Recent Developments in Atmospheric River Science, Prediction and Applications

F. Martin Ralph
Center for Western Weather and Water Extremes
UC San Diego/Scripps Institution of Oceanography

Research Aircraft at McClellan Airfield, Sacramento, CA
For the CalWater-2015 Interagency Field Campaign
25 January 2015

Photo by Marty Ralph (UCSD/Scripps/CW3E)

Seminar at the Water Resources Research Center (WRRC)
Tucson, Arizona, 12 February 2018
Atmospheric Rivers are like rivers in the sky – Rivers of water vapor

These color images represent satellite observations of atmospheric water vapor over the oceans.

Warm colors = moist air

Cool colors = dry air

ARs can be detected with these data due to their distinctive spatial pattern.

In the top panel, the AR hit central California and produced 18 inches of rain in 24 hours.

In the bottom panel, the AR hit the Pacific Northwest and stalled, creating over 25 inches of rain in 3 days.

One AR transports as much water as 25 Mississippi Rivers, but as vapor rather than liquid (from Ralph et al. 2017)
Atmospheric Rivers Emerge as a Global Science and Applications Focus
A Summary of the 1st International Atmospheric Rivers Conference


**a) Scientific literature discussing ARs**

**b) Locations of studies and scientists at IARC**
Dropsonde Observations of Total Integrated Water Vapor Transport within North Pacific Atmospheric Rivers

F.M. Ralph, S. Iacobellus, P.J. Neiman, J. Cordeira
J.R. Spackman, D. Waliser, G. Wick, A.B. White, C. Fairall

J. Hydrometeor., 2017
July 2017
This study uses 21 AR cases observed in 2005 - 2016 with full dropsonde transects

Location of the dropsonde transects listed in Table 1. The background image denotes weekly AR frequency calculated using the AR Detection Tool of Wick et al (2013) applied during the 2003-2012 cool seasons (November-February). AR frequency data west of 160°W was not available.
Atmospheric River: Plan View

(a)

Average characteristics
- 850-km wide
- 3-km deep
- $5 \times 10^8$ kg s$^{-1}$ flux

From Ralph et al. 2017, *J. Hydrometeor.*
Atmospheric River: Vertical Cross-section

Averages: 850 km wide, 3-km deep, $5 \times 10^8$ kg s$^{-1}$ total water vapor flux (a.k.a. transport)

Adapted from Ralph et al. 2004 and Cordeira et al. 2013

From Ralph et al. 2017, J. Hydrometeor.
Flooding on California’s Russian River: Role of atmospheric rivers


ARs can CAUSE FLOODS and PROVIDE WATER SUPPLY

Atmospheric Rivers, Floods and the Water Resources of California
Mike Dettinger, M. Ralph, T. Das, P. Neiman, D. Cayan (Water, 2011)

SSM/I satellite data shows atmospheric river
Stream gauge data show regional extent of high stream flow covers 500 km of coast

Russian River floods are associated with atmospheric rivers - all 7 floods over 8 years.
Was the Oroville Incident Related to an AR?

Yes. An “extreme” AR hit the area.
A few large storms (or their absence) account for a disproportionate amount of California’s precipitation variability.

A) Water-Year Precipitation, Delta Catchment

Whether a year will be wet or dry in California is mostly determined by the number and strength of atmospheric rivers striking the state.

- 85% of interannual variability results from how wet the 5% wettest days are each year.
- These days are mostly atmospheric river events.
Variability of Annual Precipitation

- CA has the largest year to year precipitation variability in the US.
- CA variability is on the order of half the annual average.
- The year to year variability in CA is largely caused by the wettest days (ARs).

Coefficient of variation for annual precipitation 1950-2008

Analysis from COOP daily precipitation observations.
- Each site uses at least 30 years of data
- The top 10 daily precip dates are found
- The season for which most of these top-10 dates occurred at that site is color coded.

- The affect of the southwest Monsoon is seen in yellow dots in AZ, CA, UT, NM, and CO (yellow sites in the Great Plains are not monsoon dominated)
- The affect of atmospheric rivers is highlighted by blue and red dots, including almost all of each coastal state, plus inland penetration of AR impacts into AZ, Western CO, SW and Central UT, and ID.
- Great Plains convective events focus in spring (light blue dots) and summer (yellow).
- Colorado front range is mostly spring.
- Nevada is a mixture.

Ralph et al, 2014, UCOWR
Schematic illustration of regional variations in the primary weather phenomena that lead to extreme precipitation, flooding and contribute to water supply in the Western U.S.

Atmospheric Rivers (fall and winter)
SSM/I IWV satellite imagery 20-21 Jan. 2010 depicts a strengthening AR making landfall

24-h precip ending 12Z 22 Jan. 2010:
Advanced Hydrological Prediction Services
COOP precip on 21-22 Jan. 2010: Rank relative to all January pairs of days between 1950-2009 for gauges with >25 Januarys of data.

USGS streamflow on 21-22 Jan. 2010 for unregulated channels: Rank relative to all January pairs of days between 1901-2009 for gauges with >25 Januarys of data.
Catchment basin characteristics, local meteorology, and implications for flooding

The Salt River basin is typical of those draining the south side of the Mogollon Rim.
Summary schematic for Jan 2010 case presented by Neiman et al. (in preparation)

Ideal conditions for creating heavy orographic rain on the Mogollon Rim and associated mountains

- 2.5 km (AGL) deep moist neutral layer
- 75% of water vapor transport in lowest 3.3 km AGL

Moist BV $(x10^{-4}$ s$^{-2}$)

Vapor flux $(kg\ s^{-1}\ m^{-1})$
The Inland Penetration of Atmospheric Rivers over Western North America: A Lagrangian Analysis

J.J. Rutz, J. W. Steenburgh and F.M. Ralph


Climatological Characteristics of Atmospheric Rivers and Their Inland Penetration over the Western United States

J.J. Rutz, J. W. Steenburgh and F.M. Ralph

Forecast Informed Reservoir Operations: Bringing Science and Decision-Makers Together to Explore Use of Hydrometeorological Forecasts to Support Future Reservoir Operations

F. Martin Ralph (Presenter)
Center for Western Weather and Water Extremes
UC San Diego/Scripps Institution of Oceanography

Jay Jasperse
Sonoma County Water Agency

Acknowledgments to the FIRO Steering Committee
US Army Corps of Engineers/ERDC and CA DWR AR Programs

Science to Action: Towards More Effective Decision Maker – Scientist Partnerships
AGU Fall 2017, New Orleans, LA
Russian River Reservoirs are Dual Purpose

Flood protection in a flood-prone watershed
(US Army Corp of Engineers)

Water supply for 600,000 people and agriculture
(Sonoma County Water Agency)

Operations Dictated by
Storage Levels Relative to “Rule Curve”

Lake Mendocino (Coyote Valley Dam)
Flood Control Pool (empty space): 48,100 AF
Water Supply Pool: 68,400 A

Lake Sonoma (Warm Springs Dam)
Flood Control Pool: 136,000 AF
Water Supply Pool: 245,000 AFF (Nov. 1 – March 1)
The Issue: Lake Mendocino’s Water Supply Is Not Reliable

Some Reasons For Low Water Supply Reliability:

- Relatively small storage capacity
- Relatively unproductive watershed
- Reduced inflow from Potter Valley Project (Eel River)
- Highly variable precipitation patterns
  - Almost 50% rainfall from atmospheric rivers
- Future growth & climate change will likely further reduce reliability
Lake Mendocino Water Years 2012 - 2014

Storage
Storage Curve
Cumulative Rainfall
Lake Mendocino FIRO Steering Committee

**Co-Chairs**
Jay Jasperse – Sonoma County Water Agency  
F. Martin Ralph – UCSD / SIO / CW3E

**Members**
Michael Anderson – California DWR  
Levi Brekke – USBR  
Mike Dillabough – USACE / SPN  
Michael Dettinger – USGS  
Joe Forbis – USACE / SPK  
Alan Haynes – NOAA / NWS  
Patrick Rutten – NOAA / NMFS  
Cary Talbot – USACE / ERDC  
Robert Webb – NOAA / OAR

A Comprehensive **Work Plan** to Evaluate FIRO for Lake Mendocino

- Viability Assessment Process
- Evaluation Framework
- Benefits Assessment
- Implementation Strategies
- Technical and Scientific Support

**Project Partners**
Forecast-Informed Reservoir Operations (FIRO) for Lake Mendocino
Feasibility Assessment Planning Workshop

4-7 August 2014
Scripps Seaside Forum
UCSD/Scripps Institution of Oceanography
(Sponsored by – SCWA and CW3E)
Lake Mendocino Forecast-Informed Reservoir Operations Concept

Hypothetical estimate of extra water retained unless an atmospheric river storm is predicted to hit the watershed; requires reliable AR prediction at 5-day lead time.

Potential FIRO-Enabled Additional Water Supply Reliability
(Enough for 20,000 homes for a year)

Due to Atmospheric river storms

10-Year Average

Max Allowable Storage

Descent into drought

Water Year 2013

October Through September
Selected results of FIRO-motivated science

• Established forecast skill requirements, e.g., 3-5 day lead time on heavy precipitation and runoff forecasts
• ARs are the main weather phenomenon that causes extremes
• AR landfall forecasts have useful skill out to a few days
• Mesoscale frontal waves are key source of forecast busts
• AR Recon offers potential to improve AR landfall prediction
• Prediction of no AR landfall has skill beyond 1 week
• Probabilistic streamflow predictions are key; developing thresholds based on ensemble methods
• Exploring roles of distributed, physics-based steamflow models
Hypothetical Impacts of FIRO on Water Supply and Flood Risk

Water Supply

- Substantial gains in water storage over existing operations by leveraging information in streamflow forecasts
- 20,000 AF greater water supply reliability in about 50% of the years

Flood Risk

- Downstream flood control benefits are not impacted
Preliminary Viability Assessment Concluded that YES! FIRO is viable for Lake Mendo, and that greater AR, precip and streamflow forecast skill could yield greater benefits.
Congressional Staff Briefing on July 13, 2016

“A New Frontier in Water Operations: Atmospheric Rivers, Subseasonal-to-Seasonal Predictions and Weather Forecasting Technology”

An interagency, cross-disciplinary team of experts convened in Washington to provide Congressional staff with a briefing on atmospheric rivers, subseasonal-to-seasonal precipitation prediction needs, and the benefits of enhanced predictive forecasting technology to the future of water management.

PANELISTS AND PRESENTATIONS

Dr. Louis W. Uccellini is Assistant Administrator for Weather Services, National Oceanic and Atmospheric Administration (NOAA), and Director, National Weather Service. His presentation may be found [HERE].

Dr. Cary Talbot is the Program Manager, Engineer Research and Development Center, U.S. Army Corps of Engineers. His presentation may be found [HERE].

Ms. Jeanine Jones serves as the Secretary-Treasurer of the Western States Water Council. Her presentation may be found [HERE].

Dr. F. Martin Ralph, Director of the Center for Western Weather and Water Extremes, UCSD / Scripps Institution of Oceanography. His presentation may be found [HERE].

MODERATOR: Ms. Shirlee Zane serves on the Sonoma County Board of Supervisors and is a Director of the Sonoma County Water Agency.
Wide range of water levels at Oroville Dam: From drought, to normal, to flood and damage
Was the Oroville Incident Related to an AR?

Yes. An “extreme” AR hit the area.
NCEP GEFS dProg/dt Examples from January and February 2017

Init: 12Z/5 Feb
Init: 12Z/6 Feb
Init: 12Z/7 Feb

Image Description: 7-day forecasts of the NCEP GEFS IVT [kg m⁻¹ s⁻¹] at 38N, 123W. The following is indicated at each forecast time: ensemble member maximum (red), ensemble member minimum (blue), ensemble mean (green), ensemble control (black), ensemble standard deviation (white shading), and each individual member (thin gray). Time advances from left to right.

Key: Variability in north-south shift of ARs result in increases or decreases in IVT magnitude at the coast. In this case the ARs ultimately ended up stronger.

J. Cordeira/M. Ralph
Image Description: Shading represents the NCEP GEFS probability that IVT will exceed 250 kg m\(^{-1}\) s\(^{-1}\) at 0.5-degree grid locations along the U.S. West Coast (dots). Each panel represents a 24-h forecast that verifies during the 24-h period starting at the time listed above the color bar. The lead time of that forecast period increases from right-to-left. For example, the left-most panel is a 15-to-16-day forecast whereas the right-most panel is the 0-to-1-day forecast.

J. Cordeira
Observed Vs Predicted Precipitation over Feather River Basin for 6-9 Feb 2017

**Predicted** (CNS) Precipitation over 3 days at 4-day lead time

- Feather River Drainage
- Max > 8"

**Observed** Precipitation over 3 days ending 1200 UTC 9 Feb

- Feather River Drainage
- Max > 12"

**Streamflow**

- **Obs**
- **Fcst**

**Flood stage**

- **Max > 8"**
- **Max > 12"**

**72 hr MAP Feather Basin 12z 6-9 Feb. 2017**

- **OBSERVED Mean Area Precip (MAP) over Feather River: 5.5 inches**

**Additional Information**

- **Cons**
- **GFS**
- **NAM12**
- **MOS**
- **WPC**
- **RFC**
- **WestWrf**
- **OBS**
Water managers, transportation sector, agriculture, etc... require improved atmospheric river (AR) predictions.

Atmospheric River Reconnaissance
FM Ralph (Scripps/CW3E), V Tallapragada (NWS/NCEP), J Doyle (NRL)

AR Forecast skill assessment establishes a performance baseline

400 km AR Landfall position forecast error at 3-day lead time


New Adjoint includes moisture – and finds AR is prime target

36-h Sensitivity (Analysis) 00Z 13 February (Final Time 12Z 14 February 2014)
J. Doyle, C. Reynolds, C. Amerault, F.M. Ralph (International Atmospheric Rivers Conference 2016)

Color contours show the forecast sensitivity to 850 mb water vapor (grey shading) uncertainty at analysis time 00Z 13 Feb 2014 for a 36-h forecast over NorCal valid 12Z 14 Feb

- Moisture sensitivity is strongest along AR axis; located > 2000 km upstream
- Moisture sensitivity substantially larger than temp. or wind sensitivity.
AR Recon – 2016 Using Two Air Force C-130s
COAMPS 36-h sensitivity with 36-h lead time
Target time 00Z 28 Jan 2016, Verification time 12Z 29 Jan.

72-h precipitation sensitivity to 36-h water vapor
700 hPa (q_v shown in gray)

Verification Time Optimal Water Vapor Perturbation valid at 12Z 29 Jan.
Note large increase in water vapor available for precipitation at final time.

Moist adjoint product from J. Doyle, C. Reynolds of NRL-Monterey
The atmospheric river as seen in SSM/I integrated water vapor (IWV). Black line marks the cross-section baseline.

**Cross-section of an AR observed using dropsondes**


**Horizontal along-front water vapor flux (×10^5 kg s^{-1}; shading: >50 ×10^5 kg s^{-1})**

**Dropsonde measurements can improve AR position and characteristics offshore for numerical weather prediction**

**Note sharp horizontal gradient in water vapor mixing ratio over 50-100 km**
Locations of C-130 AR Recon dropsondes received and successfully decoded into NCEP's production bufr data tanks for assimilation into NCEP/GFS

1st C-130 AR Recon Mission
13-14 Feb 2016
Dropsondes released for the 0000 UTC 14 Feb 2016 GFS data assimilation window

Observed IWV from SSM/I Satellite passes from 13 Z 13 – 01 Z 14 Feb Showing atmospheric river signature

Landfall of AR caused heavy rain and high river flows in WA state

NWRFC flood forecast map as of 1500 UTC 15 Feb showing several rivers predicted to reach flood stage on 15-16 Feb (red dots)
AR Recon Field Campaigns and Modeling

• Year 1 (2016): 3 storms flown with 2 aircraft over 2 weeks
• Year 2 (2018): target 6 storms with two aircraft over 6 weeks
• Year 3 (2019): target 9 storms with three aircraft over 10 weeks
• Years 1-3: Data denial analyses of 18 storms at NCEP, NRL, CW3E
2018 Atmospheric River Reconnaissance Flight Strategies

Center time: 0000 UTC
Dropsonde deployment window: 2100 – 0300 UTC

6 storms in 2018

Air Force C-130 Aircraft – Weather Recon’

NOAA G-IV
3 storms in 2018

F.M. Ralph (AR Recon PI) and AR Recon Team

Each aircraft has a range of about 3500 nm

Upper-level trough/PV anomaly

Atmospheric River (color fill: IVT)
Day-0 Plan for first AR Recon - 2018 IOP to fly on 26-27 Jan 2018

NOAA G-IV

Air Force C-130

>10 inches of rain predicted in Pacific NW

1A 38.37 -121.3
1B 45.5 -129
1C 44 -139
1D 36 -136

2A 21.59 -157.8
2B 41.5 -149.5
2C 40 -158.5
2D 29 -155

3A 47.91 -122.28
3B 50 -128
3C 49 -148
3D 46 -152
3E 36 -141

F.M. Ralph (PI) and the AR Recon 2018 team
Dropsondes Assimilated – AR Recon-2018, IOP-
"Atmospheric River" drink created for season at Harrah's and Harveys

Submitted by paula on Wed, 02/22/2017 - 1:55pm

Rivers have flooded, the lake is filling and snow is covering the slopes because of the several atmospheric rivers to hit Lake Tahoe this winter. To celebrate the epic season, the Beverage Department team at Harrah's and Harveys Lake Tahoe concocted a cocktail to honor and celebrate the winter.

The "Atmospheric River" drink "blends the frosty peaks of the Sierra Nevada with the stunning shades of blue found only at Lake Tahoe," said John Packer of Harrah's and Harveys Lake Tahoe. Named for the climatic condition that has held sway in northern California and Nevada for the past few months, the "Atmospheric River" combines fruit juices, vodka, cognac and other ingredients to produce one of the most refreshing adult beverages of the season.

The festive cocktail is available exclusively at the two California Bars, located on the main floor of both casinos in Stateline, Nevada.

Their master mixologists combine Grey Goose Vodka, Hpnotiq Liqueur, Cointreau, Curacao, Sweet and Sour with Seven-Up, blend it with ice and serve it up in a chilled, sugar-rimmed martini glass.

It's a "drought-busting libation."
WEATHER ON STEROIDS:
THE ART OF CLIMATE
CHANGE SCIENCE

LA JOLLA HISTORICAL SOCIETY FEBRUARY 11 – MAY 21
SAN DIEGO PUBLIC LIBRARY JUNE 10 – SEPTEMBER 3

“Atmospheric Rivers”
by Oscar Romo

Photo and slide Courtesy of
Dr. Sasha Gershunov (Scripps)
Co-Organizer of Art Show
Updates on the 2018 CW3E Field Campaign Supporting FIRO

Anna Wilson
Marty Ralph, PI
Brian Henn (CW3E), Douglas Alden (CW3E), Steve Turnbull (ERDC)
Maryam Lamjiri (CW3E), Leah Campbell (CW3E)

Primary sponsors: US Army Corps of Engineers, California Dept. of Water Resources, Sonoma County Water Agency

31 January 2018 – FIRO Steering Committee Meeting
Distribution of Landfalling Atmospheric Rivers on the U.S. West Coast
(From 1 Oct 2016 to 1 May 2017)

<table>
<thead>
<tr>
<th>AR Strength</th>
<th>AR Count*</th>
</tr>
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<tbody>
<tr>
<td>Weak</td>
<td>15</td>
</tr>
<tr>
<td>Moderate</td>
<td>23</td>
</tr>
<tr>
<td>Strong</td>
<td>13</td>
</tr>
<tr>
<td>Extreme</td>
<td>3</td>
</tr>
</tbody>
</table>

- 54 Atmospheric Rivers have made landfall on the West Coast thus far during the 2017 water year (1 Oct. – 12 April 2017)
- This is much greater than normal
- 1/3 of the landfalling ARs have been “strong” or “extreme”

*Ralph/CW3E AR Strength Scale

- Weak: IVT=250–500 kg m$^{-1}$ s$^{-1}$
- Moderate: IVT=500–750 kg m$^{-1}$ s$^{-1}$
- Strong: IVT=750–1000 kg m$^{-1}$ s$^{-1}$
- Extreme: IVT>1000 kg m$^{-1}$ s$^{-1}$

*Radiosondes at Bodega Bay, CA indicated the 10–11 Jan AR was strong (noted as moderate based on GFS analysis data) and 7–8 Feb AR was extreme (noted as strong)
Thank you!
Forecast Informed Reservoir Operations

FIRO is a proposed management strategy that uses data from watershed monitoring and modern weather and water forecasting to help water managers selectively retain or release water from reservoirs in a manner that reflects current and forecasted conditions.

FIRO is being developed and tested as a collaborative effort focused on Lake Mendocino that engages experts in civil engineering, hydrology, meteorology, biology, economics and climate from several federal, state and local agencies, universities and others.

Purpose
The Lake Mendocino Forecast Informed Reservoir Operations (FIRO) Preliminary Viability Assessment Work Plan (Work Plan) describes an approach for using modeling, forecasting tools and improved information to determine whether the Lake Mendocino Water Control Manual can be adjusted to improve flood–control and water supply operations. This proof–of–concept FIRO viability assessment uses Lake Mendocino as a model that could have applicability to other reservoirs.

Background
The 1995 Lake Mendocino Water Control Manual (with minor updates in 1986), specifies reservoir elevations to control flooding and establishes the volume of storage that may be used for water supply. The Manual was developed using the best information available at the time, but it has not been adjusted to reflect current climate conditions and the future climate.
The name “Chiricahua Gap” is proposed here, reflecting both the name of a key mountain range near the gap, and the region’s Native American history.

Ralph and Galarneau, *JHM*, 2017
Climatology of IVT in the Chiricahua Gap and SE Arizona Monsoon “Bursts” in 2009-2010

- “Day” defined here as 24-h period ending at 1200 UTC
- Define monsoon season as 16 Jun–15

Distribution of Daily Rainfall (mm) in 2009 and 2010

- Burst days defined as upper quartile (2.3 mm) of rain events
- Heavy bursts defined as 90th percentile (4.5 mm) of rain events
- Moderate bursts

SE Arizona defined as 31.5–33.5N; 111–109W
Gap defined as 30.5–32.5N; 109–107W
55% (71/130) of light rain events have easterly IVT
65% (17/26) of moderate bursts have easterly IVT
94% (17/18) of heavy bursts have easterly IVT