Atmospheric Rivers and Their Role in Generating Heavy Orographic Precipitation and Flooding Along the U.S. West Coast

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BIOGRAPHICAL SKETCH

I received a B.S. degree from Cornell University in 1984 and a M.S. degree from the Pennsylvania State University in 1987. I have worked as a research meteorologist with the National Oceanic and Atmospheric Administration in Boulder, Colorado, since 1986. My research interests lie in the areas of synoptic-scale and mesoscale meteorology, with a focus on orographically modulated flows and precipitation systems, extratropical frontal cyclones, and convective systems. This work has included the analysis and interpretation of numerous data sets from disparate sources, with an emphasis on combining observations recorded by state-of-the-art remote sensing instruments including radar wind profilers, land-based and airborne cloud and precipitation radars, GPS integrated water vapor units, radio acoustic sounding systems, Doppler lidars, and space-based radiometric and microwave sensors. During the last decade, much of this research has focused on the meteorology along the West Coast of the United States. I have also been involved in numerous field campaigns, including several that have concentrated on the meteorology of California (e.g., CALJET, PACJET, HMT).

ABSTRACT

The pre-cold-frontal low-level jet within oceanic extratropical cyclones represents the lower-tropospheric component of a deeper corridor of concentrated water vapor transport in the cyclone warm sector. These corridors are referred to as atmospheric rivers (ARs) because they are narrow relative to their length scale and are responsible for most of the poleward water vapor transport at midlatitudes. Using illustrative case-study examples and longer-term compositing strategies, this presentation will first briefly review the key structural and dynamical characteristics of ARs over the eastern Pacific Ocean and then comprehensively describe their hydrometeorological impacts upon landfall across westernmost North America.

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 and unusually high melting levels. Hence, ARs are critical contributors to extreme precipitation and flooding events. Despite these deleterious impacts, ARs also replenish snowpacks and reservoirs across parts of the semi-arid West, so they represent a key to understanding regional impacts of climate change on water resources. A winter-season analysis of quantitative precipitation forecasts during NOAA's Hydrometeorological Testbed (HMT) in California in 2006 reveals that the heavy precipitation associated with ARs is often challenging to predict, even though the heaviest areas of precipitation tend to be orographically anchored. These challenges arise due to hard-to-forecast frontal waves and differential rain shadowing between adjacent watersheds, among other factors.

Atmospheric Rivers (ARs) and Their Role in Generating Heavy Orographic Precipitation and Flooding Along the U.S. West Coast

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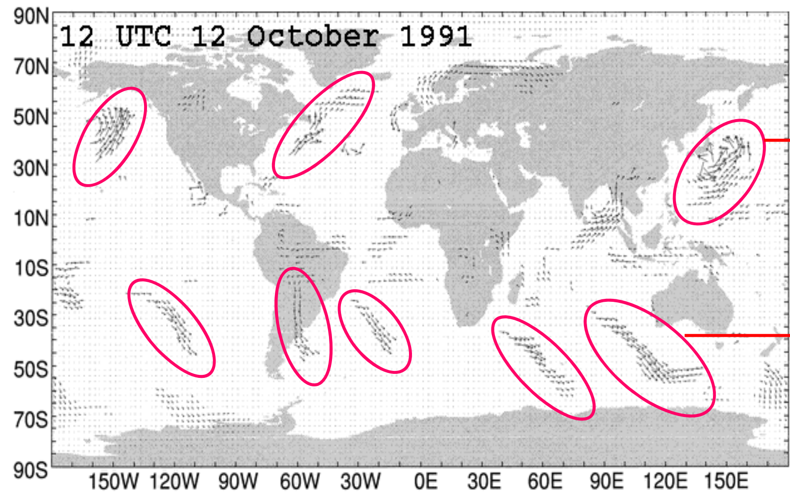
Outline

1. Brief Review of ARs
2. Landfalling Impacts of ARs
3. Forecasting Challenges
4. Concluding Remarks

<u>A few acronym definitions:</u>
AR = atmospheric river
IWV = integrated water vapor
LLJ = low-level jet
MSL = above mean sea level

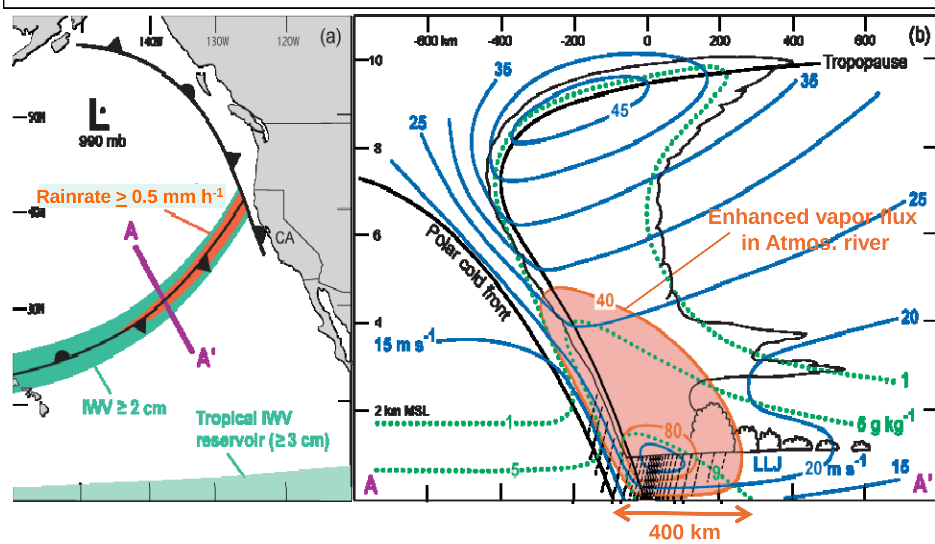
Zhu & Newell (1998) concluded in a 3-year ECMWF model diagnostic study:

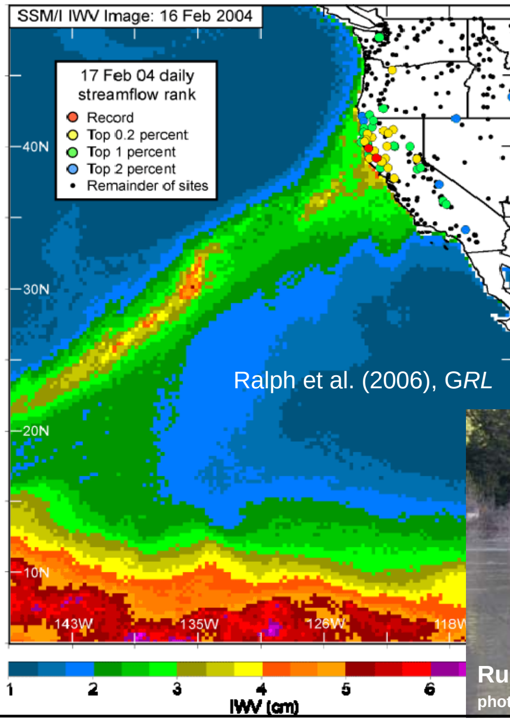
1) 95% of meridional water vapor flux occurs in narrow plumes in <10% of zonal circumference.
2) There are typically 3-5 of these narrow plumes within a hemisphere at any one moment.
3) They coined the term “atmospheric river” (AR) to reflect the narrow character of plumes.
4) ARs constitutes the moisture 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 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.

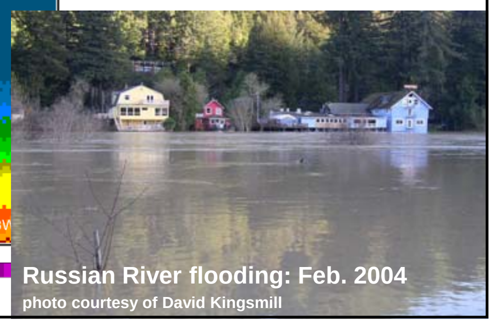




Russian River, CA Flooding

10 inches of rain in 2 days

- SSM/I satellite image shows AR.
- Stream gauge rankings for 17-Feb-04 show regional extent of high streamflow covering roughly 500 km of coast.
- All 7 flood events on the Russian River in last 10 years (1997-2006) tied to land-falling ARs.
- This result was first reported at the Extreme Precip. Symp. in 2006.



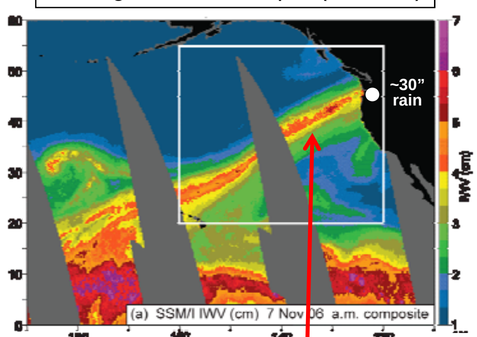
Russian River flooding: Feb. 2004

photo courtesy of David Kingsmill

Pacific Northwest Landfalling AR of early November 2006

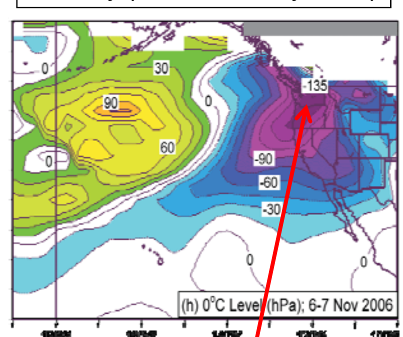
Neiman et al. (2008b)

SSM/I satellite imagery of integrated water vapor (IWV, cm)



This AR is also located near the leading edge of a cold front

Global reanalysis melting-level anomaly (hPa; rel. to 30-y mean)

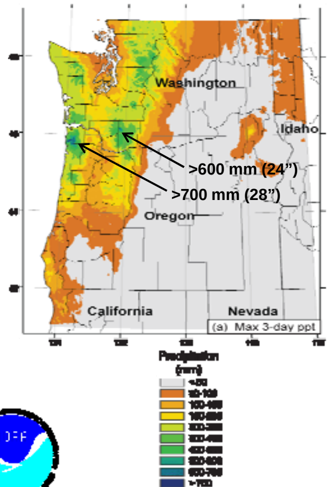


Melting level ~4000 ft (1.2 km) above normal across much of the PacNW during the landfall of this AR

- Reanalysis diagnostics reveal strong horizontal water vapor fluxes in this AR
- IWV & vapor flux anomalies are the largest in PacNW ARs in the last decade

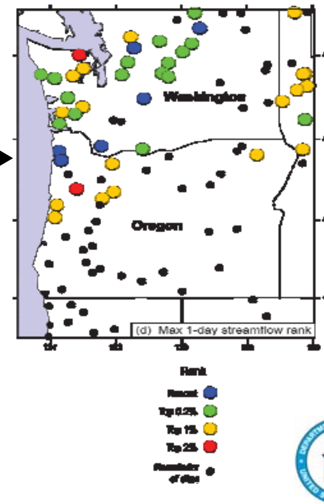
Hydroclimatic analysis for the AR of 5-9 November 2006

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



plus high melting level equals

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

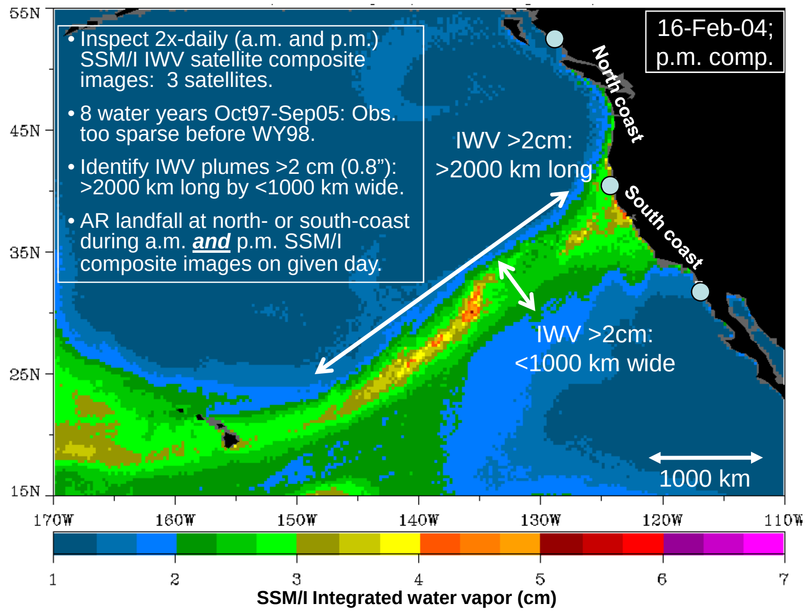


High-Impact Consequences!

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

<u>Given these results:</u> What are the long-term hydrometeorological impacts of landfalling ARs in western North America? Neiman et al. (2008c)

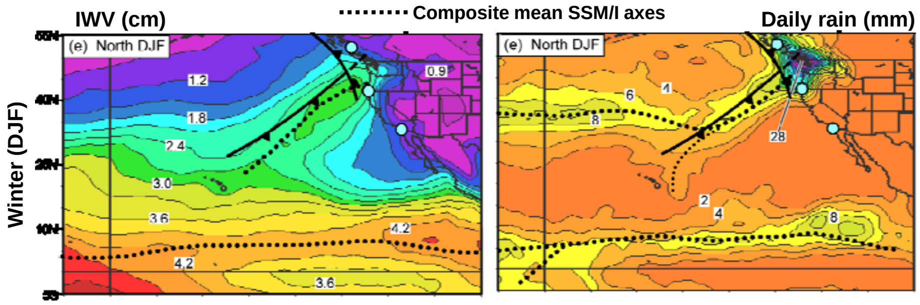
<u>Approach:</u> We developed a methodology for creating a multi-year AR inventory.



- **This methodology allows us to explore seasonal contrasts of ARs with respect to dynamics and overland impacts. (Winter is defined as DJF and summer encompasses JJA.**
- **Winter (DJF): 29 & 35 IWV plumes at N- and S-coasts.**
- **Summer (JJA): 133 & 15 IWV plumes N- and S-coasts.**

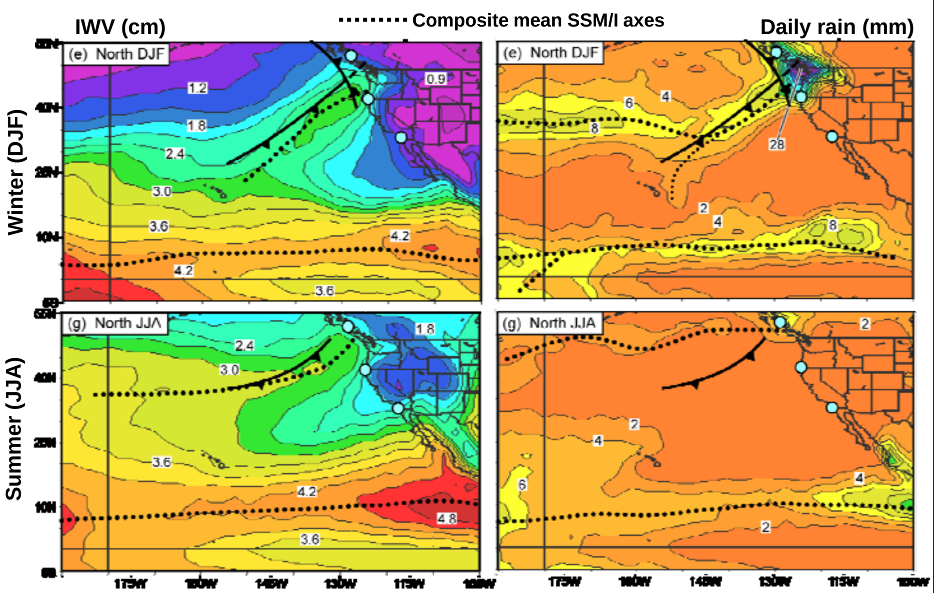
- **The mean large-scale conditions responsible for ARs, and their overland impacts, were gauged by constructing composite synoptic-scale analyses using the daily gridded NCEP–NCAR reanalysis dataset (2.5° x 2.5°; Kalnay et al. 1996).**
- **Daily gridded data for the day of each AR event were included in the synoptic composites.**

Composite Mean Reanalyses – focus on North Coast



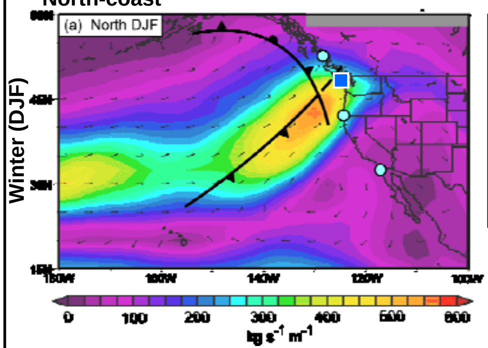
- Composite reanalysis IWV plume oriented SW-NE from the tropical eastern Pacific to the coast.
- Composite plume situated ahead of the polar cold front.
- Wintertime ARs produce copious precip along coast, & frontal precip offshore.
- Reanalysis composites accurately depict the positions of the IWV plume and precip. bands observed by the SSM/I composites... denoted by dotted lines.

Composite Mean Reanalyses – focus on North Coast

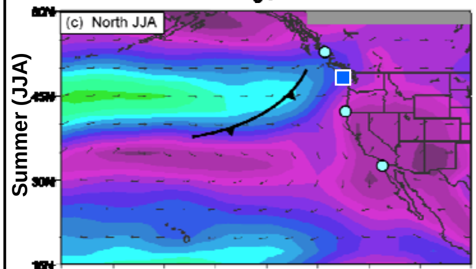


Summer ARs: (1) also tied to cold fronts; (2); zonally oriented; (3) more IWV than winter; (4) much less precip. than winter.

Composite Mean Reanalysis IVT (kg s^{-1} m^{-1}) – North Coast

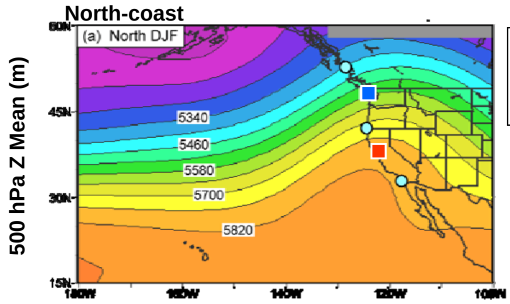


- Strong moisture transport intersected coastlines during winter, with maximum on the warm side of the cold front and vapor fluxes orthogonal to mtns.
- Transport originating from low latitudes.
- Tropical tap.

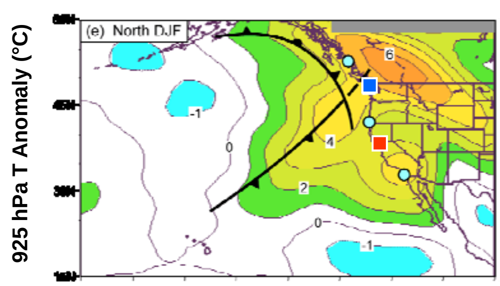


- Weaker flux due to weaker storms w/less wind.
- Zonally oriented rather than meridional.
- No tropical tap.
- Post-frontal rather than prefrontal.

Composite Reanalysis Fields – **Winter only**

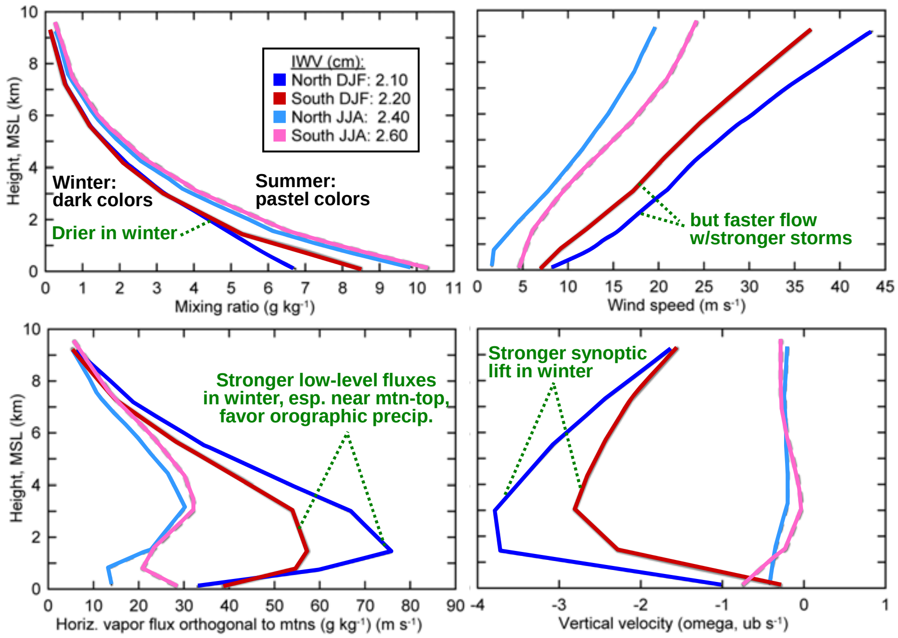


- Wintertime ARs are associated with trough/ridge couplet in the mid-troposphere (~2-6 km MSL).



Wintertime ARs are associated with anomalous warmth at low levels.

Reanalysis Soundings at the Coast : **Winter vs. Summer**

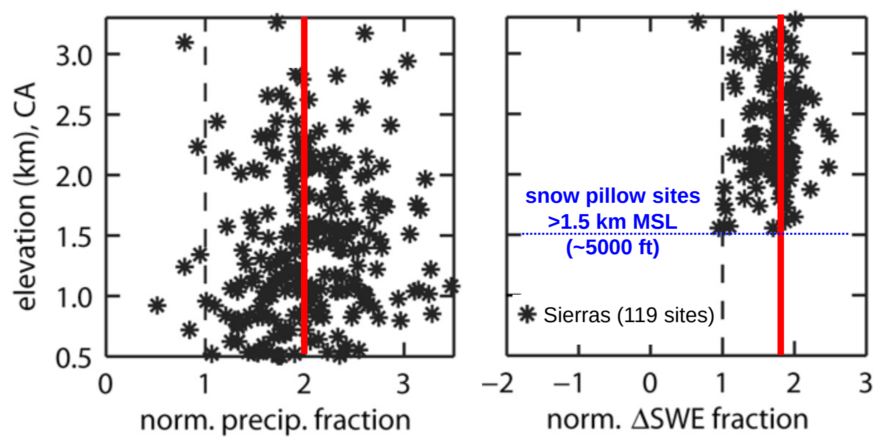


Normalized Daily Precipitation and ΔSWE in CA during DJF

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

2.0x the average precipitation

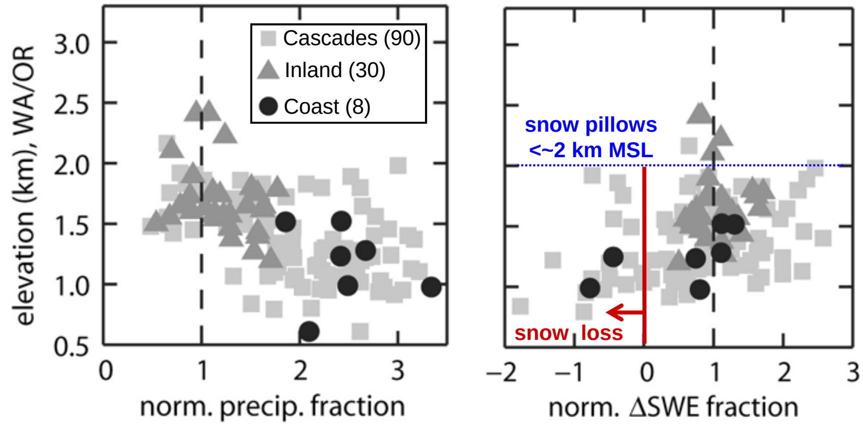
1.8x the average snow accumulation



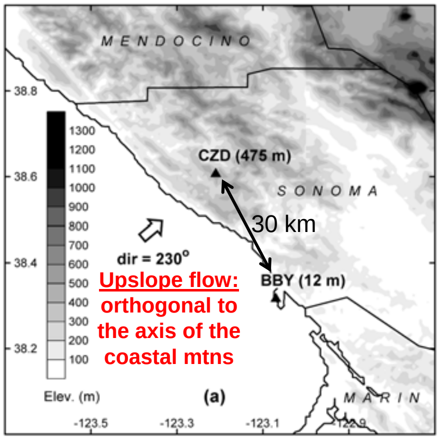
Normalized Precip. and ΔSWE Fractions in OR/WA during DJF

Compared to the average of all precipitation days in the Pacific NW ranges (observed by snow pillows), those days associated with landfalling Atmospheric Rivers produced:

Coast:	2.5x the average precip.	0.5x the average snow accumulation
Cascades:	1.8x the average precip.	1.0x the average snow accumulation
Inland:	1.1x the average precip.	1.0x the average snow accumulation



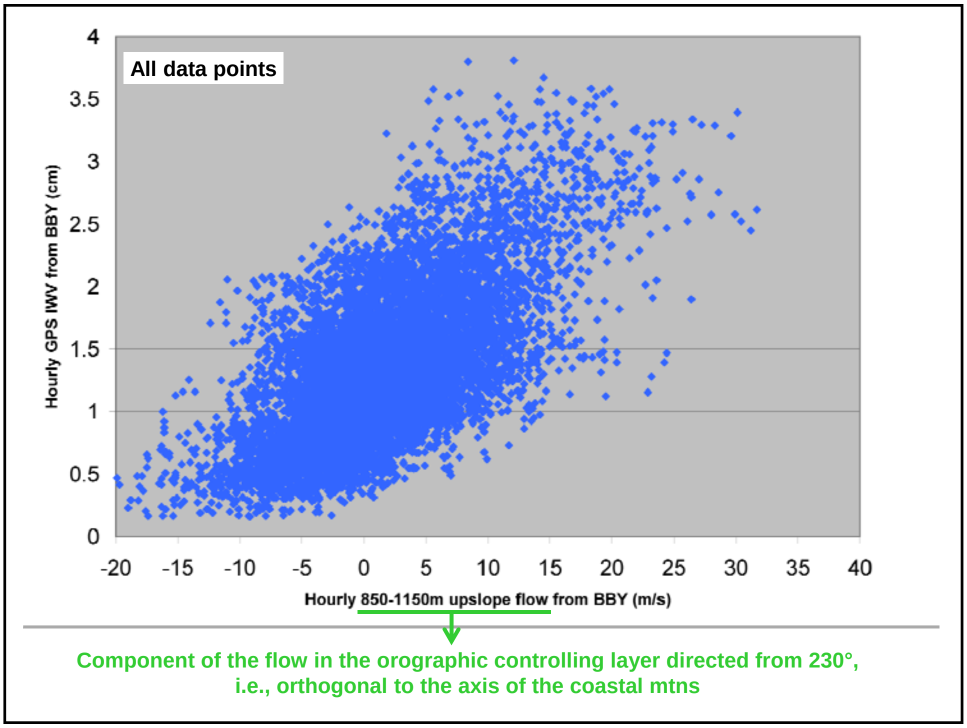
Four-winter study along northern California coast

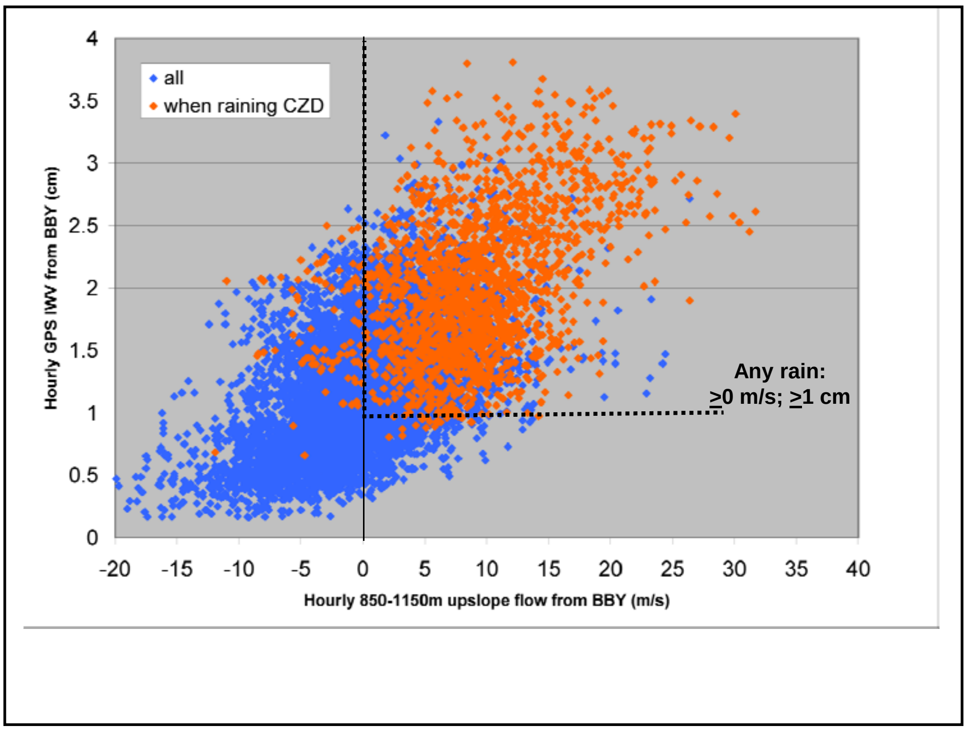


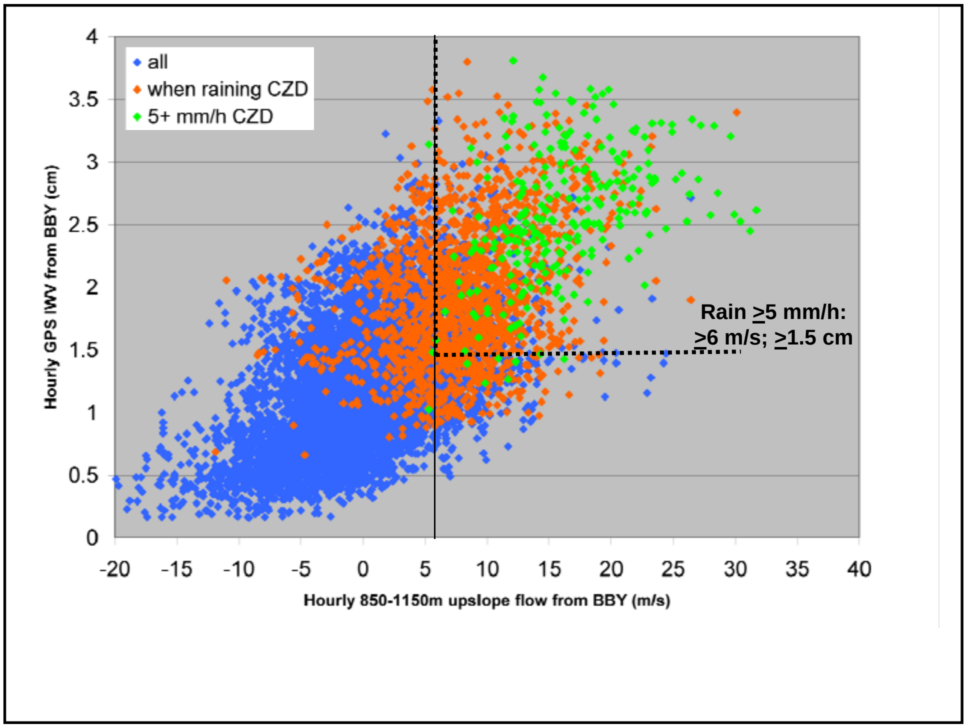
Neiman et al. (2002), *MWR*

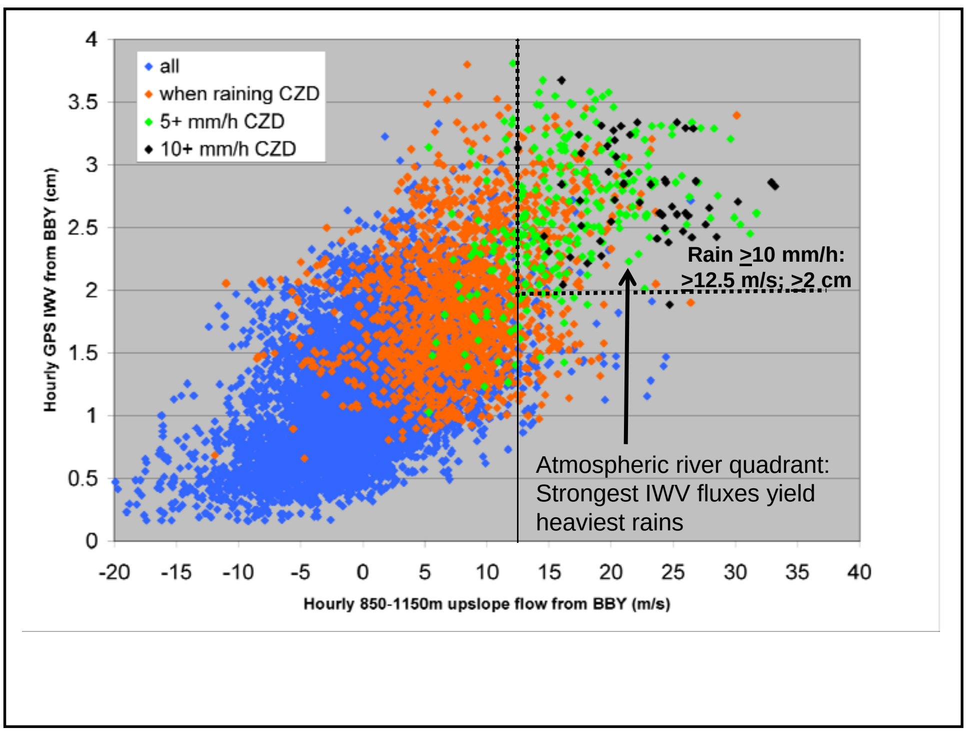
- Flood-prone Russian River Basin northwest of San Francisco: 2000/01, 2003/04, 2004/05, 2005/06
- Analyses for when the following observing systems were simultaneously operating –
  (a) Bodega Bay (BBY): GPS-IWV unit, 915-MHz wind profiler, S-band radar, rain gauge (b) Cazadero (CZD): rain gauge
- Total rainfall: CZD = 4217 mm, BBY = 2016 mm
- 9548 hourly data points

Neiman et al. (2008a), *Water Management*

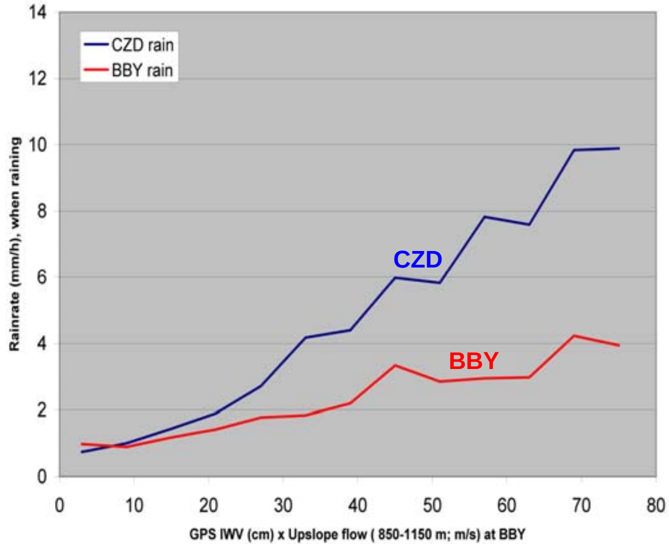

All data points
Hourly GPS IWV from BBY (cm)
Hourly 850-1150m upslope flow from BBY (m/s)
Component of the flow in the orographic controlling layer directed from 230°,
i.e., orthogonal to the axis of the coastal mtns


all
when raining CZD
Any rain:
≥0 m/s; ≥1 cm
Hourly GPS IWV from BBY (cm)
Hourly 850-1150m upslope flow from BBY (m/s)


all
when raining CZD
5+ mm/h CZD
Rain ≥5 mm/h:
≥6 m/s; ≥1.5 cm
Hourly GPS IWV from BBY (cm)
Hourly 850-1150m upslope flow from BBY (m/s)


all
when raining CZD
5+ mm/h CZD
10+ mm/h CZD
Rain ≥10 mm/h:
≥12.5 m/s; ≥2 cm
Atmospheric river quadrant:
Strongest IWV fluxes yield
heaviest rains
Hourly GPS IWV from BBY (cm)
Hourly 850-1150m upslope flow from BBY (m/s)

Bulk Upslope IWV Flux vs. Rainrate

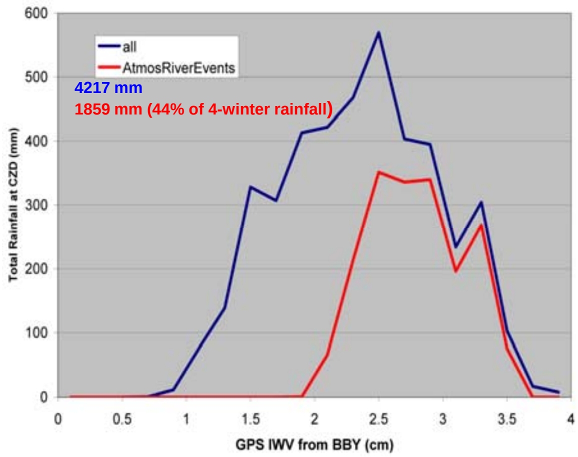


Rainrate and orographic rain enhancement at CZD increases with increasing bulk upslope IWV flux,

i.e., with strengthening AR conditions

<u>AR criteria for case selection:</u>

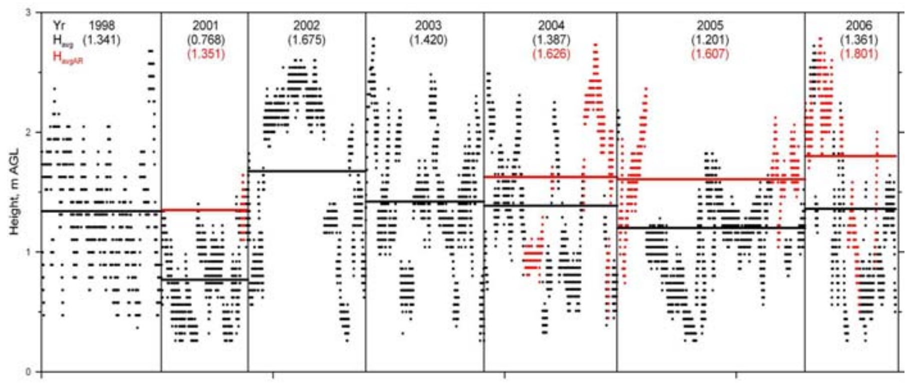
- IWV plumes ≥2 cm tagged by SSM/I satellites (as in Ralph et al. 2004) crossing BBY.
- GPS IWV ≥2 cm at BBY for at least 8 consecutive hours.
- Wind speed ≥13 m s^{-1} (~29 mph) at controlling layer (850-1150 m MSL) at BBY.



<u>Results:</u>

- 31 AR events with 1859 mm of rain in 386 h.
- ARs produced 44% of the observed rainfall in only 21% of the time it rained.
- Bulk Rainrate: 4.82 mm h^{-1} for AR events and 2.28 mm h^{-1} for all rainfall.
- 87% of the 54 hours with rainfall ≥10 mm/h fell during ARs.

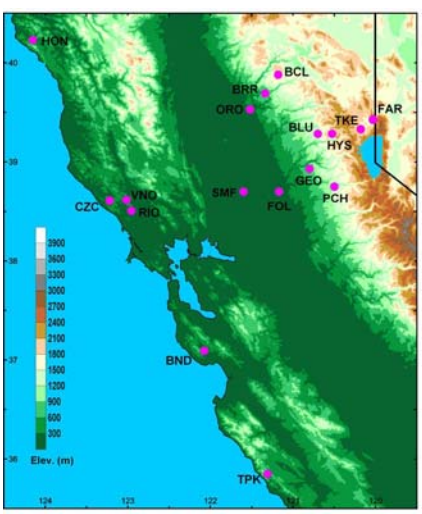
Snow levels measured by the S-band radar at CZD during the 4 winters averaged 421 m (1380 ft) higher in AR conditions:
Warm conditions & more rain = increased flooding



Assess Forecasting Challenges of ARs

Hydromet. Test-bed (HMT) 2006 QPF Verification Pilot Study

Objective: Preliminary evaluation of QPF performance for HMT's IOPs



Methodology

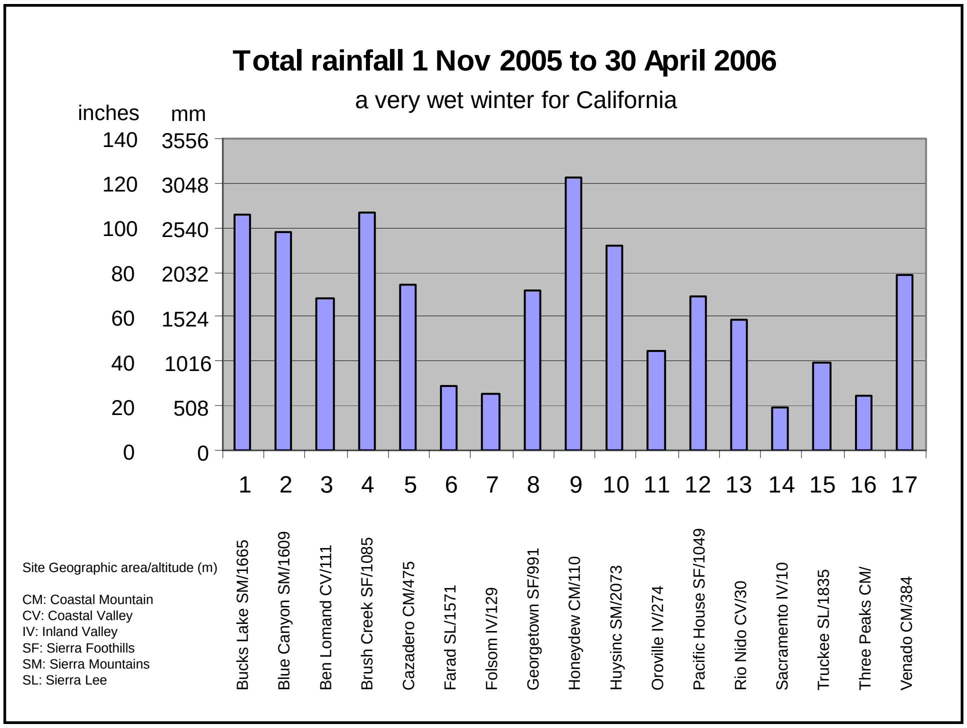
Focused on 17 verification points covering a range of geographic conditions in California.

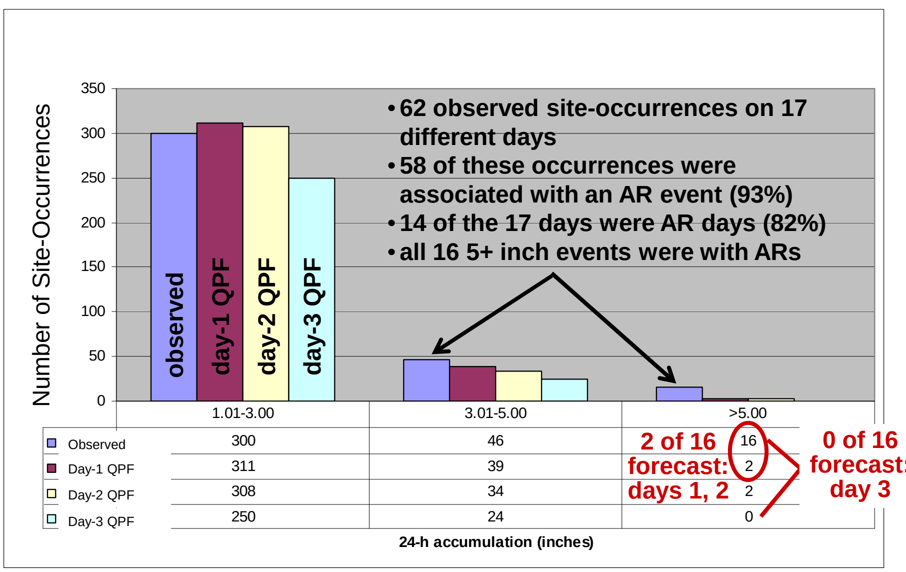
NCEP/HPC's NPVU verification data (4 km resolution) were used, which represent a slightly broader spatial scale than simply point data.

HPC's QPFs (32 km resolution) were archived daily for each site from 1-Nov-2005 to 30-Apr-2006, from 12 UTC to 12 UTC.

The QPFs were archived for Days 1, 2, & 3.

Input from Wes Junker (HPC), Dave Reynolds (WFO)



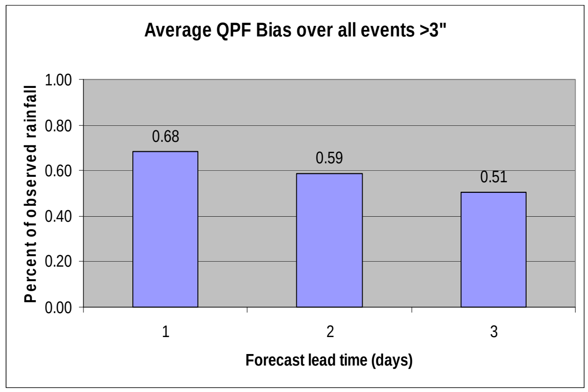


- Modest precip events (<3"/day): Best QPF performance days 1 and 2
- Heavy precip events (3-5"/day): Significantly under-forecast
- Extreme precip events (>5"/day): Practically un-forecasted

Average forecast biases in events >3”

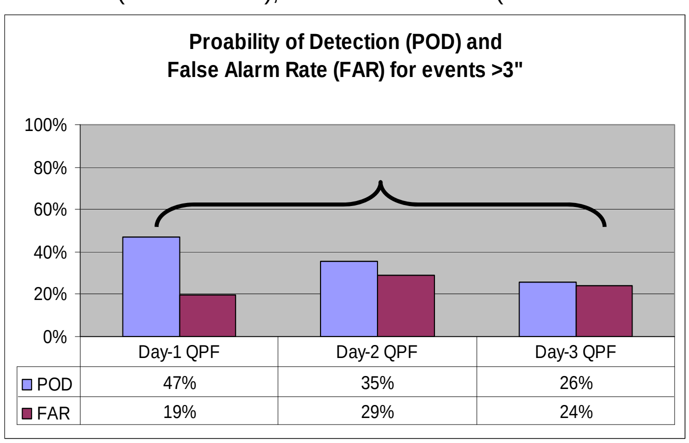
(62 observed site-occurrences)

	Mean of 17 dates	% of observed
Observed	3.58	
Day-1 QPF	2.44	0.68
Day-2 QPF	2.10	0.59
Day-3 QPF	1.81	0.51



POD & FAR for events >3 inches (62 observed site-occurrences)

POD = hits/(hits + misses); FAR = false alarms/(hits + false alarms)

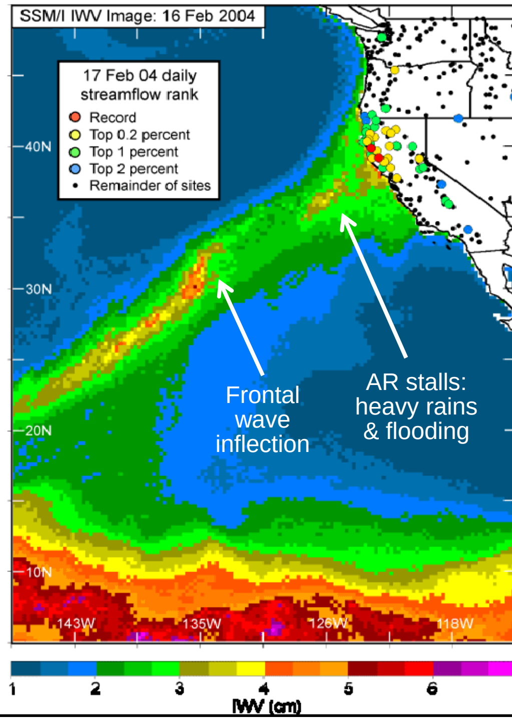


The best forecast for events >3” is at Day-1, where the POD is nearly 50% and the FAR <20%. By Day-3, POD has dropped to ~25%, and is nearly equal to the FAR.

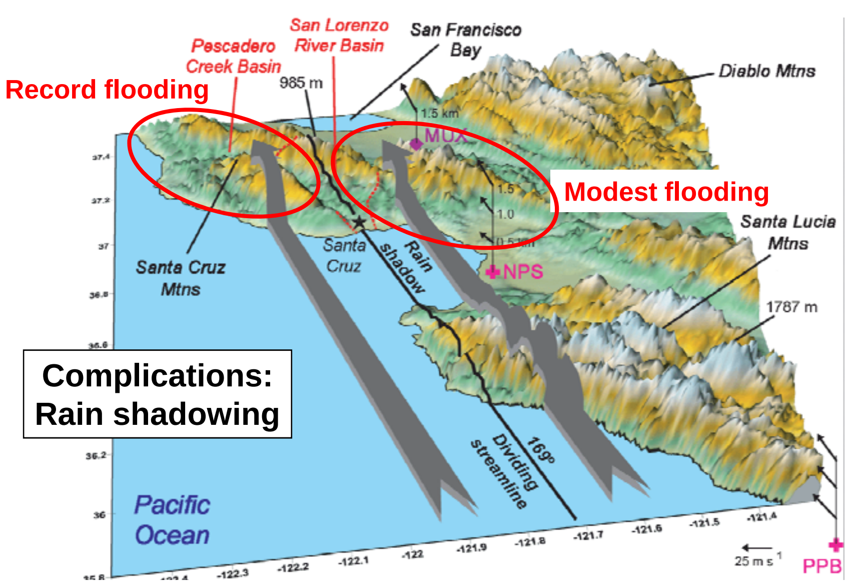
Bottom line: forecasts missed and falsely predicted many large precip. events

✓Forecast accuracy in the heaviest events is of most importance to flood control
✓Reservoir operators are most affected by these strong events
✓There is a perception that the heaviest events are predicted rather well, partly due to the orographic nature of the storms – ***not true!*** ***Why not?***

Complications: Mesoscale Frontal waves
(Ralph et al. 2006)



Complications: Rain shadowing



When atmospheric rivers strike coastal mountains (Ralph et al. 2003)

- Air ascends coastal mountains, water vapor condenses, heavy rainfall occurs
- Details of the atmospheric river determine which watersheds flood

Concluding Remarks

- Atmospheric rivers (ARs) are long and narrow corridors of enhanced water vapor transport responsible for most of the poleward transport of vapor 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 and unusually high melting levels.
- ARs play a critical role in transporting water vapor from the eastern Pacific to western North America (esp. during the cool season), resulting in significant orographic precipitation that not only generates devastating flooding but also replenishes snowpacks and reservoirs across parts of the semi-arid West.
- Because ARs contribute significantly to precipitation, snowpack modulation, and flooding in western North America, they represent a key phenomenon linking weather and climate.
- Heavy precipitation and flooding associated with ARs are often challenging to forecast despite the orographic character of the precip., because superimposed mesoscale processes (i.e., frontal waves, local rain shadowing) decrease the predictability.

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