrey Sussman1 and Weixing Zhang1,4, (1)University of California, San Diego, Scripps Institution of Oceanography, La Jolla, CA, United States, (2)University of Maryland College Park, Atmospheric and Oceanic Sciences, College Park, MD, United States, (3)Purdue University, West Lafayette, IN, United States, (4)Wuhan University, School of Geodesy and Geomatics, Wuhan, China

☐ A51L-0237 Sea-based Infrared Radiance Measurements of Ocean and Atmosphere from the ACAPEX/CalWater2 Campaign P Jonathan Gero1,2, Robert Knuteson2, Denny Hackel2, Coda Phillips2 and Matthew Westphall2, (1)University of Wisconsin, Madison, WI, United States, (2)University of Wisconsin-Madison, Space Science and Engineering Center (SSEC), Madison, WI, United States

☐ A51L-0238 Observations of Convective Development from Repeat Pass Radiometry during CalWaters 2015: Outlook for the TEMPEST Mission Shannon Thomas Brown, NASA Jet Propulsion Laboratory, Pasadena, CA, United States

☐ A51L-0239 Water isotope characteristics of landfalling atmospheric rivers in California Hari Mix1, Sean P Reilly1, Andrew Martin2 and Brian Kawzenuk2, (1)Santa Clara University, Santa Clara, CA, United States, (2)Scripps Institution of Oceanography, La Jolla, CA, United States

☐ A51L-0240 Investigation of the linkages between insoluble precipitation residues and cloud properties at Yosemite National Park during U.S. West Coast storms Jessie Creamean1, Patrick Minnis2, Rabindra Palikonda3, Douglas Spangenberg3, Kimberly A Prather4 and Allen B White5, (1)University of California, SD, Boulder, CO, United States, (2)NASA Langley Research Center, Hampton, VA, United States, (3)Science Systems & Applications, Inc., Hampton, VA, United States, (4)University of California San Diego, La Jolla, CA, United States, (5)NOAA Boulder, Boulder, CO, United States

☐ A51L-0241 Regional climate effects of aerosols on precipitation and snowpack in California Longtao Wu1, Hui Su1, Jonathan H. Jiang1, Chun Zhao2, Yun Qian2 and Thomas H Painter1, (1)NASA Jet Propulsion Laboratory, Pasadena, CA, United States, (2)Pacific Northwest National Laboratory, Richland, WA, United States

☐ A51L-0242 AAF G1 and Millimeter Wavelength ARM Radar Observations and Analysis from the ACAPEX Field Campaign Alyssa Ann Matthews1, Joseph Clinton Hardin1, Jennifer M Comstock1, Nitin Bharadwaj2 and Fan Mei3, (1)Pacific Northwest National Laboratory, Richland, WA, United States,

(2)PNNL-ASGC, Richland, WA, United States, (3)Joint Global Change Research Institute, College Park, MD, United States

☐ A51L-0243 Gap-flow Mediated Transport of Pollution to a Remote Coastal Site: Effects upon Aerosol Composition Gavin Cornwell1, Andrew Martin2, Markus Petters3, Kimberly A Prather1, Hans Taylor3, Nicholas Rothfuss3, Paul J DeMott4 and Sonia M Kreidenweis4, (1)University of California San Diego, La Jolla, CA, United States, (2)Scripps Institution of Oceanography, La Jolla, CA, United States, (3)North Carolina State University at Raleigh, Raleigh, NC, United States, (4)Colorado State University, Fort Collins, CO, United States

☐ A51L-0244 Sensitivity studies using Regional Atmospheric Modeling System to analyze the impact of dust and aerosol on precipitation in the Colorado River Basin Vandana Jha, William R Cotton, Gustavo G Carrio and Jeffrey R Pierce, Colorado State University, Fort Collins, CO, United States

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