

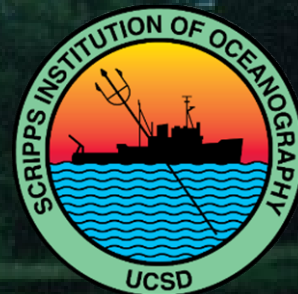
Atmospheric Rivers: Western U.S. Rainmakers and Key to Forecast-Informed Reservoir Operations

F. Martin Ralph

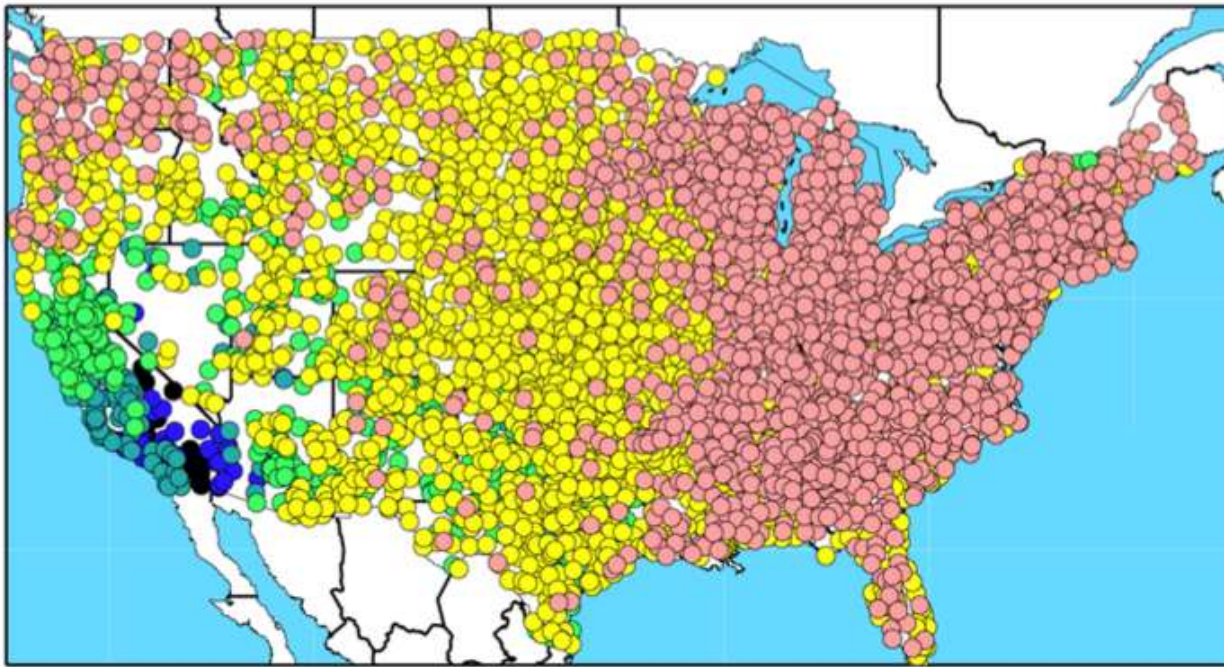
UC San Diego/Scripps Institution of Oceanography

A New Frontier in Water Operations:

Atmospheric Rivers, Subseasonal-to-Seasonal Predictions and Weather Forecasting Technology
Congressional Briefing, Washington DC, 13 July 2016,



Variability of Annual Precipitation



Dettinger et al. 2011

fraction



Coefficient of variation for annual precipitation 1950-2008

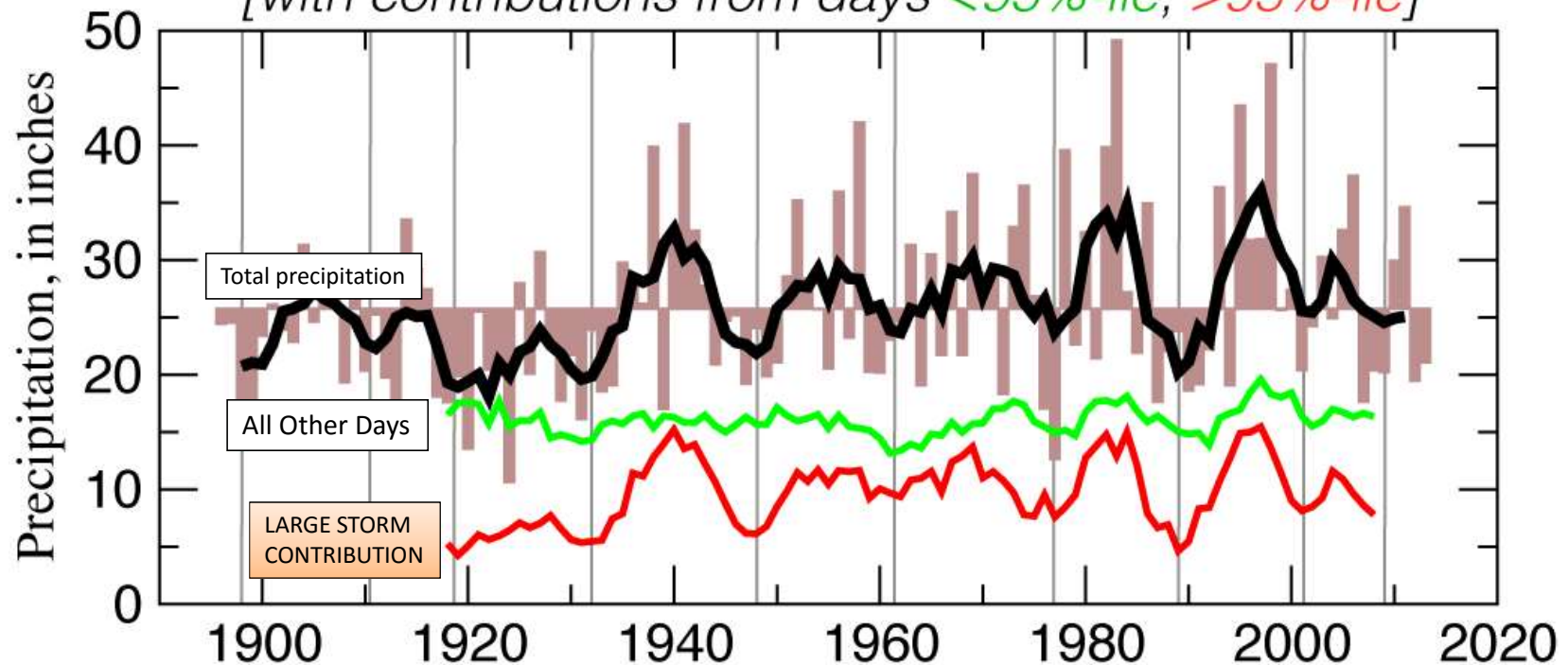
- CA has the largest year to year precipitation variability in the US.
- CA variability is on the order of half the annual average.
- The year to year variability in CA is largely caused by the wettest days (ARs).

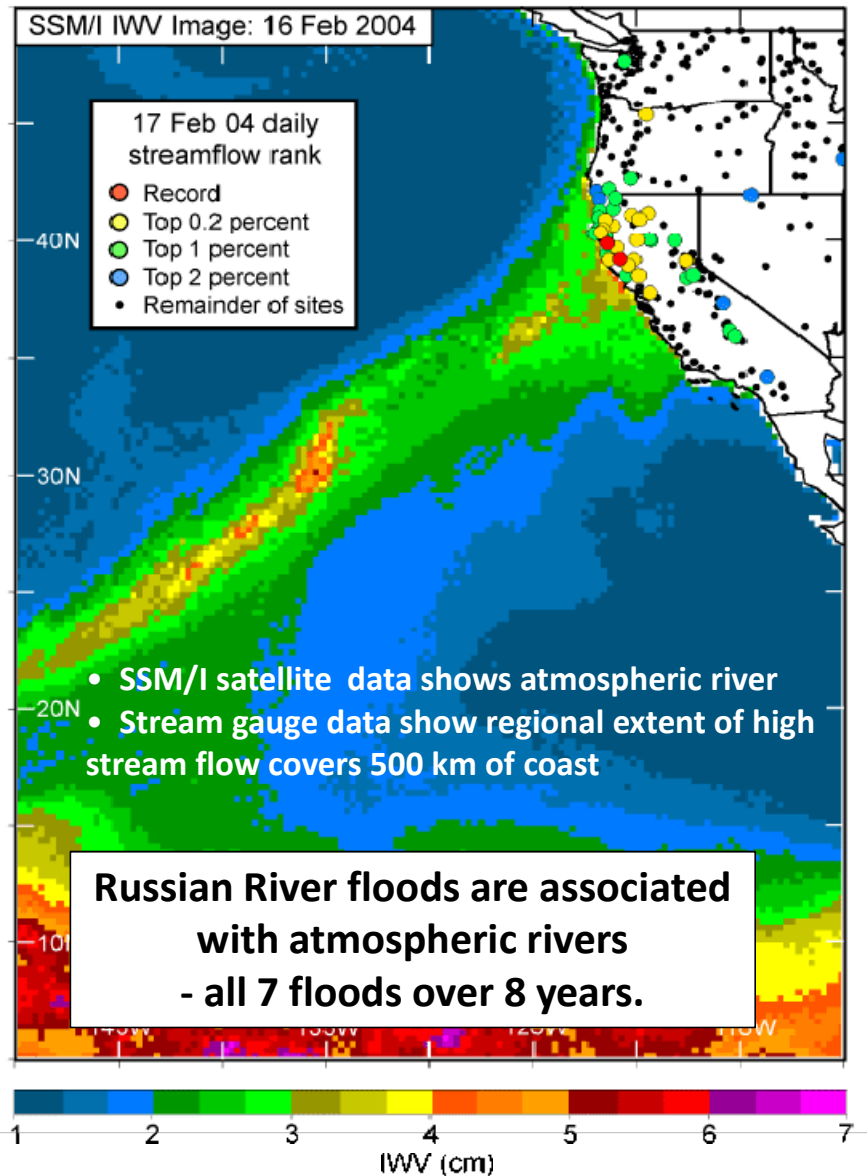
A few large storms (or their absence)

account for a disproportionate amount of California's precipitation variability

a) Water-Year Precipitation, Delta Catchment

[with contributions from days <95%-ile, >95%-ile]





Flooding on California's Russian River: Role of atmospheric rivers

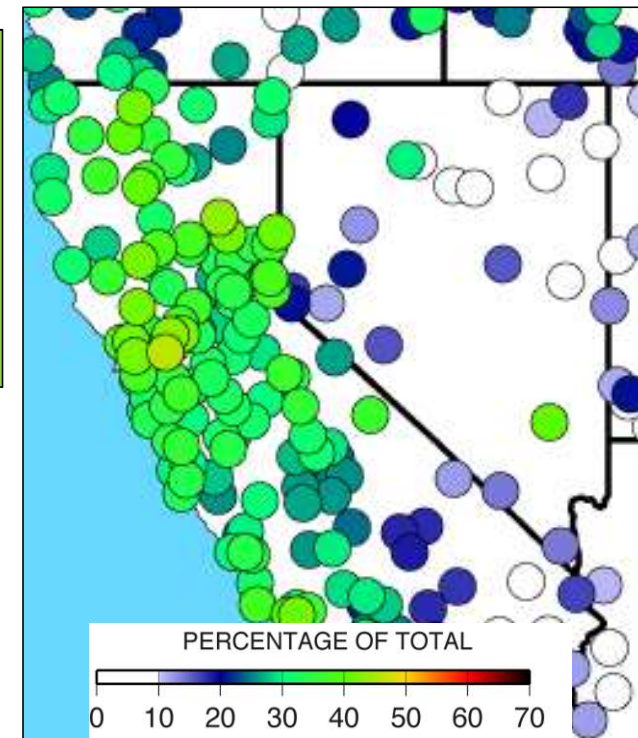
Ralph, F.M., P. J. Neiman, G. A. Wick, S. I. Gutman, M. D. Dettinger, D. R. Cayan, A. White (*Geophys. Res. Lett.*, 2006)



**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)



Rivers in the Sky

An atmospheric river is a narrow conveyor belt of vapor that extends thousands of miles from out at sea, carrying as much water as 15 Mississippi Rivers. It strikes as a series of storms that arrive for days or weeks on end. Each storm can dump inches of rain or feet of snow.

Orientation

If a river strikes perpendicular to a mountain range, much of the vapor condenses out. If it strikes at an angle (shown), a "barrier jet" can be created that flows along the range, redistributing precipitation on the mountainside.

Barrier jet

Buoyancy

The warm, moist air mass easily rises up and over a mountain range; as it does, the air cools and moisture condenses into abundant rain or snow. The river eventually decays into random local storms.

Origin

Atmospheric rivers usually approach California from the southwest, bringing warm, moist air from the tropics.

Duration

A megastorm can last up to 40 days and meander down the coastline. Smaller rivers that arrive each year typically last two to three days; "pineapple expresses" come straight from the Hawaii region.

Atmospheric river

Precipitation

Several inches of rain or feet of snow can fall underneath an atmospheric river each day. Moderate storms can bring more than 15 inches of rain.

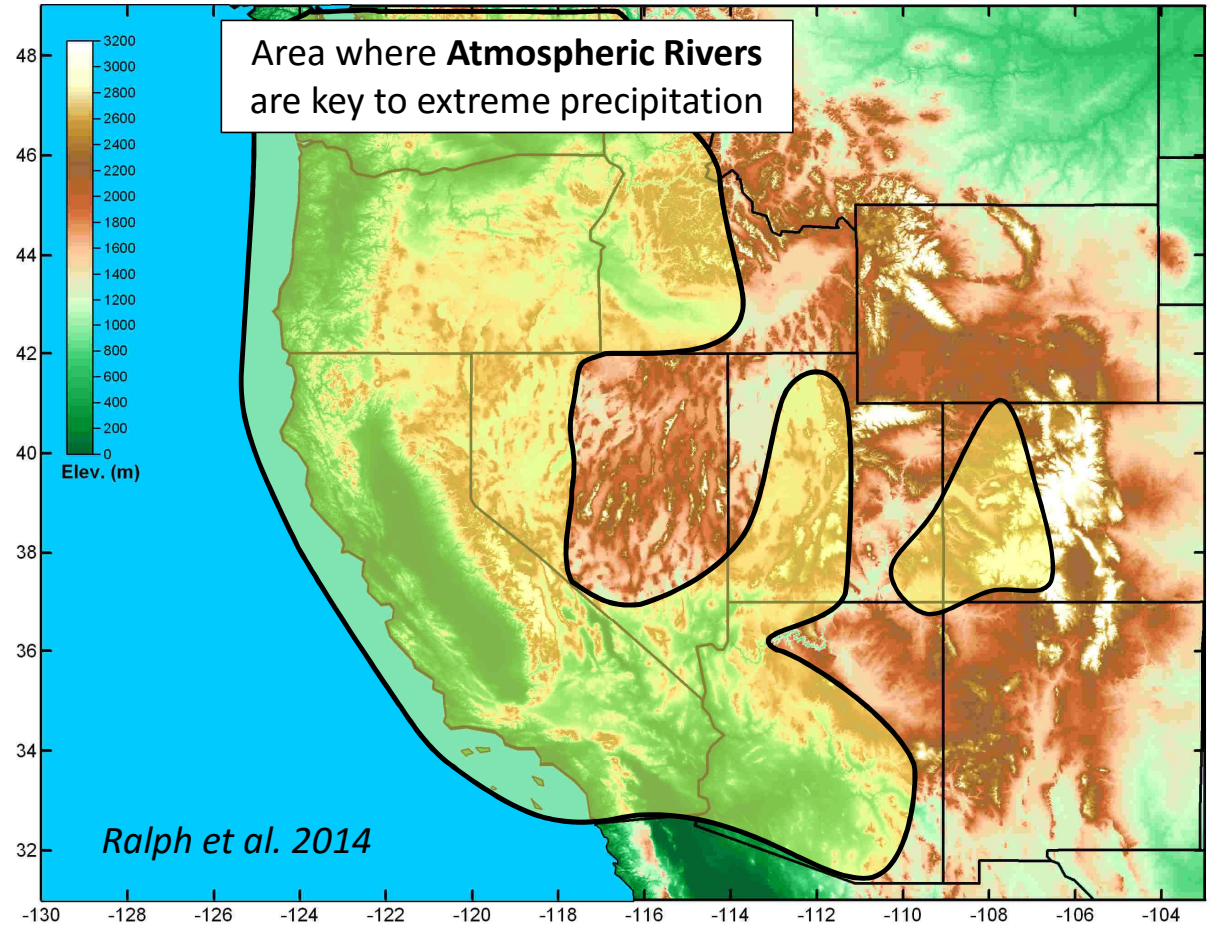
Vapor Transport

Moisture is concentrated in a layer 0.5 to 1.0 mile above the ocean. Strong winds within the layer bring very humid air from the tropics, but the river can also pull in atmospheric moisture along its path.

Dettinger and Ingram 2013

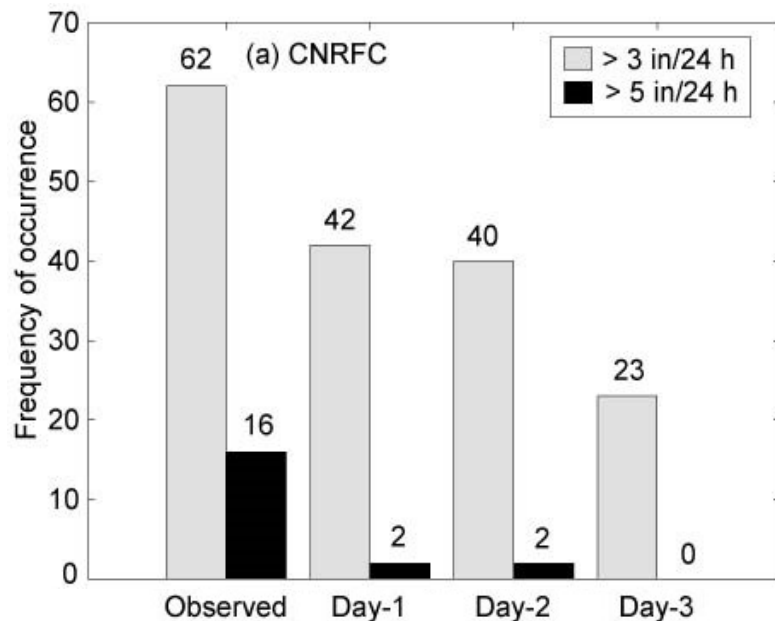
Not to scale

Area where **Atmospheric Rivers** are key to extreme precipitation



The Forecasting Challenge

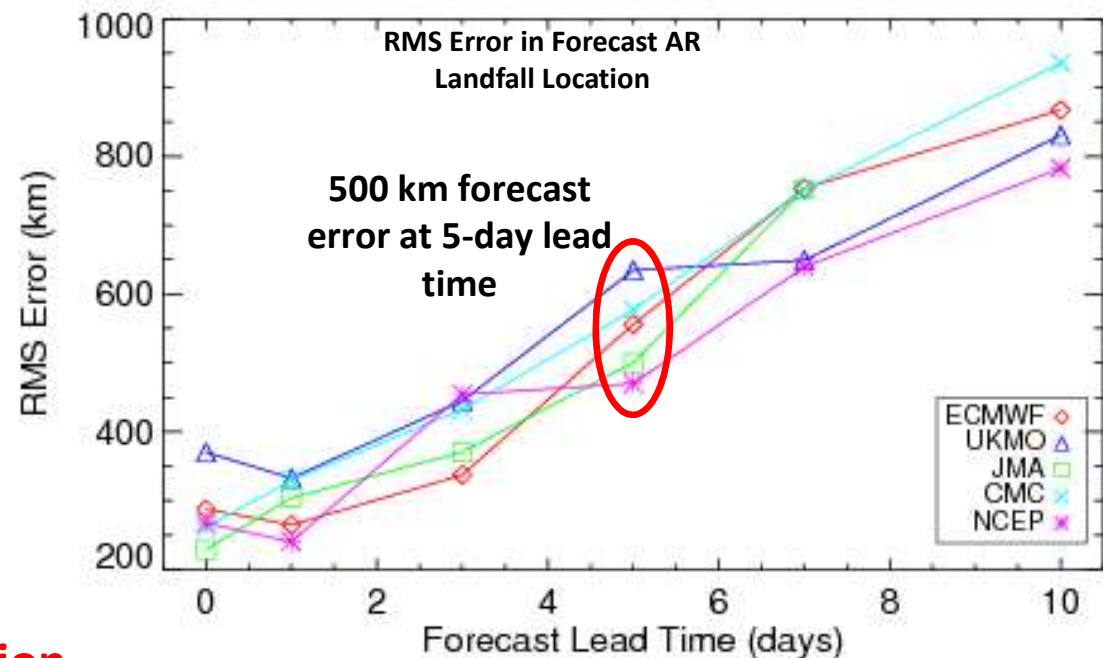
Forecasting large precipitation amounts is difficult



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

Frontal Waves:

A Key Source of Forecast Error

Ralph et al. 2016 (Bull. Amer. Meteor. Soc.)

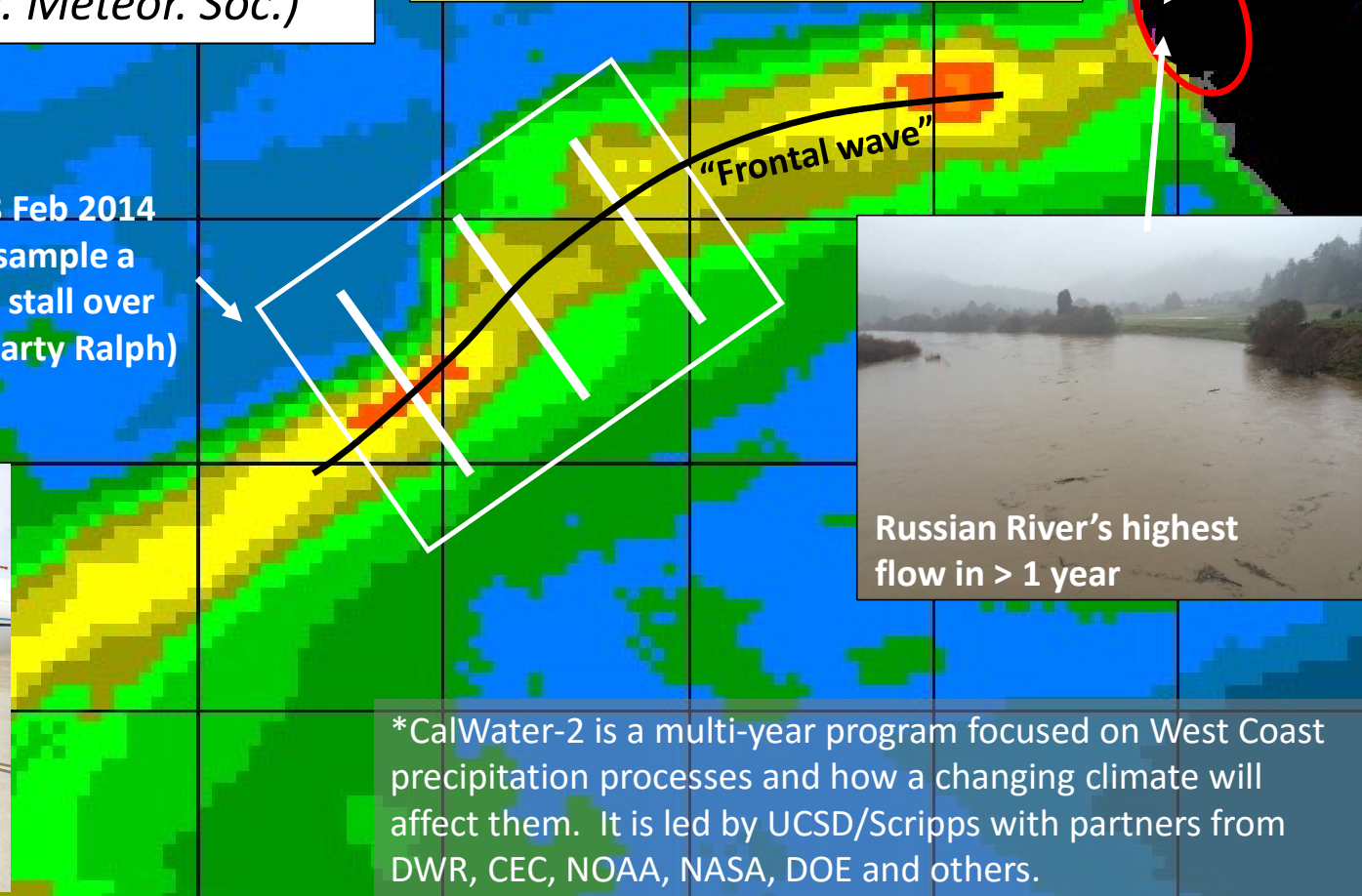
This AR increased precipitation-to-date from 16% to 40% of normal in < 4 days in key Northern California watersheds, but runoff was muted due to dry soils.

Up to > 12 inches of rain – some drought relief

Flight area for NOAA's G-IV aircraft on 8 Feb 2014
Goal: developing AR flight method to sample a "frontal wave" that can cause an AR to stall over one area at landfall (Mission Scientist: Marty Ralph)



SSM/I satellite observations of water vapor on 8 Feb 2014 (Courtesy G. Wick, NOAA)



C-130 Atmospheric River Reconnaissance in February 2016

A joint effort of Scripps/CW3E, NOAA/NWS, Air Force

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

C-130
C-130

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

Observed IWV from SSIM/I
Satellite passes from 13 Z 13 – 01 Z 14 Feb
Showing atmospheric river signature
Satellite image from NOAA/ESRL/PSD

1st C-130 AR Recon Mission

13-14 Feb 2016

Dropsondes released for the
0000 UTC 14 Feb 2016
GFS data assimilation window

14 Feb 2016

△ NOAA9
△ NA872
△ AF302
△ AF309
△ Other

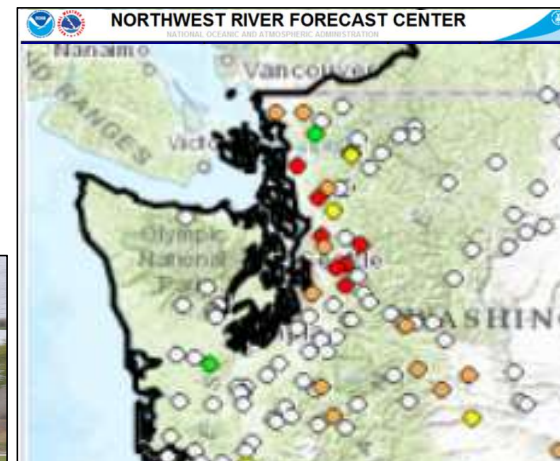
Locations of C-130 AR Recon
dropsondes received and
successfully decoded into NCEP's
production bufr data tanks for
assimilation into NCEP/GFS



Air Force C-130 Aircraft – Weather Recon' Squadron



Center for Western Weather
and Water Extremes

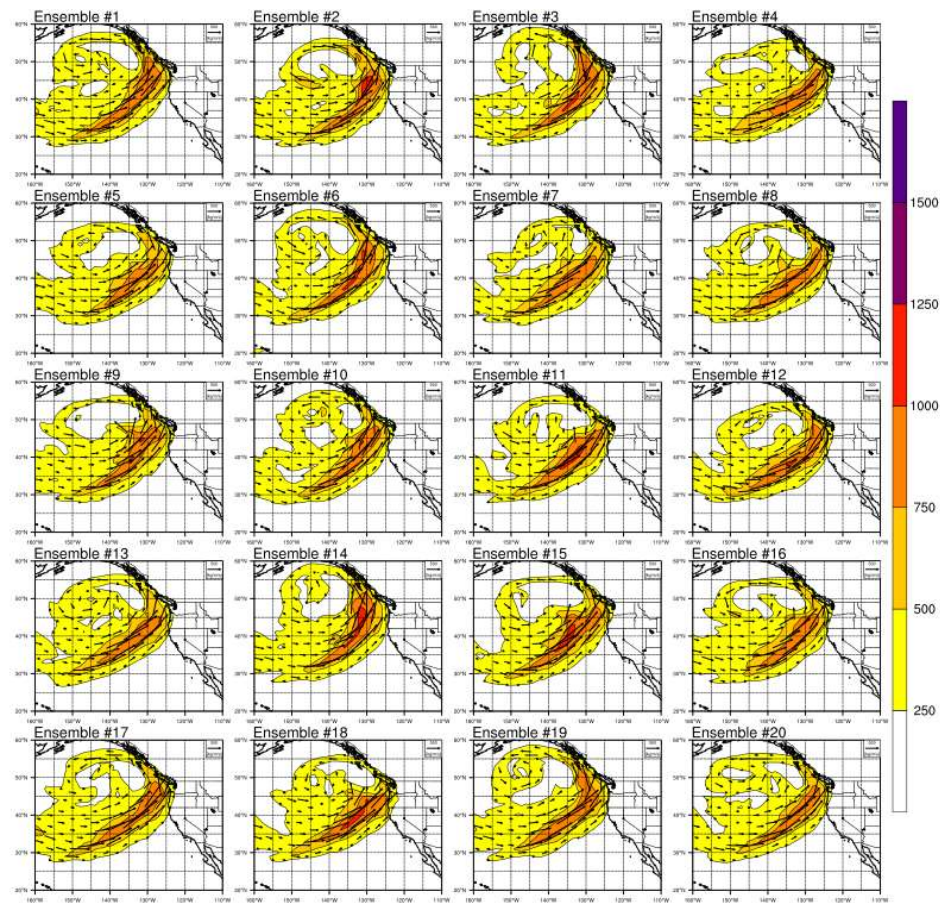


NWRFC flood forecast map as
of 1500 UTC 15 Feb showing
several rivers predicted to
reach flood stage on 15-16
Feb (red dots)

“Ensemble” prediction of ARs

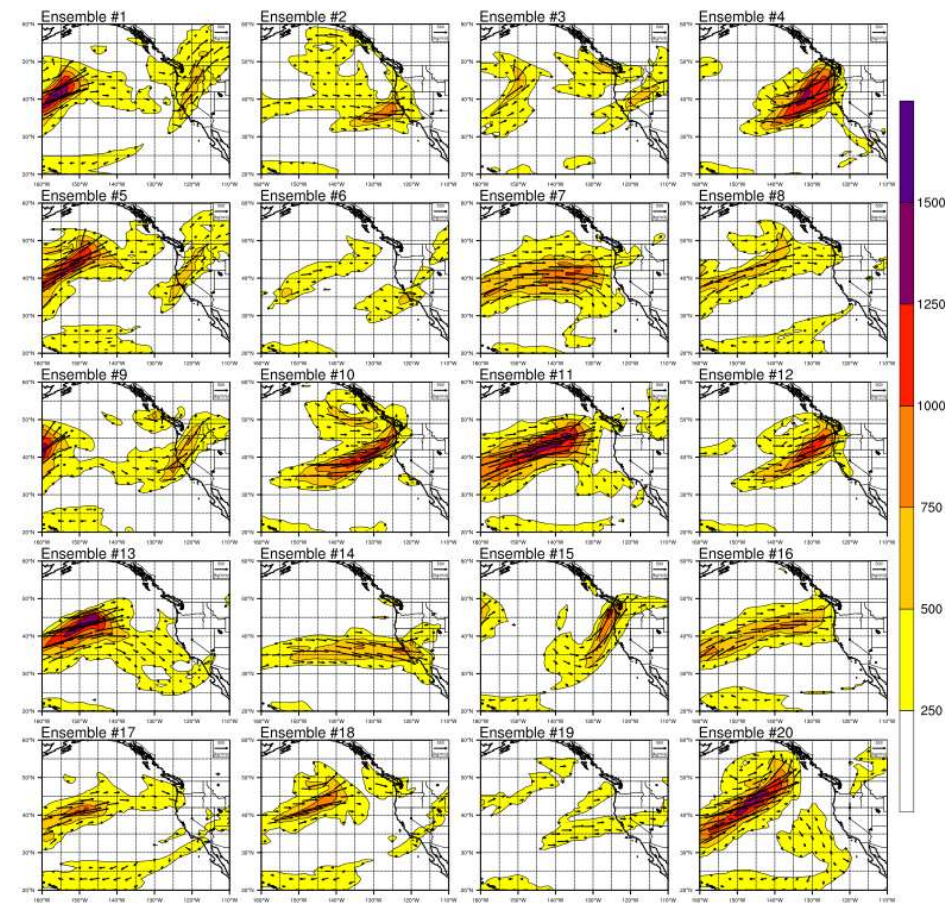
3-days lead time

GFS Ensemble IVT (kg/m/s) valid 12Z Sat 12/05/15 | F+72h



8-days lead time

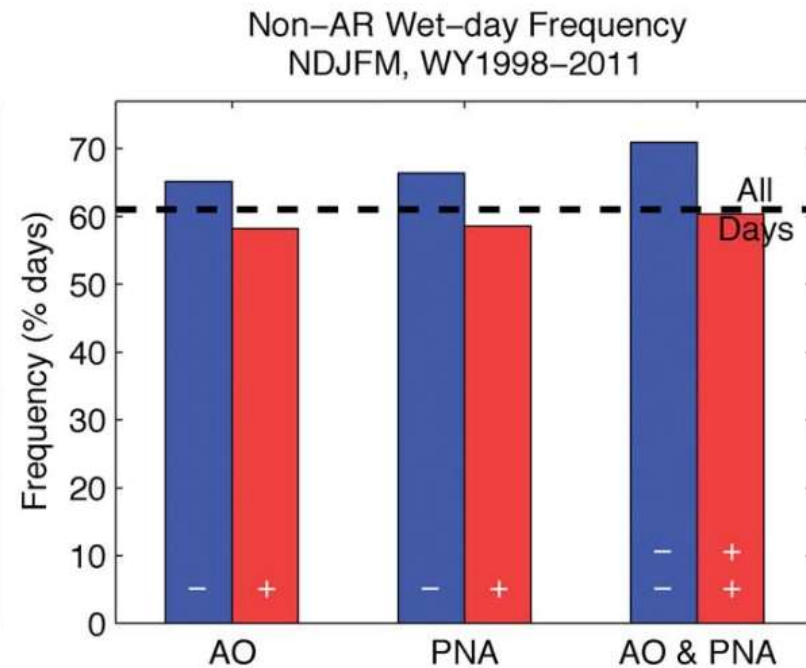
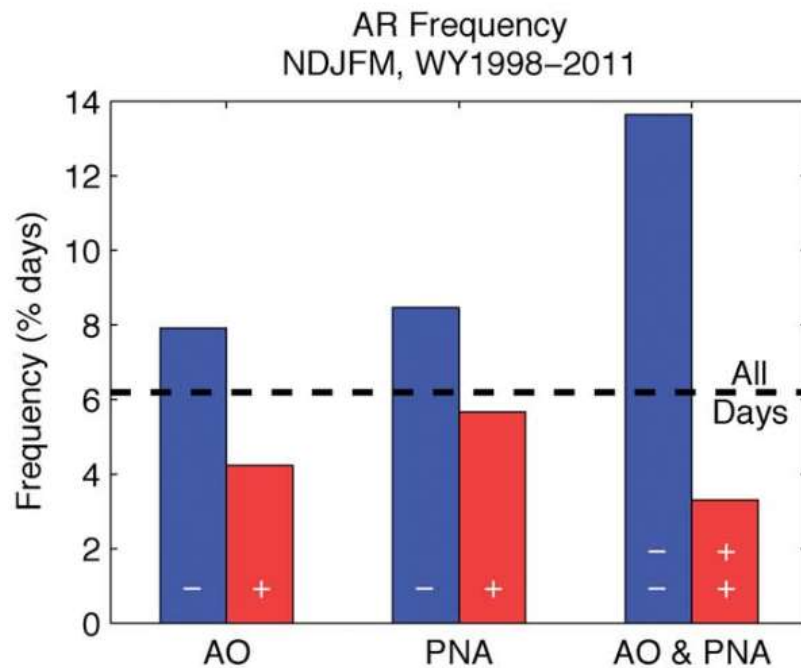
GFS Ensemble IVT (kg/m/s) valid 12Z Thu 12/10/15 | F+192h



The 2010/2011 snow season in California's Sierra Nevada: Role of atmospheric rivers and modes of large-scale variability

Guan, B., N.P. Molotch, D. E. Waliser, E. Fetzer and P.J. Neiman
Water Resources Research (2013)

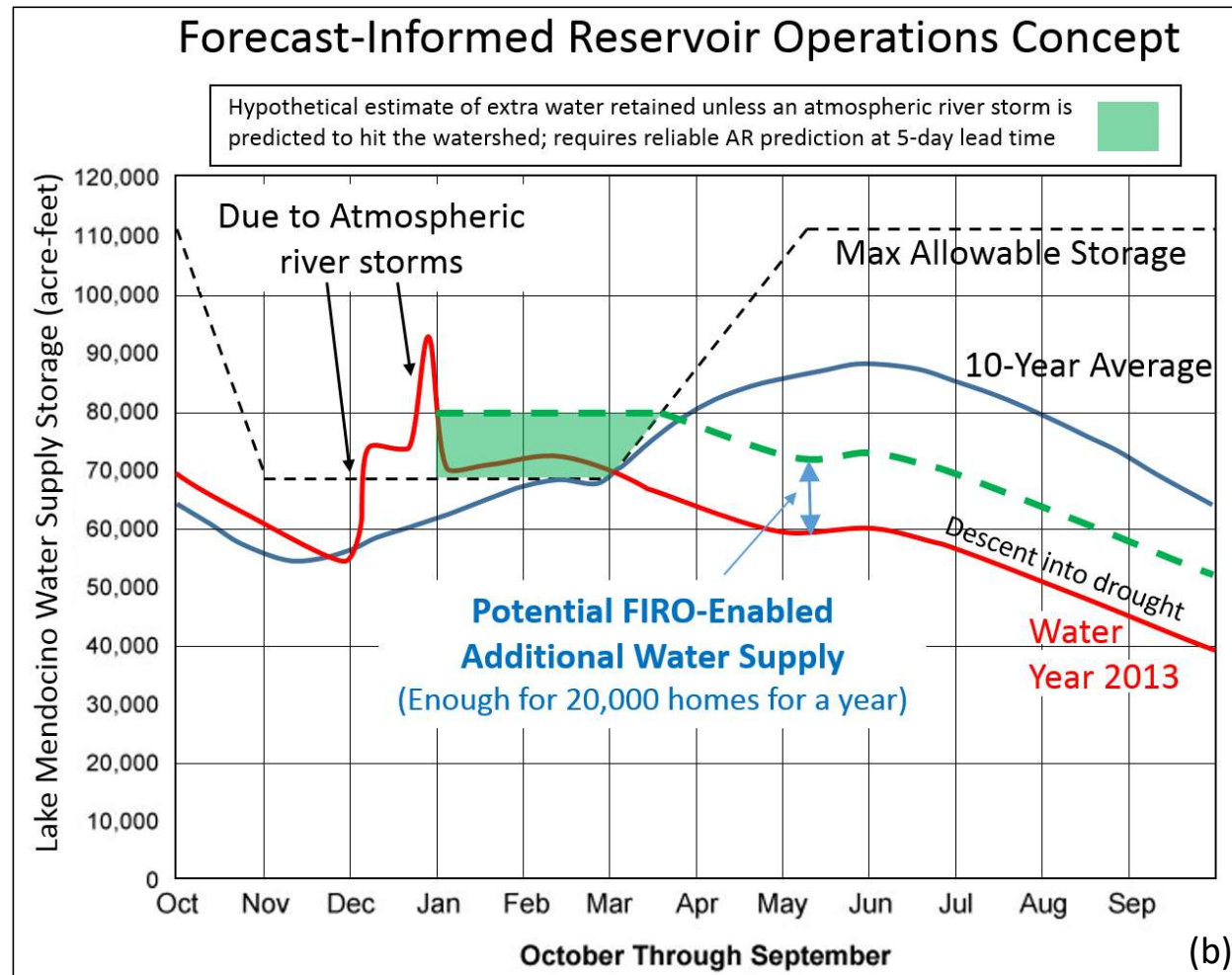
Arctic Oscillation (negative, i.e., southward cold-air outbreaks) combined with Pacific North American “teleconnections” pattern (negative, southern storm track). Favors Atmospheric river conditions striking the Sierra and causing precipitation





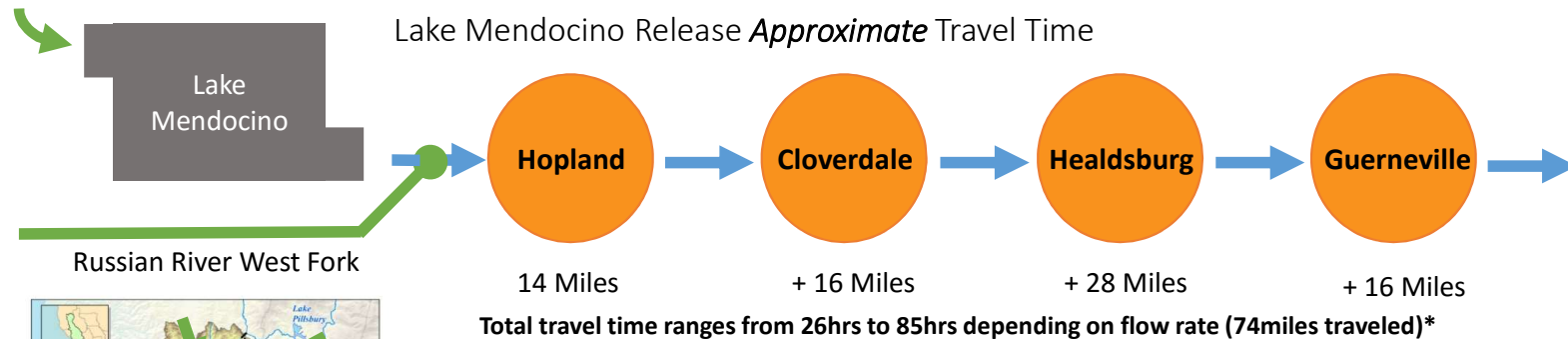
**Thank
you!**

Backup



How much forecast lead time is required to enable FIRO on Lake Mendocino?

10,000 AF could be released at 2500 cfs, which would take **2 days**



Bottom Line: It takes 2 days to release 10,000 AF at 2500 cfs, plus 1.1 to 3.5 days for water released from Lake Mendocino to get past vulnerable communities downstream. In situations this would be needed, travel times will be on the short end of range.

- This sets a forecast lead time requirement of 3-5 days to predict landfalling atmospheric rivers.

*Uses information from Coyote Valley Dam and Lake Mendocino Water Control Manual (1986)

Lake Mendocino in Sonoma County – Drought July 2014

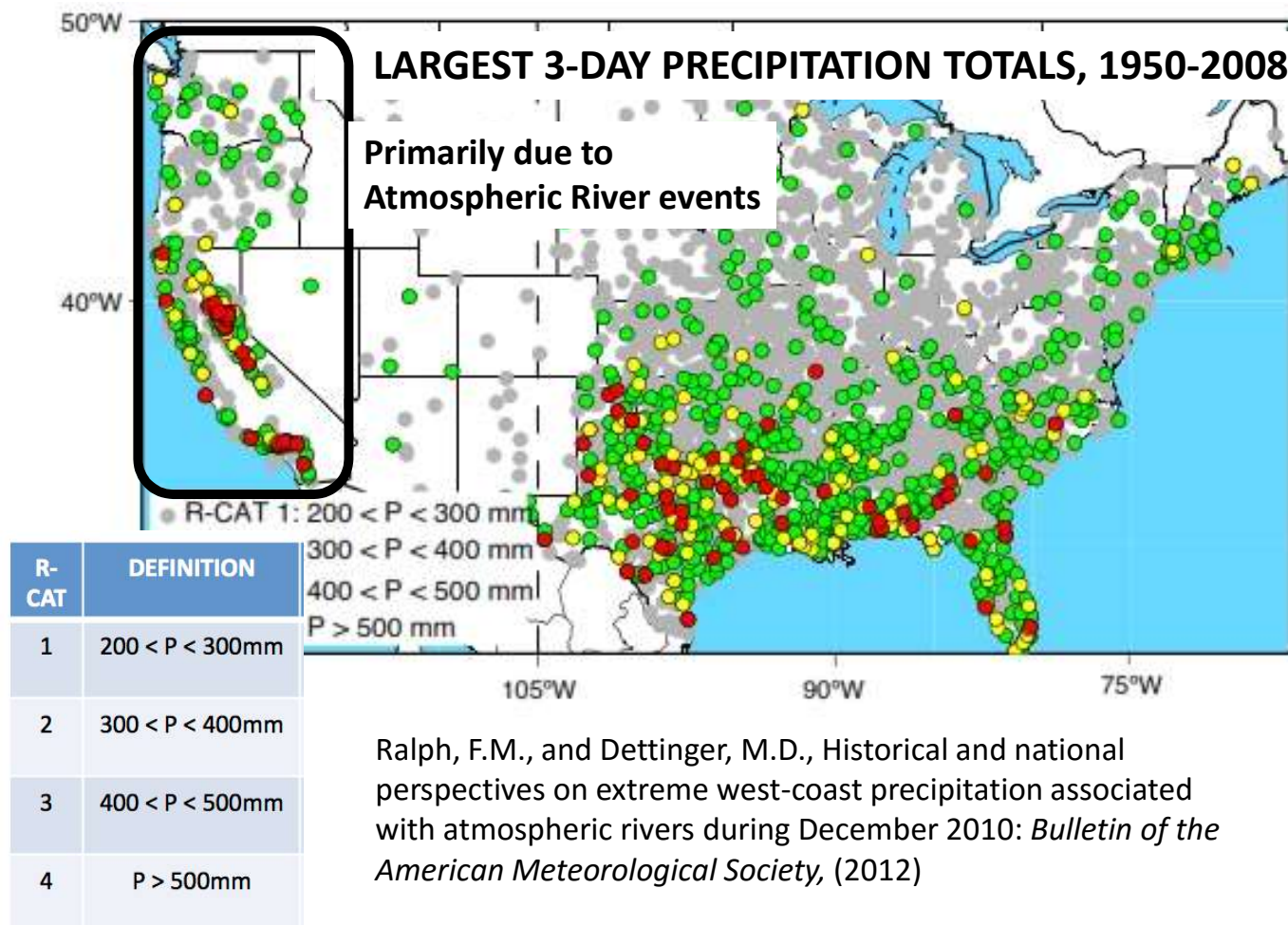


Lake Mendocino, July 2014

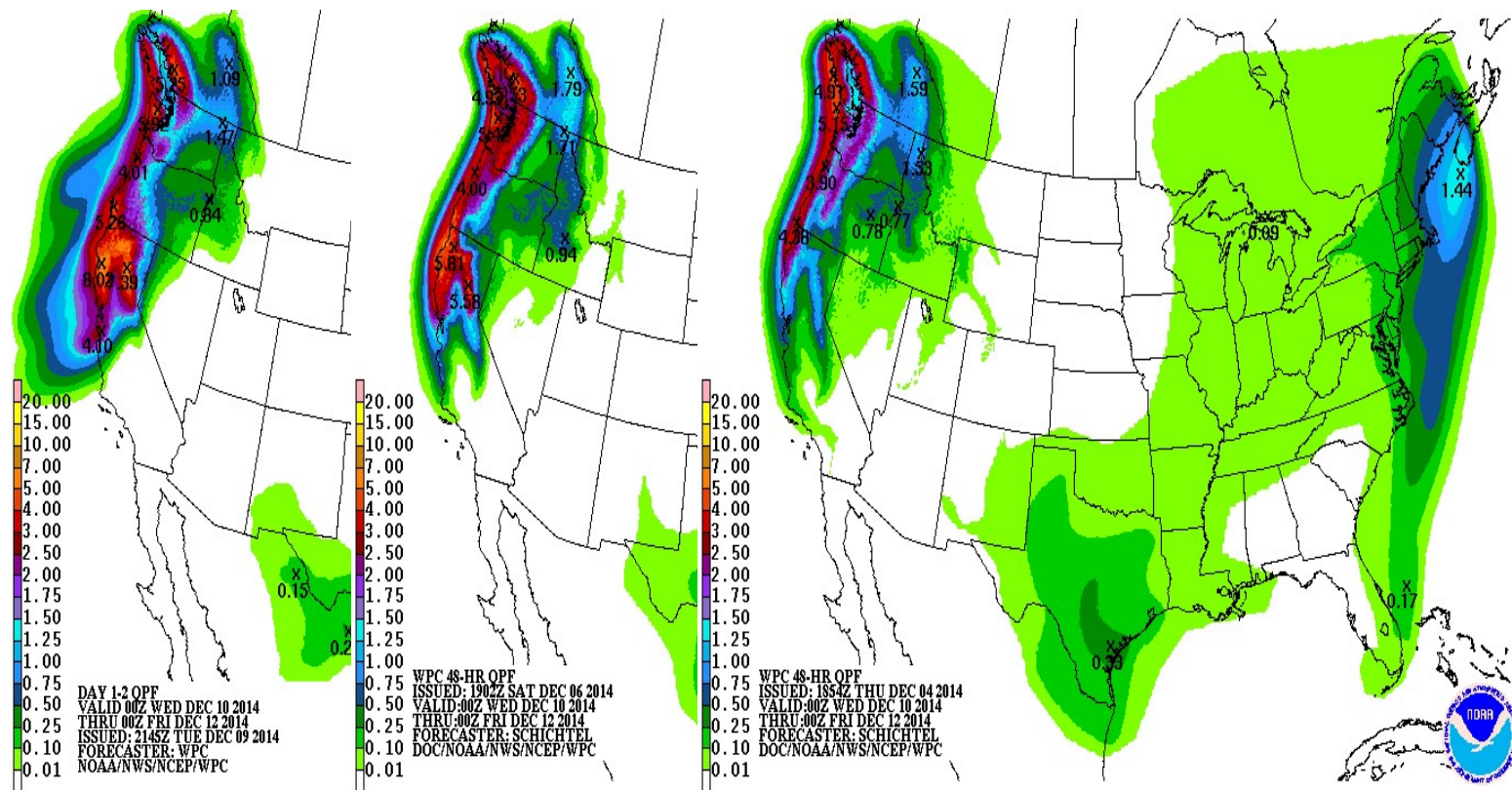
Russian River in Sonoma County – Flood February 2014

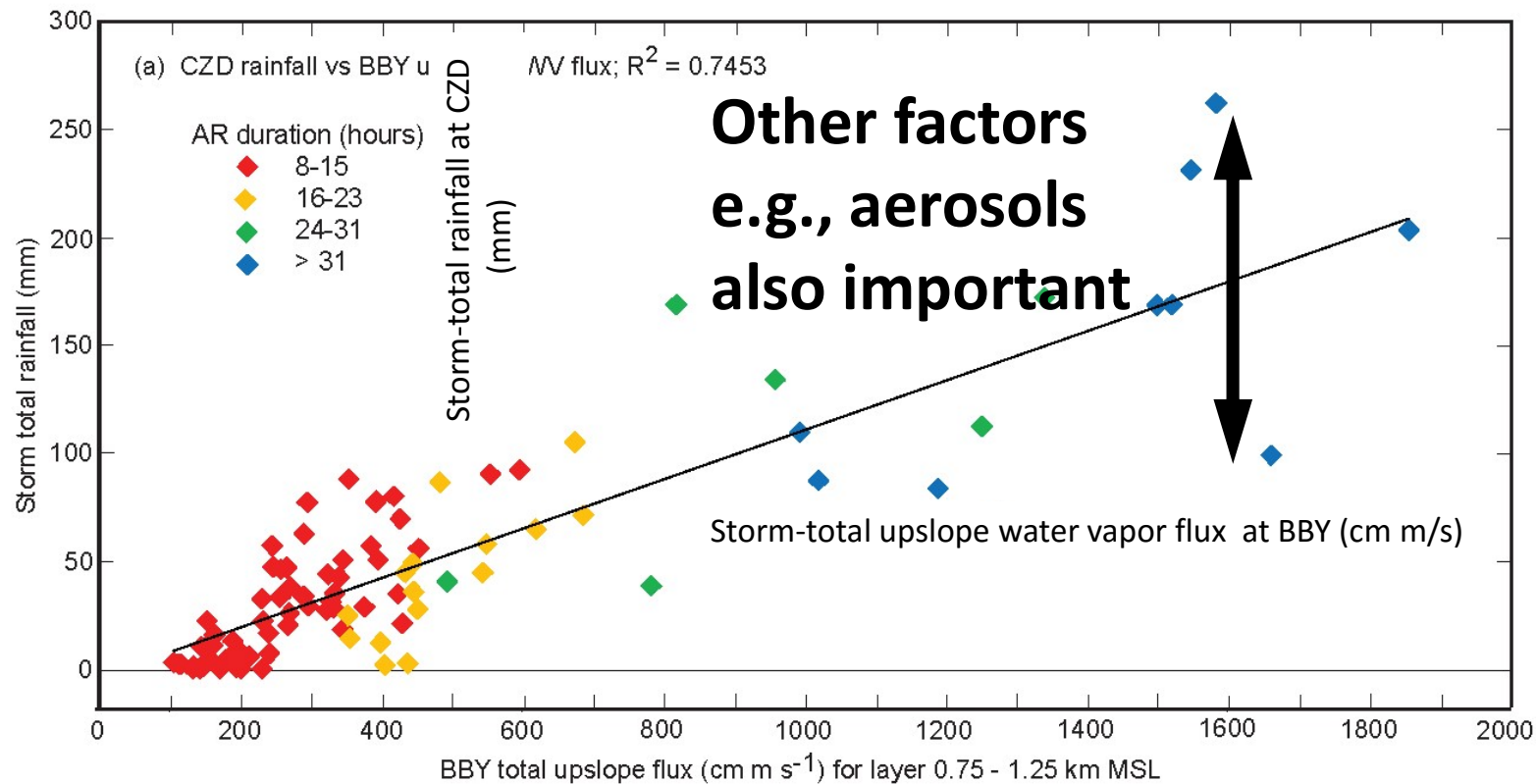


Russian River near Monte Rio, 9 Feb 2014 (*M. Ralph*)



48-h QPF Dprog-Dt out to 7 days lead time ending 0000 UTC 12 Dec 2014



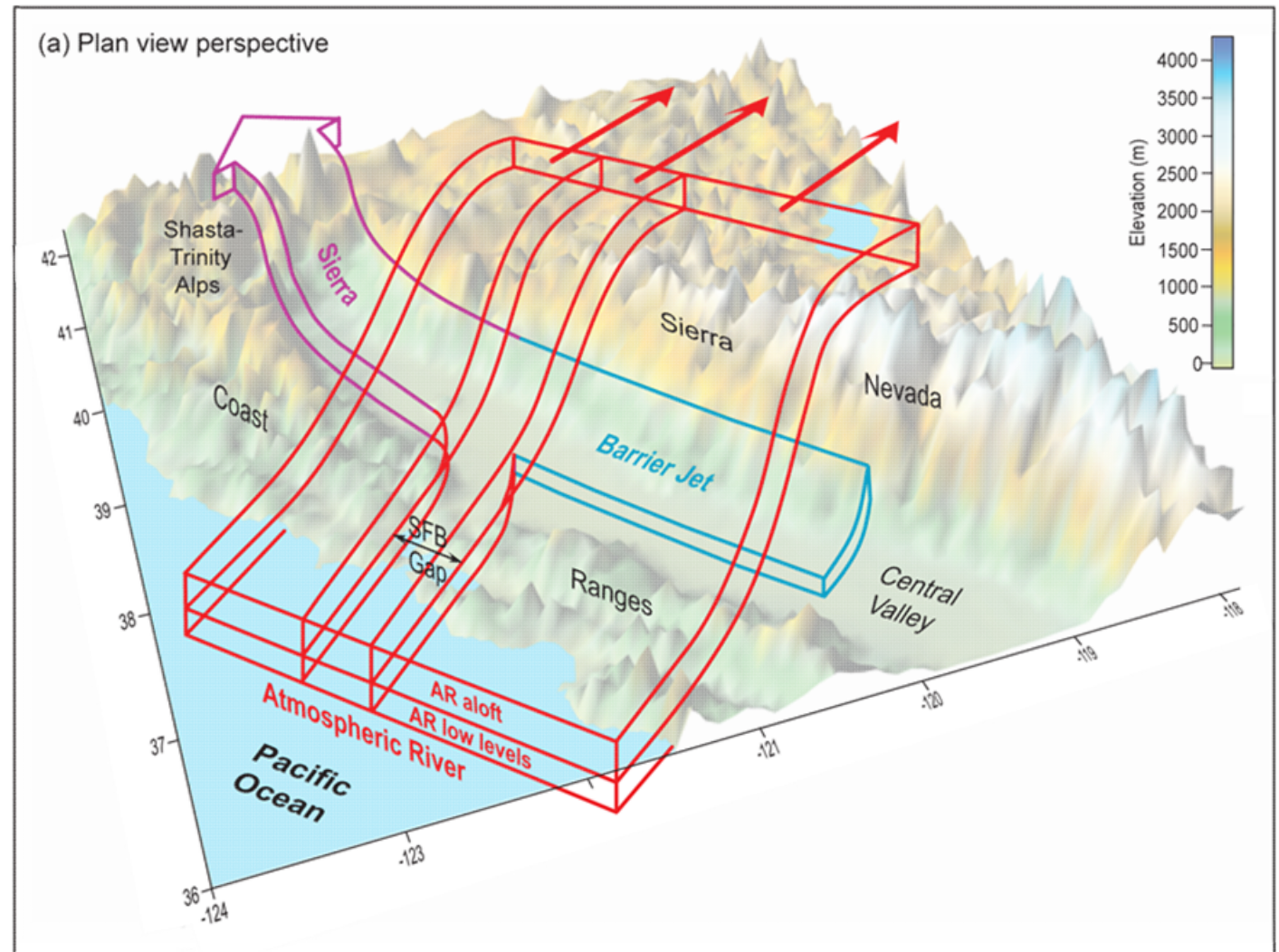


The greater the AR strength and duration

The greater the precipitation

From Ralph et al. 2013, *J. Hydrometeorology*

The Sierra Barrier Jet is key to regional precipitation

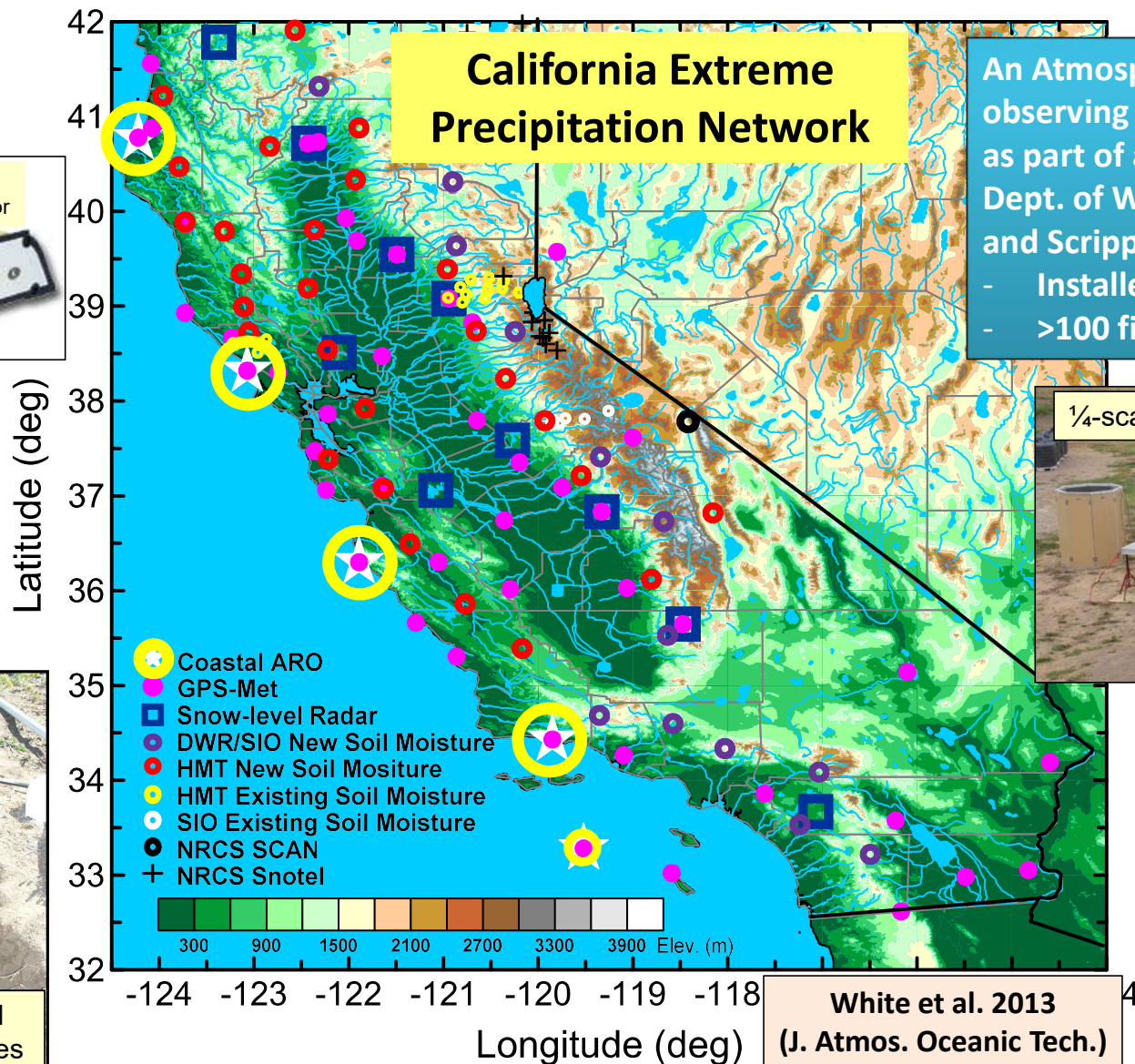


Neiman, Hughes, Moore, Ralph, and Sukovich (MWR 2013)

California Extreme Precipitation 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



GPS receiver for integrated water vapor



1/4-scale 449-MHz wind profiler with RASS



FM-CW snow-level radar



Soil Moisture and Temperature Probes





CalWater 2

Precipitation, Aerosols, and Pacific
Atmospheric Rivers Experiment

F. Martin Ralph, K. Prather, D. Cayan (Co-Leads)
UC San Diego/Scripps Institution of Oceanography

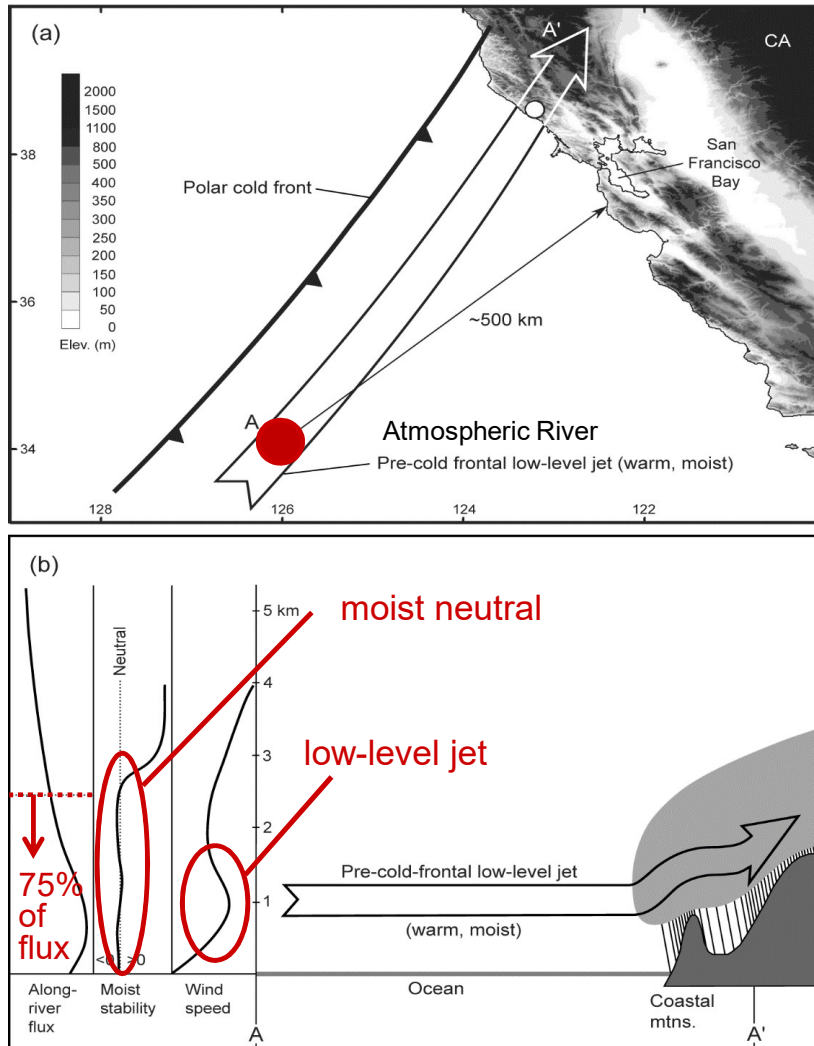
Key Agencies

NOAA, DOE, NSF, CA DWR, NASA, ONR

Overview article

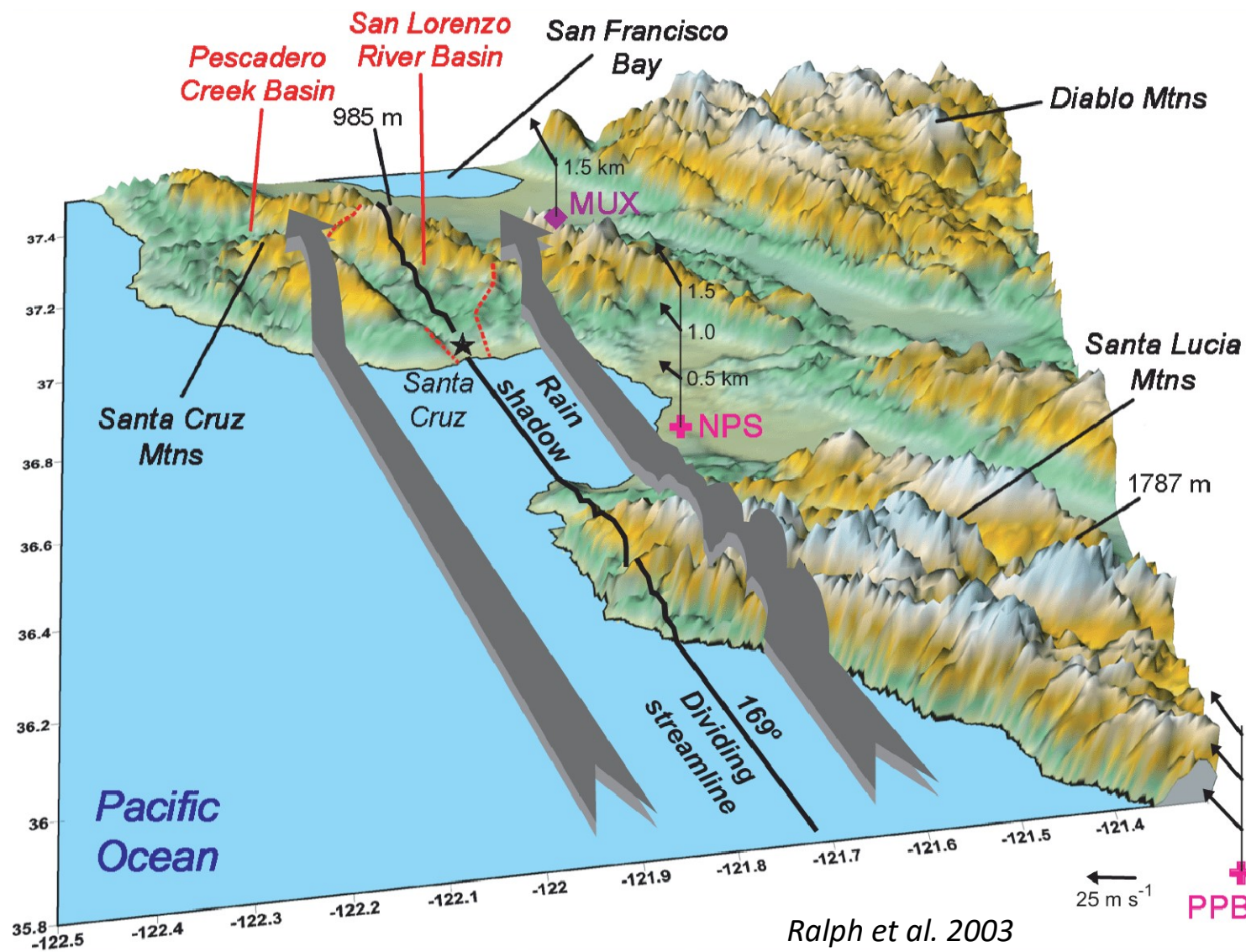
Ralph et al. 2015 (Bull. Amer. Meteor. Soc.)

Experiments in 1998,2001 provided a mean vert profile in ARs



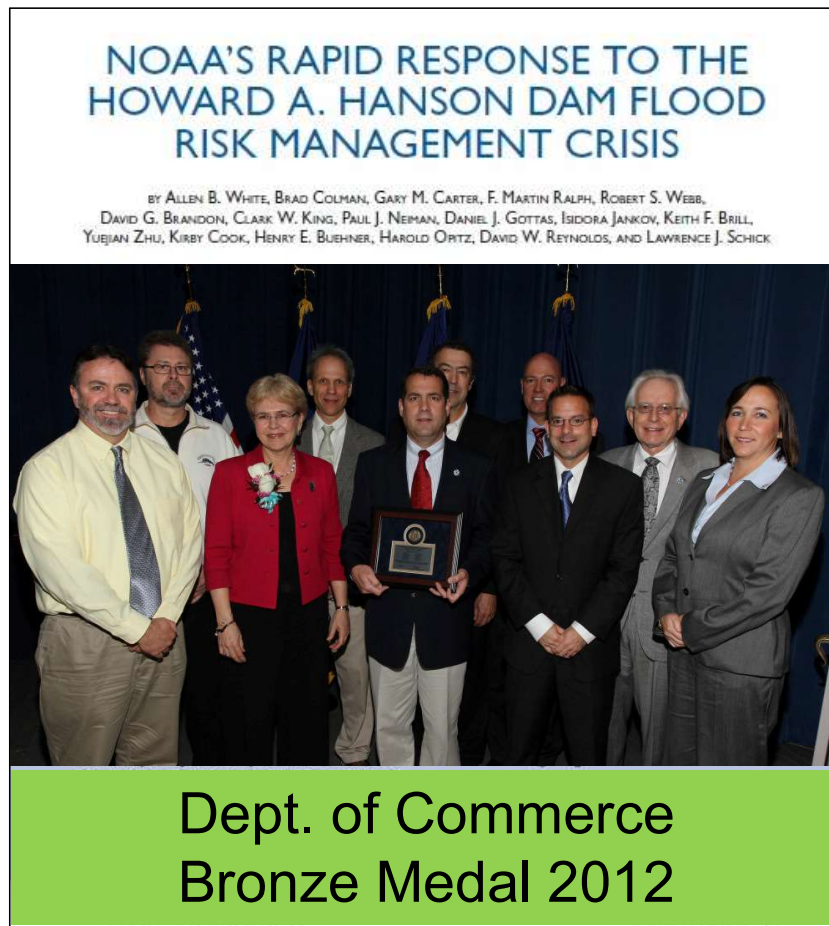
- CALJET and PACJET field experiments used the NOAA P-3 aircraft to profile ARs
- Composite sounding located 500 km off CA coast in atmos. river & pre-cold-frontal LLJ
- LLJ directed toward coast and situated at 1 km MSL
- Most (75%) of pre-cold-frontal along-river moisture flux is below 2.5 km MSL
- Moist neutral stratification below 2.8 km MSL, hence no resistance to orographic lifting
- Overlapping set of conditions conducive to orographic rain enhancement in coastal mtns

Ralph et al. (2005), *MWR*



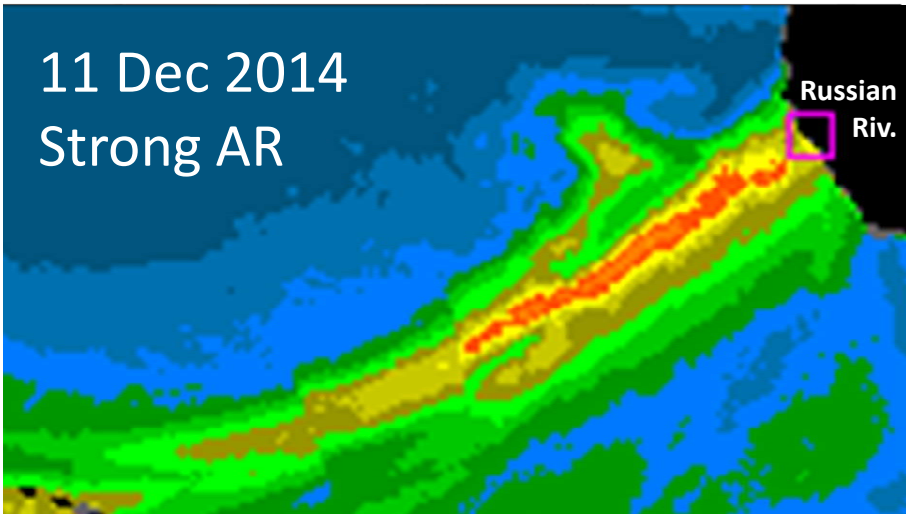
AR “Angle of Attack” can determine flooding in mountainous areas

HMT-West innovations were key elements in NOAA's rapid response to a flood risk crisis



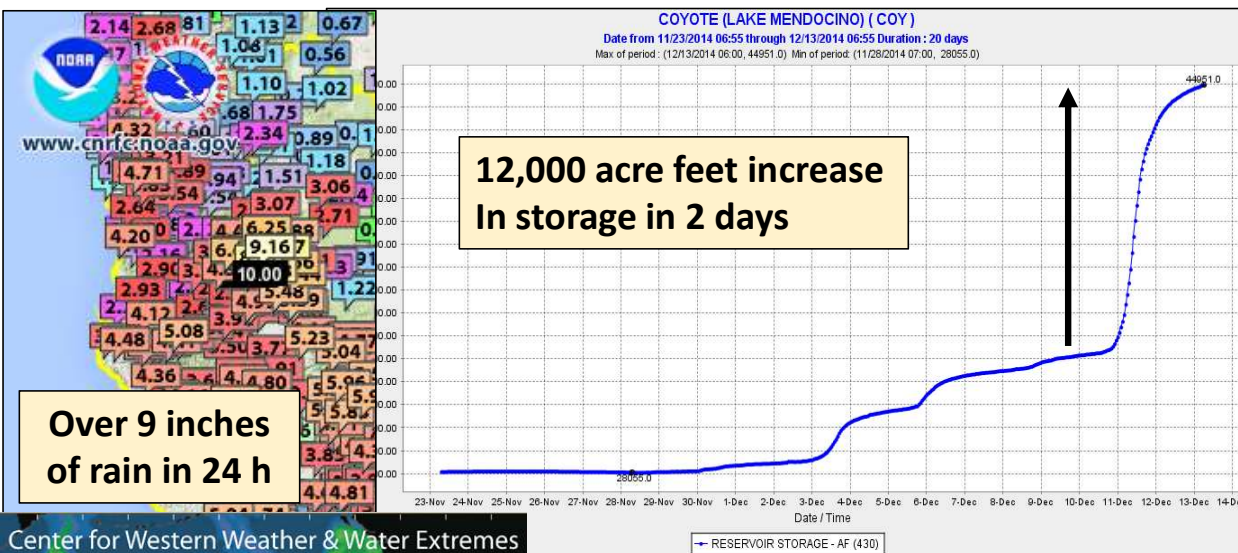
- USACE was considering taking over operation of a dam in Washington State during a recent storm.
- Using the HMT ARO at the coast and NWS forecasts, USACE saw the back edge of the AR was coming ashore and thus heavy rain was about to end, so they did not take over operation from the local water agency.
- See recent journal article by White et al. (February 2012; Bulletin of the American Meteorological Society).

11 Dec 2014
Strong AR

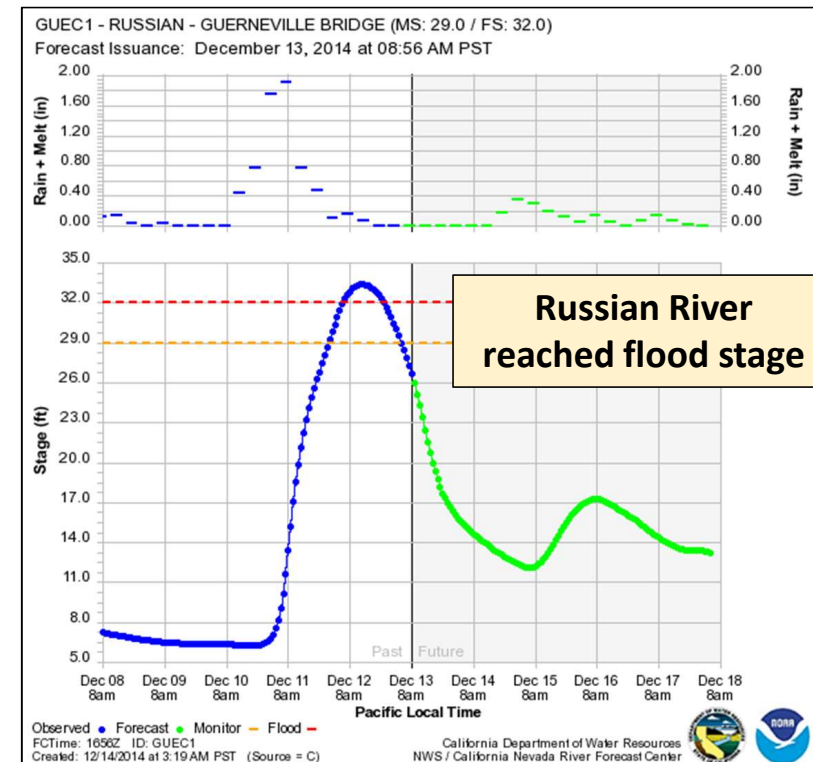


Storm of 10-12 December 2014
Floods Can Happen During Drought

*A more complete summary is
available at ***cw3e.ucsd.edu****



Center for Western Weather & Water Extremes
<http://cw3e.ucsd.edu>



CalWater-2015



NOAA G-IV

NOAA P-3

DOE G-1

Research Aircraft at McClellan Airfield, Sacramento, CA
25 January 2015

Photo by Marty Ralph (UCSD/Scripps/CW3E)

DOE G-1 aircraft: measuring cloud, rain and snow particles, as well as aerosols such as dust and smoke from sources near and far

NOAA G-IV aircraft: measuring atmospheric river strength and structure offshore using dropsondes and precipitation radar

NOAA P-3 aircraft: measuring ocean and atmosphere with radars for precipitation, cloud & ocean waves, and air & ocean sondes

NOAA Ron Brown Ship: measuring aerosols, clouds, atmospheric rivers, ocean surface and subsurface conditions

DOE AMF2: many sensors mounted on the NOAA ship; measuring aerosols, precipitation, clouds & winds aloft and at the surface

CA Dept. of Water Resources extreme precipitation network: measuring atmospheric rivers, snow level and soil across California

NSF - sponsored aerosol and rain measurements at the coast

NASA ER-2 aircraft: measuring aerosols, clouds, water vapor w/radar, lidar, radiometer

**Ralph et al., 2015, Bulletin of the American Meteorological Society (Overview article in press)*