Atmospheric River Observations:  
A Summary of Recent Results

F. M. Ralph

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UC San Diego’s Scripps Institution of Oceanography

*Western States Water Council Workshop on S2S Precipitation Forecasting*  
*San Diego California, 7 June 2016*

Outline

- The role of atmospheric rivers and Sierra barrier jet in extreme precipitation in Northern California
- Summary of Water year 2016 “Top-10” precipitation events in Northern California
- Airborne AR observations
A Vision for Future Observations for Western U.S. Extreme Precipitation and Flooding

F.M. Ralph¹, M. Dettinger², A. White³, D. Reynolds⁴, D. Cayan², T. Schneider⁶, R. Cifelli⁴, K. Redmond⁵, M. Anderson⁷, F. Gherke⁷, J. Jones⁷, K. Mahoney⁴, L. Johnson⁸, S. Gutman⁹, V. Chandrasekar¹⁰, J. Lundquist¹¹, N. Molotch¹², L. Brekke¹³, R. Pulwarty¹⁴, J. Horel¹⁵, L. Schick¹⁶, A. Edman¹⁷, P. Mote¹⁰, J. Abatzoglou¹⁸, R. Pierce²⁰, G. Wick³
Landfalling Atmospheric Rivers, the Sierra Barrier Jet and Extreme Daily Precipitation in Northern California’s Upper Sacramento River Watershed

F. M. Ralph, J. Cordeira, P. Neiman, M. Hughes

In Press at J. Hydrometeorology

Supported by DWR
Data from HMT and DWR
Sierra Barrier Jets, Atmospheric Rivers, and Precipitation Characteristics in Northern California: A Composite Perspective Based on a Network of Wind Profilers

Neiman, Hughes, Moore, Ralph, and Sukovich, MWR 2013

Based on observations from the CalWater field campaign 2009-2011; described in Ralph et al. (2016), BAMS

*Schematic based on a composite of the 13 strongest SBJ cases observed at the SHS profiler between 2009-2011.

*Profilers at CCO, CFC, and CCR also recorded data and composited during these SBJ cases.

*A 6-km regional reanalysis dataset from the WRF model provided additional information.

*The SBJ parallels the Sierra over the eastern Central Valley (CV): core 1 km above ground.

*The SBJ core increases in altitude up Sierra windward slope and poleward over Northern CV.

*Inland penetration of AR through San Francisco Bay gap contributes to SBJ deepening/moistening over Nern CV.

*Aloft, AR airstream rides over SBJ.

*Sierra-perpendicular vapor fluxes linked to heavy precip. along Sierra’s windward slope, & SBJ-parallel fluxes tied to heavy precip. at N end of CV.
Landfalling storm 14-16 February 2011
- Multi-Doppler scanning-radar retrievals
- Multi-wind-profiler time series diagnostics
- Balloon soundings

Observing network clearly monitored both the AR and SBJ during two sub-periods within the 2-day IOP
- SBJ western edge detected
- SBJ deepened toward the north
- AR rode up and over the SBJ
Chico wind profiling radar (NOAA/HMT)
Composites of Top-10 Extreme Daily Precipitation from NARR Reanalyses

(c) Top 10 EDP: Large Domain

(b) Top 10 EDP AR-Parallel Cross Section

Integrated water vapor – IWV (cm)

Horizontal water vapor transport

Ralph et al. (J. Hydrometeor., 2016, in press)
Conclusions – Part 1

92% 46 of 50 extreme daily precipitation events are associated with landfalling ARs on either the day before or the day of precipitation.

90% 45 of 50 extreme daily precipitation events are associated with SBJ conditions on either the day before or the day of precipitation.

76% 38 of 50 extreme daily precipitation events are associated with both landfalling ARs and SBJ conditions on either the day before or the day of precipitation.
Conclusions – Part 2

100% The 10 wettest days in the Northern Sierra 8-station Index (i.e., the top 0.3% of all days in 10 years) were all associated with both a landfalling AR and an SBJ.

Can we build a tool that uses this result to produce an alert of high risk based on associated diagnoses of forecast model output?

And uses ARO and SSM/I data to validate and monitor in real-time?
Representation of the Sierra Barrier Jet in 11 years of a high-resolution dynamical reanalysis downscaling compared with long-term wind profiler observations.


**Method**
- 11 years of profiler-observed SBJs (256)
- Compared with reanalyses ranging from 275 km, 32 km, 10 km to 6 km grid sizes

**Results**
- NNRP (275 km) does not have SBJs
- NARR (32 km) and CARD (10 km) SBJ is 2 times as deep as observed
- WRF RD (6 km) has 80% of SBJs
- **SBJs in WRF RD (6 km) are best match to observed strength and depth**
- WRF RD misses stable layer below 500 m MSL in SBJs (compared to radiosondes)
- **Vapor transport in 6-km WRF-RD differs greatly from 32-km NARR**
- NARR 35% too much flux into Sierra
- NARR 20% too little flux along Sierra
Top Ten Precipitation Events in Water Year 2016: Northern Sierra 8-Station Index

Prepared by Brian Kawzenuk, Marty Ralph, Julie Kalansky

Per request from DWR and building on Elissa Lynn example from 2005
Top precipitation events were determined based on storm total precipitation measured by the Northern Sierra 8-Station Index.

All events were analyzed to determine if an Atmospheric River was present:
- Defined by IVT > 250 kg m\(^{-1}\) s\(^{-1}\) and
- IWV > 20 mm in a long narrow feature*
- **All top-10 precip events included AR conditions during the event**
  - 8 were considered moderate ARs (IVT > 500 kg m\(^{-1}\) s\(^{-1}\) over land)
  - 6 were considered strong ARs (IVT > 750 kg m\(^{-1}\) s\(^{-1}\) over land)

*See Ralph et al. 2004; Rutz et al. 2014 for the bases of these thresholds defining AR conditions.
# Top-Ten NS8SI Precipitation Events – Water Year 2016

<table>
<thead>
<tr>
<th>Date</th>
<th>Rank</th>
<th>Precipitation (8-Station Index; in/cm)</th>
<th>AR Conditions</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max Daily</td>
<td>Storm Total</td>
<td>% of WY16*</td>
</tr>
<tr>
<td>3/12-3/14</td>
<td>1</td>
<td>2.33 / 5.91</td>
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<td>3.08 / 7.83</td>
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<tr>
<td>3/9-3/11</td>
<td>5</td>
<td>1.69 / 4.29</td>
<td>2.78 / 7.07</td>
<td>5.0%</td>
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<tr>
<td>1/17-1/18</td>
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<td>2.74 / 6.97</td>
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*Data through May 31, 2016

Maximum IWV/IVT values are calculated along the U.S. West Coast and may not be at the same time or location

IVT/IWV data from GFS analysis
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22% of WY in 10 days in March

Maximum IWV/IVT values are calculated along the U.S. West Coast and may not be at the same time or location.

*Data through May 31, 2016
• Each arrow is representative of an AR associated with one of the top ten precipitation events in the Northern Sierra Nevada during the cool season of water year 2016.

• Each arrow represents the approximate AR corridor and initial landfall location at the time of initial landfall

• Color of each arrow represents the accumulated precipitation measured by the 8-Station Index during the event (48, 72, or 96 hours)
Each of the top-10 wettest events of WY 2016 were identified and examined in terms of their strength and nature of the storms that produced them:

- The 10 events produced 54% of WY16 precip.
- All 10 were atmospheric river (AR) events*
- All 10 had winds from west or southwest
- All struck NorCal or OR coast and forced water vapor into the northern Sierra/Shasta area

Each dot represents the central landfall location of the associated atmospheric river:
- Dot’s color represents the maximum AR strength (i.e., its water vapor transport – IVT)

Dates and AR orientations are shown:
- Arrow’s color represents total precip. measured by the 8-Station Index in that event (over 48, 72, or 96 hours)

*See Ralph et al. 2016 for study of the relationship between NS8SI extreme events and landfalling ARs.
Location of All AR Conditions

AR conditions are defined as IWV > 20 mm and IVT > 250 kg m⁻¹ s⁻¹. Data from the GFS 0.5° analysis.
AR conditions are defined as IWV >20 mm and IVT >250 kg m\(^{-1}\) s\(^{-1}\). Data from the GFS 0.5° analysis

- Shading shows where AR criteria were met during the Top-10 NS8SI events*
- Locations within the ten contour (purple) experienced AR conditions during all ten events
  - AR conditions penetrated inland to the north central valley in all cases
- 90% of these ARs also made landfall over central and northern California

*See Ralph et al. 2016 for study of the relationship between NS8SI extreme events and landfalling ARs
AR conditions are defined as IWV >20 mm and IVT >500 kg m$^{-1}$ s$^{-1}$. Data from the GFS 0.5° analysis.

- Shading shows where moderate strength AR conditions were met during the ten events.
- Moderate strength AR conditions penetrated inland to the northern central valley and northern Sierra Nevada during 7 events.
- Eight ARs made landfall over central/northern CA with moderate strength.
Top-10 Events

- 54% of total WY to date precipitation
- All 10 events were associated with landfalling atmospheric rivers

Precipitation event rankings relative to all WY 2016 events
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

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

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

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

Air Force C-130 Aircraft – Weather Recon’ Squadron

NORTHWEST RIVER FORECAST CENTER

NWRFC flood forecast map as of 1500 UTC 15 Feb showing several rivers predicted to reach flood stage on 15-16 Feb (red dots)
C-130 Atmospheric River Reconnaissance Mission
Flights centered on 0000 UTC 14 Feb


Summary by F. Martin Ralph

C-130 base | Waypoint | Lat (deg N) | Long (deg W) | Distance (time at 300 kt)
--- | --- | --- | --- | ---
McChord AFB WA | TO: 1810 UTC | 47.14 | 122.48 | To 1A:
1A: 2041 | 40 | 133 | No Pt 1B
1C: 2340 | 50 | 144 | 49 sondes
1D: 0157 | 39.1 | 141.6 |
10.6 h | Ld: 0445 | To McChord:
Hickam AFB HI | TO: 1721 UTC | 21.34 | 157.95 | To 2A:
2A: 2032 | 33.5 | 148.5 |
2C: 2322 | 45 | 157 | 53 sondes
2D: 0318 | 30 | 155 |
12.3 h | Ld: 0537 | To Hickam:

[Map showing atmospheric river with Waypoints and distances]
Locations of C-130 AR Recon dropsondes received and successfully decoded into NCEP’s production bufr data tanks for assimilation into NCEP/GFS

2nd C-130 AR Recon Mission
15-16 Feb 2016
Dropsondes released for the 0000 UTC 16 Feb 2016 GFS data assimilation window

Observed IWV from SSM/I (ESRL/PSD)
Satellite passes from 13 Z 15 – 01 Z 16 Feb
Showing atmospheric river signature
Satellite image from NOAA/ESRL/PSD

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

Seattle NWS Office flood warnings, watches and advisories at 0400 UTC 16 Feb 2016

FM Ralph (Scripps Inst. Of Oceanography)
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


- 22 CMIP-5 GCM runs
- 2073-2099 (RCP4.5 and 8.5) vs 1979-2005 (“HIST”)
- Percentage mean IVT increase (RCP8.5 / HIST) in Dec/Jan/Feb.
- 20-30% increases near CA

Percentage increase in vertically Integrated Vapor Transport (IVT)
1. The mean and variance of atmospheric water vapor flux will intensify under projected climate change.

2. In key areas this flux will directly increase orographic precipitation.

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

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

Observations of Water Vapor Transport by North Pacific Atmospheric Rivers


In Preparation

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

Composite AR Cross section (26 Mississippi's)

Aircraft transects with dropsondes across 17 ARs
A few large storms (or their absence) Account for a disproportionate amount of California’s precipitation variability

Water year precipitation, Delta catchment with contributions from days <95%-ile, >95%-ile

Dettinger and Cayan 2014, San Francisco Estuary and Watershed Science
Thank you

mralph@ucsd.edu
cw3e.ucsd.edu
NorCal Landfalling Atmospheric River Events Identified Using SSM/I IWV Data

- Long, narrow plume of enhanced atmospheric water vapor in warm sector of winter storms
- Identified via integrated water vapor (IWV) in numerical models or observed in SSM/I/S Satellite estimates
- Example from 2014 illustrates AR landfall in California

IWV >2cm:
- >2000 km long
- <1000 km wide

Sierra Barrier Jet Identification

- A barrier jet is a low-level, barrier-parallel core of locally strong winds composed primarily of ageostrophic flow at ~1 km AGL.

- SBJs are identified from data collected from a 915-MHz radar wind profiler at Chico (CCO), CA deployed by NOAA/ESRL.

- SBJs are identified using the Neiman et al. (2010) methodology: (1) meridional (V) wind component >12 m s\(^{-1}\) below 3 km, (2) maximum V-wind (\(V_{\text{max}}\)) must be located ≥200 m AGL, and (3) V-wind must decrease by >2 m s\(^{-1}\) between level of \(V_{\text{max}}\) and 3 km.

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**SBJ Identification Criteria**

*Time–height section of hourly averaged wind profiles (every other range gate shown) and barrier-parallel isotachs (m s\(^{-1}\); directed toward 340°) at Chico (CCO), CA on 25 Feb 2004 (wind flags = 25 m s\(^{-1}\), barbs = 5 m s\(^{-1}\), half barbs = 2.5 m s\(^{-1}\)). Figure from Neiman et al. (2010).*