Atmospheric River Reconnaissance: Needs, Approaches and Underlying Science

ECMWF Workshop: Observational Campaigns for Better Weather Forecasts
10-13 June 2019
Reading, UK

AR Recon Data Assimilation and Impacts Assessment
Steering Committee:
F. Martin Ralph, Scripps Institution of Oceanography/CW3E
Vijay Tallapragada (presenter), NOAA/NWS/NCEP
James Doyle, Naval Research Lab.
Chris Davis, NCAR
Florian Pappenberger, ECMWF
Aneesh Subramanian, CU Boulder

Photo of Guerneville, CA, USA
Courtesy Noah Burger
Overarching concept for AR Recon

• Forecasts of landfalling storms on the U.S. West Coast in winter are impacted by limitations in the accuracy of initial conditions over the Eastern North Pacific used for numerical weather prediction.

• Impacts of landfalling storms in the cool-season include
  • Extreme precipitation and flooding
  • Coastal erosion and coastal flooding due to waves and high sea levels
  • Damaging high winds

• Extreme precipitation and flooding is mostly associated with landfalling atmospheric rivers, and landfall position errors are +/- 200-500 km at 1-5 days lead time (Wick et al. 2013)

• The initial condition errors that produced the greatest error in forecasts of a major landfalling storm in Europe at 2 days lead time were the offshore position and characteristics of an atmospheric river (Doyle et al. 2014)

• On average the greatest sensitivity coincides with the AR and its edges. (Reynolds et al. 2019)
**ATMOSPHERIC RIVER**

A long, narrow and transient corridor of strong horizontal water vapor transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapor in atmospheric rivers is supplied by tropical and/or extratropical moisture sources. Atmospheric rivers frequently lead to heavy precipitation where they are forced upward, e.g., by mountains or by ascent in the warm-conveyor-belt. Horizontal water vapor transport in the mid-latitudes occurs primarily in atmospheric rivers and is focused in the lower troposphere.

Figures from Ralph et al. 2017 (JHM)
Atmospheric Rivers are like rivers in the sky – Rivers of water vapor

One AR transports as much water as 25 Mississippi Rivers, but as vapor rather than liquid (from Ralph et al. 2017)

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.
AR Impacts
SSM/I satellite data shows atmospheric river
Stream gauge data shows 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.

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)
**ARs drive flood losses**

84% of insured losses in the 11 western states were caused by ARs

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Proportion of Losses Due to ARs

Post-Fire debris flows pose a serious hazard. This case killed >20 people near Montecito, CA.

(Case study: Oakley et al. 2018, EGU's Natural Hazards and Earth System Sciences)

Cordeira et al., 2019 (BAMS, in press), “San Francisco Bay Area landslide days predominantly occur during December–March in Sonoma, Marin, San Mateo, and Santa Cruz counties where 82% of these days coincide with landfalling atmospheric rivers.”
Local Water Districts Involved in Studies Exploring Use of Atmospheric River Forecasts in Water Operations

Water Supply hinges on ARs in this region.

Agencies responsible for providing water for the public, agriculture, and industry, while maintaining healthy (water-dependent) ecosystems, can improve their operations through use of better forecasts of ARs and their associated extreme precipitation and runoff.
Forecasting challenges associated with landfalling ARs
The Forecasting Challenge:
Floods

The predicted crest of the flood increased by 14 feet (from stage of 25 to 39 ft) in the 3-4 days prior to the observed flood peak.

Each line represents a different forecast (FCST) issued on either 10, 11, 12, 13 or 14 Feb, which were either 0, 1, 2, 3, or 4 days prior to when the flood crest was observed.
Forecasting large precipitation amounts is difficult (only 2 of 16 extreme precip. events were predicted to be that strong at just 1 day lead time)

Of the 20 dates with >3 inches of precipitation in 1 day, 18 were associated with ARs.

Ralph et al. 2010

Forecasting AR landfall includes position errors larger than watersheds

Wick et al. 2013
AR Reconnaissance ("AR Recon")
Targeting and Operations
Water managers, transportation sector, agriculture, etc... require improved atmospheric river (AR) predictions.

Atmospheric River Reconnaissance Sampling Concept and Example from 27 Jan 2018

Example of a target for the NOAA G-IV

Example of Atmospheric River target for AF C-130s (color fill: IVT)

F. Martin Ralph (AR Recon PI; Scripps/CW3E), Vijay Tallapragada (AR Recon Co-PI; NWS/NCEP) and AR Recon Team
AR Recon 2016 to 2020
Two Air Force C-130s and NOAA’s G-IV

✓ Feb 2016: 3 Storms (2 aircraft/storm; AF C-130s)
✓ Jan-Feb 2018: 6 Storms (3 aircraft/storm in 3 storms – 2 AF C-130s plus the NOAA G-IV (With Airborne GPS Radio Occultation, J. Haase); 2 C-130s in 1 storm; 1 C-130 in 2 storms)
✓ 1 Feb-14 Mar 2019:
  Core program: 6 storms (2 AF C-130s/storm; 25 dropsondes/aircraft/storm flight; 300 sondes)
  Addit’l data: 32 drifting buoys supplemented with barometers in AR Alley (L. Centurioni, B. Inglesby)
  o Jan-Mar 2020 (in planning): 9-12 storms (3 aircraft/storm)
  o 2021 and beyond: Long-term requirements captured in the US’ National Winter Storm Operating Plan

o **Target total number of cases: 27 storms, with 1, 2 or 3 aircraft sampling each storm**
✓ Interagency, International Steering Committee in place
  • Carry out assessments
  • Refine data assimilation methods
  • Create appropriate evaluation metrics
  • Provide impact results in peer-reviewed publications

Contacts
PI: F. M. Ralph (mralph@ucsd.edu)
Co-PI: V. Tallapragada (vijay.tallapragada@noaa.gov)
Airborne Radio Occultation (ARO) Concept

Delays in the travel time of low elevation GPS and Galileo signals as the satellites set are used to derive temperature and moisture of successively lower atmospheric layers.

NOAA GIV Installation
Small instrument profile for easy installation in any aircraft, uses existing GPS antenna.
Drifting Buoy locations (no guarantee on residence time)

Air Force requirement:
Starting point, direction, and spacing
For Jan deployment, must be below 40N.

Figure provided by Forest Cannon, CW3E

PI: F. Martin Ralph

Sponsored by California’s Atmospheric Rivers Research, Mitigation, and Climate Forecasting Program
Managed by CA DWR

Proposed Drop Locations

Buoys WITH pressure
Buoys WITHOUT pressure
Buoy locations Sept 2018

Air Force requirement: Starting point, direction, and spacing
For Jan deployment, must be below 40N.

Sponsored by California’s Atmospheric Rivers Research, Mitigation, and Climate Forecasting Program
Managed by CA DWR

PI: F. Martin Ralph
Forecast Informed Reservoir Operations (FIRO): Supporting Forecast Improvements through Targeted Data Collection

Anna M. Wilson¹, F. Martin Ralph¹, Jay Jasperse², Cary A. Talbot³, Brian Kawzenuk¹, Carly Ellis¹, and Stephen Turnbull³

¹Center for Western Weather and Water Extremes, ²Sonoma Water, ³US Army Engineer Research and Development Center

See Wilson et al Poster on hydrologic and hydrometeorological measurements onshore, which supports better physical understanding, model development and verification - critical components of improving forecasts.

- FIRO: How can we better use existing infrastructure to meet competing needs (flood mitigation, water supply, ecosystem services)?
- Test watershed: Lake Mendocino in northern California – ARs bring most significant precipitation and control storage regimes in soil and reservoirs
- Need better forecasts of AR landfall location, intensity, and duration, to accurately predict precipitation patterns
AR Recon – 2018 Flight Operations Planning and Execution

NWS Co-PI
V. Tallapragada (NCEP) – Co-PI
A. Edman (NWS WR) – Co-PI

AR Recon PI and Mission Director
F.M. Ralph (SIO/CIMEC & CW3E)
J. Doyle (NRL) – Alternate
Coordinators: A. Wilson, J. Kalansky, F. Cannon (CW3E)

Flight Execution
Major A. Lundry (AF C-130s)
J. Parrish (NOAA G-IVV)
“Flight Directors”

AR Core Target Planning
Two C-130s
J. Rutz (NWS WR) – Primary
J. Cordeira (Plym. St.) – Alternate
AR Core Target - Advisors
C. Reynolds (NRL) - backup
C. Smallcomb (NWS)
D. Lavers (ECMWF)
R. Demirdjian (SIO/CW3E)

Secondary Target Planning
NOAA G-IV
C. Davis (NCAR) – Primary
T. Galarneau (U.AZ) – Alternate
Secondary Target - Advisors
J. Doyle (NRL)
L. Bosart (SUNY Albany)
R. Demirdjian (SIO/CW3E)
TBD

Flight Track Assessment
Air Force Navigator
NOAA (Parrish/Cowan)
Coordinator: F. Cannon (CW3E)

Daily Forecasts, Flight Summaries and Planning 800 AM PT*

*Meetings led by either Cordeira, Rutz, Lavers, or alternate
*Attended by “primary” and “alternate” from each group (not by all members of each group)

Flight Execution
Major A. Lundry (AF C-130s)
J. Parrish (NOAA G-IV)
“Flight Directors”

Modeling and Data Assimilation SC
F.M. Ralph (SIO/CW3E) – Co-Chair
V. Tallapragada (NCEP) – Co-Chair
J. Doyle (NRL),
C. Davis (NCAR)
F. Pappenberger (ECMWF),
A. Subramanian (SIO/CW3E)

AR Recon Forecasting Team
J. Cordeira (Plymouth St.) – Primary
D. Lavers (ECMWF) – Alternate
J. J. Rutz (NWS WR) – Alternate
C. Hecht (SIO/CW3E) - Alternate
B. Kawzenuk (SIO/CW3E)
K. Howard (NCEP), Other TBD

Moist Adjoint Team
C. Reynolds (NRL) – Primary
J. Doyle (NRL) – Alternate
R. Demirdjian (SIO/CW3E) - Support

Planning Data and Flight Summaries
TBD - (SIO/CW3E) – PDocs/GrStud

Key dates
19 January: commit where to deploy the 2nd C-130
25 Jan - 10 Feb: G-IV is available for 3 storm flights from Seattle
25 Jan - 27 Feb: two C-130s available for 6 storm flts from Hawaii, Seattle, Travis AFB or San Diego

CARCAH
Atmospheric River Reconnaissance 2018

Contacts: F. M. Ralph (PI; mralph@ucsd.edu); V. Tallapragada (Co-PI; vijay.tallapragada@noaa.gov)

Integrated Vapor Transport (kg s\(^{-1}\) m\(^{-1}\))

IOP1 – Jan 27, 2018 – 00Z

IOP2 – Jan 29, 2018 – 00Z

IOP3 – Feb 1, 2018 – 00Z

IOP4 – Feb 3, 2018 – 00Z

IOP5 – Feb 26, 2018 – 00Z

IOP6 – Feb 28, 2018 – 00Z
Early analysis
An example comparison between observed and model initial condition in an AR transect

Significant differences were found between the observed AR characteristics and the ECMWF first guess, especially near the MBL top.

~20% difference in water vapor transport predicted at the location observed by AR Recon
Adjoint Sensitivity of North Pacific Atmospheric River Forecasts

On average, sensitivity of the wind forecasts (top) and precipitation forecasts (bottom) are very similar, with maxima occurring on average north of the strongest IVT and near the latitudinal maximum in baroclinic instability.

On average the greatest sensitivity coincides with the AR and its edges.

Vertically averaged optimal perturbations for moisture (left panels) and wind (right panels) for wind forecasts (top) and precipitation forecasts (bottom). Moisture figures include IVT (blue vectors) and Eady growth rate (black contours, day⁻¹). Wind panels include 700-hPa wind speed (green contours, m s⁻¹). The locations of individual maxima are indicated by triangles and circles (circles represent the 20 largest sensitivity cases).

Reynolds et al. MWR in press (2019)
Errors in Predicting a Mesoscale Frontal Wave on an AR Can Create Major Errors in Flood Forecasts

A. Martin, F.M. Ralph, A. Wilson, L. DeHaan, B. Kawzenuk (J. Hydrometeor., in press June 2019)

00 UTC 11 Dec 2014, (36 h prior to flood crest)

Mesoscale Frontal Wave

Crest forecast rose 8 feet in 2 days

Stage (ft)
0 10 20 30
Dec 08/12 10/12 12/12
Day/Hour (UTC)

Flood Stage
Monitor Stage
10 Dec Forecast
8 Dec Forecast
Observations
A moderate AR case during 2016 AR Recon IOP1

- Analyzed IVT (ECMWF analysis) at 0000 UTC Feb 14, 2016

Max IVT: 508.3 kg m\(^{-1}\) s\(^{-1}\)
Location: 124.0° W, 46.3° N

IOP1: collected data for 0000 UTC Feb 14 (6h window)

Data distribution of (non)conventional observations

- Assimilated in West-WRF for 2016 IOP1 at 0000 UTC Feb 14, 2016

- Radiosonde
- Profiler
- VADRAD
- Surface SYNOP + METAR (land)
  SHIP+BUOY (ocean)
- AI/PIREP
- GPSRO
- ASCATW (ocean)
- AMV below 500mb
- AMV above 500mb
- Dropsonde
  From AR Recon

*AI/PIREP: aircraft/pilot report
*ASCATW: scatterometer wind
**# of obs over the areas btw 150°W-124°W on AR object (Guan and Waliser 2015)**

<table>
<thead>
<tr>
<th>Pressure Level (mb)</th>
<th>DROPS + RSONDE</th>
<th>PROFILER + VADWND</th>
<th>Surface</th>
<th>GPSRO + AI/PIRES</th>
<th>ASCATW</th>
<th>AMV</th>
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<td>0</td>
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<td>350</td>
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<td>50</td>
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<td>22</td>
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<td>&gt;900</td>
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<td>62</td>
<td>342</td>
<td>11</td>
<td>0</td>
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<tr>
<td>All Levels</td>
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<td>276</td>
<td>342</td>
<td>596</td>
<td>0</td>
<td>1780</td>
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<tr>
<td>&gt;700 (AR)</td>
<td>1179</td>
<td>140</td>
<td>342</td>
<td>44</td>
<td>0</td>
<td>72</td>
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*Areas east of 150°W are directly linked to the 2.5-day fcst along the coast assuming a 10 m/s synoptic phase speed.

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<td>dropsonde obs can contribute to 2/3 of the total obs over the upstream AR object</td>
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<td></td>
<td>66.3% of total obs</td>
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</tr>
</tbody>
</table>

- **DROPS + RSONDE**
- **PROFILER + VADWND**
- **Surface**
- **GPSRO + AI/PIRES**
- **ASCATW**
- **AMV**

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*66.3% of total obs*
Assessing the predictability of mesoscale precipitation processes in landfalling atmospheric rivers using AR Recon dropsonde observations

Forest Cannon, Nina Oakley, Chad Hecht, Allison Michaelis, Brian Kawzenuk, Reuben Demerdjian, Meredith Fish, Anna Wilson, Jason Cordeira, and F. Martin Ralph

Center for Western Weather and Water Extremes at UC San Diego/Scripps Institution of Oceanography, La Jolla, CA

This presentation discusses the synoptic and mesoscale origins of a band of intense precipitation that developed within the AR that was observed in IOP 1 of AR Recon 2019.

Hazard precipitation rates over the West Coast associated with these features have not received substantial attention from the scientific community, yet are an important consideration for emergency management during AR events.

AR Recon dropsondes ahead of landfall provide a unique data source for studying the event’s meteorology and evaluating the ability of CW3E’s West-WRF model skill.
Impact of Dropsonde Observations on the Predictability of Landfalling Atmospheric Rivers

Minghua Zheng, Bruce Cornuelle, Luca Delle Monache, F. Martin Ralph

Center for Western Weather and Water Extremes (CW3E)
UC San Diego/Scripps Institution of Oceanography, La Jolla, California, USA

See Zheng et al. Poster on the Impact of Dropsondes Assimilation

- West - Weather Research and Forecasting (West-WRF) model
- Community Gridpoint Statistical Interpolation (GSI) data assimilation system (Hybrid 4D-EnVar)

(a) NoDROP IVT Error (filled)  (b) WithDROP IVT Error (filled)

- Tests over 15 AR Recon IOPs
- DA of conventional data, satellite derived winds, GPS RO refractivity, and dropsondes (right panel only)
- Improvements for most lead times (0-5 days)
- Improvements for most IOPs
- Largest improvements for consecutive IOPs
- Next: add DA of satellite radiances
Thank You

• More information on AR Recon is available at
  – http://cw3e.ucsd.edu/arrecon_overview/

• Thank you to our primary sponsors and partners

  Sponsors: US Army Corps of Engineers, California Dept. of Water Resources
  Operational weather forecasting centers: NWS/NCEP, NWS/Western Region, ECMWF
  Weather Research Centers: Naval Research Laboratory, National Center for Atmospheric Research
  Universities: UC San Diego, Plymouth State Univ., SUNY Albany, CU Boulder
AR Scale introduced by Ralph et al. 2019 (BAMS)

- **AR CAT (1-5)** (Denoted by color)
  - **AR Intensity Name**
    - Exceptional
    - Extreme
    - Strong
    - Moderate
    - Weak
    - Not an AR

- **Maximum IVT (kg m\(^{-1}\) s\(^{-1}\))**
  - Weak
  - Moderate
  - Strong
  - Extreme
  - Exceptional
  - Not an AR

- **AR Duration** (IVT > 250) (h)
  - 0
  - 24
  - 48
  - 72

- **Flood Damages by AR CAT**
  - Weak
  - Moderate
  - Strong
  - Extreme
  - Exceptional

- **$0.1m\quad$0.4m\quad$3m\quad$20m\quad$260m**
  - (130)
  - (168)
  - (201)
  - (99)
  - (11)
Adjoint Sensitivity of North Pacific Atmospheric River Forecasts

Adjoint allows for the mathematically rigorous calculation of forecast sensitivity of a response function to changes in the initial state

COAMPS® Moist Adjoint Model

• Dynamics: nonhydrostatic, nested
• Physics: PBL, surface fluxes, microphysics
• 40-km resolution, 24-h and 36-h optimization times
• Response function (RF) $J$:
  • KE in box (1 km deep);
  • PRCP (21-24h),
• Optimal Perturbations (1 m/s, 1 K, 1 g/kg)
• Cases: 00Z and 12Z 01JAN to 20FEB 2017

Manuscript (Reynolds, Doyle, Ralph and Demirdjian) submitted to MWR, currently being revised.

Reynolds et al. MWR in revision Dec 2018
IOP 3: Obs Impact for Dropsondes and NA Radiosondes in NAVGEM: Wind Observations

Forecast Error Increase (not beneficial)

Forecast Error Decrease (beneficial)

Wind observations have larger impact than moisture observations (true for both dropsondes and radiosondes).

Currently investigating why moisture observations have smaller impact than winds/temp (qc? metric? model?). Moisture obs are rejected at higher rate than temperature or wind obs.

courtesy: Carolyn Reynolds (NRL)
Dropsonde impact on initial errors for IOP6

WestWRF Experiments for AR
Recon
NoDROP run IVT error (shaded)

CTRL IVT (Magenta contour) and CTRL-Ana (Shaded)
Valid: 0000 UTC 02/28/2018

DROP-NoDROP IVT (shaded)

DROP IVT (Magenta contour) and DROP-CTRL (Shaded)
Valid: 0000 UTC 02/28/2018

courtesy: Minghua Zheng (CW3E)
Assimilated Obs.
AR Recon IOP-3
13 Feb. 2019 00Z

AR Recon PI – F.M. Ralph
Scripps Institution of Oceanography, UCSD

All-Sky Radiances
Below 700-hPa

GOES IR
IMERG Precip.
A Scale to Characterize the Strength and Impacts of Atmospheric Rivers

F. Martin Ralph (SIO/CW3E), J. J. Rutz (NWS), J. M. Cordeira (Plymouth State), M. Dettinger (USGS), M. Anderson (CA DWR), D. Reynolds (CIRES), L. Schick (USACE), C. Smallcomb (NWS); Bull. Amer. Meteor. Soc. (Feb. 2019); DOI/10.1175/BAMS-D-18-0023.1

The AR CAT level of an AR Event* is based on its Duration** and max Intensity (IVT)***

Step 1: Pick a location
Step 2: Determine a time period when IVT > 250 (using 3 hourly data) at that location, either in the past or as a forecast. The period when IVT continuously exceeds 250 determines the start and end times of the AR, and thus also the AR Duration for the AR event at that location.
Step 3: Determine AR Intensity - Determine max IVT during the AR at that location - This sets the AR Intensity and preliminary AR CAT
Step 4: Determine final value of AR CAT to assign - If the AR Duration is > 48 h, then promote by 1 Category - If the AR Duration is < 24 h, then demote by 1 Category

* An “AR Event“ refers to the existence of AR conditions at a specific location for a specific period of time.
** How long IVT>250 at that location. If duration is <24 h, reduce AR CAT by 1, if longer than 48 h, add 1.
*** This is the max IVT at the location of interest during the AR.

Determining AR Intensity and AR Category

<table>
<thead>
<tr>
<th>AR Intensity Name</th>
<th>AR CAT 1 (1-5) (Denoted by color)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exceptional</td>
<td>5</td>
</tr>
<tr>
<td>Extreme</td>
<td>4</td>
</tr>
<tr>
<td>Strong</td>
<td>3</td>
</tr>
<tr>
<td>Moderate</td>
<td>2</td>
</tr>
<tr>
<td>Weak</td>
<td>1</td>
</tr>
</tbody>
</table>

Maximum AR Category

AR Duration (IVT > 250) (h) 1250 1000 750 500 250 0
AR Intensity (kg m^-1 s^-1) 14 12 10 8 6 4 2 0
Not an AR

The Oroville Event AR

On the Web: CW3E.UCSD.EDU
On Twitter: @CW3E_Scripps
NCEP GEFS dProg/dt Example from February 2017 – "Oroville Case" (dam spillway issue)

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.

F. M. Ralph (mralph@ucsd.edu) and J. Cordeira