Landfalling Impacts of Atmospheric Rivers:
From Extreme Events to Long-term Consequences

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Motivation: Atmospheric rivers (ARs) generate devastating floods, and also replenish snowpacks and reservoirs, across the semi-arid West. Hence, it is crucial to understand this key phenomenon, both as a major weather producer and as one that contributes significantly to climate-scale impacts.

Outline

1. Brief Review of ARs
2. ARs as extreme weather events
3. Long-term impacts of ARs
4. Concluding Remarks

A few acronym definitions:
AR = atmospheric river
IWV = integrated water vapor
LLJ = low-level jet
MSL = above mean sea level
SWE = snow water equivalent
APDF = annual peak daily flow
NARR = North American regional reanalysis
Zhu & Newell (1998) concluded in a 3-year ECMWF model diagnostic study:
1) 95% of meridional water vapor flux occurs in narrow plumes in <10% of zonal circumference.
2) There are typically 3-5 of these narrow plumes within a hemisphere at any one moment.
3) They coined the term “atmospheric river” (AR) to reflect the narrow character of plumes.
4) ARs constitute the moisture component of an extratropical cyclone’s warm conveyor belt.
5) ARs are very important from a global water cycle perspective.
Observational studies by Ralph et al. (2004, 2005, 2006) extend model results:
1) Long, narrow plumes of IWV >2 cm measured by SSM/I satellites considered proxies for ARs.
2) These plumes (darker green) are typically situated near the leading edge of polar cold fronts.
3) P-3 aircraft documented strong water vapor flux in a narrow (400 km-wide) AR; See section AA’.
4) Airborne data also showed 75% of the vapor flux was below 2.5 km MSL in vicinity of LLJ.
5) Moist-neutral stratification <2.8 km MSL, conducive to orographic precip. boost & floods.
Global reanalysis melting-level anomaly (hPa; rel. to 30-y mean)

Melting level ~4000 ft (1.2 km) above normal across much of the PacNW during the landfall of this AR

This AR is also located near the leading edge of a cold front, with strong vapor fluxes (as per reanalysis diagnostics)
Hydroclimatic analysis for the AR of 5-9 November 2006

Greatest 3-day precip. totals during the period between 5-9 Nov. 2006

>600 mm (24”)

>700 mm (28”)

Historical Nov. ranking for the max. daily streamflow between 5-9 Nov. 2006

plus high melting level equals
High-Impact Consequences!

Aftermath of flooding and a debris flow on the White River Bridge in Oregon

Courtesy of Doug Jones, Mt Hood NF
SSM/I satellite image shows AR.

- Frontal wave stalls AR on coast, causing prolonged heavy rains.
- Stream gauge rankings for 17-Feb-04 show regional extent of high streamflow covering ~500 km of coast.
- All 7 flood events on the Russian River between 1997-2006 were tied to land-falling ARs.

Russian River, CA Flooding

250 mm of rain in 2 days
(Ralph et al. 2006)

- SSM/I satellite image shows AR.

Russian River flooding: Feb. 2004
(photo courtesy of David Kingsmill)
Given these results: **What are the long-term hydrometeorological impacts of landfalling ARs in western North America?** Neiman et al. (2008b)

**Approach:** We developed a methodology for creating a multi-year AR inventory.

- Inspect 2x-daily SSM/I IWV satellite composite images
- 8 water years Oct97-Sep05:
  - Identify IWV plumes >2 cm (0.8”): >2000 km long by <1000 km wide.
  - AR landfall at north- or south-coast
  - Focus on cool season when most precip falls in western U.S., and on the north-coast domain
The daily gridded NCEP–NCAR reanalysis dataset (2.5 x 2.5 ; Kalnay et al. 1996) was used to create composite analyses during AR conditions – 29 dates.

Composite reanalysis IWV plume oriented SW-NE from the tropical eastern Pacific to the coast.

Composite plume situated ahead of the polar cold front.

Wintertime ARs produce copious precip along coast, & frontal precip offshore.

Reanalysis composites accurately depict the positions of the IWV plume and precip. bands observed by the SSM/I composites... denoted by dotted lines.
• Strong vapor transport intersects coastline during winter, with maximum on the warm side of the cold front.

• Transport originating from low latitudes
Wintertime ARs are associated with trough/ridge couplet in the mid-troposphere (~2-6 km MSL).

Wintertime ARs are associated with anomalous warmth at low levels.
Composite Winter Reanalysis Soundings at North Coast

Flow strengthens with height...

...in pre-cold-frontal warm-advection shear

Moisture decreases with height

Max. moisture flux at mtn top... favors mtn precip. enhancement.

Mountain top height
Normalized Daily Precipitation and ΔSWE in CA* during DJF

Compared to the average of all precipitation days in the Sierra Nevada (observed by rain gauges and snow pillows), those days associated with landfalling Atmospheric Rivers produced:

- 2.0x the average precipitation
- 1.8x the average snow accumulation

*Qualitatively similar to, but quicker to explain than, north-coast results.
Now let’s turn the problem on its head: **What causes the largest annual runoffs on major watersheds in western Washington?** (Neiman et al. 2010)
Annual peak daily flows (APDFs) and atmospheric river (AR) events for WY1998-2009

- AR
- non-AR [determined from 2x-daily SSM/I IWV satellite imagery]

APDF dates for WY 1998-2009

- Green River
- Sauk River
- Satsop River
- Queets River

46 of 48 annual peak daily flows in last 12 years at the 4 sites due to AR landfalls

Results consistent with Dettinger (2004) in CA: ARs yield daily increases in streamflow that are an order of magnitude larger than those from non-AR storms
Ranked APDFs for WY1980-2009 (NARR period)

The APDFs occur most often Nov. - Jan.

Dates from the top-10 APDFs are used to create composite analyses from the North American Regional Reanalysis (NARR; Mesinger et al. 2006) to assess the composite meteorological conditions that produced flooding in each of the 4 basins.
Basin altitude attributes above gauges, and mean NARR top-10 melting-level altitudes* *(300 m below 0°C altitude)
Anomalously high melting levels + heavy precip = floods
NARR Composite Mean Integrated Vapor Transports (kg s\(^{-1}\) m\(^{-1}\)) for top-10 APDFs

(a) HHDW1

(b) SAKW1

(c) SATW1

(d) QUEW1
NARR Composite Mean Geopotential Heights (m) at 925 hPa for top-10 APDFs

(a) Green
(b) Sauk
(c) Satsop
(d) Queets
NARR Composite Mean profiles at coast for top-10 APDFs

Max. orographic forcing in AR conditions at coast. Minimal terrain lift would place it in weakest stability – optimal for heavy precip!
Atmospheric rivers (ARs) are long, narrow corridors of enhanced water vapor transport responsible for most of the poleward vapor flux at midlatitudes.

Lower-tropospheric conditions during the landfall of ARs are anomalously warm and moist with weak static stability and strong onshore flow, resulting in orographically enhanced precipitation, high melting levels, and flooding.

Because ARs contribute significantly to precipitation, reservoir and snowpack replenishment, and flooding in western North America, they represent a key phenomenon linking weather and climate.

The highly 3-D character of the terrain in western Washington yields basin-specific impacts arising from landfalling ARs (i.e., strong dependence on flow direction).

Next steps include quantifying the role of ARs in the global climate system and estimating the modulation of AR frequency and amplitude (and associated extreme precipitation and flooding upon landfall) due to projected climate change. Mike Dettinger is delving into this research (Dettinger et al. 2009).
Thank you!

Crater Lake from Watchman Peak (©2009 Paul Neiman)
References


Neiman, P.J., F.M. Ralph, G.A. Wick, J. Lundquist, and M.D. Dettinger, 2008b: Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the West Coast of North America based on eight years of SSM/I satellite observations. J. Hydrometeor., 9, 22-47.


