Pierce et al 2013 (J. Clim.): Model disagreements in the projected change in occurrence of the heaviest precipitation days (>60 mm day$^{-1}$) account for the majority of disagreement in the projected change in annual precipitation, and occur preferentially over the Sierra Nevada and Northern California.
# CalWater 2 Core Scientific Steering Group
(formed in 2012 – created a Science White paper by 2013)

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<tr>
<th>Investigator</th>
<th>Affiliation</th>
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<td>A. B. White</td>
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Key Science Gaps

**Major goal:** Measure influx of moisture to California from landfalling atmospheric rivers and study the influence of transported (cross Pacific) or local (Central Valley) aerosols on precipitation from the coast to Sierra.

- **Evolution and structure of ARs**, including quantifying terms in the water vapor transport budget (air-sea flux, rainout, frontal convergence, entrainment from tropics)

- **Prediction of aerosol burdens and properties** during intercontinental transport from remote source regions to the U.S. West Coast, including dust, biological and ice nuclei

- **Effects of climate variability and change on these phenomena**
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$17$ M total
NOAA*
DOE*
CEC*
NSF*
DWR
ONR
NASA
½ for aerosols
½ for ARs
*Primary Sponsors
Origins of CalWater - CEC

• 2005-2008: CEC sponsored studies on the role of aerosols in precipitation
  • “SUPRECIP” experiment (Rosenfeld)
Origins of CalWater – NOAA, SIO

• 2002-2008: Research in NOAA’s Hydrometeorology Testbed (HMT) and at Scripps identified atmospheric rivers as the key cause of heavy precipitation and flooding in California.
Atmospheric Rivers: A Key to Extremes

• Atmospheric Rivers (ARs) are narrow bands of strong water vapor transport
• ARs often cause heavy precipitation in CA and can cause flooding
• More ARs lead to a wetter year and fewer ARs lead to a drier year – even drought
• Decadal scale fluctuation in precipitation is tied to the number of extreme events

Ralph and Dettinger, 2012

Dettinger & Cayan, 2014
CalWater 1
2009-2011

CalWater and Key HMT Observing Sites - Winter 2011

Atmospheric River and Barrier Jet 3-D Wind Retrieval Domain

Aerosol-Precipitation Couplet

Orographic Precipitation Couplet

ESRL C-band Doppler Radar (SKYWATER)
3-D Multiple Doppler wind retrieval domain

915 MHz Profiler
GPS IWV
S-band Profiler
Impact (JW) Disdrometer
Optical (Parsivel) Disdrometer
S-band FMCW Profiler
Sfc Met & TB Precip Gauge
Hot Plate Precip Gauge
ETI Precip Gauge
Snow Depth
ATOFMS Aerosol Sampler
Mobile ATOFMS Aerosol Sampler
Aircraft Sampling
Operational & Long-Term Observing Systems
NWS WSR-88D
NWS Rawinsonde
The greater the AR strength and duration

Other factors e.g., aerosols also important

From Ralph et al. 2013, *J. Hydrometeorology*
Potential Impacts of Aerosols on California Precipitation and Water Supply

- **CalWater** field experiment has documented a potentially important role of Asian dust and related aerosols on Sierra Nevada precipitation
- CalWater involves CEC, NOAA, SIO, DOE, NASA, and other partners
- Initial results published in JGR Sept 2011 (Ault et al.)
- 40% greater precipitation in a storm with Asian dust and aerosols versus a very similar storm without them
- Creamean et al. 2013 (Science) used aircraft data to confirm Ault et al. 2011
Origin of dust in Sierra snow
HYSPLIT trajectories, March 3, 2009
Creamean et al. (2013) *Science*

Schematic synopsis of aerosol, AR, SBJ interactions and their impacts on clouds and precipitation.
Orographic precipitation in Upper Sacramento River, an area vital to CA water supply, involves both inland penetrating atmospheric rivers (ARs) and the Sierra Barrier Jet (SBJ)


- 46 of 50 (92%) events are associated with landfalling ARs*
- 45 of 50 (90%) events are associated with SBJ conditions*
- 38 of 50 (76%) events are associated with both landfalling ARs and SBJ conditions*

*on either the day before or the day of precipitation

Composite cross section of the 50 extreme precipitation days illustrates SBJ water vapor flux (shaded), AR water vapor flux (contoured), and total wind barbs (m s⁻¹ convention)

50 largest daily precipitation totals in "index" for 10 water years from Oct 2000–Sep 2011

Fig. from Neiman et al. MWR 2013
## CalWater Timeline

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### CalWater 1

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- X for 2009
- X for 2010
- X for 2011
- X for 2012
- X for 2013
- X for 2014
- X for 2015
- X for 2016
- X for 2017
- X for 2018

### CalWater 2 Planning

- X for 2008
- X for 2009
- X for 2010
- X for 2011
- X for 2012
- X for 2013
- X for 2014
- X for 2015
- X for 2016
- X for 2017
- X for 2018

### CalWater 2

- X for 2008
- X for 2009
- X for 2010
- X for 2011
- X for 2012
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- X for 2016
- X for 2017
- X for 2018
This AR increased precipitation-to-date from 16% to 40% of normal in < 4 days in key Northern California watersheds, but runoff was muted due to dry soils.

Russian River’s highest flow in > 1 year

SSM/I satellite observations of water vapor on 8 Feb 2014
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 & ocean waves, and air & ocean sondes
NOAA Ron Brown Ship: measuring aerosols, clouds, atmospheric rivers, ocean surface and subsurface conditions
DOE AMF2: many sensors mounted on the NOAA ship; measuring aerosols, precipitation, clouds & 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
NSF-supported aerosol and precipitation measurements at **Bodega Bay**: UCSD, Colorado State University, North Carolina State University

**PIs:** Kim Prather (UCSD/Scripps), Sonia Kreidenweiss (CSU), Marcus Petters (NCSU)
Also Paul Demott (CSU) and Andrew Martin (UCSD/Scripps)

- Precipitation collections for residue chemical, biological and ice nucleation
- Aerosols
  - Single particle aerosol mass spectrometry
  - IMPROVE chemically-speciated PM2.5 and PM10
  - WIBS-4A bioaerosols and fluorescence microscopy collections
  - Continuous aerosol size distribution
- Cloud-active aerosols
  - Ice nucleation filter samples (integrated periods for offline analysis)
  - Selected periods of single particle ice nuclei mass spectral composition
  - Real-time ice nucleation measurements 4-8 hours daily
  - Continuous scanning CCN
- Meteorology (NOAA and CA DWR)
CalWater 2 Dropsonde Data from NOAA G-IV and P-3 Aircraft

- 30 NOAA flights
- 537 dropsondes
- Primarily focused on atmospheric rivers

Map courtesy of R. Demirdjian (Scripps/CW3E)
Between Feb 5 – 8, DOE G-1 flew five missions to sample aerosols and clouds in different AR conditions.

On Feb 6 afternoon, G-1 sampled clouds and aerosols in Sierra Nevada during AR landfall.

Shortly after take off – flooded area during AR landfall.

On Feb 7, G-1 repeated the same legs in Sierra Nevada in post-frontal conditions.

On Feb 8, a Sierra Barrier Jet developed in the Central Valley. G-1 flew in the northern valley and Sierra Nevada to study aerosols and clouds influenced by different circulations.

Convective clouds over Sugar Pine Dam at 16,000 ft.

Snowing near Carson City.
CALWATER-2015: Ship-based Sensors

- DOE AMF2 - PNNL (Leung) (Aerosols, radars, lidars, wind profiler, ...)
- Fluxes and Near-Surface Meteorology-ESRL/PSD (Fairall)
- Balloon soundings - NOAA/NESDIS (Nalli)
- Wave dissipation (SWIFT buoys) –UW/APL (Thompson)
- GPS water vapor - U Hawaii (Almanza, Businger)

Observed strong ARs

Ron Brown track from Hawaii to initial operating location at 38 N, 140 W, then to 37 N, 127 W
Preliminary air-sea flux from Ron Brown
Bulk vs Turbulent vs OAflux grid

*Courtesy of Chris Fairall*
Composite
17 aircraft-observed ARs

Preliminary analysis from
F.M. Ralph, S. Iacobellus, J. Cordeira

CFSR/GFS Composite IWV (cm), IVT [kg/(m*s)], IVT Vector, and SLP (hPa)
75% of Total IVT occurs below ~3 km MSL

1% of Total IVT occurs above ~7 km MSL

Average Total Water Vapor Transport in an AR is $4.5 \times 10^8$ kg s$^{-1}$
Equivalent to roughly half the discharge of all rivers globally
Coordinated flights, February 5, 2015
Climate change intensification of horizontal water vapor transport in CMIP5

D.A. Lavers, F.M. Ralph, D.E. Waliser, A. Gershunov, and M.D. Dettinger

Main conclusions

1. The mean & variance of atmospheric water vapor flux will intensify under projected climate change.

2. The high-latitude (Arctic) water vapor flux exhibits the largest percentage increases.

3. The increased water vapor flux is almost exclusively due to increased low-level specific humidity.

Percentage mean IVT increase (RCP8.5 / HIST) in DJF. 20-30% increases near California.
CalWater Field Studies Designed to Quantify the Roles of Atmospheric Rivers and Aerosols in Modulating U.S. West Coast Precipitation in a Changing Climate.

F. M. Ralph,1 K. A. Prather,1 D. Cayan,2 J.R. Spackman,3,4 P. DeMott,5 M. Dettinger,2 C. Fairall,4 R. Leung,6 D. Rosenfeld,7 S. Rutledge,5 D. Waliser,8 A. B. White,4 J. Cordeira,9 A. Martin,1 J. Helly,1,10 and J. Intrieri4

Capsule

Quantifying the roles of atmospheric rivers and aerosols in modulating U.S. West Coast precipitation, water supply, flood risks and drought in a changing climate

Abstract

The variability of precipitation and water supply along the U.S. West Coast creates major challenges to the region’s economy and environment, as evidenced by the recent California drought. This variability is strongly influenced by atmospheric rivers (AR), which deliver much of the precipitation along the U.S. West Coast and can cause flooding, and by aerosols (from local sources and transported from remote continents and oceans) that modulate clouds and precipitation. A better understanding of these processes is needed to reduce uncertainties in weather predictions and climate projections of droughts and floods, both now and under changing climate conditions.

To address these gaps a group of meteorologists, hydrologists, climate scientists, atmospheric chemists, and oceanographers have created an interdisciplinary research effort, with support from multiple agencies. From 2009-2011 a series of field campaigns (CalWater 1) collected atmospheric chemistry, cloud microphysics and meteorological measurements in California and associated modeling and diagnostic studies were carried out. Based on remaining gaps, a vision was developed to extend these studies offshore over the Eastern North Pacific and to enhance land-based measurements from 2014-2018 (CalWater 2). The data set and selected results from CalWater 1 are summarized here. The goals of CalWater-2, and measurements to date, are then described.

CalWater is producing new findings and exploring new technologies to evaluate and improve global climate models and their regional performance and to develop tools supporting water and hydropower management. These advances also have potential to enhance hazard mitigation by improving near-term weather prediction and subseasonal and seasonal outlooks.

Corresponding Author: F. Martin Ralph, UC San Diego/Scripps Institution of Oceanography, 9500 Gilman Dr., #0224, La Jolla, CA 92039, mralph@ucsd.edu, 858-822-1809 (office), 858-822-2028 (fax)
Atmospheric Rivers

Integrated Water Vapor (IWV) Perspective

Pac NW AR
Nov 2006
Record rain

TN Flood
May 2010
> $2B damage

“Snowmageddon”
Feb 2010
East Coast Paralyzed

Integrated Water Vapor Transport (IVT) Perspective

Integrated Water Vapor (IWV) Perspective

kg m$^{-1}$ s$^{-1}$
For a CalWater overview, see Ralph et al. 2015 BAMS Early Online Release

mralph@ucsd.edu
cw3e.ucsd.edu
AR frequency in aquaplanet simulations

Hagos et al. 2015 JC

Southeast Pacific AR frequency in AMIP simulations

Eddy-driven jet shifts poleward and weakens with increasing resolution

Lu et al. 2015 JC

- AR frequency consistently decreases with increasing model resolution
- This sensitivity is traced to the poleward shift of subtropical jet with increasing model resolution
- Uncertainty in projecting changes in AR frequency in the future is partly related to uncertainty in projecting the jet shift

*Slide courtesy of Ruby Leung*