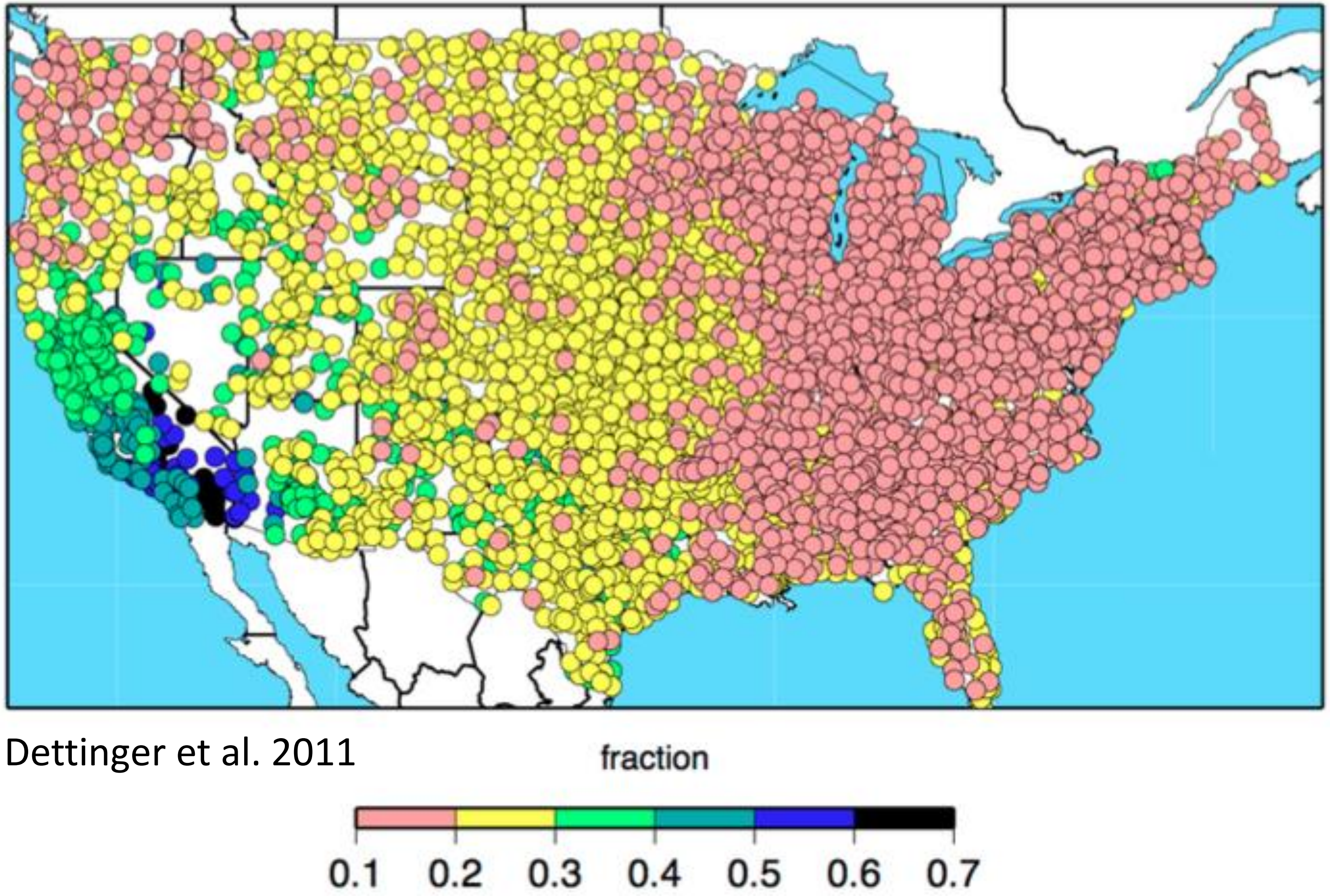
Opportunities for Improving S2S Forecasting in the West: Extreme Precipitation and Atmospheric Rivers

F. Martin Ralph
UC San Diego/Scripps Institution of Oceanography

Sub-Seasonal and Seasonal Precipitation Forecasting and FIRO
Western States Water Council and California Dept. of Water Resources
28 September 2016, St. George Utah

Variability of Annual Precipitation



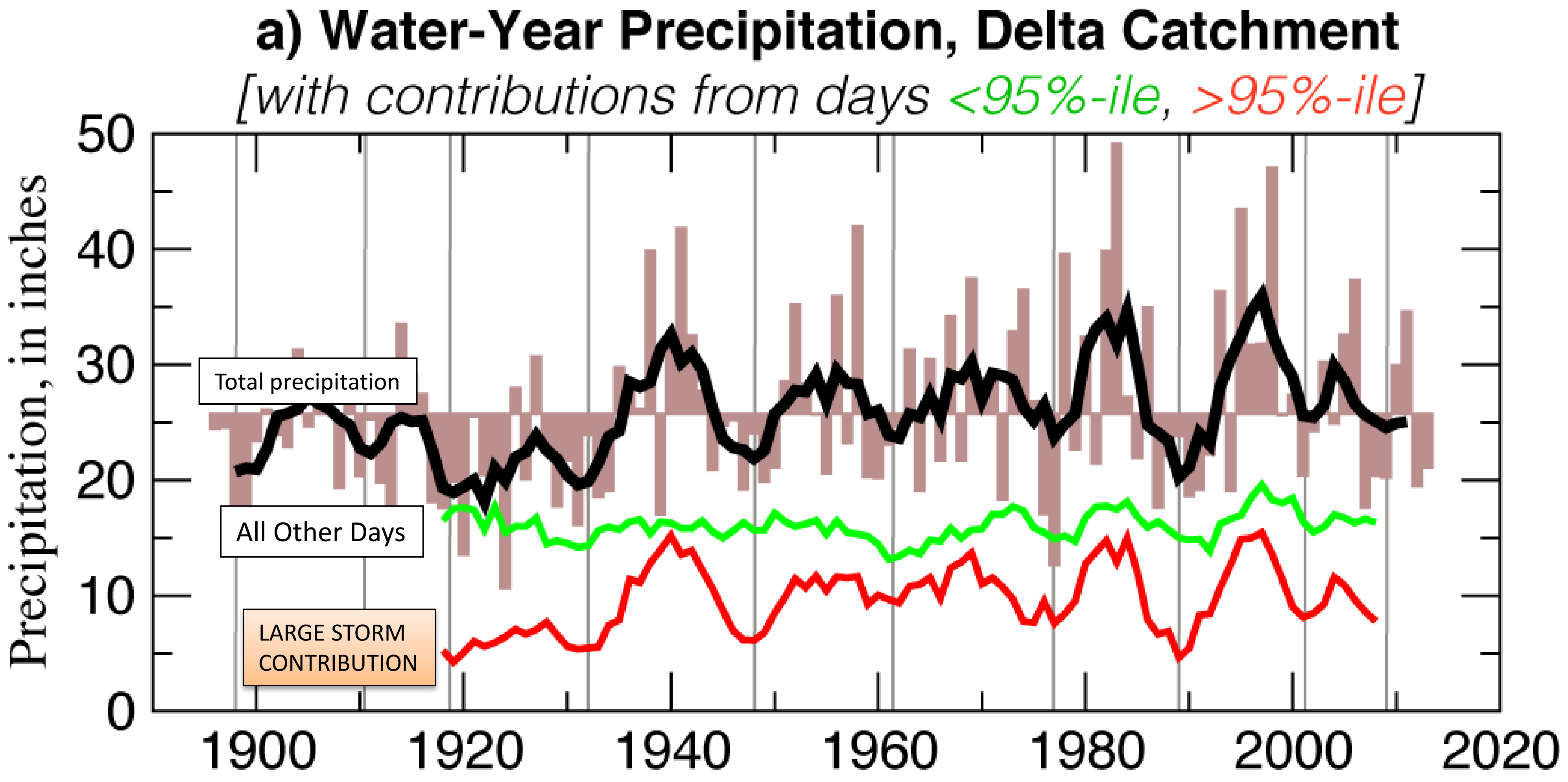
Dettinger et al. 2011

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).

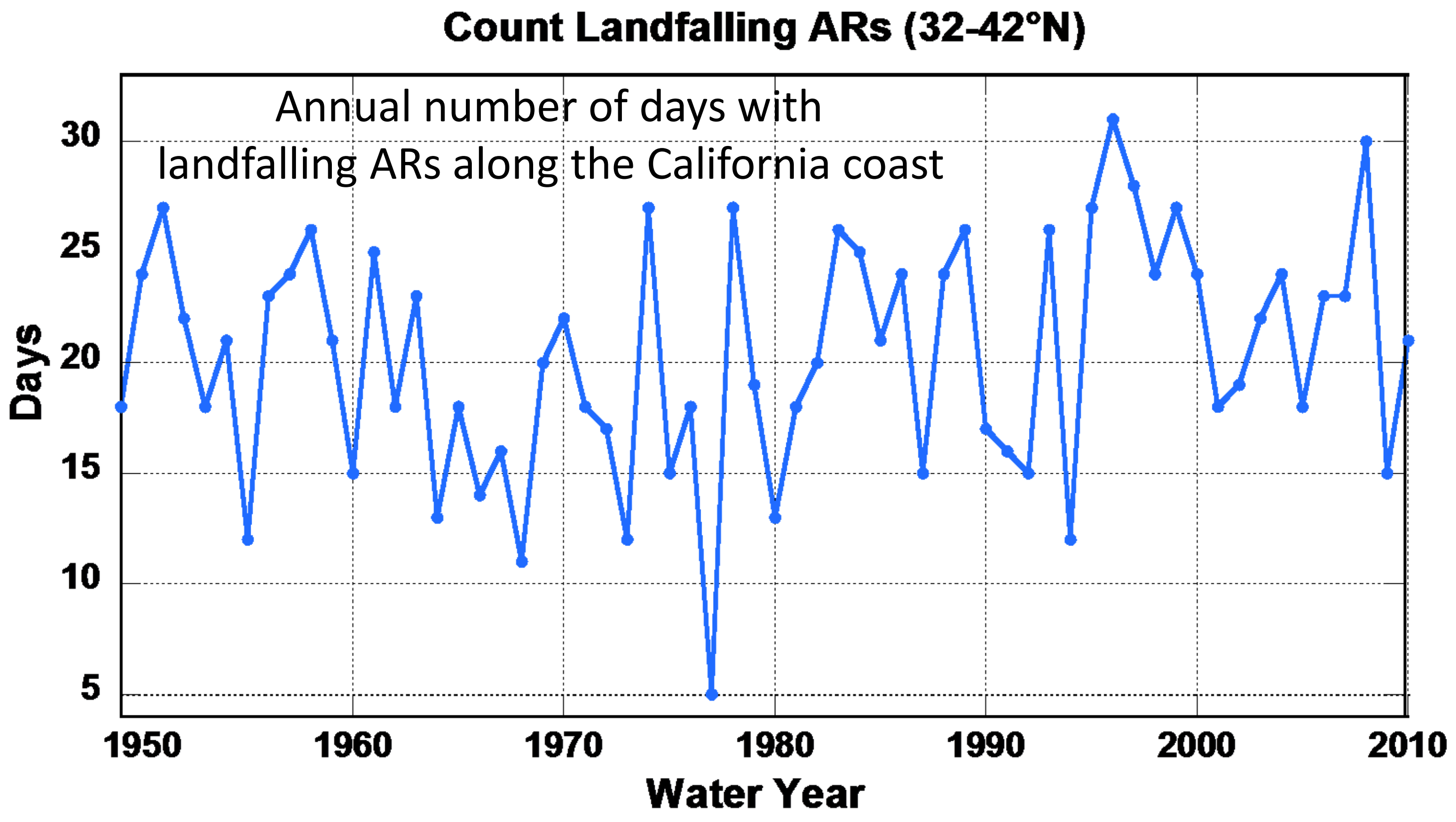
A few large storms (or their absence)

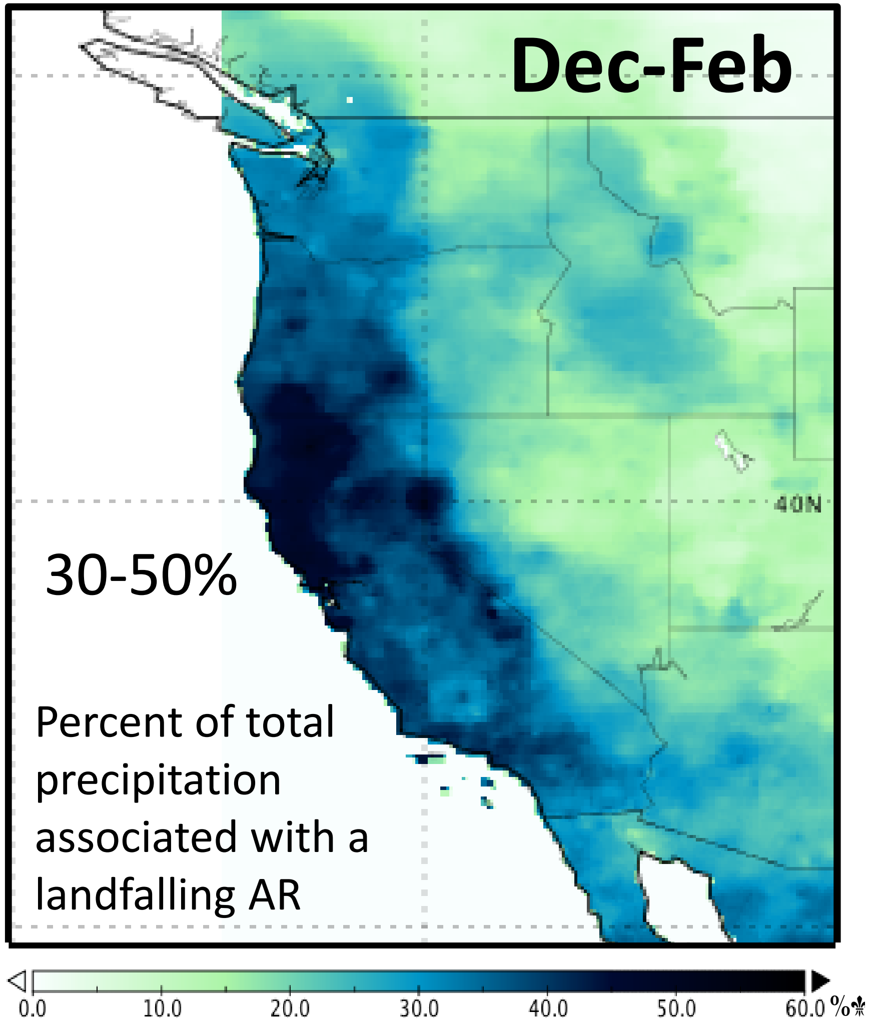
account for a disproportionate amount of California's precipitation variability



Dettinger and Cayan **Drought and the Delta—A Matter of Extremes**
San Francisco Estuary and Watershed Science, April 2014

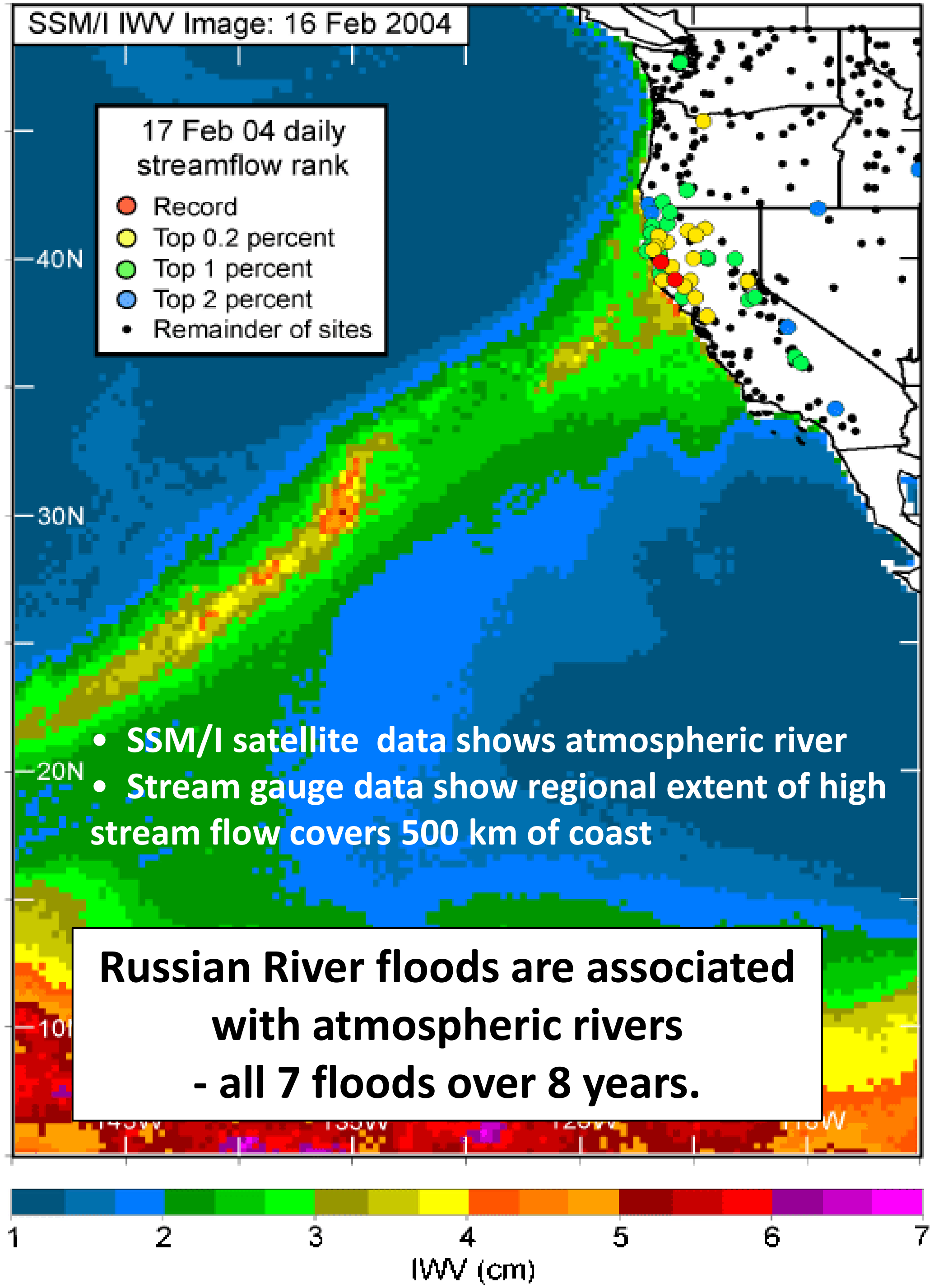
Preliminary Application of New AR Detection Scheme to Reanalysis Output





Center for Western Weather and Water Extremes

Gershunov, Shulgina, Ralph



- SSM/I satellite data shows atmospheric river
- Stream gauge data show 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.

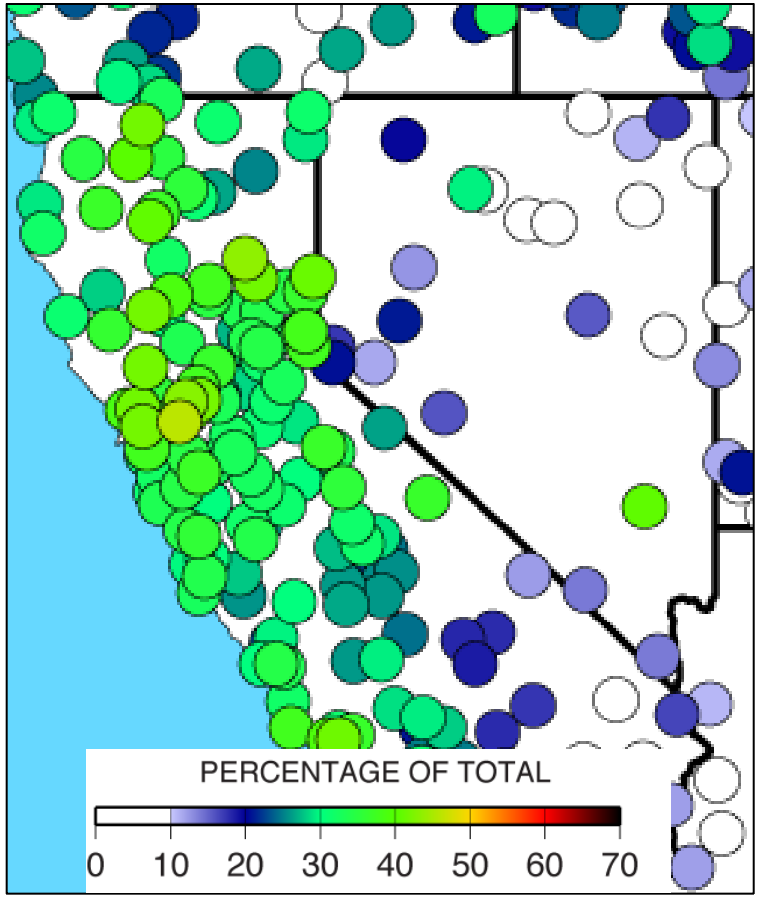
Flooding on California's Russian River: Role of atmospheric rivers

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

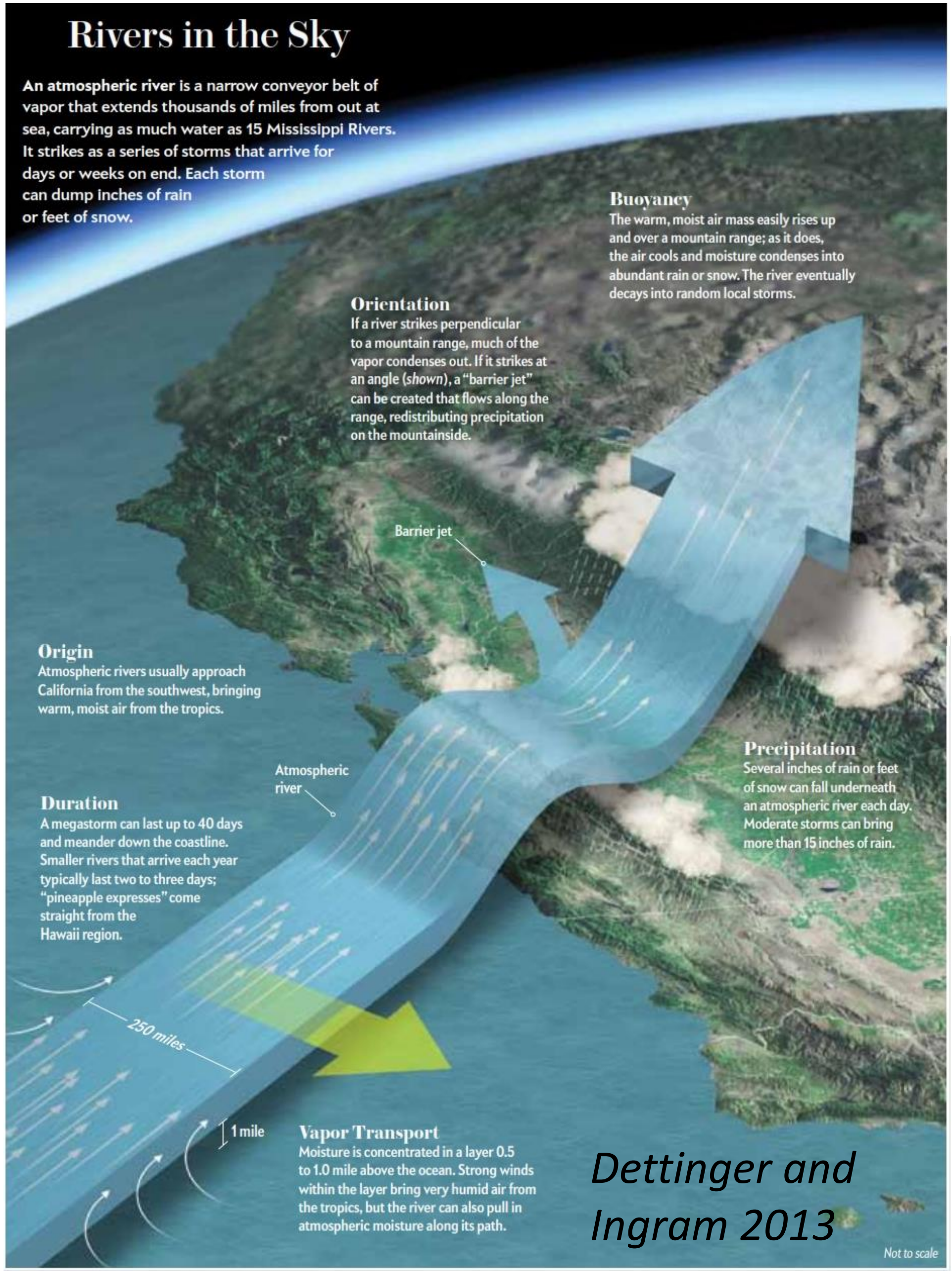
ARs can CAUSE FLOODS and PROVIDE WATER SUPPLY

Atmospheric Rivers, Floods and the Water Resources of California

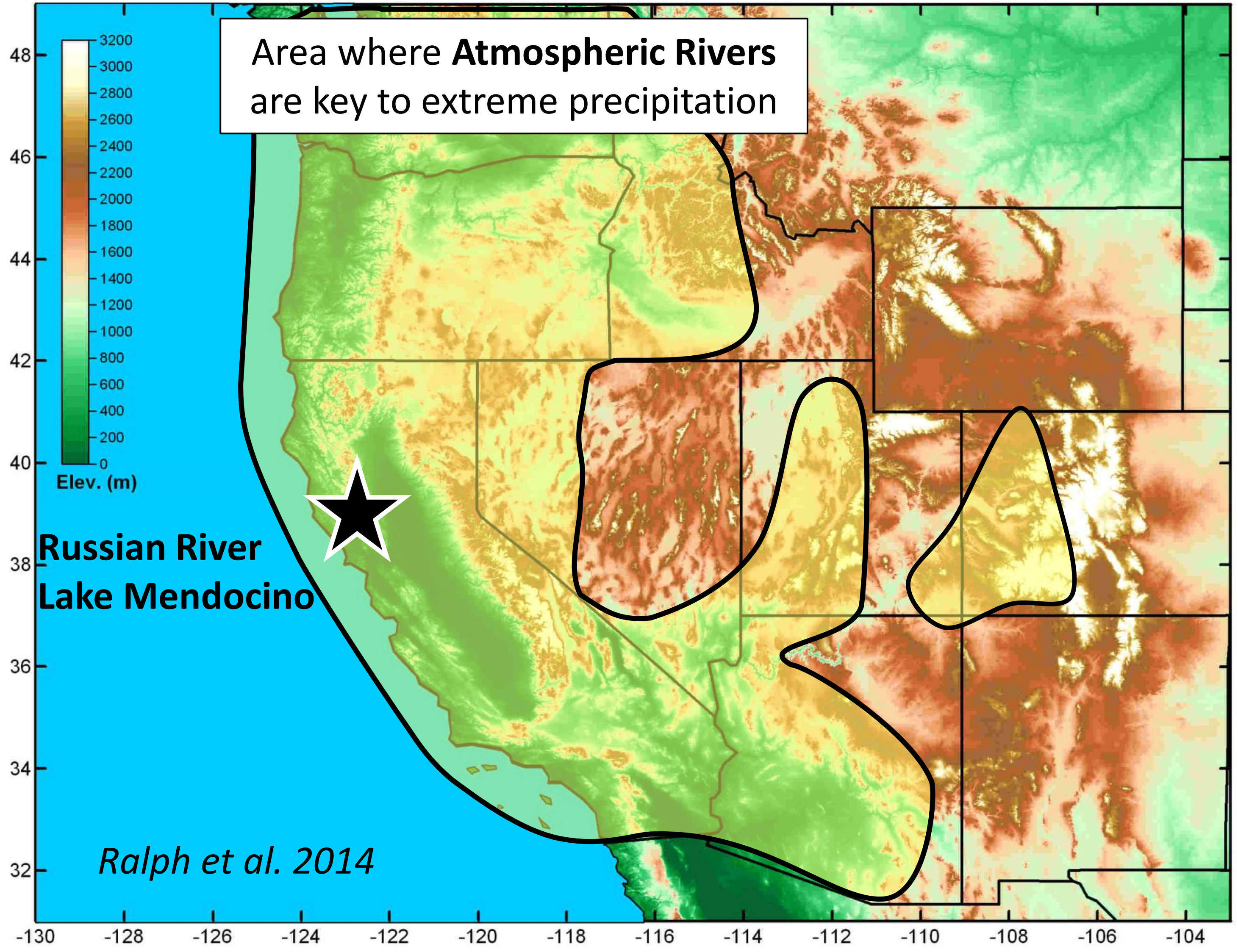
Mike Dettinger, M. Ralph, , T. Das, P. Neiman, D. Cayan (*Water, 2011*)



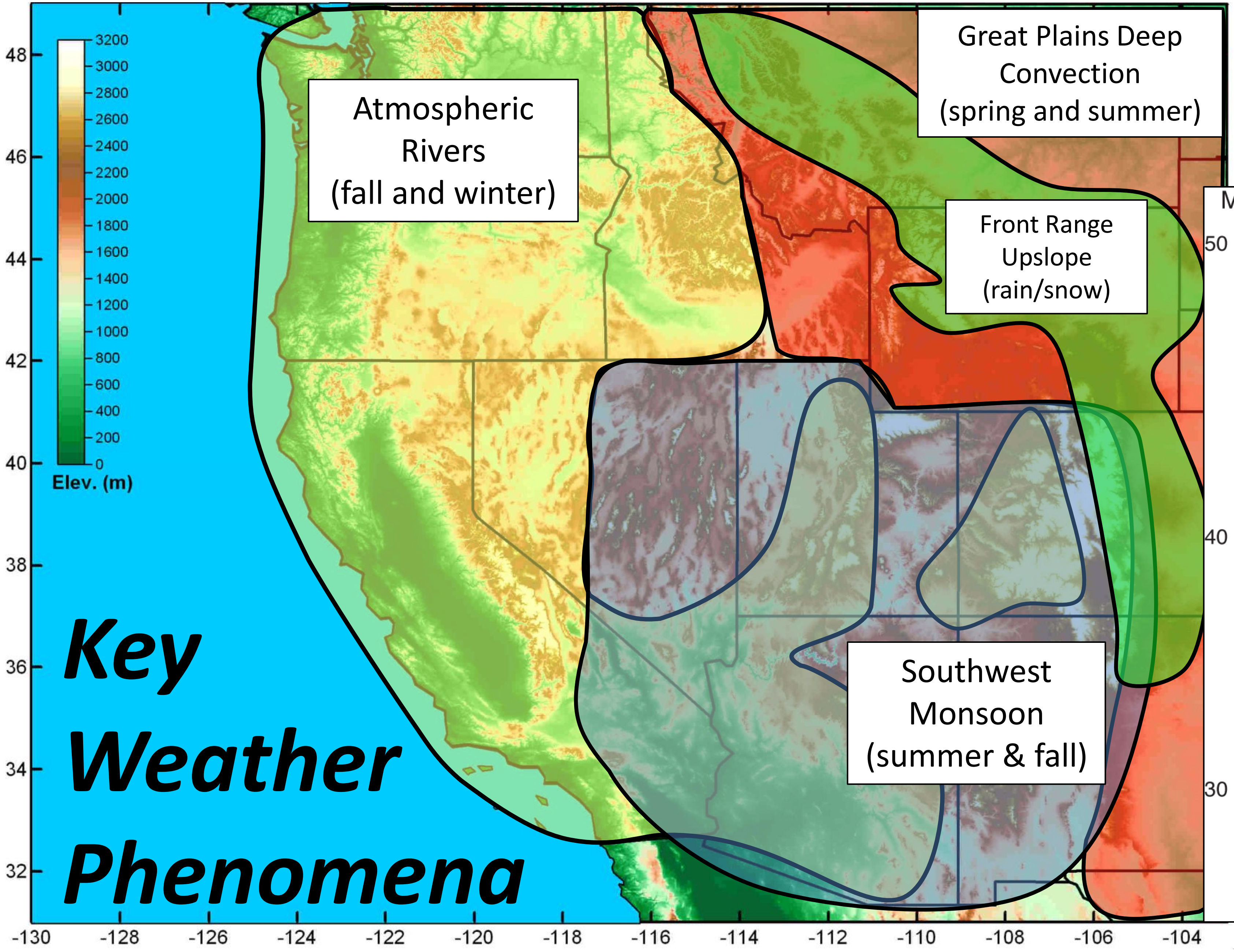
Rivers in the Sky

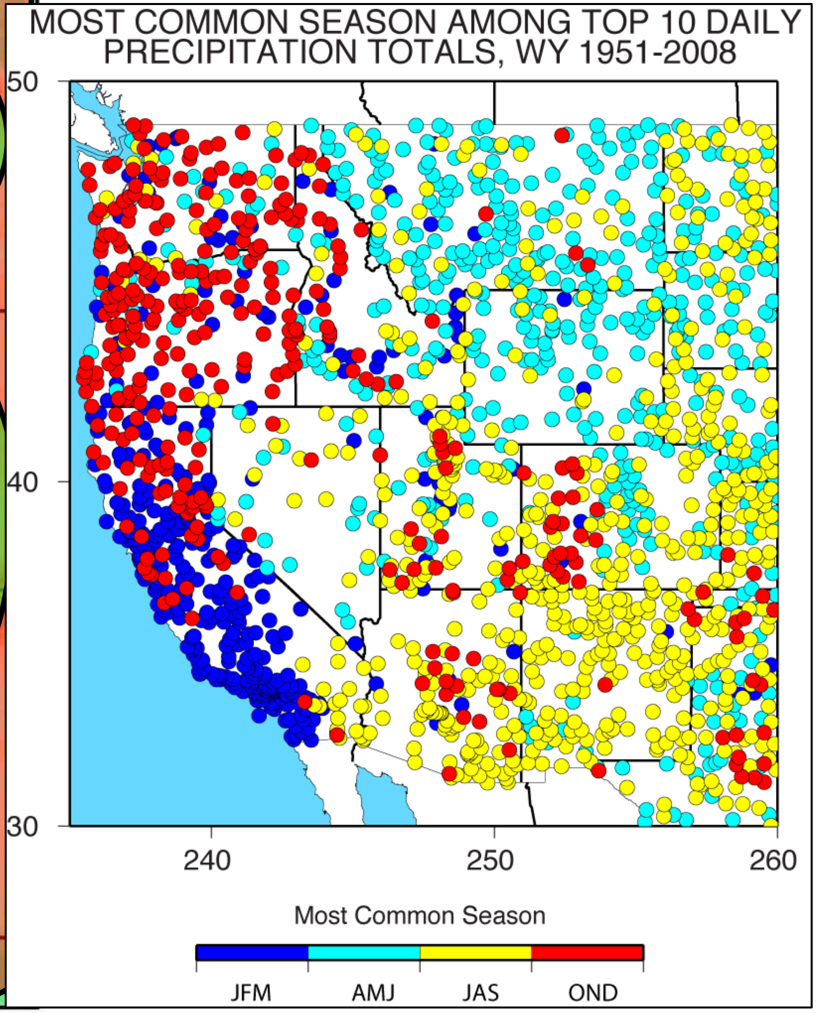


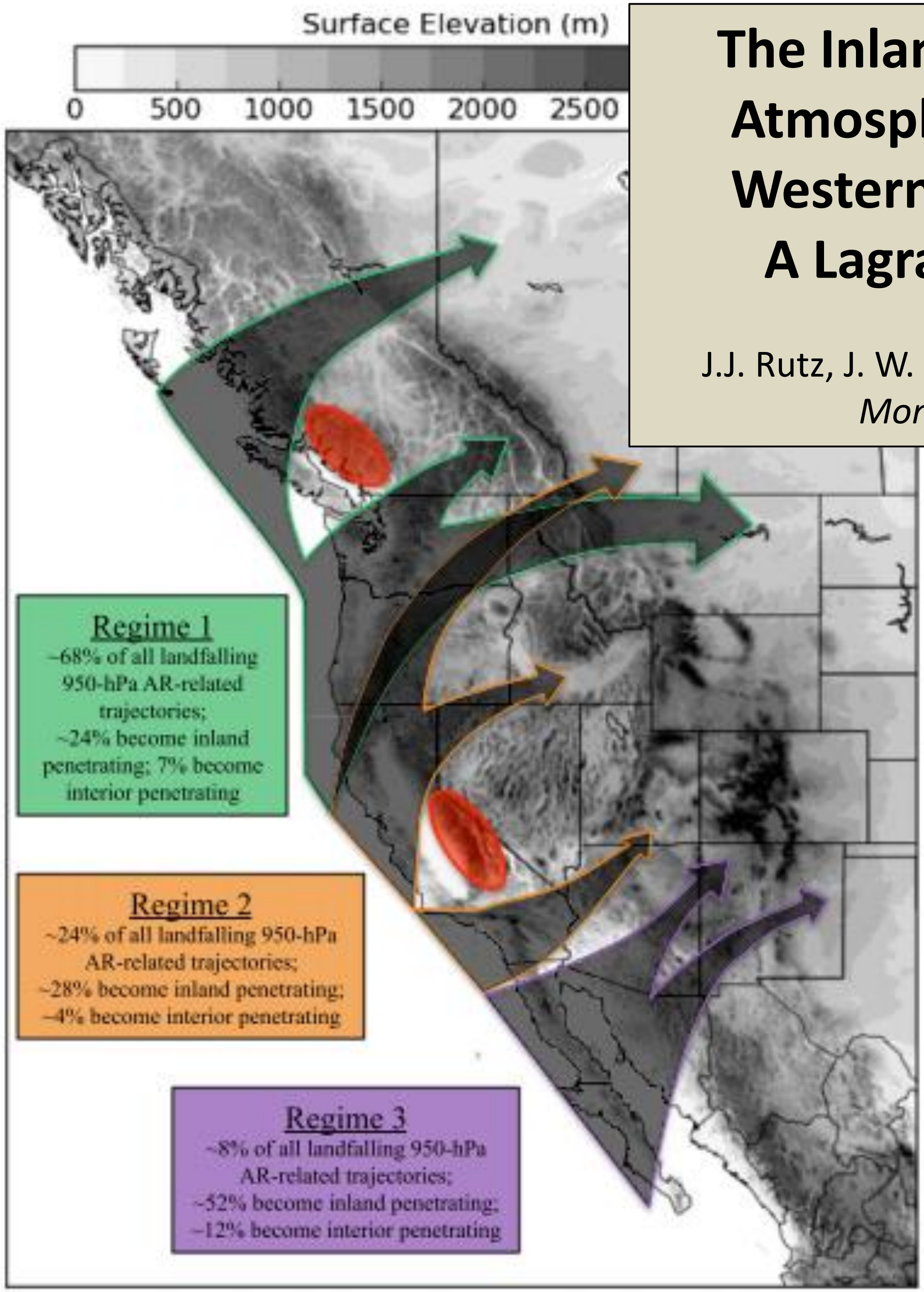
ARs Affect Large Areas of the U.S. West



Schematic illustration of regional variations in the primary weather phenomena that lead to extreme precipitation, flooding and contribute to water supply in the Western U.S. (Ralph et al. 2014)

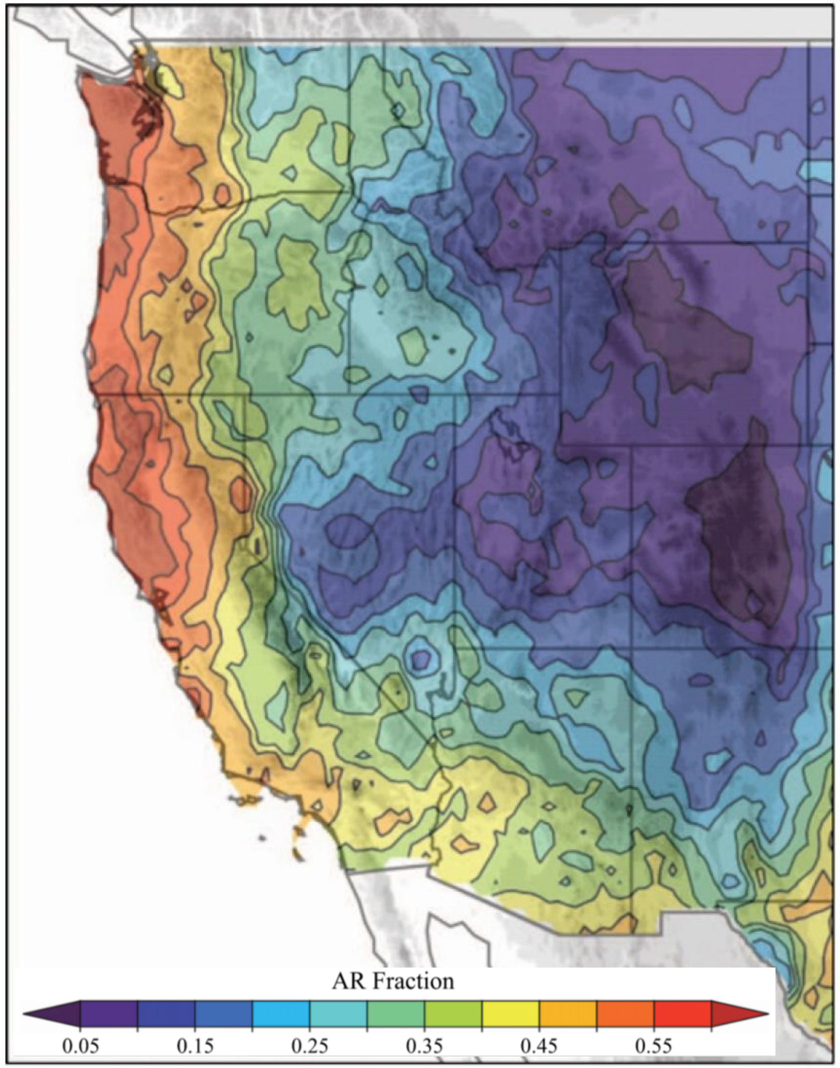






The Inland Penetration of Atmospheric Rivers over Western North America: A Lagrangian Analysis

J.J. Rutz, J. W. Steenburgh and F.M. Ralph
Mon. Wea. Rev., 2015

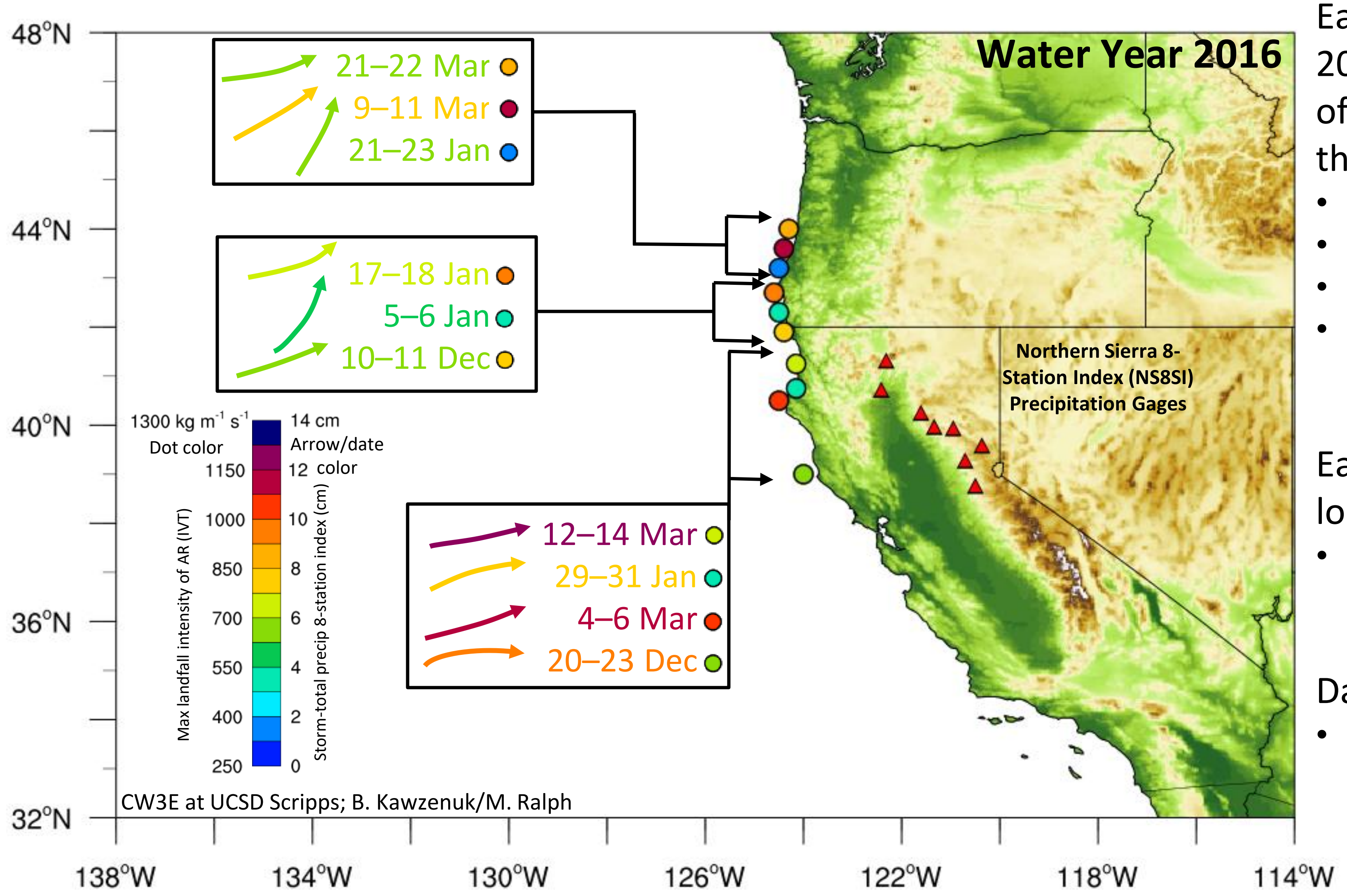


Climatological Characteristics of Atmospheric Rivers and Their Inland Penetration over the Western United States

J.J. Rutz, J. W. Steenburgh and F.M. Ralph
Mon. Wea. Rev., 2014

WY 2016 Storm Summary: Top-10 Wettest Events - Northern Sierra 8-Station Index

Dates, Landfall Locations, Storm Orientations – All Were Atmospheric Rivers



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

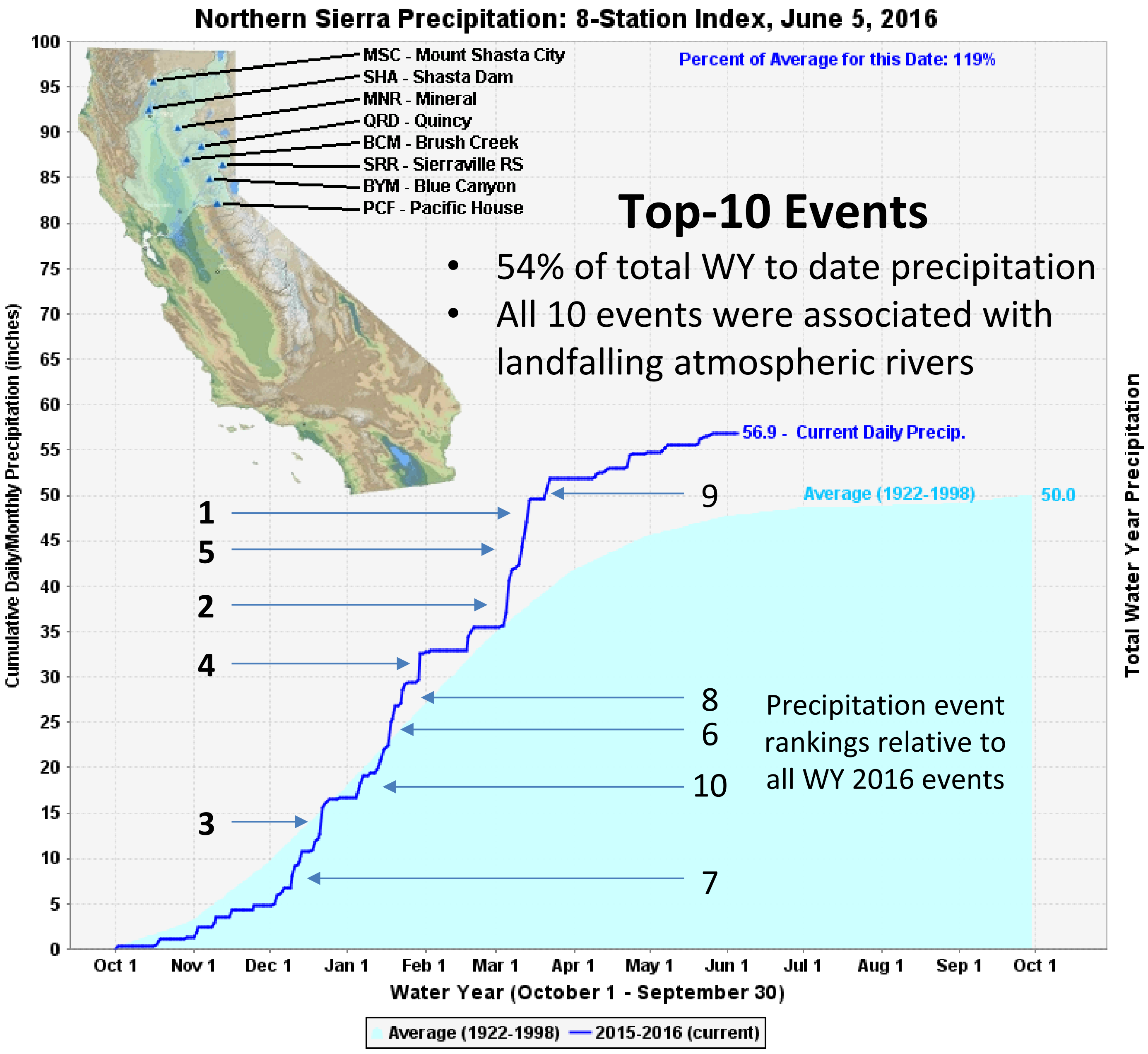
Each dot represents the central landfall location of the associated atmospheric river

- 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

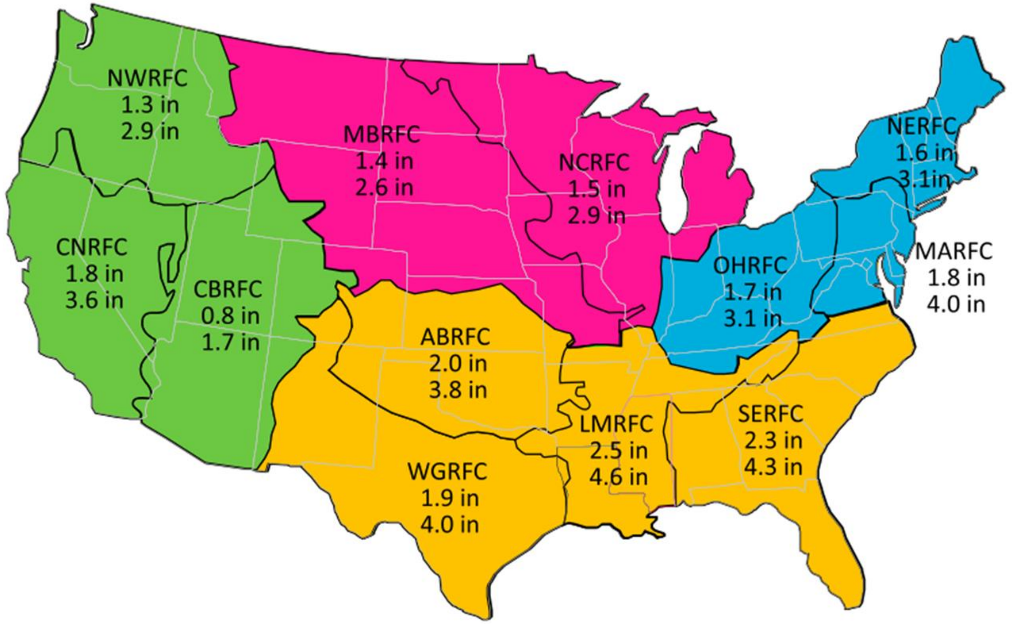

Northern Sierra Precipitation: 8-Station Index, June 5, 2016
MSC - Mount Shasta City
SHA - Shasta Dam
MNR - Mineral
QRD - Quincy
BCM - Brush Creek
SRR - Sierraville RS
BYM - Blue Canyon
PCF - Pacific House
Percent of Average for this Date: 119%
Top-10 Events
• 54% of total WY to date precipitation
• All 10 events were associated with landfalling atmospheric rivers
56.9 - Current Daily Precip.
Average (1922-1998)
50.0
1
5
2
4
3
9
8
6
10
7
Precipitation event rankings relative to all WY 2016 events
Cumulative Daily/Monthly Precipitation (inches)
Total Water Year Precipitation
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Oct 1
Nov 1
Dec 1
Jan 1
Feb 1
Mar 1
Apr 1
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1
Water Year (October 1 - September 30)
Average (1922-1998)
2015-2016 (current)

Predictions

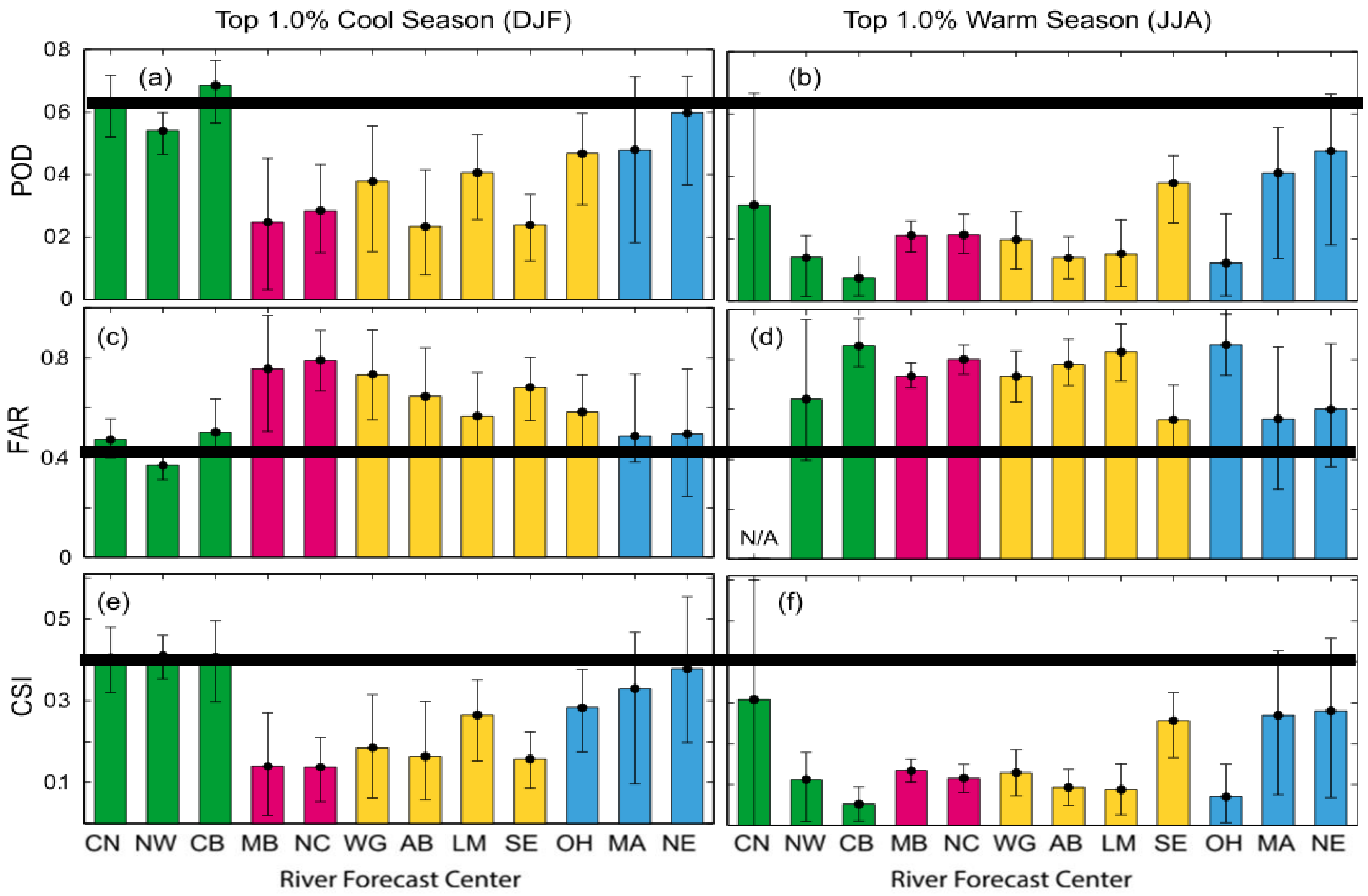
Extreme quantitative precipitation forecast performance at the Weather Prediction Center from 2001 to 2011

Sukovich, E. M., F. M. Ralph, F. E. Barthold, D. W. Reynolds and D. R. Novak *Wea. Forecast.* (2014)

Regional thresholds for
Top 1% heaviest daily precipitation



Used 32 km gridded QPE from NCEP/WPC from 2001-2011
>12,000,000 wet days

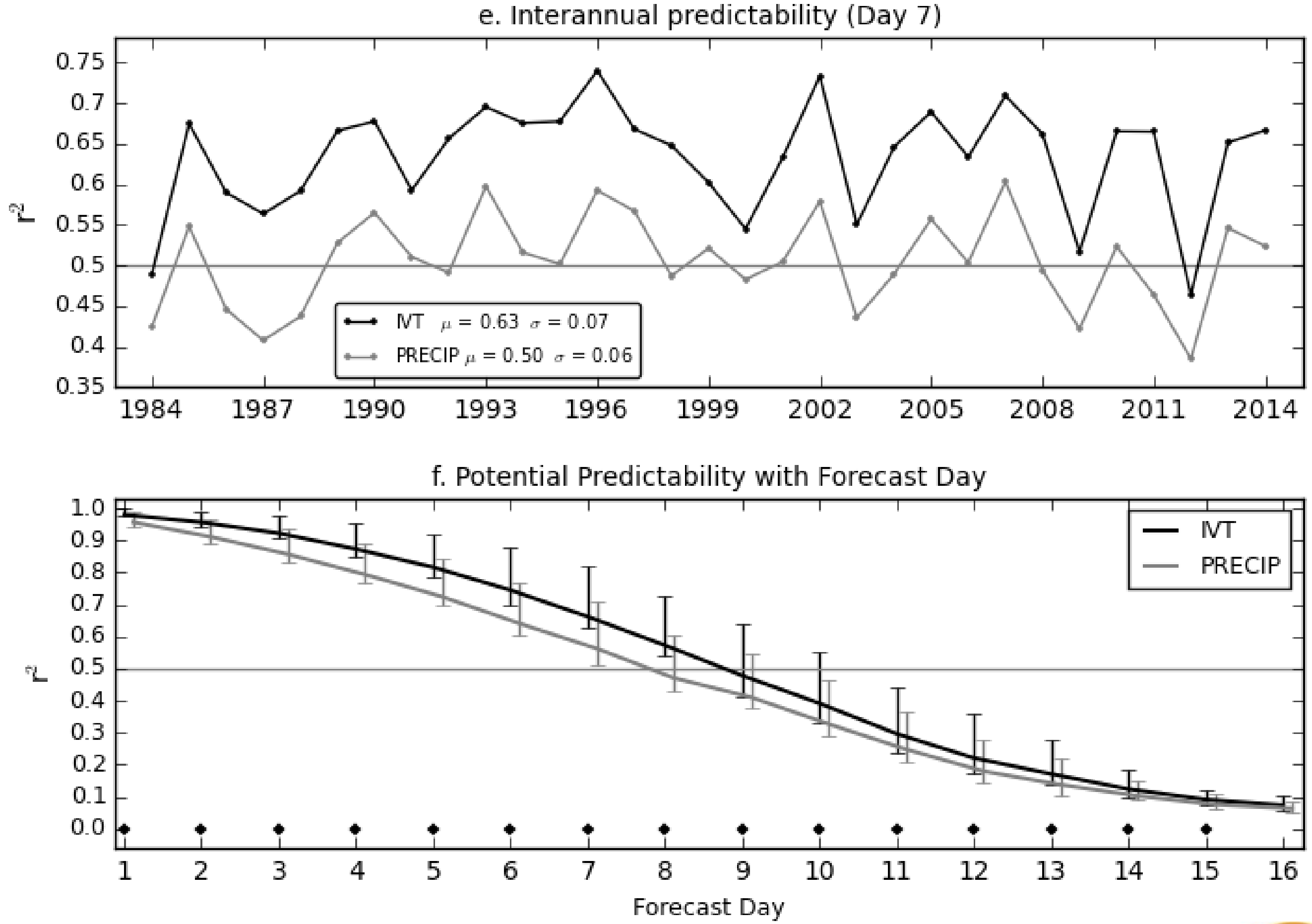


Slide courtesy of F.M. Ralph, Scripps/CW3E

Used 32 km gridded QPE and QPF from NCEP/WPC from 2007-2011. For 1-day lead time. Note QPF for Western RFC's and New England are best.

Predictability of horizontal water vapor transport relative to precipitation

Applying the potential predictability concept to the NCEP global ensemble reforecasts, across 31 winters, IVT is found to be more predictable than precipitation.



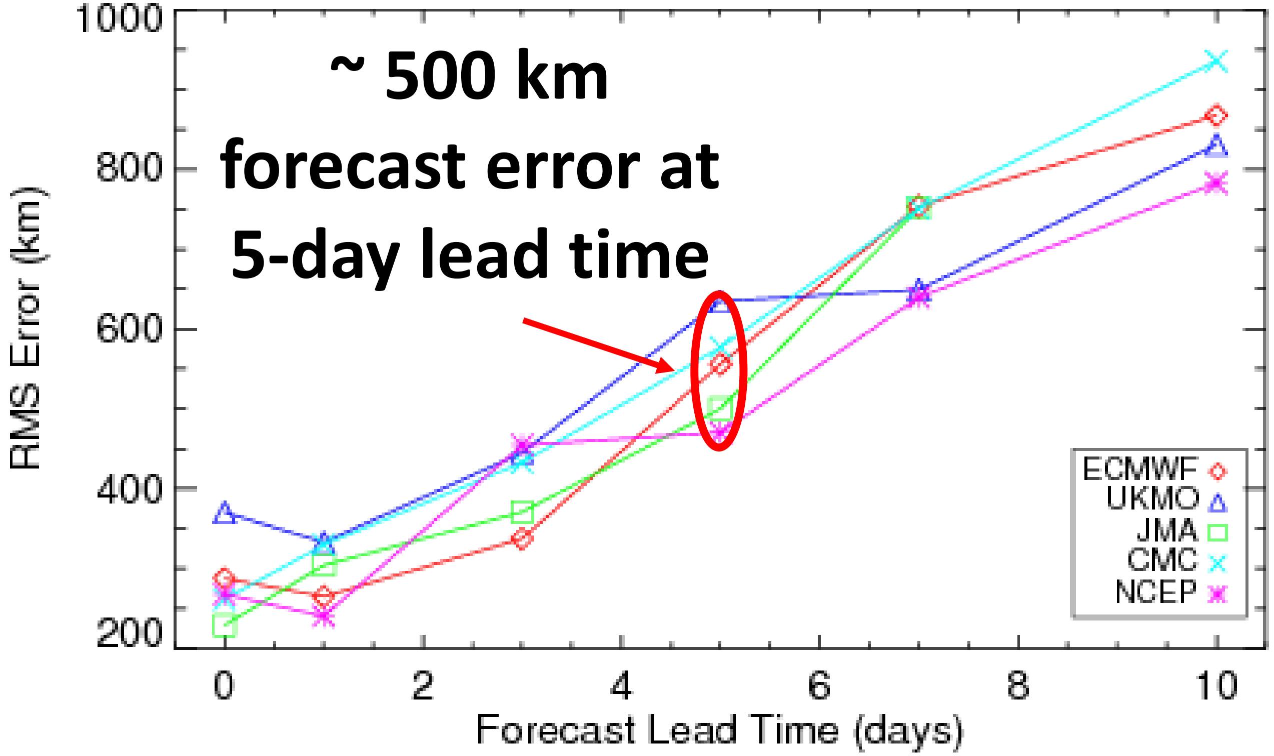
Courtesy of Lavers, Waliser, Ralph, Dettinger GRL 2015

Center for Western Weather and Water Extremes

AR Landfall Position Forecast Errors Quantified

While overall occurrence well forecast out to 10 days, landfall is less well predicted and the location is subject to significant errors, especially at longer lead times

RMS Error in Forecast AR Landfall Location



- Errors in location increase to over 800 km at 10-day lead
- Errors in 3-5 day forecasts comparable with current hurricane track errors
- Model resolution a key factor

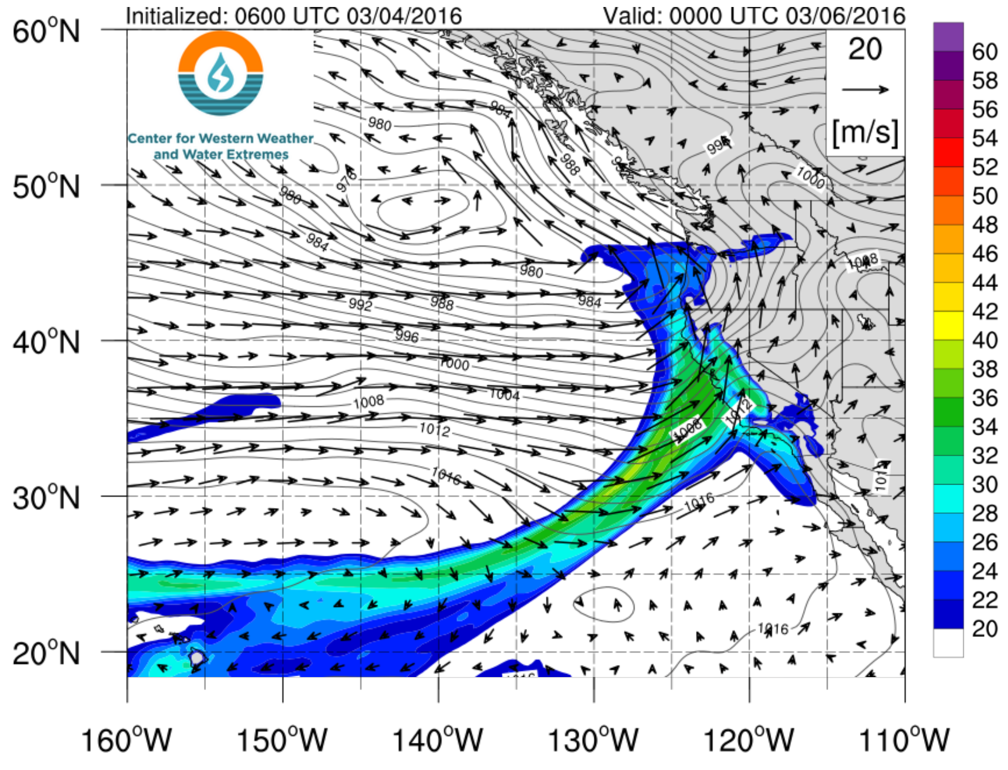
From Wick et al., 2013 (Weather and Forecasting)

- **Models provide useful heads-up for AR impact and IWV content, but location highly uncertain**
- **Location uncertainty highlights limitations in ability to predict extreme precipitation and flooding**
- **Improvements in predictions clearly desirable**

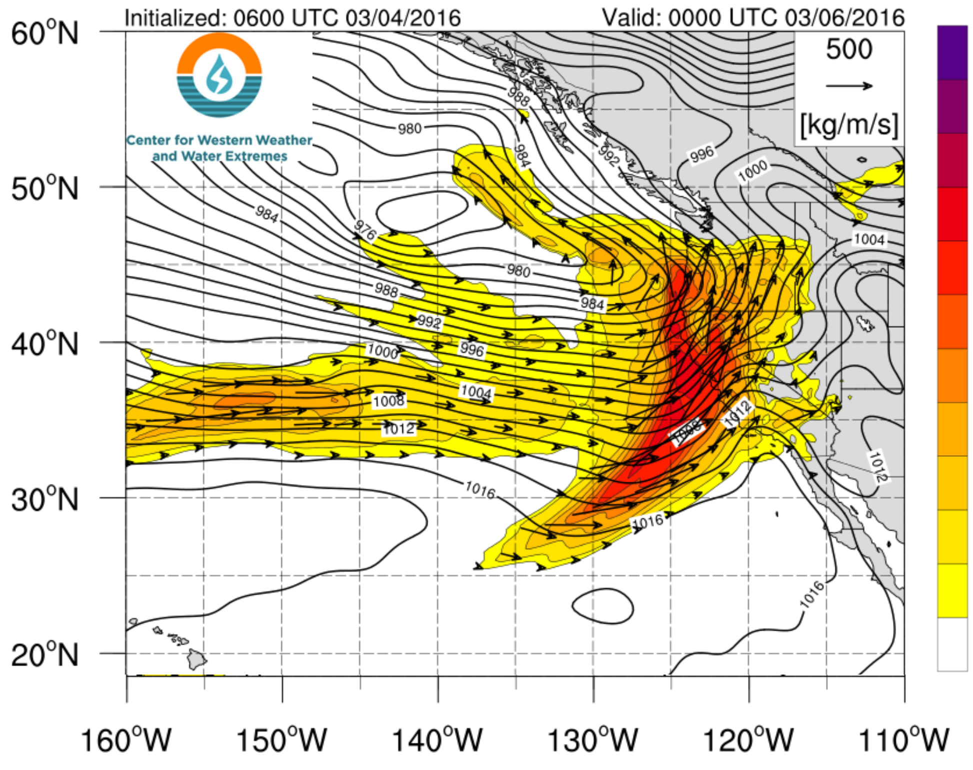
Atmospheric River Forecast Example

Incoming storm of 5-7 March 2016 has characteristics of an atmospheric river

- Strikes mostly northern and central California
- Moderate strength
- Average duration at landfall (12-24 hours)



NCEP GFS IWV (mm; shaded), 850-hPa Wind (vectors), and SLP (hPa)



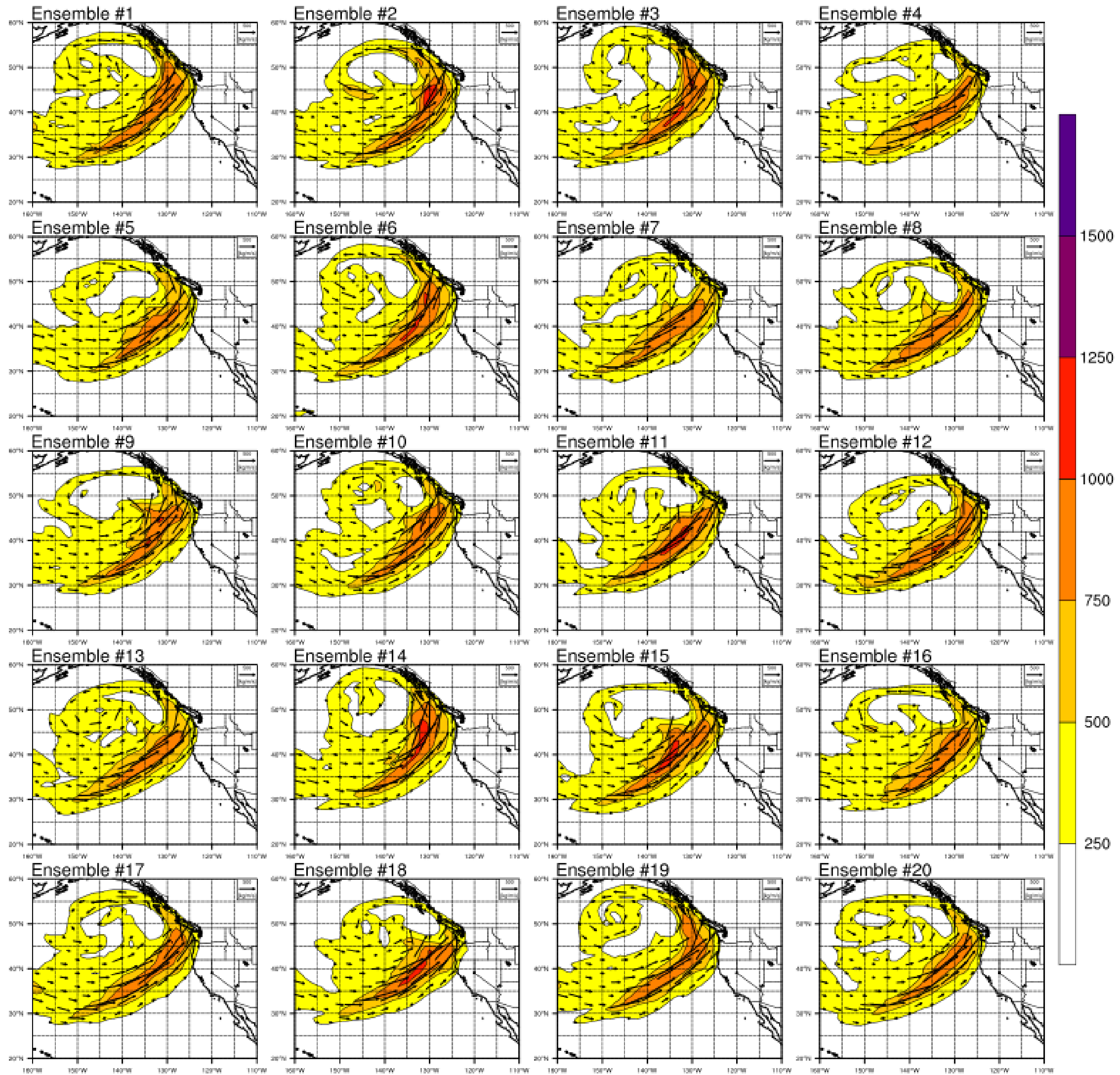
NCEP GFS IVT (kg/m/s; shaded), IVT Vector, and SLP (hPa; contours)

Summary by F.M. Ralph 8 AM PT Fri 4 March 2016

“Ensemble” prediction of ARs

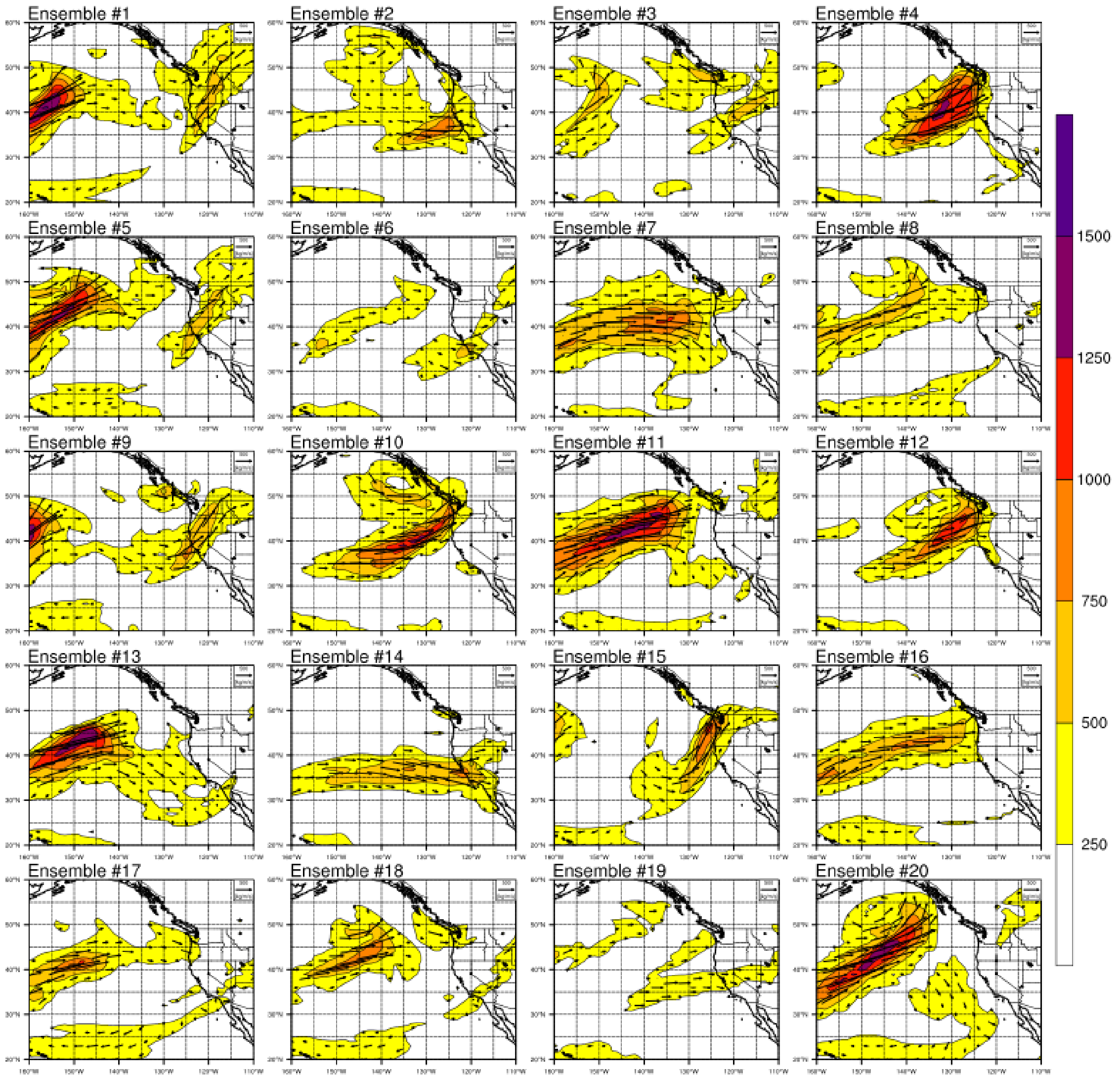
3-days lead time

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



8-days lead time

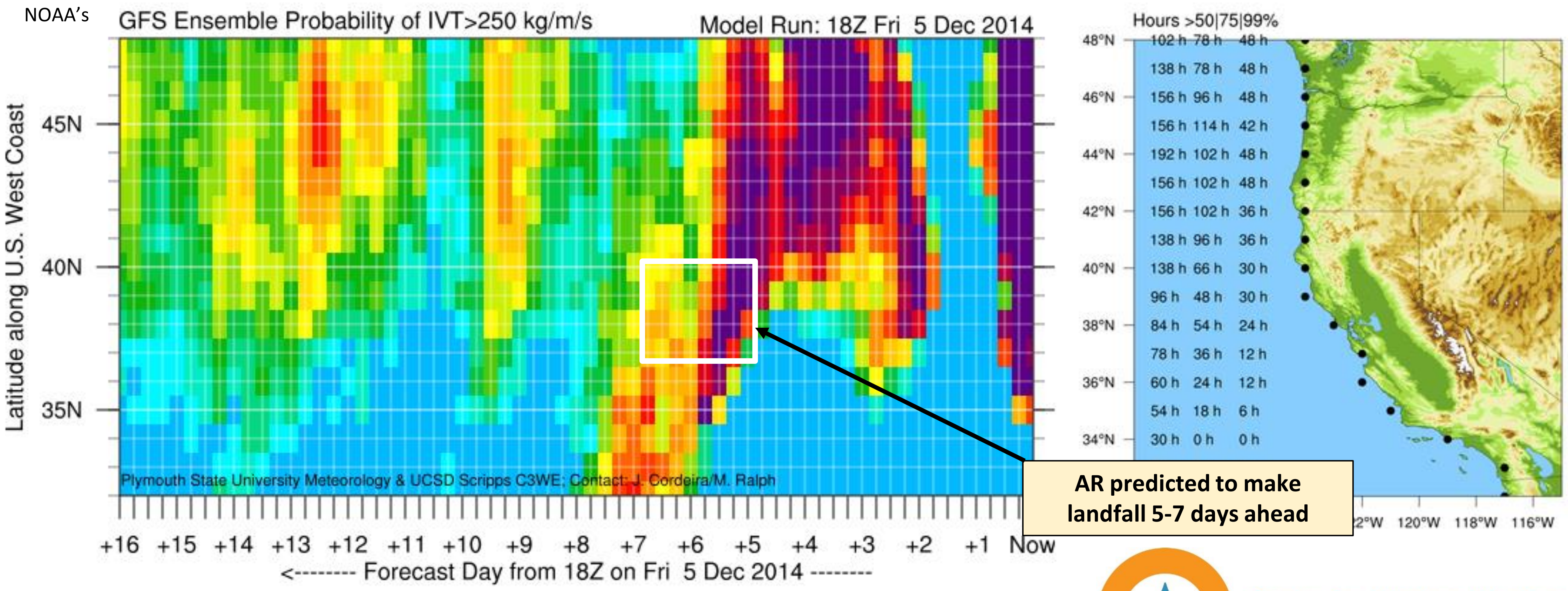
GFS Ensemble IVT (kg/m/s) valid 12Z Thu 12/10/15 | F+192h



Example of a new AR Forecast Tool: Dec 2014

From J. Cordeira of Plymouth State Univ. and Scripps/CW3E
Available real-time at cw3e.ucsd.edu

NOAA's



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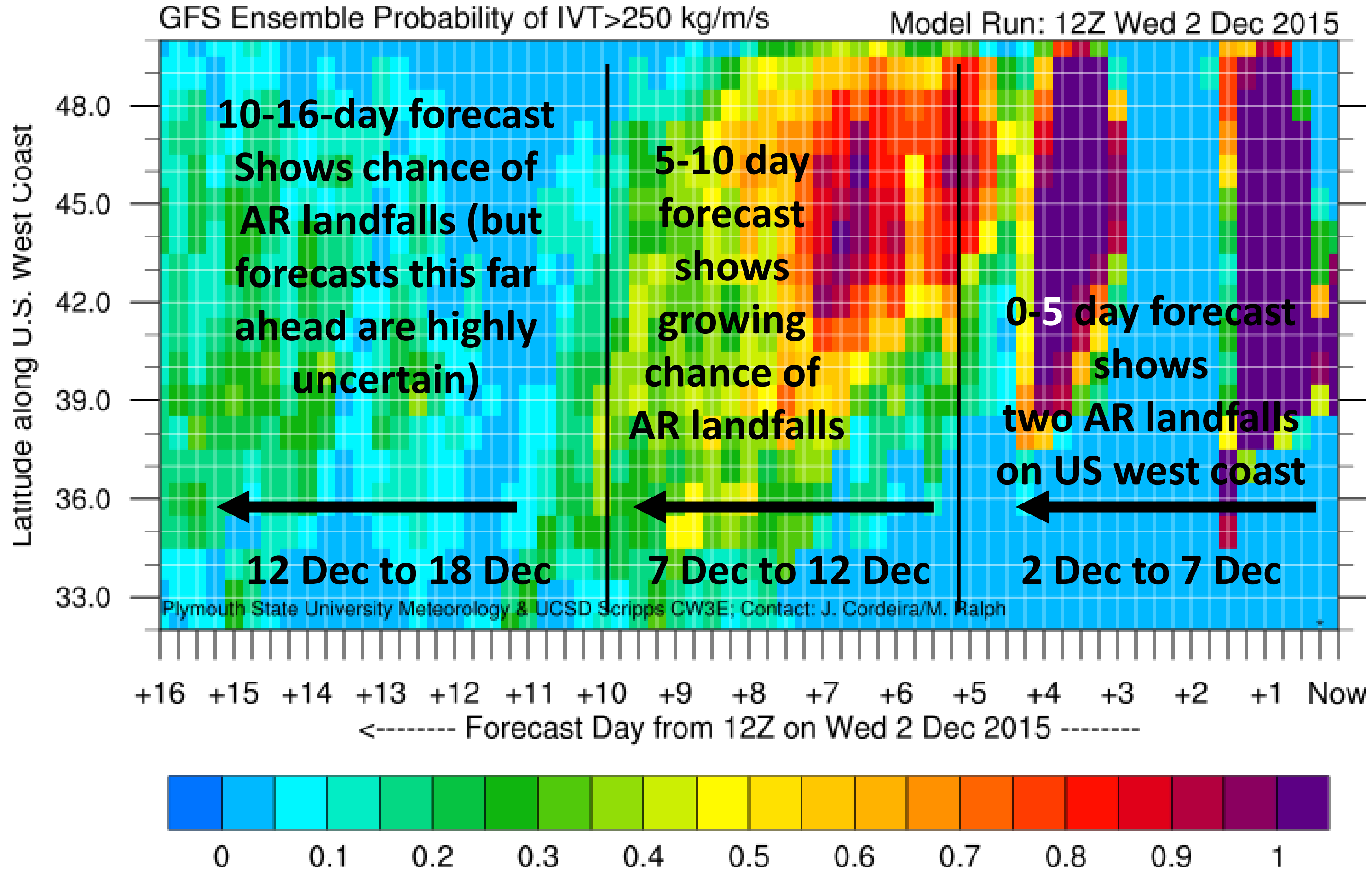
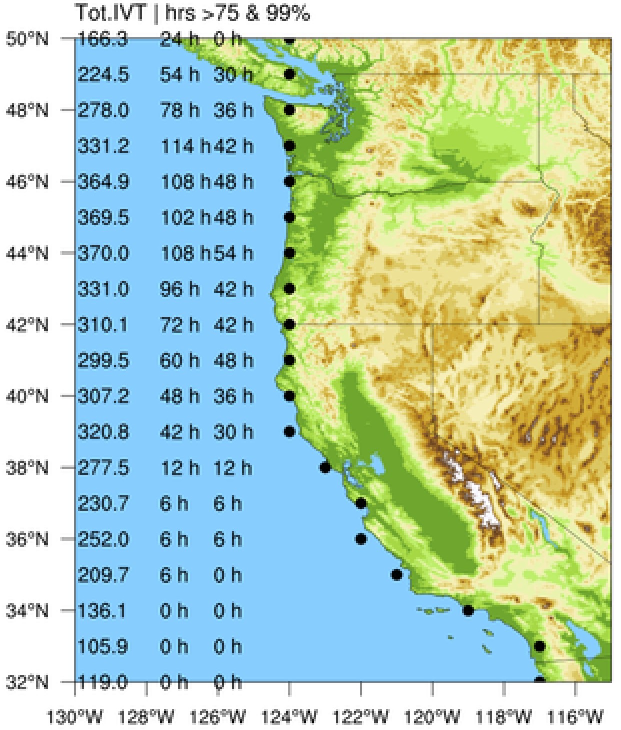
Weekly Lead-times

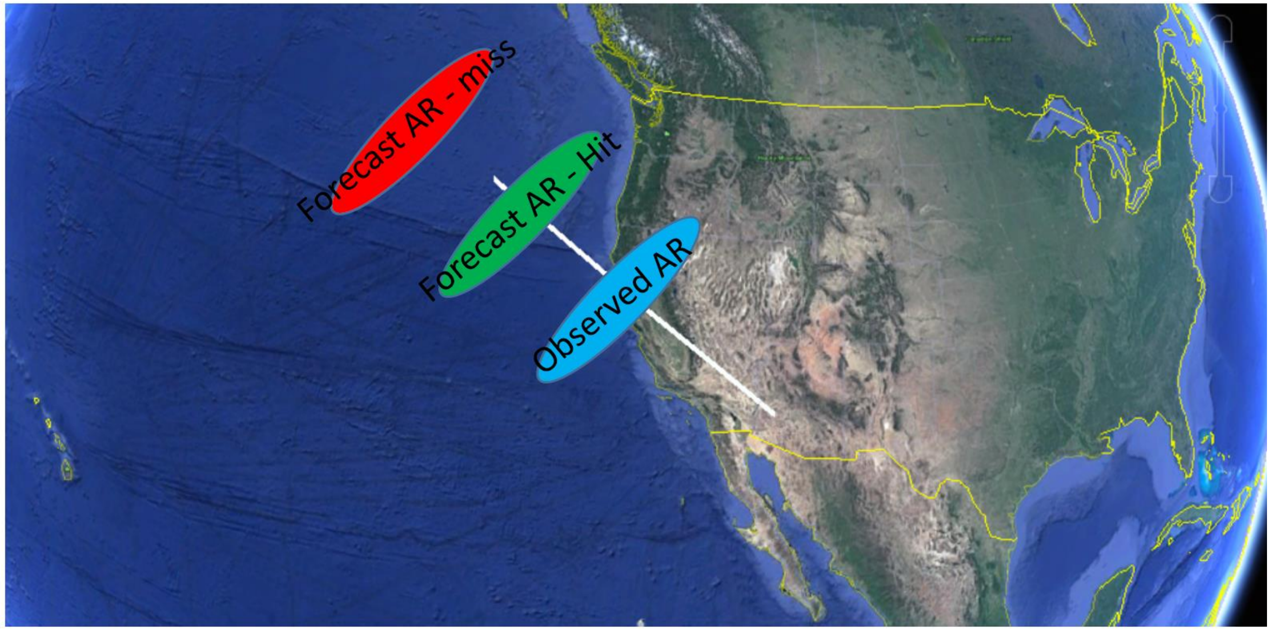
Forecast chances of landfall of at least WEAK Atmospheric River conditions on the U.S. West Coast from 2-18 Dec 2015 - updates available at cw3e.ucsd.edu *(Cordeira et al. BAMS 2016, in press)*





This AR Landfall probability tool is from a partnership between Plymouth State Univ. (Cordeira) and CW3E (Ralph and Kawzenuk)

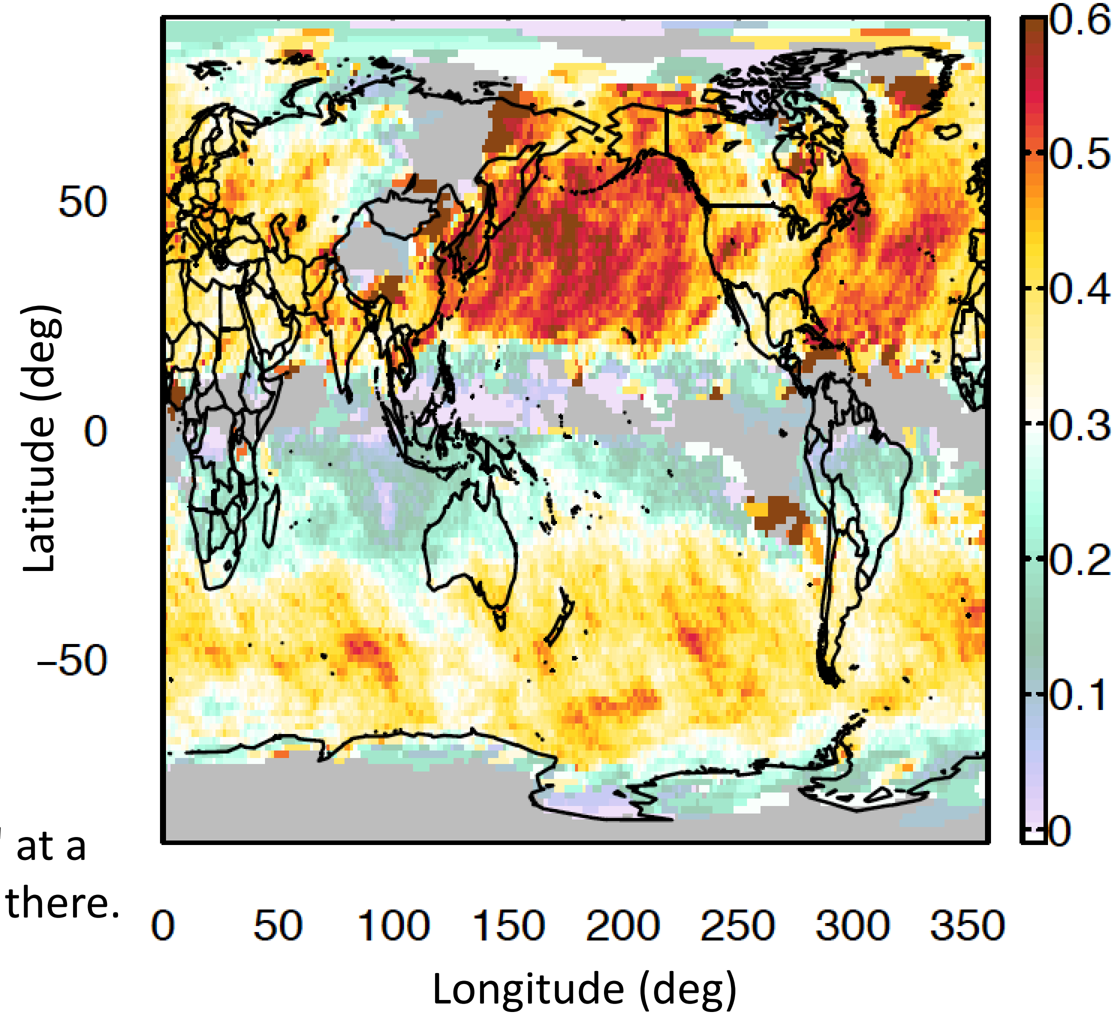
"1000km" AR hit threshold



Preliminary results from DeFlorio, Guan and Waliser

Encouragingly, there is some skill in predicting atmospheric rivers a week ahead in west coast's wettest season (Dec-Feb)

December through February



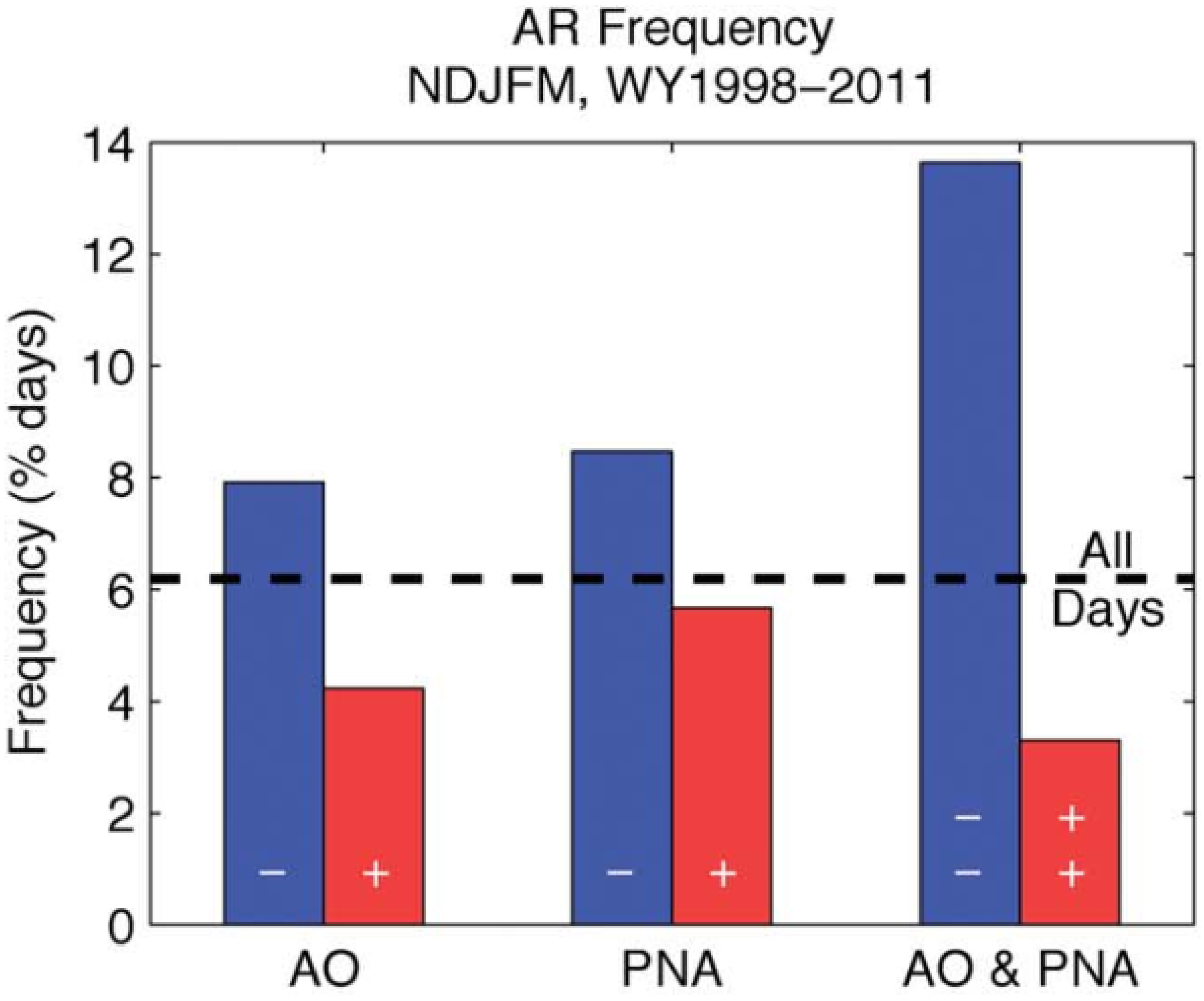
ECMWF 1996–2013 prediction skill, 1wk lead (1000km thresh)

The shading represents the average fraction of ECMWF ensemble members that record a "hit" at a given grid cell when an observed AR is present there.

Orange and red areas have some skill with 1-week lead time in predicting the presence of an AR within 1000 km of that location.

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)



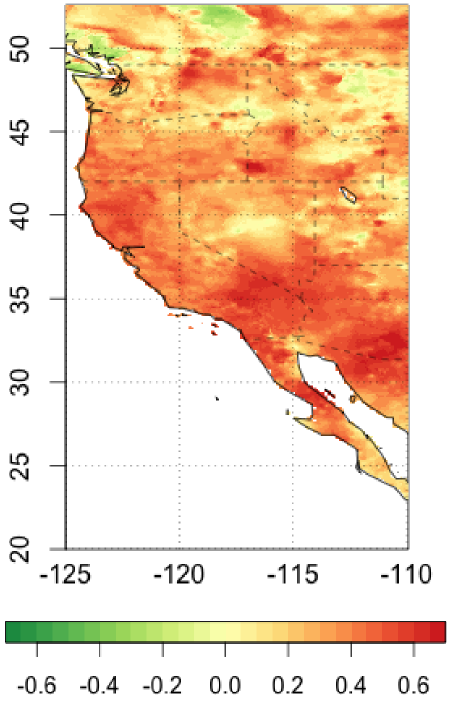
Arctic Oscillation (negative , i.e., southward cold-air outbreaks) combined with Pacific North American "teleconnections" pattern (negative, southern storm track). Favors Atmospheric river conditions striking the Sierra and causing precipitation

Canonical Correlation Analysis

CCA Predictability: JFM, 1950-2013

Predictor: JFM SST

Predictand:
JFM totPRCP anomaly %
Skill: PCs = 8, CCs = 8

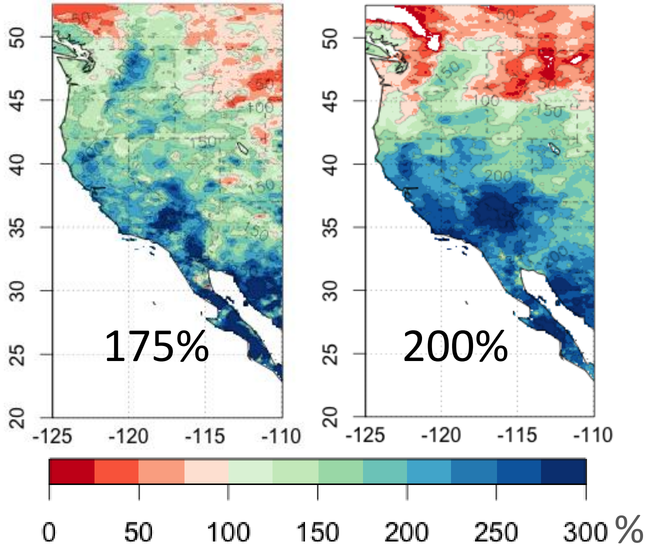


Cross-validated skill: correlations of predicted vs. observed JFM precipitation

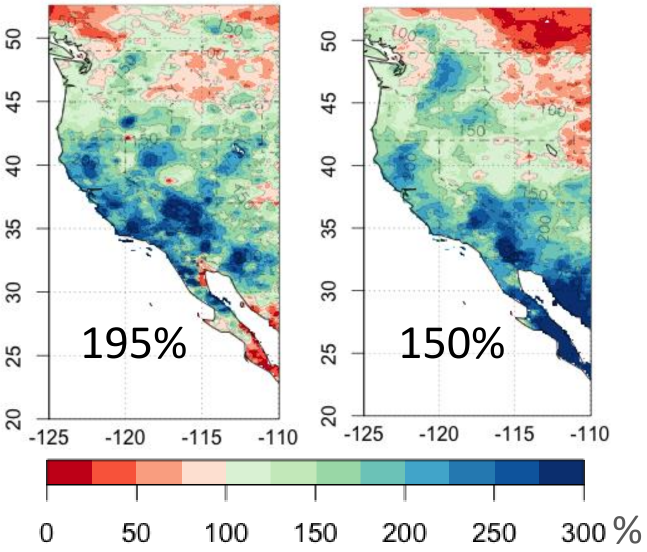
Gershunov and Cayan, *J. Clim.* (2004)

CCA Prediction Model: PRCP anomaly, JFM, 1983/1998/2016

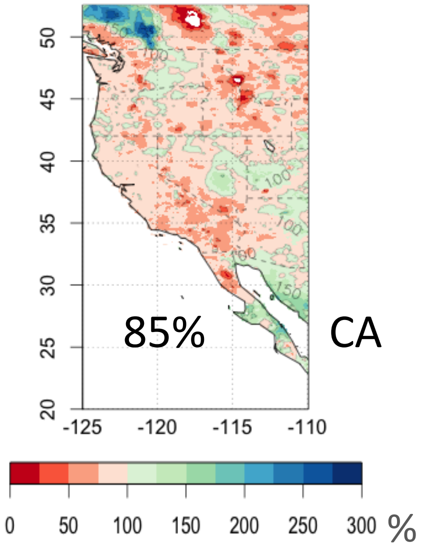
All PRCP anomaly (%), JFM 1983



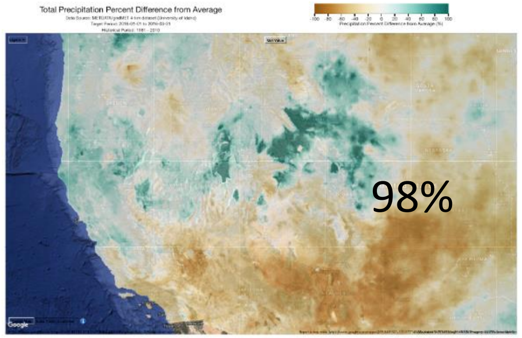
All PRCP anomaly (%), JFM 1998



All PRCP anomaly (%), JFM 2016



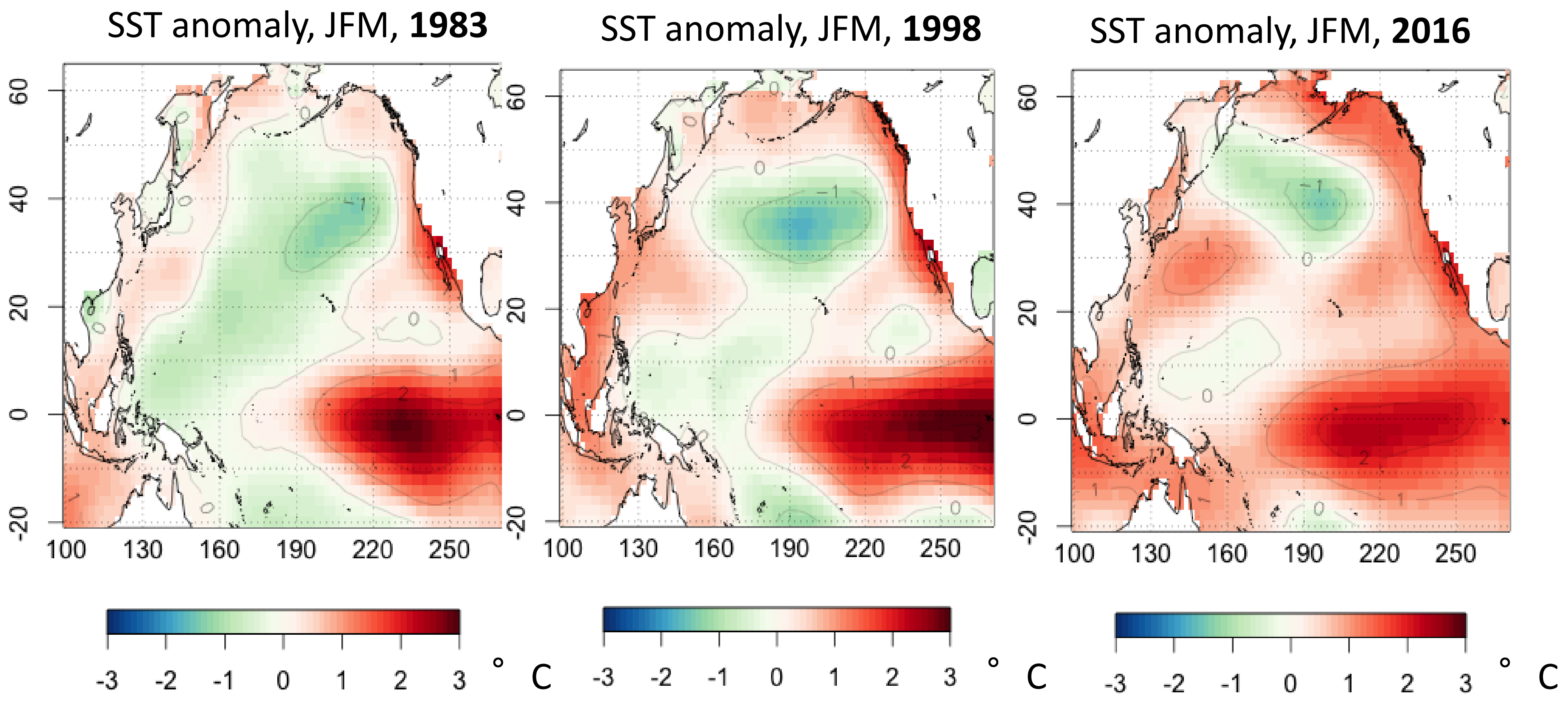
Observed



Slide courtesy of
A. Gershunov and
T. Shulgina, CW3E

20 September 2016 - DWR and NWS Workshop: What if 2017 is Dry?

CCA Prediction Model – SST differences



Slide courtesy of
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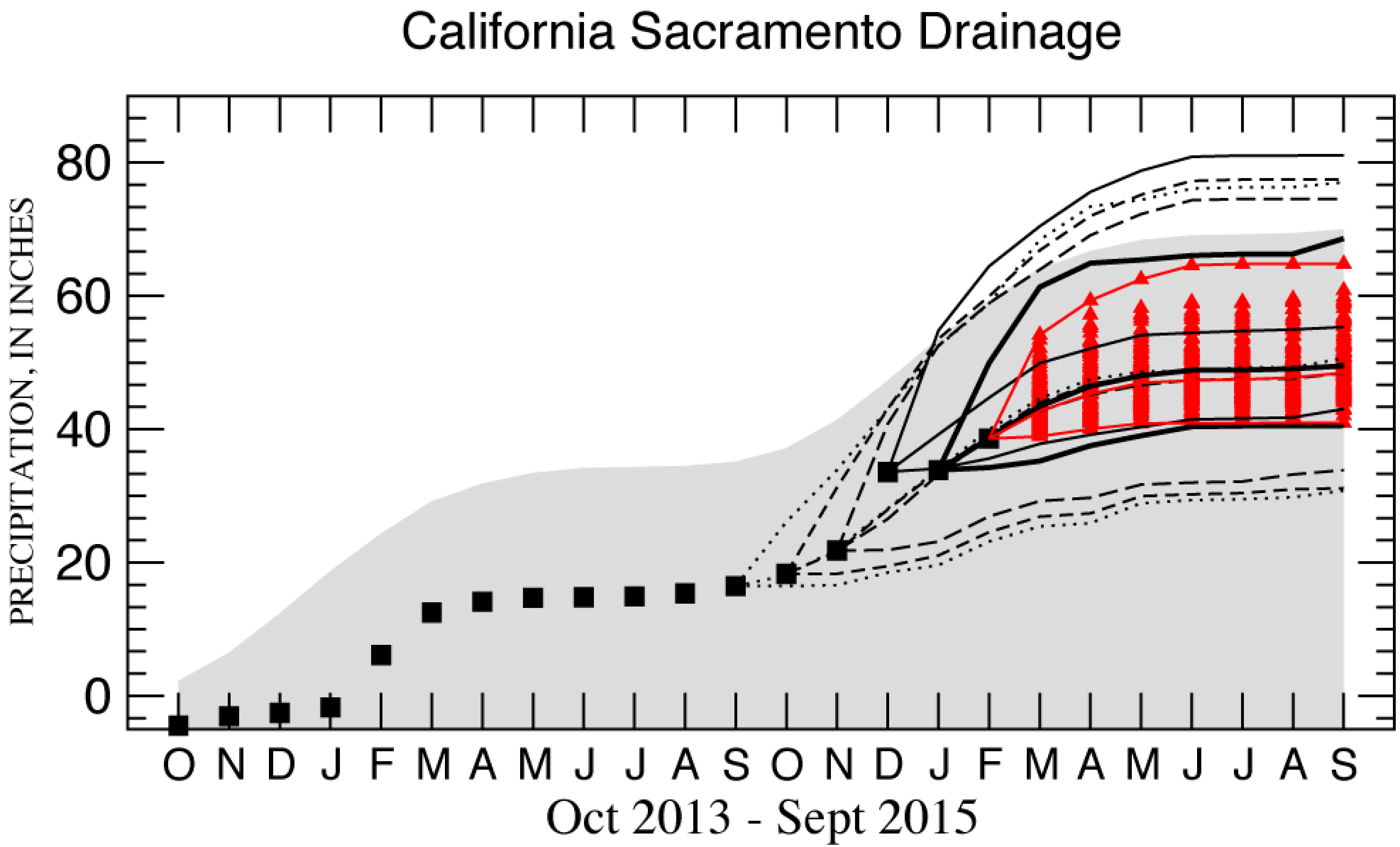

Courtesy of Mike Dettinger

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SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

CW3E Post-Event Summary 21-22 September 2016

Brian Kawzenuk, Meredith Fish, F. Martin Ralph, Brian Henn

Discussion

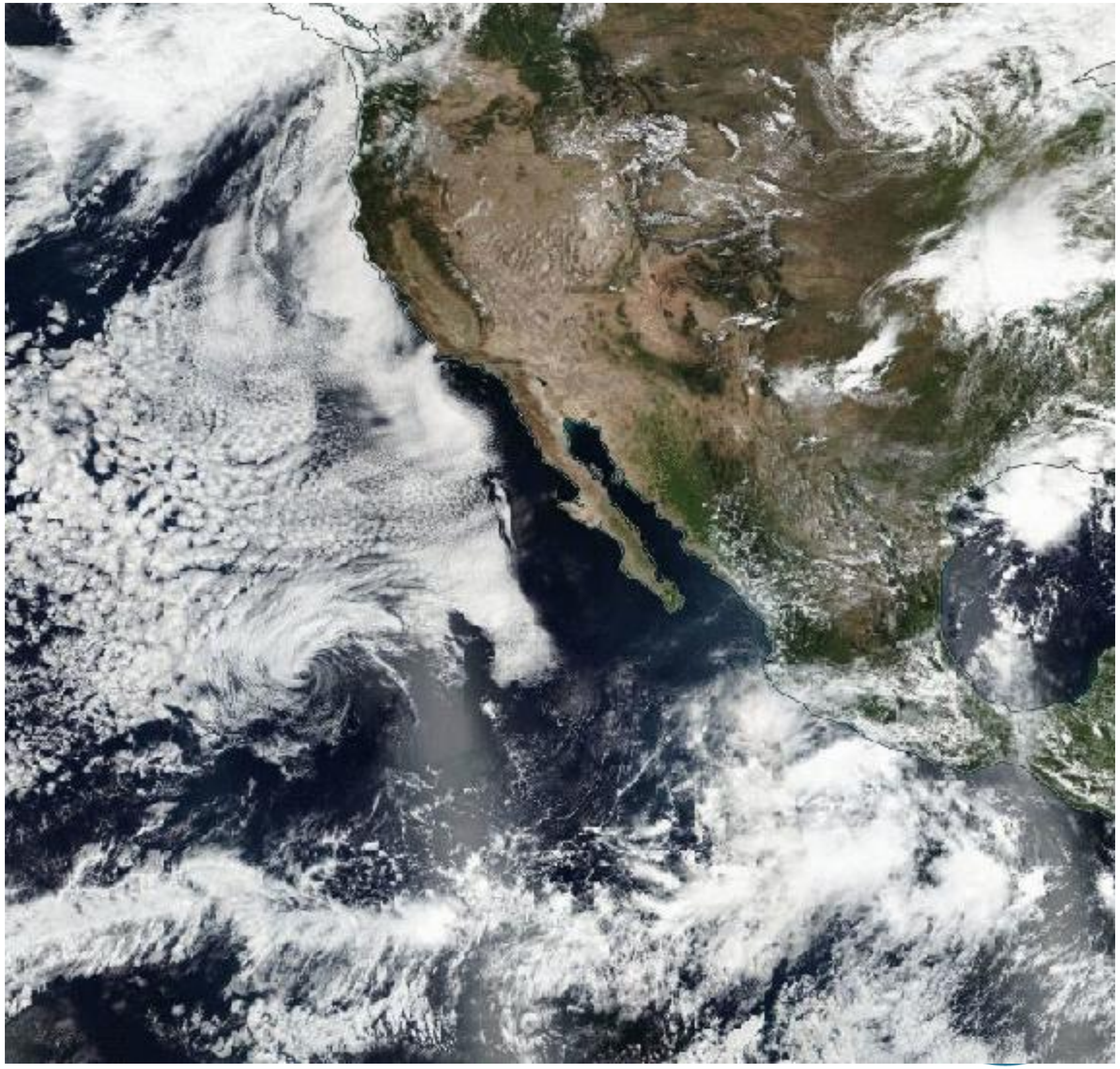
- Former Hurricane Paine moved North off the Baja California coast prior to making landfall as a Post-Tropical Depression over central Baja California

- Paine was considered a hurricane for <24 hours (Sep 19) with maximum sustained winds >90 mph

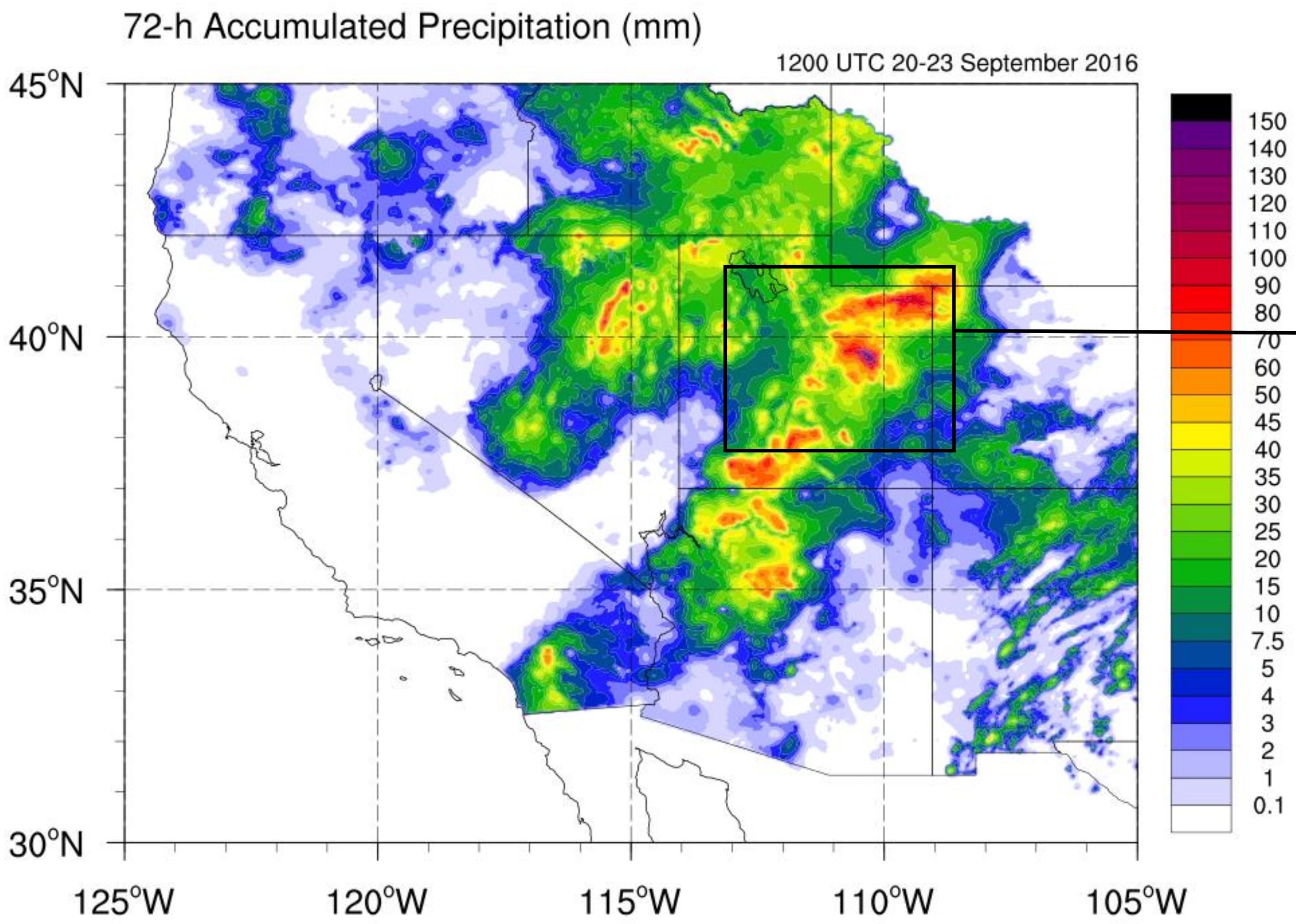
- Despite being dissipating prior to landfall moisture in advance of Paine moved inland over the Southwestern U.S. and produced heavy precipitation in California, Arizona, Utah, and Nevada

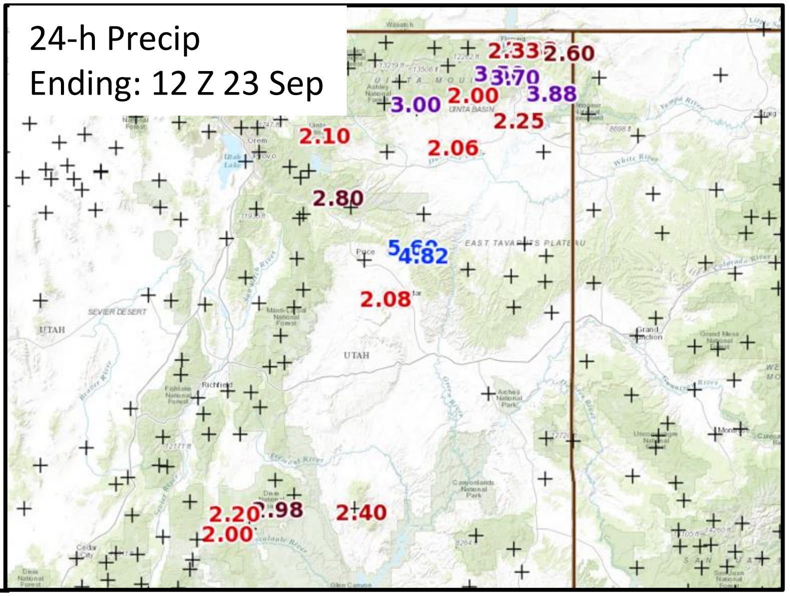
- Moisture from Paine interacted with a weak mid-latitude cyclone over UT and produced heavy precipitation and thunderstorms

MODIS (Moderate Resolution Imaging Spectroradiometer) true-color during 17-24 Sep 2016



Gridded Precipitation

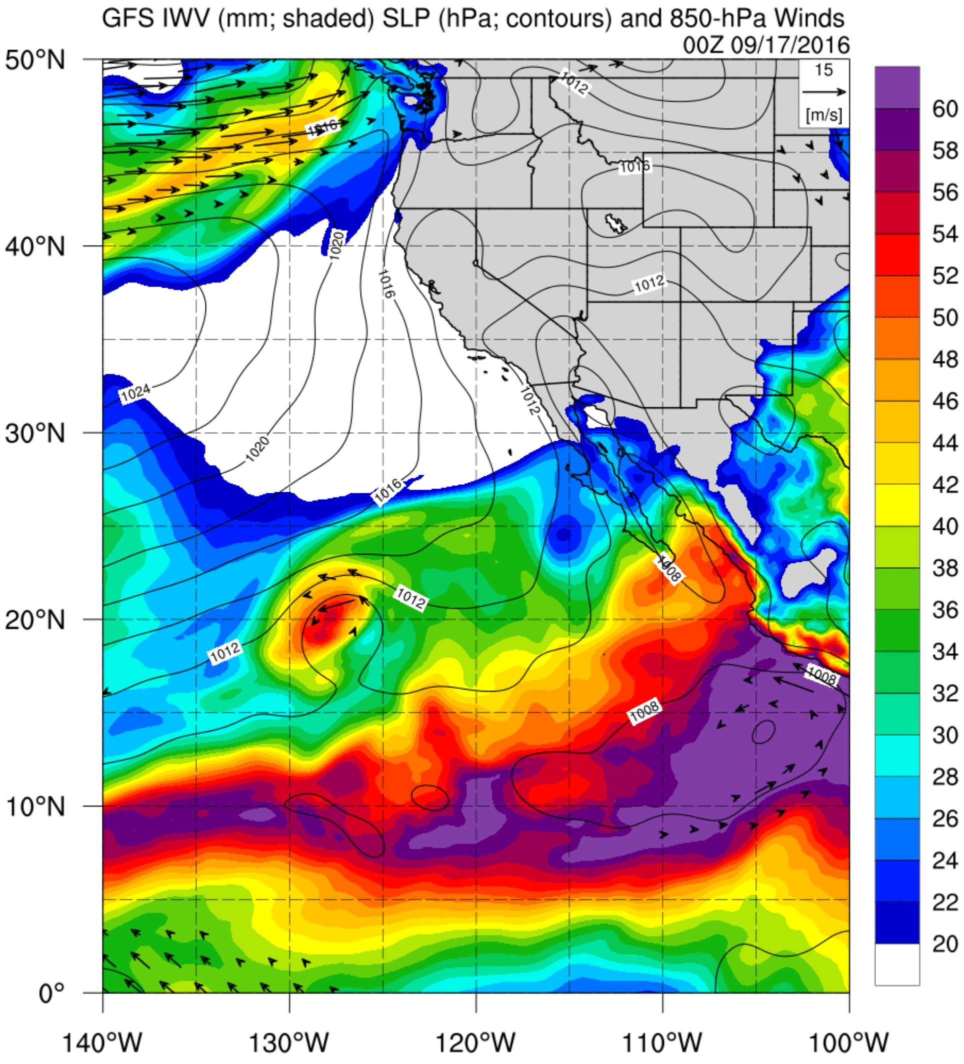


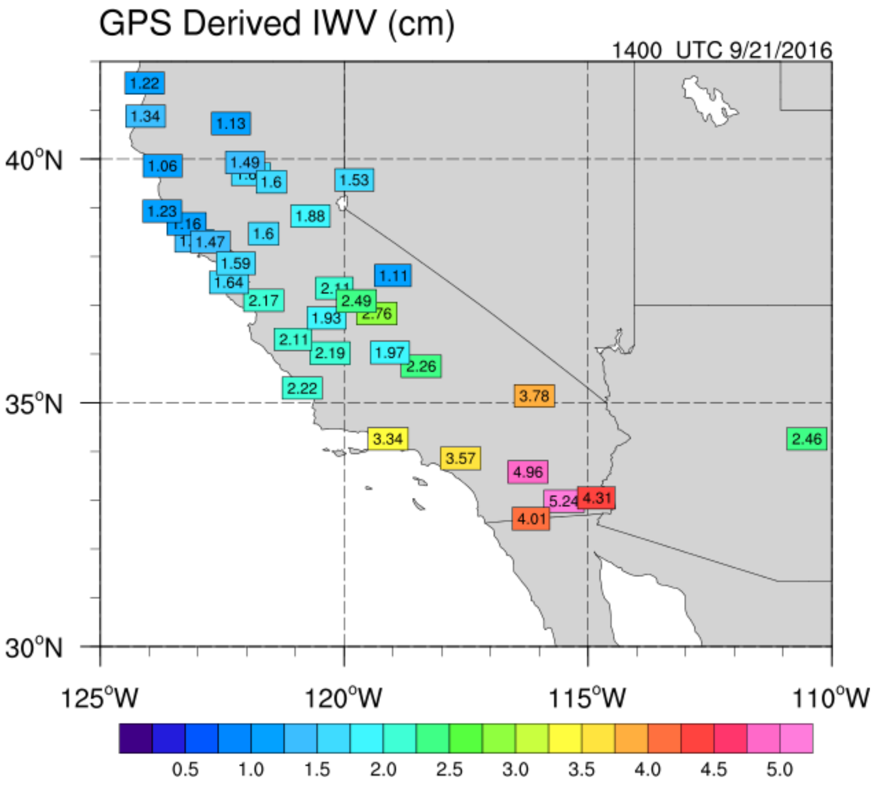


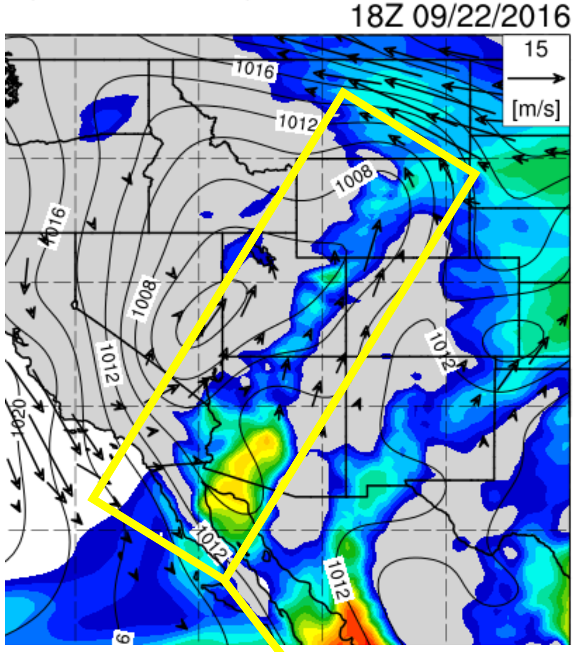
- Stage IV precipitation data shows up to 150 mm (~6 in.) of 72-hr accumulated precipitation occurred over the Southwestern U.S.
- Several individual rain gauges in Arizona and Utah showed > 5 in. of precipitation

CW3E

Integrated Water Vapor







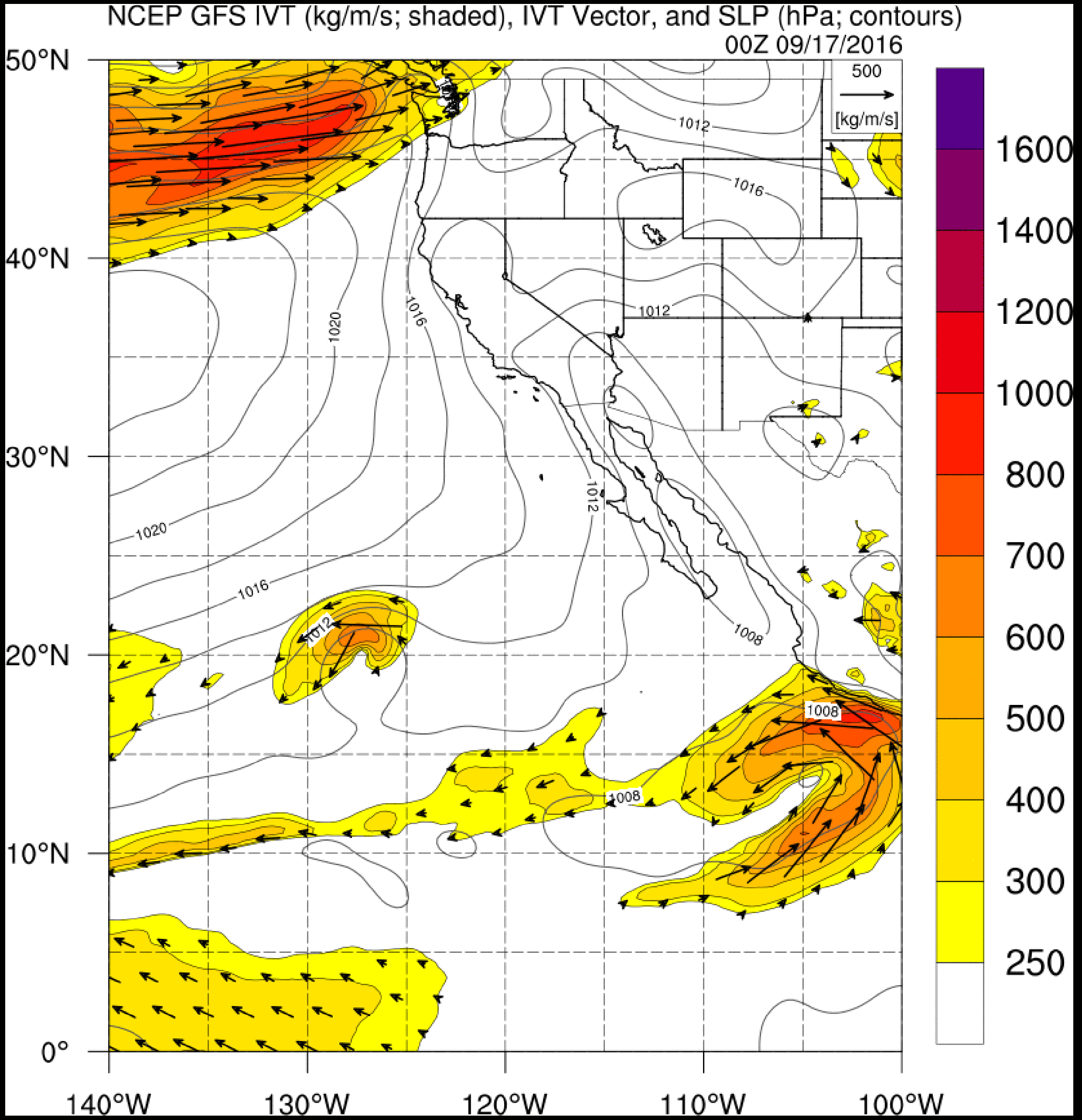
Highest precipitation amounts produced along thin corridor with highest IWV

- Integrated water vapor (IWV) >5 cm associated with former Hurricane Paine moved inland over California and Arizona
- The moisture originated and was transported out of the tropics to the mid-latitudes

CW3E

Integrated Vapor Transport

- Due to high moisture content and high winds Hurricane Paine had high values of integrated vapor transport (>1600 kg m^{-1} s^{-1})
- IVT >500 kg m^{-1} s^{-1} penetrated inland over the southwestern U.S.
- IVT was oriented from the south and moved through the Colorado River lowlands inland
- This system produced Atmospheric River Conditions (IWV >20 mm and IVT >250kg m^{-1} s^{-1}) over most of SW U.S., however, this is not considered an AR as it was not a long, filament-like structure.

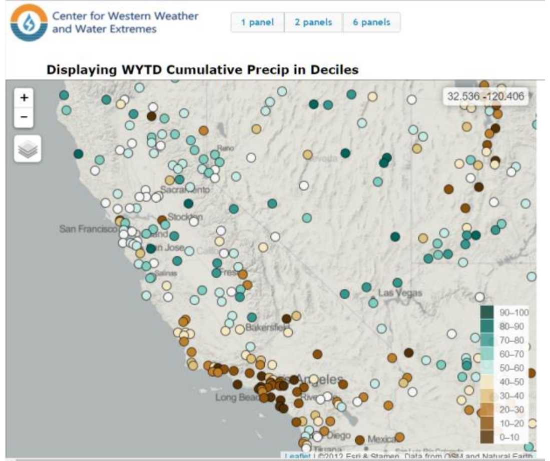


Steamboat CO 24 Sept 2016

CW3E

Available at CW3E.UCSD.EDU

1. Accumulated precip so far this water year, at *stations*



- Long time series high quality GHCN stations
- Also shows El Nino/La Nina response at stations
- Scroll/pan/zoom map with station results

http://cirrus.ucsd.edu/~pierce/staweb/

2. *Regional* WYTD accum precip in historical context

- Plus 1-, 2-, and 3-day changes, in context
- All CA, plus selected regions
- (8-station index, LA basin, etc.)

http://cirrus.ucsd.edu/~pierce/sdprecip/

Northern Sierra Nevada 8-Station Index (station list; a traditional indicator of CA water supply)

Current:	109.5%	1-day Δ:	0.00%	2-day Δ:	0.00%	3-day Δ:	0.00%
	(1977/09/26)						
Rec_low:	35.5%	50-ptile:	0.10%	50-ptile:	0.14%	50-ptile:	0.18%
Typ_low:	69.8%	90-ptile:	1.31%	90-ptile:	1.92%	90-ptile:	2.44%
Mean:	100.0%	95-ptile:	2.18%	95-ptile:	3.27%	95-ptile:	4.07%
Typ_high:	134.4%	99-ptile:	4.01%	99-ptile:	6.00%	99-ptile:	7.43%
Rec_high:	172.7%	Record:	11.48%	Record:	20.55%	Record:	25.56%
	(1983/09/26)		(1962/10/12)		(1962/10/13)		(1962/10/14)

3. R-CAT (Rainfall-category) heavy rain alerts

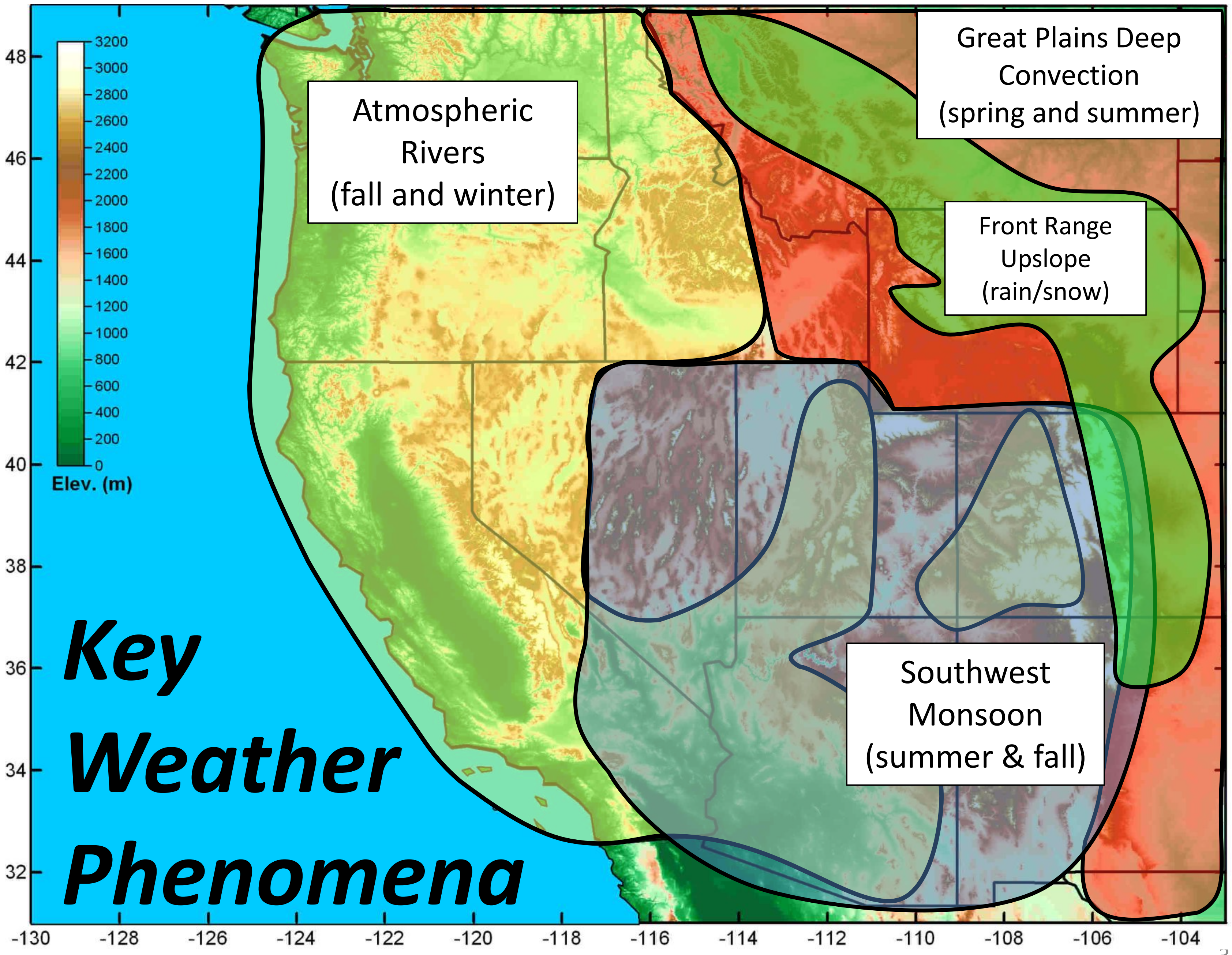
- Automated email service
- Alert sent if R-cat event (>200 mm in past 3 days)
- Based on Ralph and Dettinger (2011, BAMS)
- Uses the same thresholds everywhere for 3-day totals
- R-CAT level 3 & 4 events are as uncommon as EF 4-5 tornadoes or CAT 3-5 landfalling Atlantic hurricanes
- Email shows map of location and amount

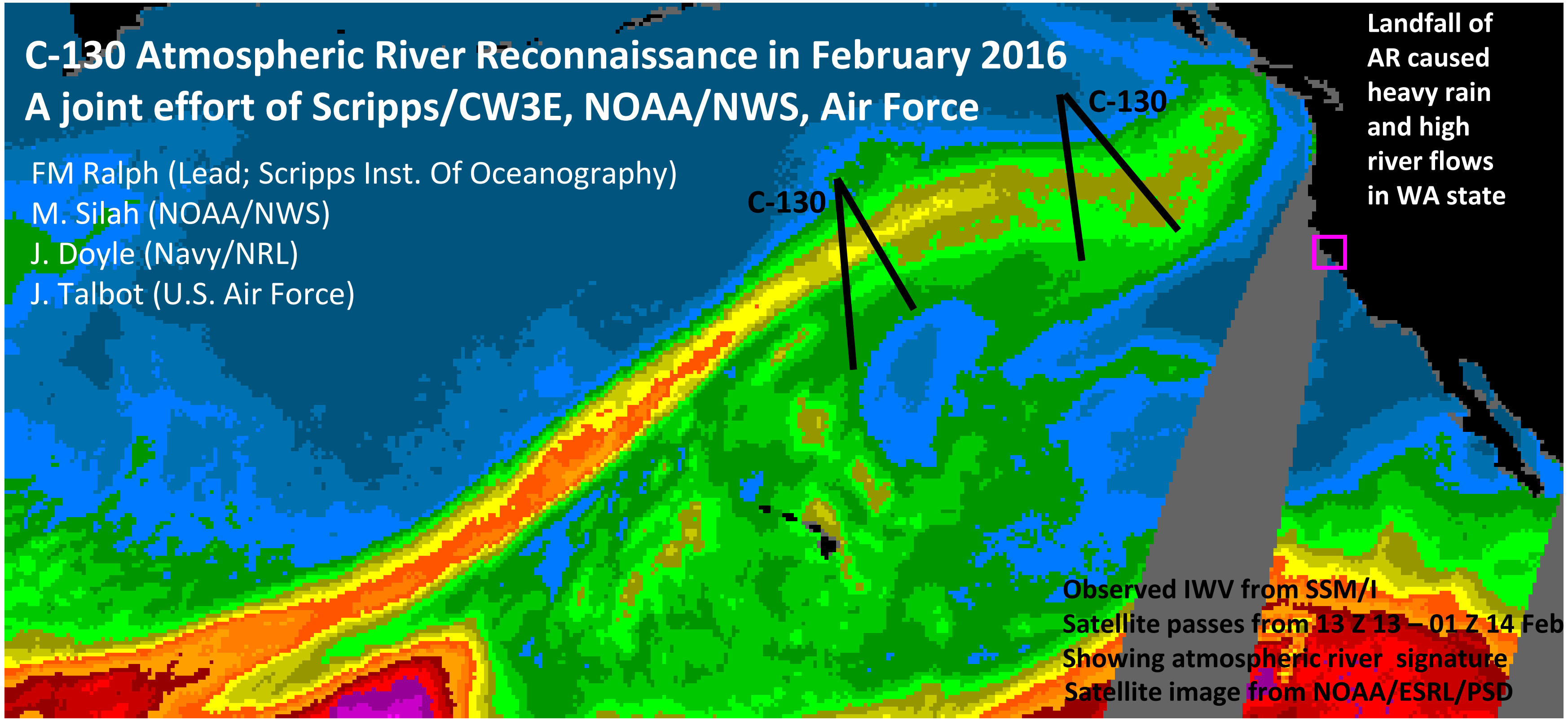
Center for Western Weather and Water Extremes

Email with subject “subscribe” to rcatalert@cirrus.ucsd.edu

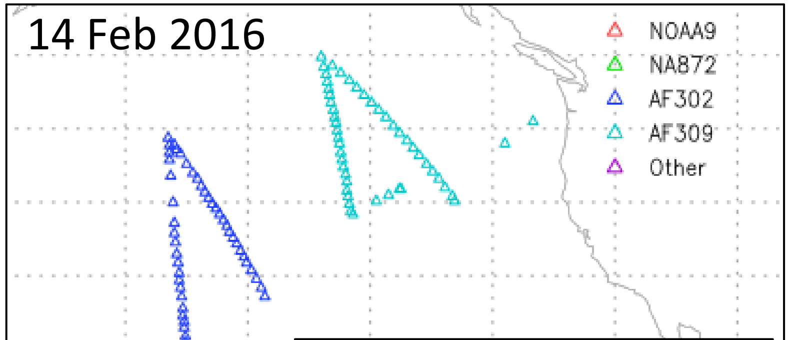

Thank you!

Schematic illustration of regional variations in the primary weather phenomena that lead to extreme precipitation, flooding and contribute to water supply in the Western U.S. (Ralph et al. 2014)





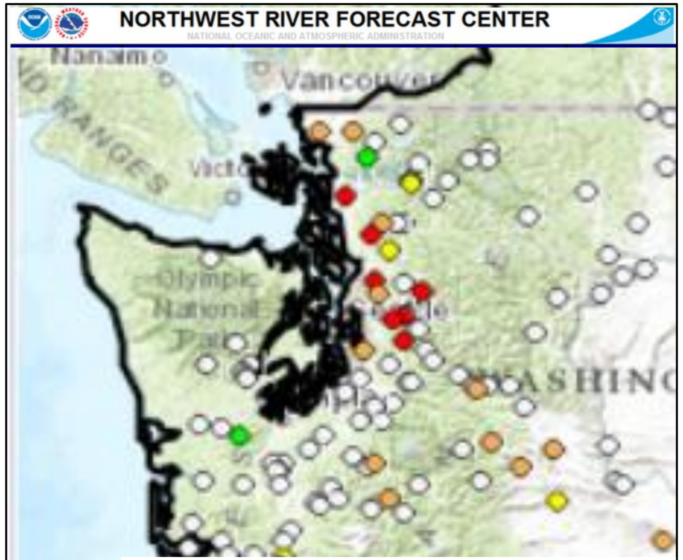
1st C-130 AR Recon Mission
13-14 Feb 2016
Dropsondes released for the
0000 UTC 14 Feb 2016
GFS data assimilation window



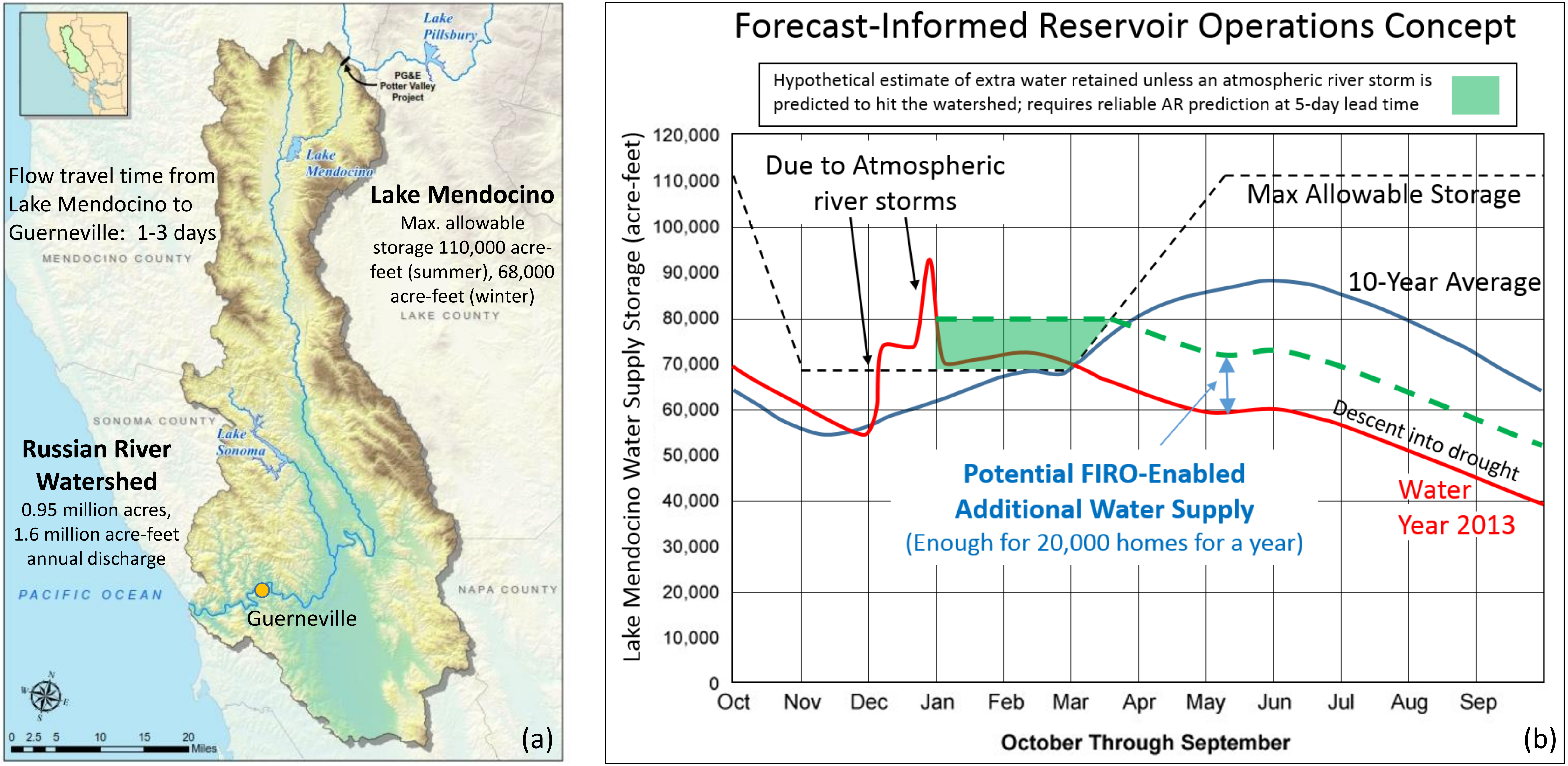
Locations of C-130 AR Recon dropsondes received and successfully decoded into NCEP's production bufr data tanks for assimilation into NCEP/GFS

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)



Lake Pillsbury
PG&E Potter Valley Project
Lake Mendocino
Flow travel time from Lake Mendocino to Guerneville: 1-3 days
Lake Mendocino
Max. allowable storage 110,000 acre-feet (summer), 68,000 acre-feet (winter)
MENDOCINO COUNTY
LAKE COUNTY
SONOMA COUNTY
Lake Sonoma
Russian River Watershed
0.95 million acres, 1.6 million acre-feet annual discharge
PACIFIC OCEAN
NAPA COUNTY
Guerneville
0 2.5 5 10 15 20 Miles
(a)
Forecast-Informed Reservoir Operations Concept
Hypothetical estimate of extra water retained unless an atmospheric river storm is predicted to hit the watershed; requires reliable AR prediction at 5-day lead time
Due to Atmospheric river storms
Max Allowable Storage
10-Year Average
Descent into drought
Water Year 2013
Potential FIRO-Enabled Additional Water Supply
(Enough for 20,000 homes for a year)
Lake Mendocino Water Supply Storage (acre-feet)
120,000
110,000
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
October Through September
(b)

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**

Lake Mendocino

Russian River West Fork

Lake Mendocino Release *Approximate* Travel Time

Hopland → **Cloverdale** → **Healdsburg** → **Guerneville**

14 Miles | + 16 Miles | + 28 Miles | + 16 Miles

Total travel time ranges from 26hrs to 85hrs depending on flow rate (74miles traveled)*

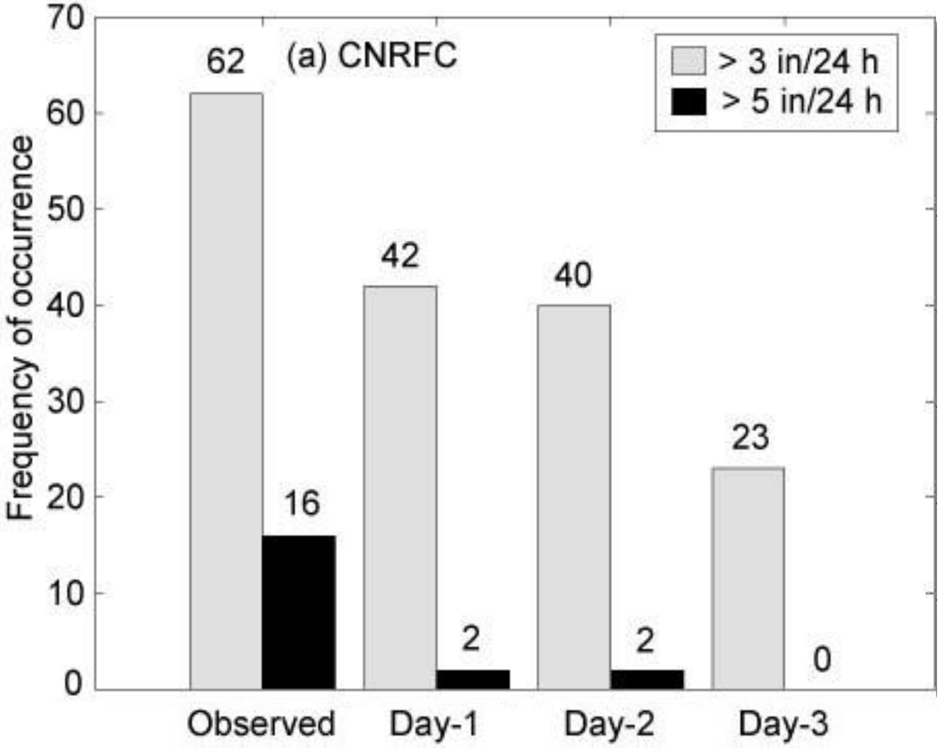
Bottom Line: It takes 2 days to release 10,000 AF at 2500 cfs, plus 1.1 to 3.5 days for water released from Lake Mendocino to get past vulnerable communities downstream. In situations this would be needed, travel times will be on the short end of range.

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

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

The Forecasting Challenge

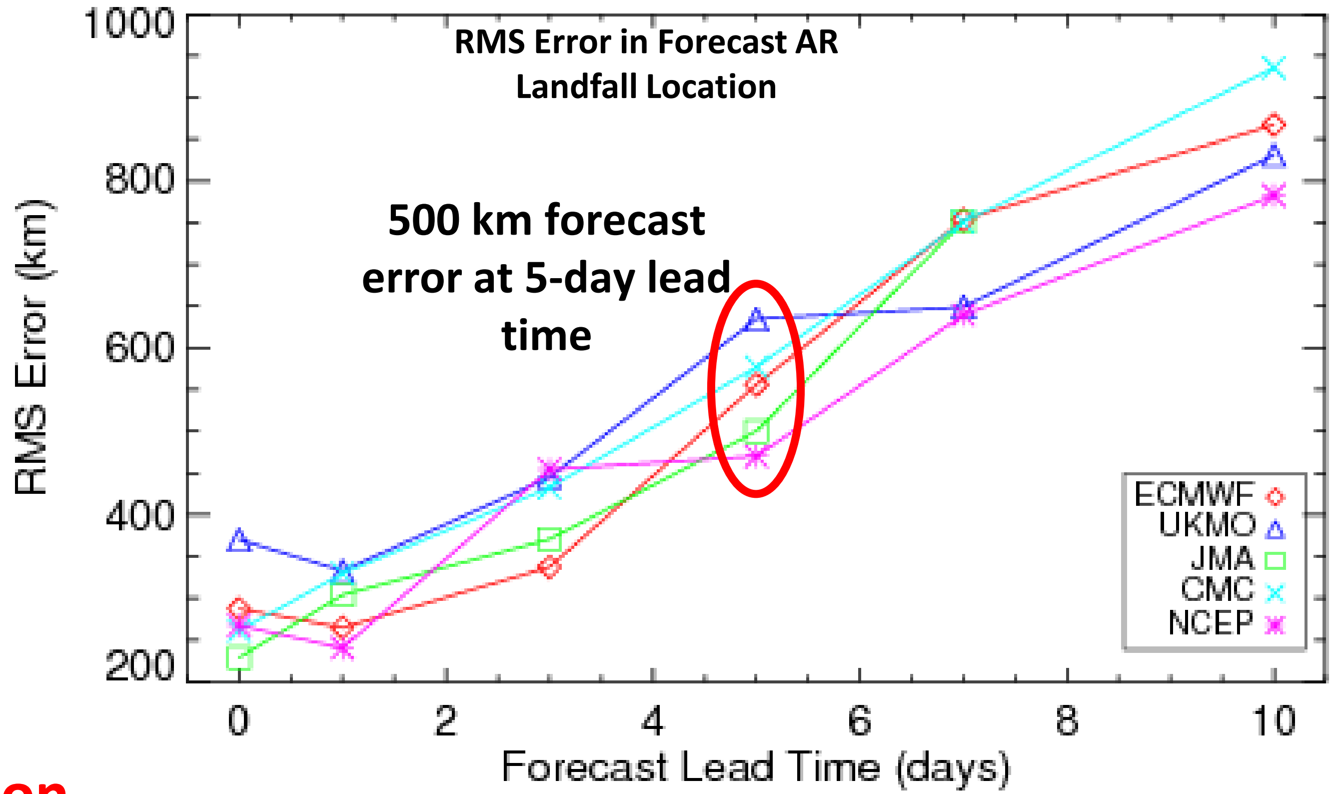
Forecasting large precipitation amounts is difficult



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

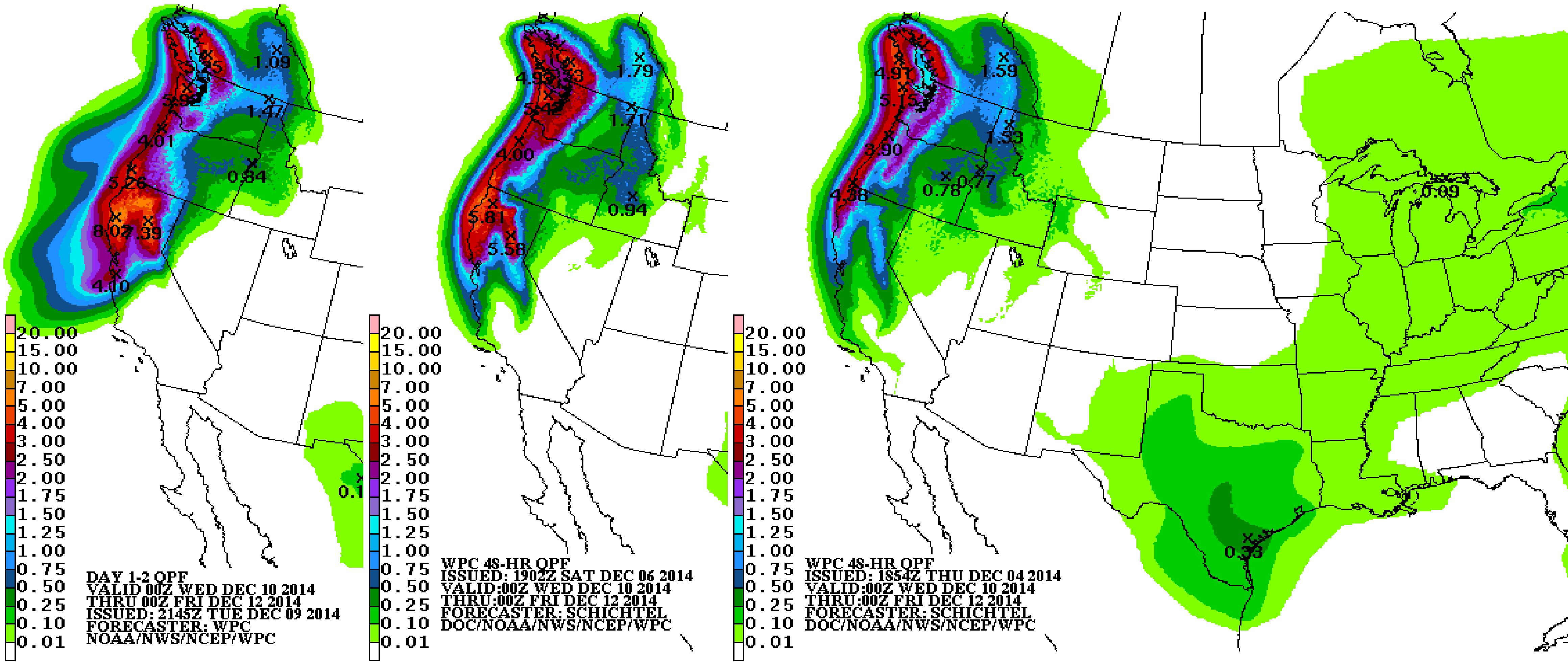
Ralph et al. 2010

Forecasting AR landfall includes position errors larger than watersheds

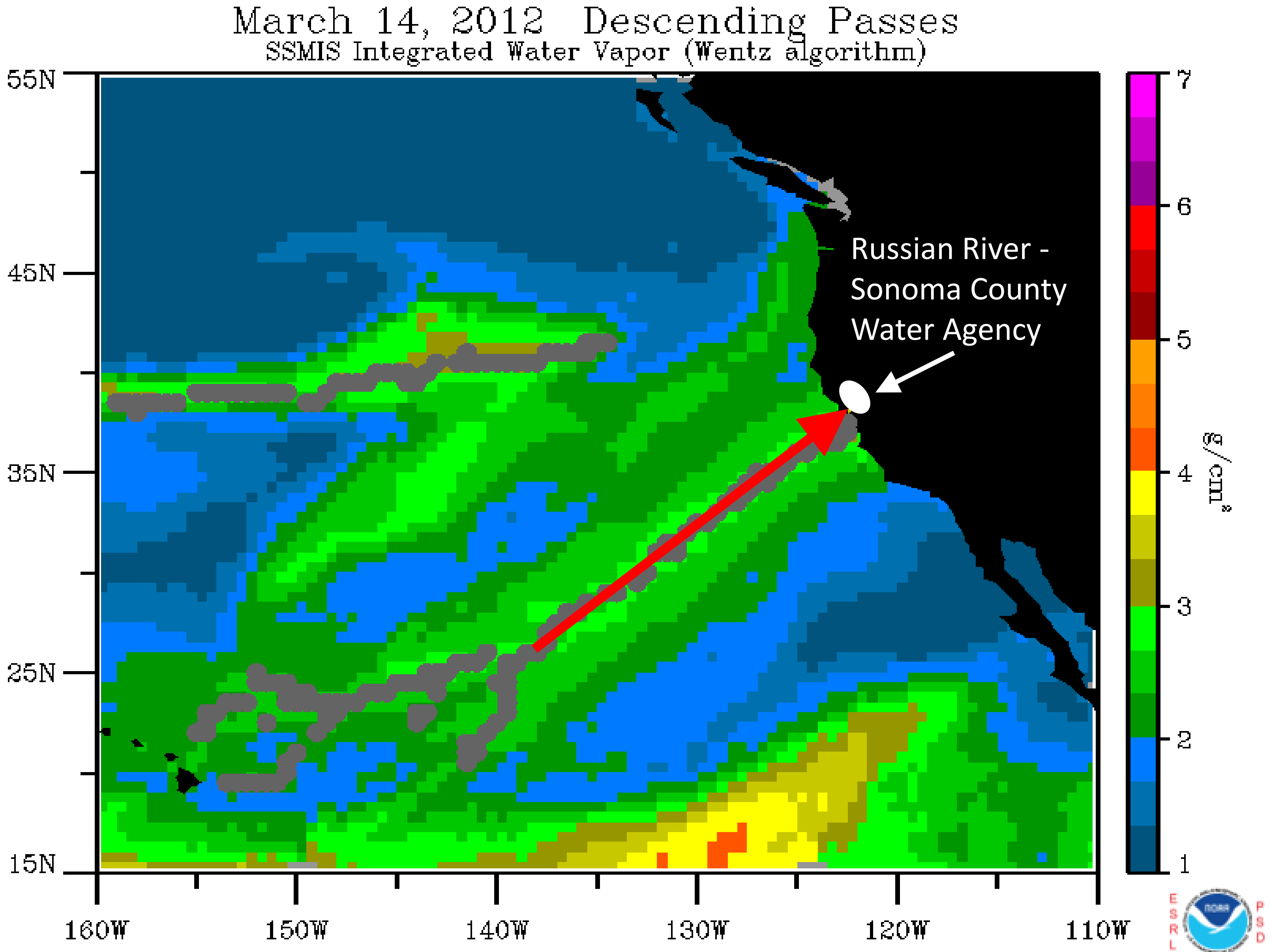


Wick et al. 2013

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

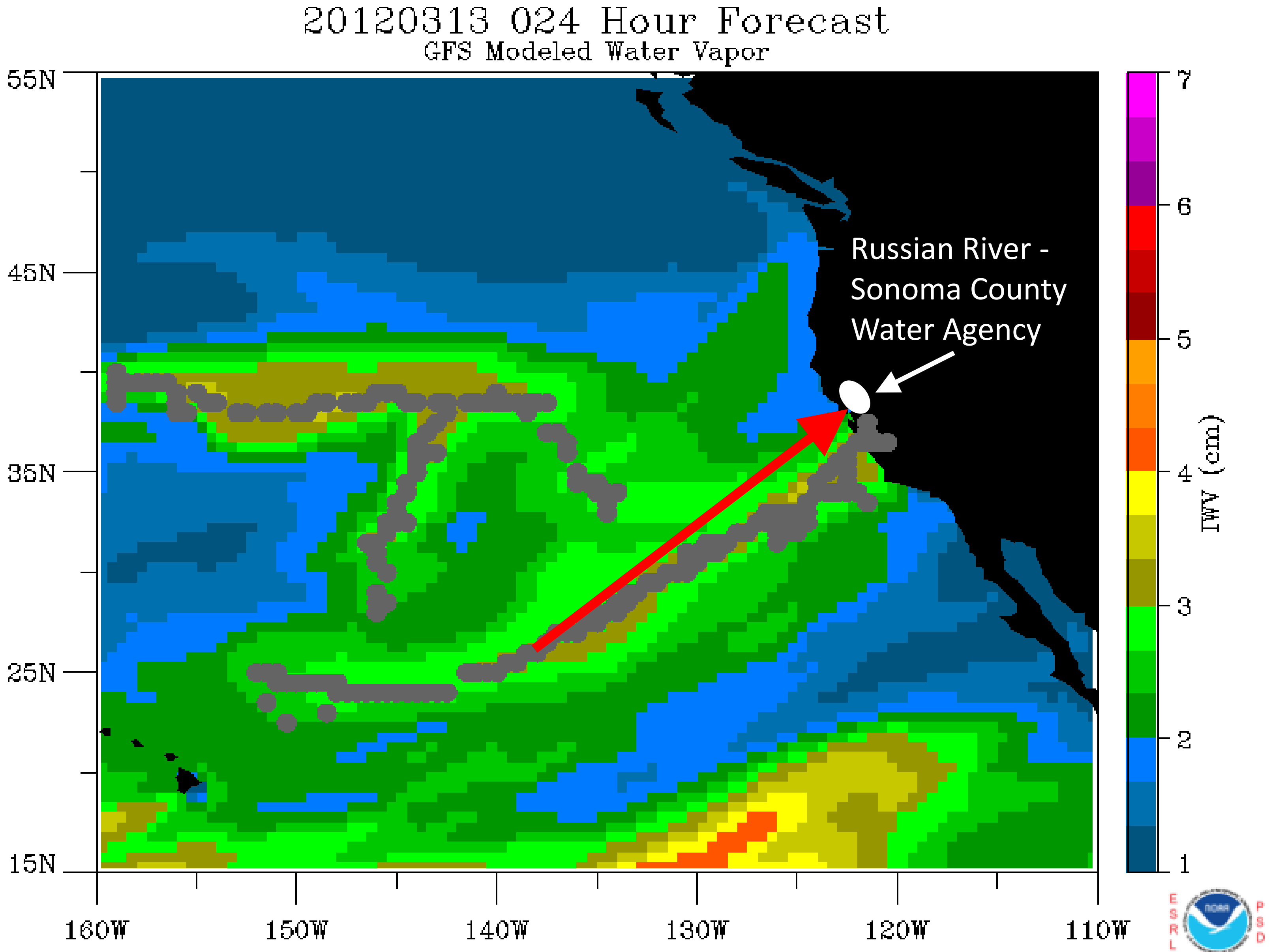


Observed

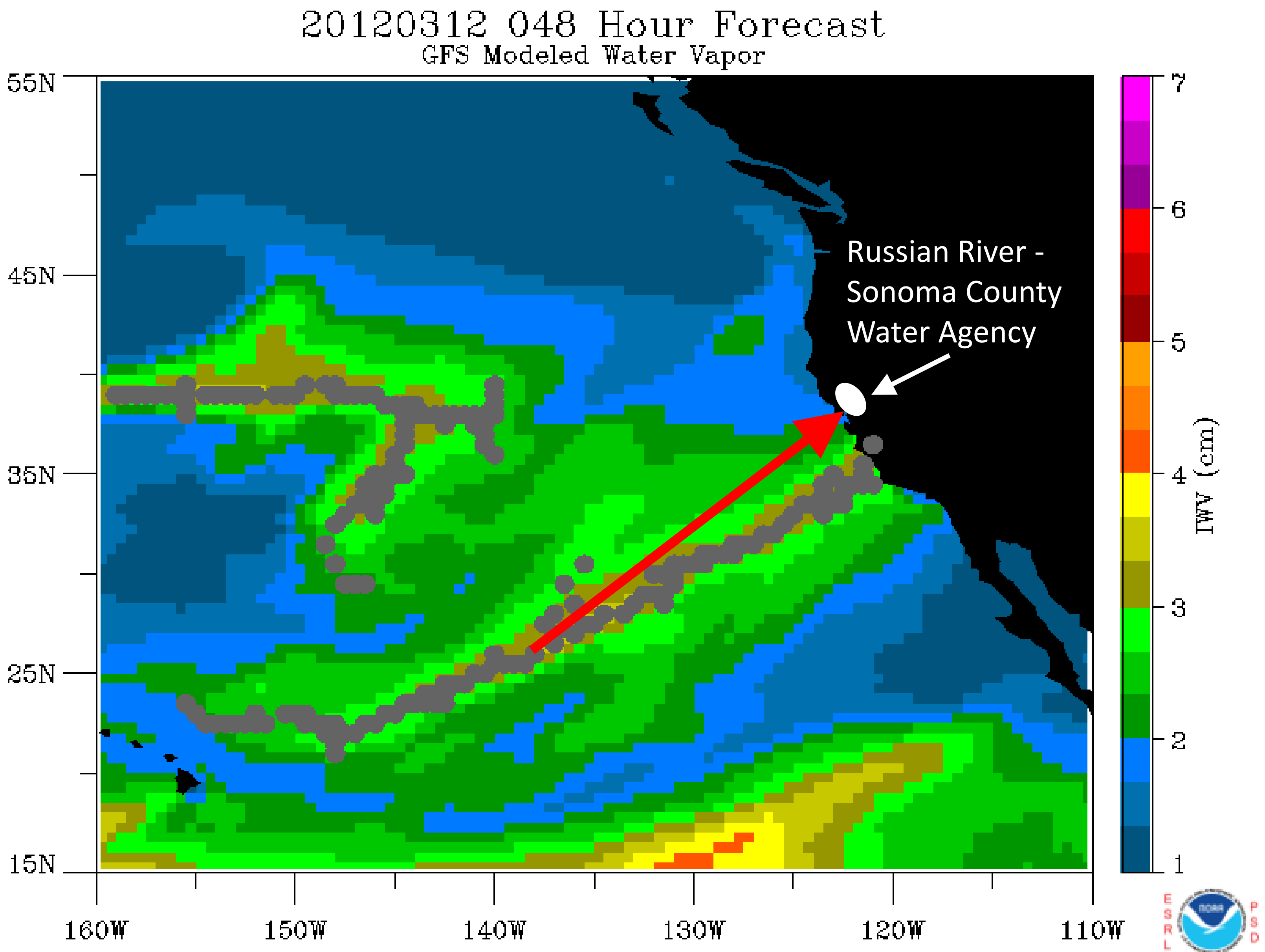


March 14, 2012 Descending Passes
SSMIS Integrated Water Vapor (Wentz algorithm)
55N
45N
35N
25N
15N
160W
150W
140W
130W
120W
110W
Russian River -
Sonoma County
Water Agency
7
6
5
4
3
2
1
g/cm²

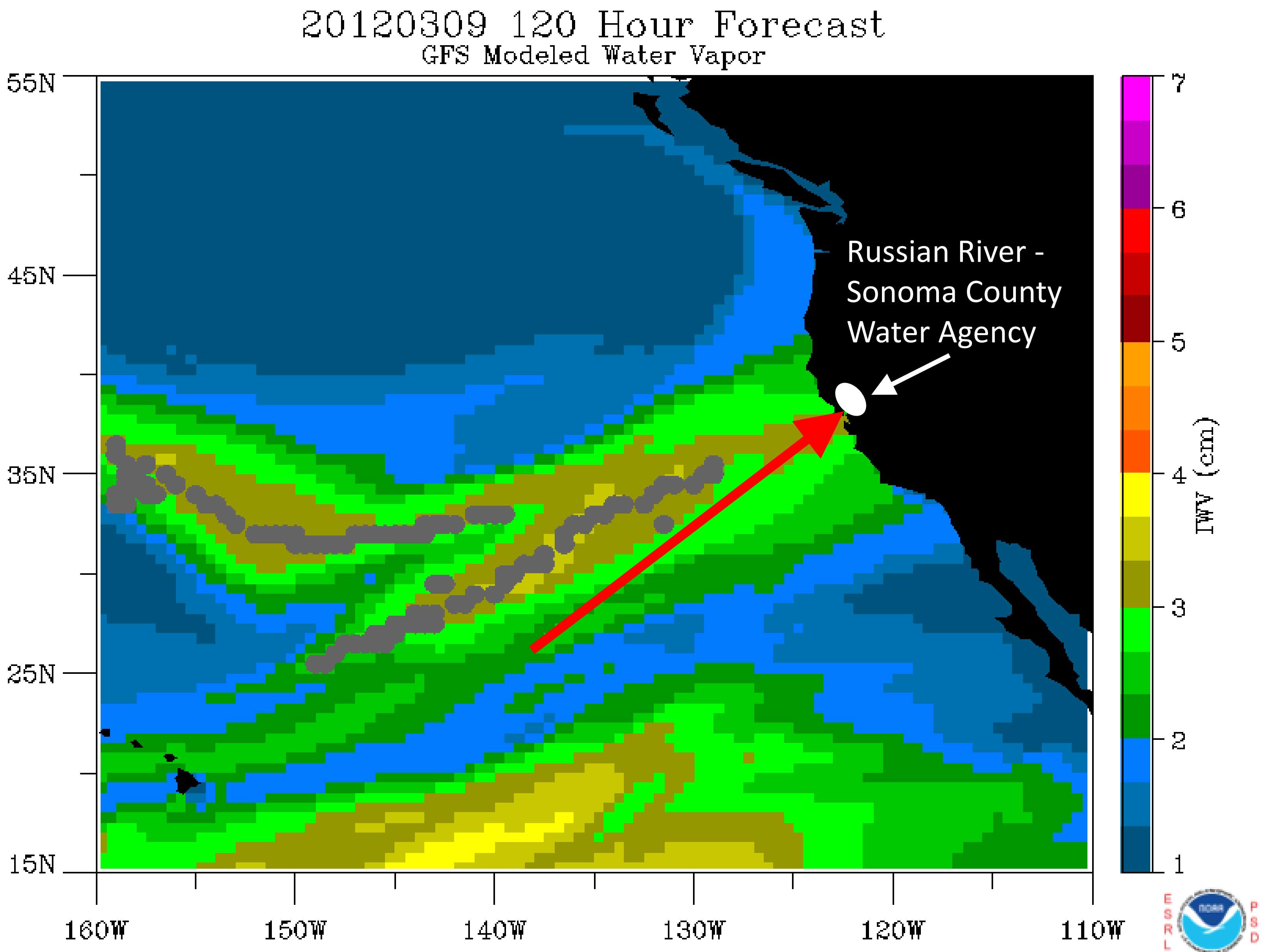
1-day GFS Forecast



2-day GFS Forecast



5-day GFS Forecast



7-day GFS Forecast