Atmospheric Rivers

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

WRPI
San Jose State University, CA, 6 April 2017
Outline

• What is an atmospheric river (aka “AR”) and how do they impact water supply, flood and drought?

• Can ARs be predicted?

• Were atmospheric rivers involved in the Oroville incident?
Rivers in the Sky

An atmospheric river is a narrow conveyor belt of vapor that extends thousands of miles from out to sea, carrying as much water as 15 Mississippi Rivers. It strikes as a series of storms that arrive for days or weeks on end. Each storm can dump inches of rain or feet of snow.

Atmospheric Rivers are key to extreme precipitation

Ralph et al. 2014

Dettinger and Ingram 2013

Area where Atmospheric Rivers are key to extreme precipitation

ARs Affect Large Areas of the U.S. West

Russian River
Lake Mendocino

Ralph et al. 2014
Observations of Water Vapor Transport by North Pacific Atmospheric Rivers


*In Preparation*

Composite AR Plan View (Color fill IWV; dashed lines IVT)

An average AR transports (as water vapor) the equivalent of
• 20 times the average discharge of the Mississippi River (as liquid), or
• 20 M acre feet/day
An exceptionally wet winter

SSMI Observed Total Integrated Water Vapor

83 inches as of 30 March 2017
201% of normal Wettest Water Year to Date

Green dots are sites where WY-to-date through 26 Feb 2017 is in the top 10% of its period of record (> 50 years)

- Coastal IVT magnitude >1000 kg m\(^{-1}\) s\(^{-1}\)
- IVT>250 kg m\(^{-1}\) s\(^{-1}\) penetrates inland over Utah
Distribution of Landfalling Atmospheric Rivers on the U.S. West Coast
(From 1 Oct 2016 to 31 March 2017)

**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\(^{-1}\)

<table>
<thead>
<tr>
<th>AR Strength</th>
<th>AR Count*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak</td>
<td>11</td>
</tr>
<tr>
<td>Moderate</td>
<td>19</td>
</tr>
<tr>
<td>Strong</td>
<td>13</td>
</tr>
<tr>
<td>Extreme</td>
<td>3</td>
</tr>
</tbody>
</table>

- 46 Atmospheric Rivers have made landfall on the West Coast thus far during the 2017 water year (1 Oct. – 31 March 2017)
- This is much greater than normal
- 1/3 of the landfalling ARs have been “strong” or “extreme”

*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)
Atmospheric River Forecast Example

Incoming storm of 5-7 March 2016 has characteristics of an atmospheric river
- Strikes mostly northern and central California
- Moderate strength
- Average duration at landfall (12-24 hours)

Example of a 2 day lead-time forecast
Was the Oroville Incident Related to an AR?

Yes. An “extreme” AR hit the area.
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.
**Image Description:** Shading represents the NCEP GEFS probability that IVT will exceed $250 \text{ kg m}^{-1} \text{s}^{-1}$ 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.
While overall occurrence well forecast out to 10 days, landfall is less well predicted and the location is subject to significant errors, especially at longer lead times.

- Errors in location increase to over 800 km at 10-day lead
- Errors in 3-5 day forecasts comparable with current hurricane track errors
- Model resolution a key factor

**RMS Error in Forecast AR Landfall Location**

*~ 500 km forecast error at 5-day lead time*

*From Wick et al., 2013 (Weather and Forecasting)*

- Models provide useful heads-up for AR impact and IWV content, but location highly uncertain
- Location uncertainty highlights limitations in ability to predict extreme precipitation and flooding
- Improvements in predictions clearly desirable
C-130 Atmospheric River Reconnaissance in February 2016
A joint effort of Scripps/CW3E, NOAA/NWS, Air Force

FM Ralph (Lead; Scripps Inst. Of Oceanography)
V. Talapragada (NOAA/NWS)
M. Silah (NOAA/NWS)
J. Doyle (Navy/NRL)
J. Talbot (U.S. Air Force)

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

C-130 Atmospheric River Reconnaissance in February 2016
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Observed IWV from SSM/I
Satellite passes from 13 Z 13 – 01 Z 14 Feb
Showing atmospheric river signature

C-130

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)

Satellite image from NOAA/ESRL/PSD

Air Force C-130 Aircraft – Weather Recon’ Squadron

Center for Western Weather and Water Extremes

NORTHWEST RIVER FORECAST CENTER
Lake Mendocino Vulnerability
Need to Update

Atm. River Events

WY 2013 Rainfall

WY 2012 Rainfall

Reservoir Storage Curve

Atmospheric River Events

Can we save some of this water?

To avoid this

Atmospheric River Events
FACT SHEET: LAKE MENOCINO FORECAST INFORMED RESERVOIR OPERATIONS
PRELIMINARY VIABILITY ASSESSMENT WORK PLAN

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.

STEERING COMMITTEE CO-CHAIRS
Jay Jasperse
Sonoma County Water Agency
F. Martin Ralph
Center for Western Weather and Water Extremes at Scripps Institute of Oceanography

STEERING COMMITTEE MEMBERS
Michael Anderson
California State Climate Office, Department of Water Resources
Rob Hartman
NOAA's National Weather Service
Christy Jones
US Army Corps of Engineers

STEERING COMMITTEE MEMBERS
Levi Brekke
Bureau of Reclamation
Mike Dillabough
US Army Corps of Engineers

SUPPORT STAFF
Patrick Rutten
NOAA Restoration Center
Cary Talbot
US Army Corps of Engineers
Robert Webb
NOAA’s Earth System Research Laboratory

David Ford
David Ford Consulting Engineers
Arleen O’Donnell
Eastern Research Group
Ann DuBay
Sonoma County Water Agency

September 2015
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.

Due to Atmospheric river storms

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

Max Allowable Storage

10-Year Average

Descent into drought

Water Year 2013

Lake Mendocino Water Supply Storage (acre-feet)

October Through September
AR Update: 4 April 2017

AR conditions Forecast for Entire U.S. West Coast

- An AR is currently impacting the Pacific Northwest while another AR is forecast to make landfall over Northern CA on Thursday.
- A mesoscale frontal wave that develops during the second AR could prolong the duration of AR conditions but uncertainty is currently high.
- 1–5 day precipitation forecasts are >6 inches over the high elevations of the Coastal Mts., Northern Sierra Mts., and Trinity Alps.
- Freezing levels are forecast to start at ~7,000 feet before dropping to ~3,000 feet, causing this to be a snow event for higher elevations.
- Wet soil and the potential for rain on snow at lower elevations raises the concern for flooding in eastern California and northern Nevada.
**AR Update: 4 April 2017**

**Monterey, CA could experience strong AR conditions IVT > 750 kg m⁻¹ s⁻¹**

**Magnitude of AR over Monterey**
- Maximum possible IVT: ~900 kg m⁻¹ s⁻¹
- Mean IVT: ~800 kg m⁻¹ s⁻¹
- Uncertainty: ~±12%

**High Confidence in onset of AR conditions:**
- 1 PM PT Thursday 06 April ±4 h

**Duration of AR conditions**
- Weak: ~36 hours ±20 h
- Moderate: ~10 hours ±20 h
- Strong: ~3 hours ±3 h

There is more uncertainty in IVT magnitude associated with the development of the mesoscale frontal wave, which creates large uncertainty in the duration of AR conditions over Monterey.
AR Forecast Tools

Extreme Event Summaries

Lake Mendocino FIRO summary information

Are available at

CW3E.UCSD.EDU

Contact: mralph@ucsd.edu
The Storm of 4-5 Jan 2008

Note that major impacts were focused >500 miles south of the Low pressure center in this storm.

This differs significantly from hurricanes, but the impacts are enormous and spread over a large area.

Many major impacts are associated with the landfall of the “atmospheric river” element of the storm, the precise characteristics of which are not operationally monitored offshore or onshore.

**Atmospheric river**

GOES IR image of major West Coast storm
- Time = 0030 UTC 5 January 2008
- Low pressure center is off WA coast
Annual Cycle of AR Conditions Near Lake Oroville, California Based on Daily Maximum IVT Magnitude

Provided to Mike Anderson (DWR State Climatologist) For consideration by Oroville Spillway Incident Unified Command From F. M. Ralph, J. Cordeira, C. Hecht, B. Kawzenuk of CW3E


- Frequency of Atmospheric River related conditions striking a location near Oroville Dam based on 37 years of past analyses of vertically integrated water vapor transport (IVT; the key defining characteristic of ARs)
- The frequency of daily max IVT >250 kg m⁻¹ s⁻¹ and 500 and 750 kg m⁻¹ s⁻¹ on any given calendar day is shown
- Table: average number of days per month with IVT >250 kg m⁻¹ s⁻¹, 500 and 750
- Dec–Feb contain, on average, ~0.20-to-0.25 days/mon with IVT >750 kg m⁻¹ s⁻¹: IVT magnitudes >750 kg m⁻¹ s⁻¹ were not observed during May-Sep

<table>
<thead>
<tr>
<th>Month</th>
<th>IVT &gt; 250 Avg number of days</th>
<th>IVT &gt; 500 Avg number of days</th>
<th>IVT &gt;750 Avg number of days</th>
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<tr>
<td>Jan</td>
<td>7.2</td>
<td>1.32</td>
<td>0.19</td>
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<tr>
<td>Feb</td>
<td>6.4</td>
<td>1.35</td>
<td>0.24</td>
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<tr>
<td>Mar</td>
<td>6.1</td>
<td>0.81</td>
<td>0.08</td>
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<td>Apr</td>
<td>3.8</td>
<td>0.22</td>
<td>0.03</td>
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<tr>
<td>May</td>
<td>3.4</td>
<td>0.24</td>
<td>0.00</td>
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<tr>
<td>Jun</td>
<td>2.6</td>
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<td>Jul</td>
<td>1.4</td>
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<td>Aug</td>
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<td>Sep</td>
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<td>Oct</td>
<td>4.4</td>
<td>0.78</td>
<td>0.16</td>
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<tr>
<td>Nov</td>
<td>7.0</td>
<td>1.35</td>
<td>0.16</td>
</tr>
<tr>
<td>Dec</td>
<td>8.4</td>
<td>1.59</td>
<td>0.22</td>
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</table>

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
16 inches of rain in 1 day in Central California

Forecast-Informed Reservoir Operations*:
A Concept Supporting Water Security, Flood Control, Ecosystems

FIRO Steering Committee:
Co-Chairs Jasperse & Ralph

Local, State, Federal and University weather and water experts working to evaluate the potential viability of using forecasts of atmospheric rivers, rain and streamflow to enable safe retention of extra water if major storms are not predicted over the watershed in the coming days, or to enhance flood control if strong storms are predicted.

*http://cw3e.ucsd.edu/FIRO/
Atmospheric River Events 20 Nov-3 Dec 2012

Animation courtesy of Don Murray (NOAA/ESRL/PSD)
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
- Lake Oroville
- **Max > 8”**

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

- Feather River Drainage
- Lake Oroville
- **Max > 12”**

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

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

**Streamflow**

- **Flood stage**
- **Obs**
- **Fcst**

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

- Feather River Drainage
- Lake Oroville
- **Max > 12”**

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

**Flood stage**

- **Obs**
- **Fcst**
CW3E-SDSC Partnership

“West-WRF” Weather Model to Focus on Western U.S. Extreme Events

- Interdisciplinary team of SIO & SDSC Scientists, post-docs and grad students
- Working to an integrated research and operations plan
- West-WRF implemented in < 6 months now supporting Calwater2 mission planning

✓ SDSC Director and UCSD Physics Professor Mike Norman is fully-supportive of CW3E
✓ Contributing Staff time (J. Helly), computer time and disk storage on the Gordon supercomputer

CalWater Observations will be used to evaluate, explore and improve the physics in CW3E’s West-WRF Model from air-sea interaction, to mesoscale dynamics, aerosols and cloud microphysics and data assimilation.
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

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.
The Inland Penetration of Atmospheric Rivers over Western North America: A Lagrangian Analysis

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

40-50% of annual precipitation falls during AR events in key areas

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

J.J. Rutz, J. W. Steenburgh and F.M. Ralph
Atmospheric rivers: SSM/I Satellite data for two recent examples that produced extreme rainfall and flooding

From Ralph et al. 2011, Mon. Wea. Rev.

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.
Droughts, on average, end with a bang (and begin with a whimper) all over the U.S.

- Atmospheric rivers provide the bang in a large fraction of the west coast drought breaks, especially in winters

LARGEST 3-DAY PRECIPITATION TOTALS, 1950-2008

Primarily due to Atmospheric River events

Table 1. Rainfall categories used in this study, and national frequencies of occurrence. Note that an “episode” is defined as a single 3-day period for which one or more stations observed at least 200 mm (~8 inches) of precipitation in the same general area.

<table>
<thead>
<tr>
<th>Rainfall Category</th>
<th>Rainfall Category 2</th>
<th>Rainfall Category 3</th>
<th>Rainfall Category 4</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>200 ≤ P &lt; 300</td>
<td>300 ≤ P &lt; 400</td>
<td>400 ≤ P &lt; 500</td>
</tr>
<tr>
<td>Number of stations reaching these 3-day totals per year</td>
<td>173</td>
<td>23</td>
<td>4</td>
</tr>
<tr>
<td>Number/year of 3-day episodes with station(s) reaching this level</td>
<td>48</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>Average stations &gt; 200 mm/episode</td>
<td>2</td>
<td>7</td>
<td>13</td>
</tr>
</tbody>
</table>

**Mission**
Provide 21st Century water cycle science, technology and outreach to support effective policies and practices that address the impacts of extreme weather and water events on the environment, people and the economy of Western North America

**Goal**
Revolutionize the physical understanding, observations, weather predictions and climate projections of extreme events in Western North America, including atmospheric rivers and the North American summer monsoon as well as their impacts on floods, droughts, hydropower, ecosystems and the economy

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**Key Phenomena Causing Extreme Precipitation in the Western U.S.**
- **Atmospheric Rivers** (fall and winter)
- **Southwest Monsoon** (summer & fall)
- **Great Plains Convection** (spring and summer)
- **Front Range Upslope** (rain/snow)

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**CW3E’s Core Efforts**
- **Forecast-Informed Reservoir Operations**
- **Tools for California Water Extremes**
- **Climate Science**
- **Subseasonal-to-Seasonal Outlooks**

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**Director:** F. Martin Ralph, Ph.D.  
**Website:** [cw3e.ucsd.edu](http://cw3e.ucsd.edu)

**Strategies:** Observations, physical processes, modeling, decision support

**Scope:** A group of roughly 40 people with 10 major projects

**Partners:** California DWR, Sonoma County Water Agency, CNAP, USGS, San Diego Supercomputing Center

**Sponsors:** CA DWR, USACE/ERDC, NOAA, SCWA, NASA, USBR
The 2010/2011 snow season in California’s Sierra Nevada: Role of atmospheric rivers and modes of large-scale variability

*Water Resources Research* (2013)

Arctic Oscillation (negative, i.e., southward cold-air outbreaks) combined with Pacific North American “teleconnections” pattern (negative, southern storm track). Favors Atmospheric river conditions striking the Sierra and causing precipitation.

Thursday 930-1100 AM: Exhibitor Technical Presentation I
“Actions to Improve the Skill of Long-term Precipitation Forecasting”
Panelists from WSWC, NOAA/NWS, and NASA/JPL
Location: “Grand Ballroom G”