The meteorology of extreme orographic precipitation in California—A synthesis as of 2014

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A Major Result from 10-years of Research: **Atmospheric rivers** are key to understanding & forecasting extreme precipitation in the mountains along the U.S. West Coast
Outline

• What are atmospheric rivers?
• Why do they produce so much precipitation?
• What controls how much precipitation they produce?
• How are we building on this new information?
Atmospheric Rivers

- **Vertical structure:** Intense jets transporting vapor, between 0 – 2.5 km above sea level--*from airplanes & AROs*

- **Map-view structure:** ~400 km width & 2000 km long--*from satellite data*

*Ralph et al., MWR, 2004; Ralph et al., MWR, 2005; Dettinger & Ingram, Sci Am 2013*
Why do landfalling ARs yield heavy rain?

- Composite sounding located 500 km off CA coast in pre-cold-frontal Low Level Jet (atmospheric river)

- LL Jet directed toward coast and situated at 1-2 km MSL, wind speeds 15 to 20 m/s

- Most (75%) of pre-cold-frontal along-river moisture flux is below 2.5 km MSL

- Vapor transport ~ 10-20 Mississippis

- Moist neutral stratification below 2.8 km MSL, hence no resistance to orographic lifting

- Overlapping set of conditions very conducive to orographic rain enhancement in coastal mtns & Sierra Nevada

*Ralph et al. (2004, 2005) MWR*
Just how BIG are these storms?

RCats 3-4: 92% due to Atmospheric Rivers

Largest 3-day storm totals in >30 yrs COOP records

Ralph & Dettinger, BAMS, 2012
California extremes since 1950

- **Russian River Floods** (87%)
  - ARs: 34/39 Russian River floods
  - Other: 5

- **Floodplain Inundations** (78%)
  - ARs: 25/32 Yolo Bypass floodplain inundations > 21 days
  - Other: 7

- **Levee Breaks** (81%)
  - ARs: 104/128 Central Valley levee breaks
  - Snowmelt: 19

- **Drought Endings** (41%)
  - ARs: 7/17 Drought breaks in NoCalif
  - Other: 10

Other:
- ARs: 7/17

Florsheim & Dettinger, book chapter, 2014; Dettinger, JHM, 2013
Component of the flow in the orographic controlling layer directed from 230°, i.e., orthogonal to the axis of the coastal mtns

Neiman et al. (2008), Water Management
Any rain: >0 m/s; >1 cm

Raining on ridgeline at Cazadero

Component of the flow in the orographic controlling layer directed from 230°, i.e., orthogonal to the axis of the coastal mtns

Total water vapor Overhead, Bodega Bay
Component of the flow in the orographic controlling layer directed from 230°, i.e., orthogonal to the axis of the coastal mtns.
Rain falling at 10 mm/hr on the ridgeline at Cazadero.

Orographic precipitation depends on:
- Orientation of AR relative to mountains
- Wind speed at about 1.5 km msl
- Vapor content

Component of the flow in the orographic controlling layer directed from 230°, i.e., orthogonal to the axis of the coastal mountains.
91 AR events observed over 6 years

75% of precip explained by upslope vapor flux

Storm-total upslope water vapor flux at BBY (cm m/s)

Ralph et al. (2013) JHM
91 AR events observed over 6 years

75% of precip explained by upslope vapor flux

62% of runoff explained, with 17% more explained by antecedent soil moisture

Storm-total discharge, Austin Ck (millions of m³)

Storm-total upslope water vapor flux at BBY (cm m/s)

Ralph et al. (2013) JHM
Orographic precipitation depends on:

- Orientation of AR rel to mountains
- Wind speed at about 1.5 km msl
- Vapor content

→ Relevant vapor transport

With >1460 AR-hours from >91 AR landfalls in hand, we are increasingly able to intelligently compare the extremity (or not) of current or predicted events to historical extremes

Ralph et al. (2013) JHM
The **Sierra Barrier Jet** is another key to patterns of precip in California.

*Neiman et al. (2013) MWR 2013*
A strong Sierra Barrier Jet focuses orographic precipitation up towards Shasta/Oroville catchments.

More SBJ → More focus

Neiman et al. (2013) MWR

Average mix of storms → Less focus

PRISM winter precipitation, 30-yr avg
Schematically, this looks like:

Across the Central Valley

“Orographic” lifting of AR starts well before range front

Along the Central Valley

Additional uplift where SBJ encounters barriers towards north end of CV

Neiman et al. (2013) MWR
Mesoscale waves on cold front (& thus on AR) can > double the time an AR spends overhead at a particular location.

This Feb 2014 AR increased precipitation-to-date from 16% to 40% of normal in < 4 days in key Northern California watersheds; runoff was muted due to dry soils.

> 12 inches of rain & some drought relief

* SSM/I satellite observations of water vapor on 8 Feb 2014
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SSM/I satellite observations of water vapor on 8 Feb 2014
What determines intensity, totals, distribution & impacts of orographic precipitation from ARs?

- Number of landfalls per year
- Vapor transport onshore by ARs  
  *Wind speed in low-level jet & vapor content*
- Orientation of transport wrt topography
- Duration of AR passage overhead  
  *Mesoscale frontal waves*
- **Temperature of AR**  
  *Snowline altitude*
- **Closeness to saturation**  
  *How much uplift before precipitation begins*
- **Stability of atmosphere**  
  *How readily is AR lifted by orography*
- Presence/absence of resulting SBJ
- Antecedent soil moisture
What are we doing with this knowledge?

Continued research obs & NEW statewide monitoring network built upon these “AR principles”
Surface Observing Systems

- Precipitation gauges
- Precipitation droplet sizes/rates (disdrometers)
- Soil moisture
- Surface meteorology & snow depth
- Stream stage/flow
- Real-time data access
Remote Sensing Observing Systems

- 915-MHz wind profiler with RASS
- ¼-scale 449-MHz wind profiler with RASS
- S-band precipitation profiling radar (S-PROF)
- C-band scanning Doppler radar (SKYWATER)
- X-band polarimetric, scanning Doppler radar (HYDRO-X)
- FM-CW snow-level radar
- GPS receiver for integrated water vapor
What are we doing with this knowledge?

Continued research obs & NEW statewide monitoring network

An Atmospheric River-focused long-term observing network is being installed in CA as part of a 5-year project between CA Dept. of Water Resources (DWR), NOAA and Scripps Inst. Of Oceanography
- Installed 2008-2014
- >100 field sites

White et al. (2013) JAOT
What are we doing with this knowledge?

Statewide monitoring

**Preparing the way for offshore reconnaissance**

*CalWater2* – Field campaigns, winters 2015-2018

*SIO, DOE, NOAA, CEC, NSF, NASA, USGS, DWR ...

-- AR structure/evolution onshore/offshore
-- Aerosols & precip, local/Asian

CalWater 2 / DOE ACAPEX Observational Campaign
Jan – Mar 2015

Air- & ship-borne Reconnaissance
Atmospheric River Experiment (AREX) Proposal to NASA Earth Ventures
*Winters 2015-2018*

Marty Ralph (PI)
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Ryan Spackman (Deputy PI)

Scripps Institution of Oceanography
NASA JPL
Science and Technology Corporation
NOAA-Earth Syst Research Lab

Water vapor budget of ARs offshore and impacts on landfall
- NASA Global Hawk (3 winters)
- NASA DC-8 (2 winters)
- AR Obs network onshore
What are we doing with this knowledge?

Statewide monitoring

Preparing the way for offshore reconnaissance

Exploring ARs in climate-change projections

Central California:
- Stability declines ~ 20%
- Temps increase ~ 4ºC (+600 m snowline)
- Lifting-condensation levels rise ~ 200 m
- Number of persistent ARs triples !?

West Coast:
- Width of ARs increase a bit
- Numbers of ARs increase more in NORTH
- AR intensities increase more in SOUTH

*Updates to Dettinger, JAWRA, 2011*
What are we doing with this knowledge?

Statewide monitoring

Preparing the way for offshore reconnaissance

Exploring ARs in climate-change projections

New CENTER FOR WESTERN WEATHER & WATER EXTREMES
*(centered at Scripps and teaming w/groups across California & the West)*

- Designing, using & serving data from new observing systems
- Developing regional weather model tailored for ARs & extreme precip
- Providing unique forecast products
- Conducting research to push forward even more

http://cw3e.ucsd.edu/


• Ralph, F.M., Coleman, T., Neiman, P.J., Zamora, R., & Dettinger, M., 2013, Observed impacts of duration and seasonality of atmospheric river landfalls on soil moisture and runoff: J. Hydrometeor., 14(2), 443-459.


• Dettinger, M.D., 2011, Climate change, atmospheric rivers and floods in California—A multimodel analysis of storm frequency and magnitude changes: J. American Water Resources Association, 47, 514-523.
<table>
<thead>
<tr>
<th>Atmospheric Rivers (ARs) historically...</th>
<th>Quantitative Finding</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cause the heaviest West Coast rains</td>
<td>92% of West Coast’s heaviest 3-day rain events fed by ARs</td>
<td>Ralph &amp; Dettinger, BAMS, 2012</td>
</tr>
<tr>
<td>Fill CA reservoirs &amp; provide supplies</td>
<td>30-50% of Sierra Nevada rain, snow &amp; streamflow from ARs</td>
<td>Guan et al., GRL, 2010; Dettinger et al. Water, 2011</td>
</tr>
<tr>
<td>Bring cycles of wet &amp; dry years</td>
<td>Account for 85% of year-to-year precipitation variance over northern California</td>
<td>Dettinger &amp; Cayan, SFEWS, 2014</td>
</tr>
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<td>End West Coast droughts</td>
<td>40% of droughts in northern California ended by an AR</td>
<td>Dettinger, JHM, 2013</td>
</tr>
<tr>
<td>Cause CA floods</td>
<td>80-100% of major floods in central California rivers have been fed by ARs</td>
<td>Ralph et al., GRL, 2006; Dettinger &amp; Ingram, Sci Am, 2013</td>
</tr>
<tr>
<td>Sustain wetlands, floodplains &amp; fisheries</td>
<td>ARs initiated 77% of ecologically significant inundations of Yolo Bypass, Central Valley</td>
<td>Florsheim &amp; Dettinger, book chapter, 2014</td>
</tr>
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<td>Breach levees</td>
<td>81% of Central Valley levee breaks have happened during landfalling ARs</td>
<td>Florsheim &amp; Dettinger, book chapter, 2014</td>
</tr>
<tr>
<td>Can cause catastrophes</td>
<td>“ARkStorm” California flood scenario yields estimated &gt;$500B impacts</td>
<td>Porter et al., USGS OFR 2010-1312</td>
</tr>
<tr>
<td>Sometimes penetrate far inland</td>
<td>ARs have caused major storms in Arizona, Utah, and other Western states</td>
<td>Neiman et al., JHM, 2013; Rutz et al., MWR, 2014</td>
</tr>
<tr>
<td>Can be forecast</td>
<td>ARs can be seen &gt;5 days ahead; landfall position error is still large</td>
<td>Wick et al., WAF, 2014</td>
</tr>
</tbody>
</table>


• Dettinger, M.D., 2013, Atmospheric rivers as drought busters on the US west coast: J. Hydrometeorology, 14, 1721-173.


• Neiman, P.J., Ralph, F.M., Moore, B.J., Hughes, M., Mahoney, K.M. & Dettinger, M.D., 2013, The landfall and inland penetration of a flood-producing atmospheric river in Arizona—Part I, Observed synoptic-scale and hydrometeorological characteristics: J. Hydrometeorology, 14, 460-484.

**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.