Atmospheric Rivers

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WRPI
San Jose State University, CA, 6 April 2017

Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

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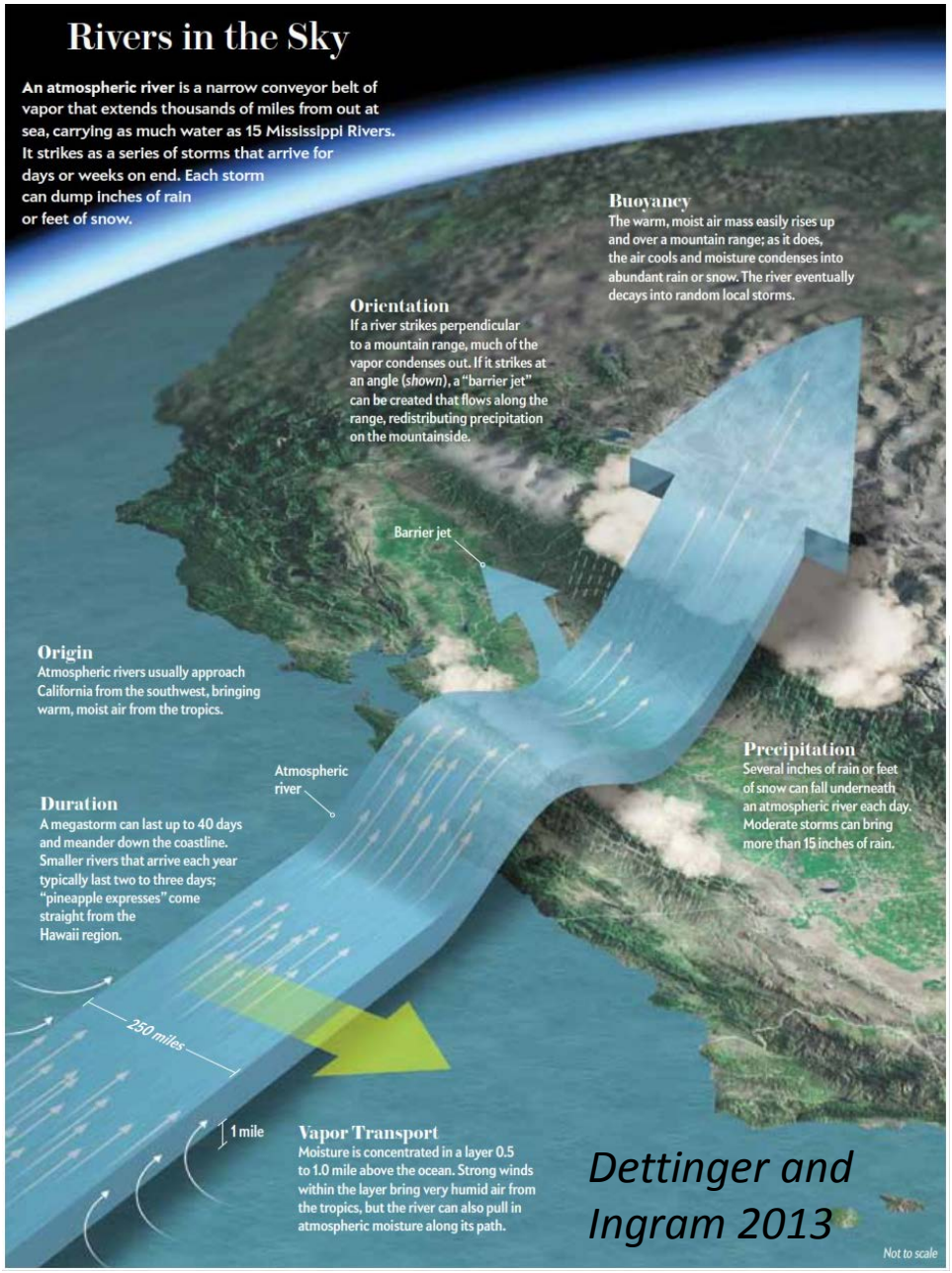
Outline

- What is an atmospheric river (aka “AR”) and how do they impact water supply, flood and drought?
- Can ARs be predicted?
- Were atmospheric rivers involved in the Oroville incident?

California Central valley in flood on 21 January 2017 near Sacramento

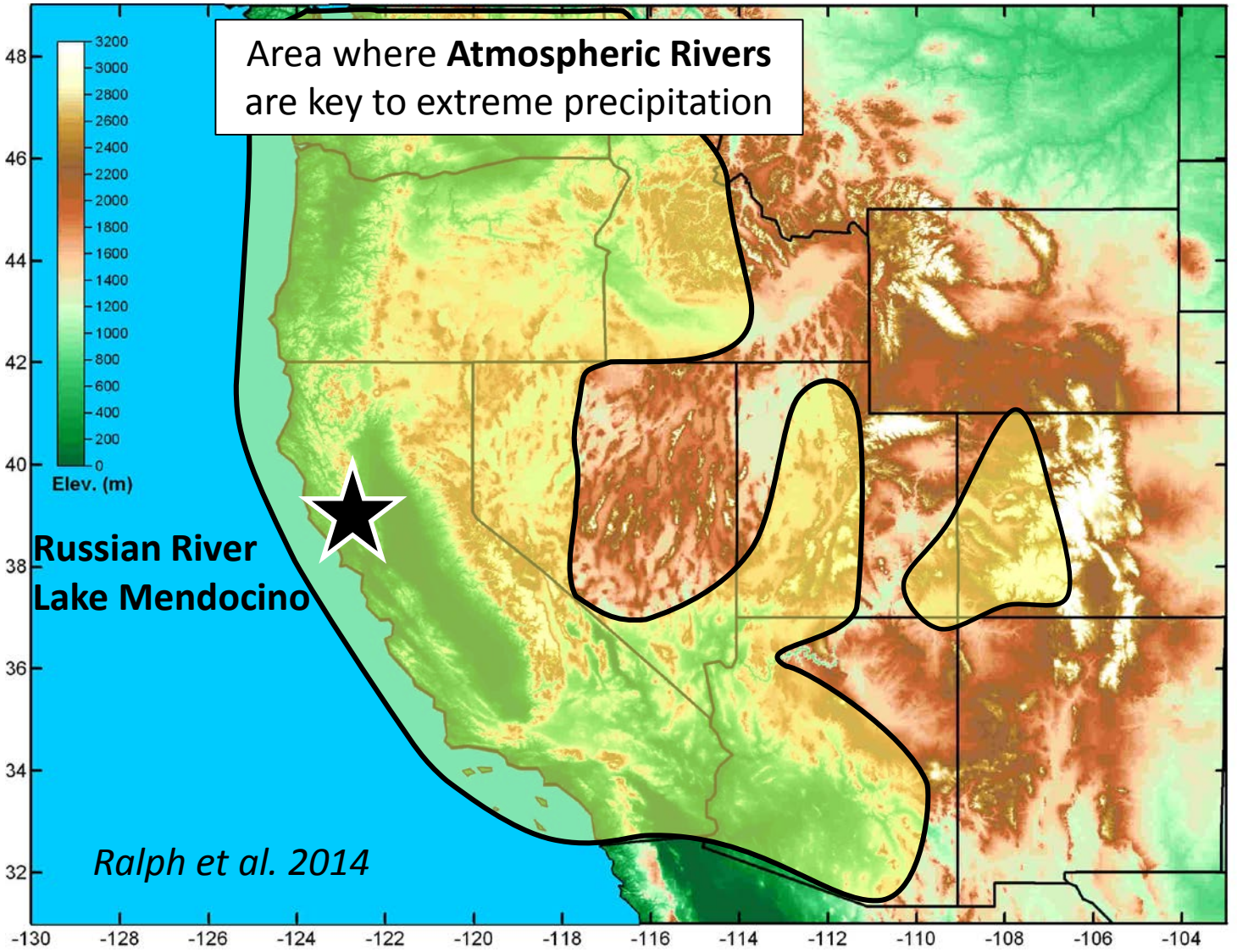
Photo Courtesy of John Nielsen-Gammon
View north of Sacramento, CA Saturday 21 January 2017

Rivers in the Sky



Dettinger and Ingram 2013

ARs Affect Large Areas of the U.S. West



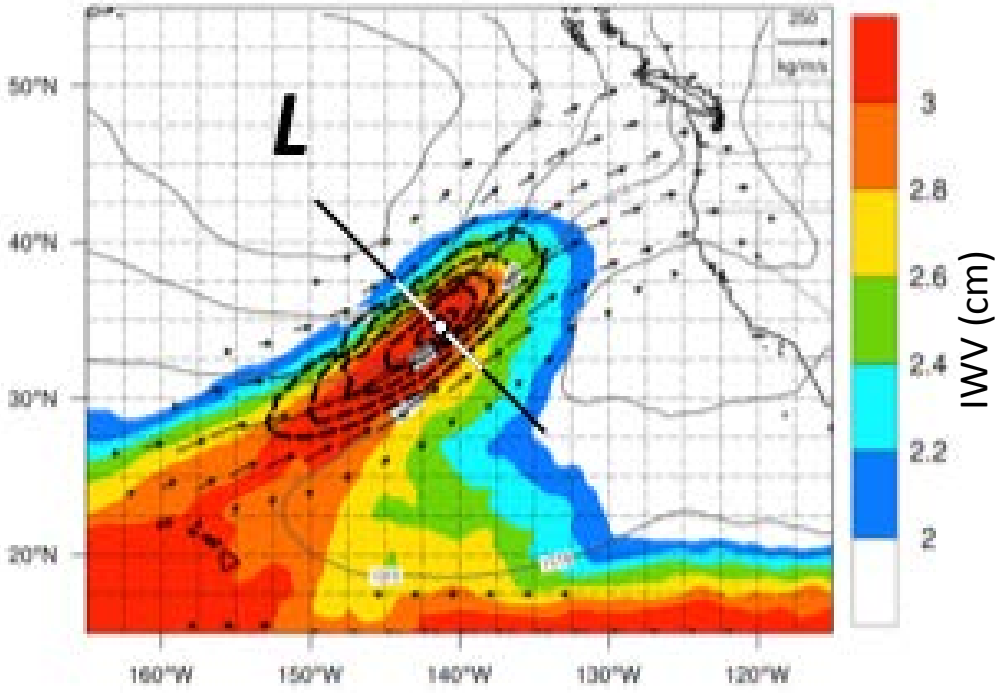
Ralph et al. 2014

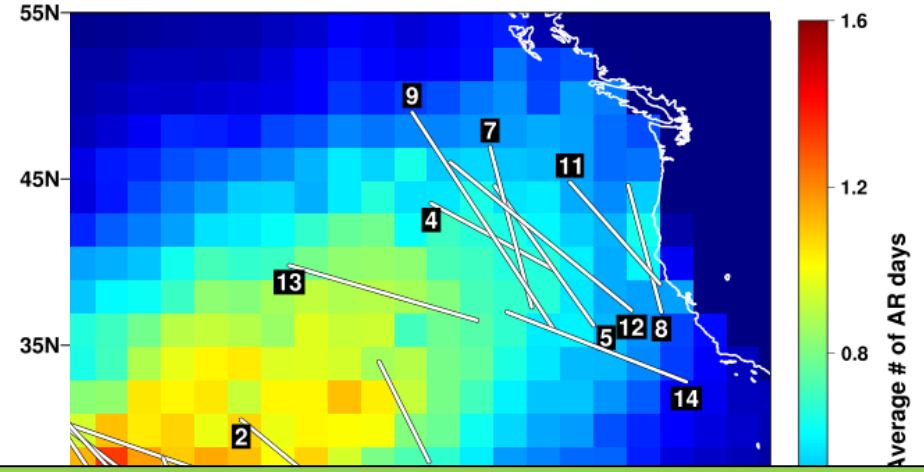
Observations of Water Vapor Transport by North Pacific Atmospheric Rivers

F.M. Ralph, S. Iacobellus, P.J. Neiman, J. Cordeira, J.R. Spackman, D. Waliser, G. Wick, A.B. White, C. Fairall

In Preparation

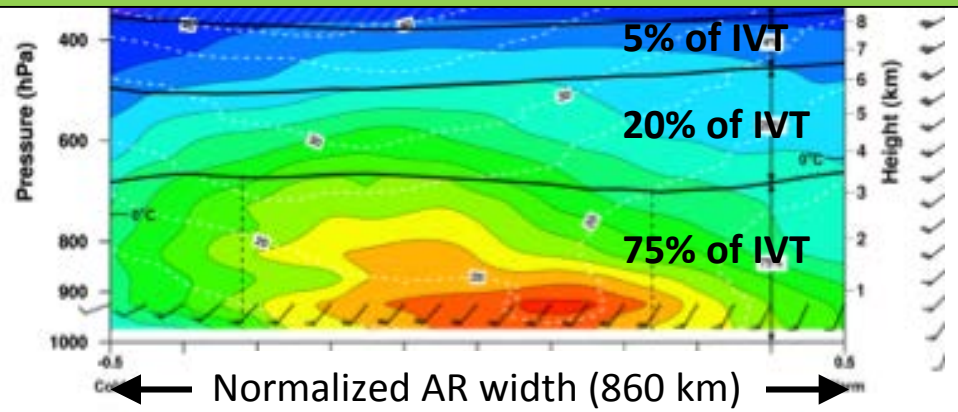
Composite AR Plan View (Color fill IWV; dashed lines IVT)





An average AR transports (as water vapor) the equivalent of

- **20 times the average discharge of the Mississippi River (as liquid), or**
- **20 M acre feet/day**



Vapor transport (color fill)

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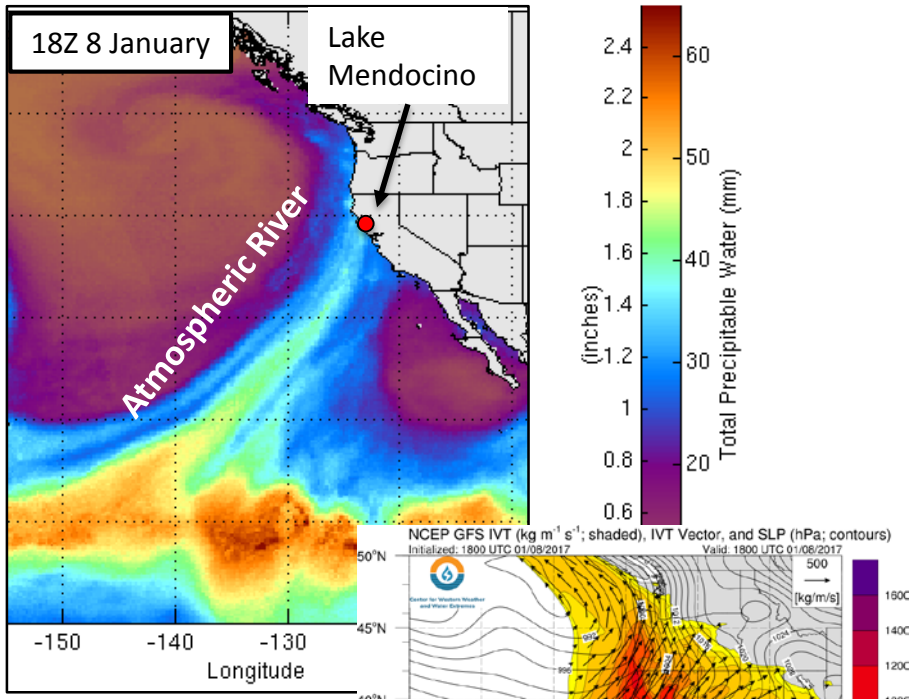
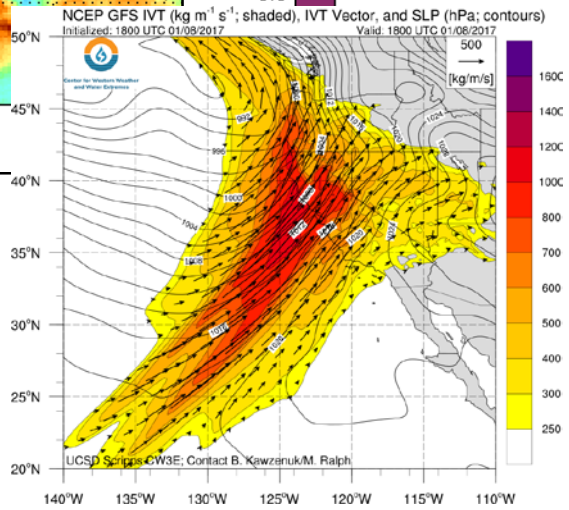
An exceptionally wet winter

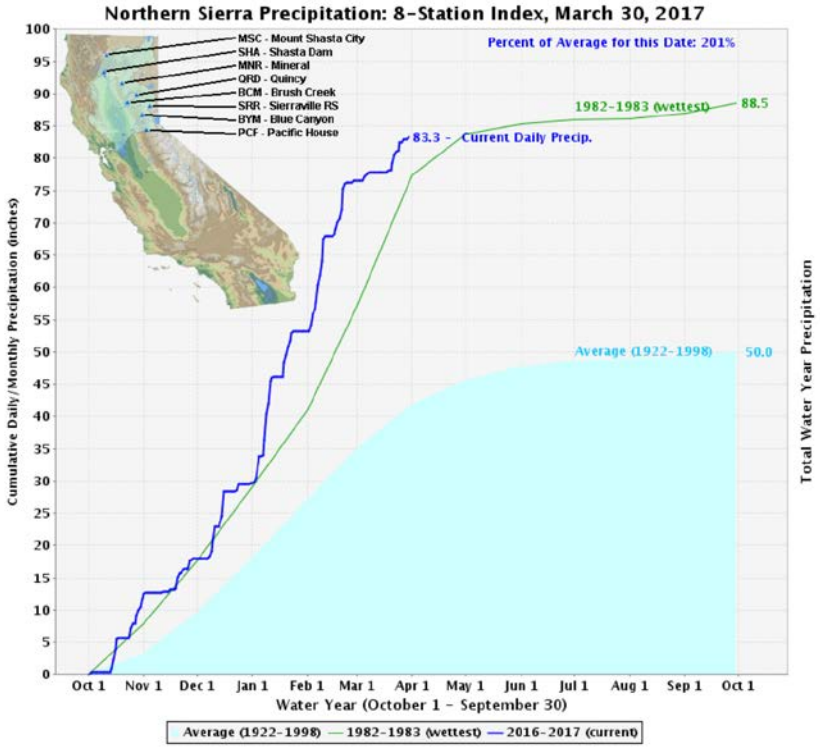
SSMI Observed Total Integrated Water Vapor





Corridor of enhanced SSMI IWV extending from tropics to California along landfalling AR

83 inches as of 30 March 2017
201% of normal Wettest Water Year to Date



- Coastal IVT magnitude >1000 kg m^{-1} s^{-1}
- IVT>250 kg m^{-1} s^{-1} penetrates inland over Utah

Green dots are sites where WY-to-date through 26 Feb 2017 is in the top 10% of its period of record (> 50 years)

Distribution of Landfalling Atmospheric Rivers on the U.S. West Coast
(From 1 Oct 2016 to 31 March 2017)

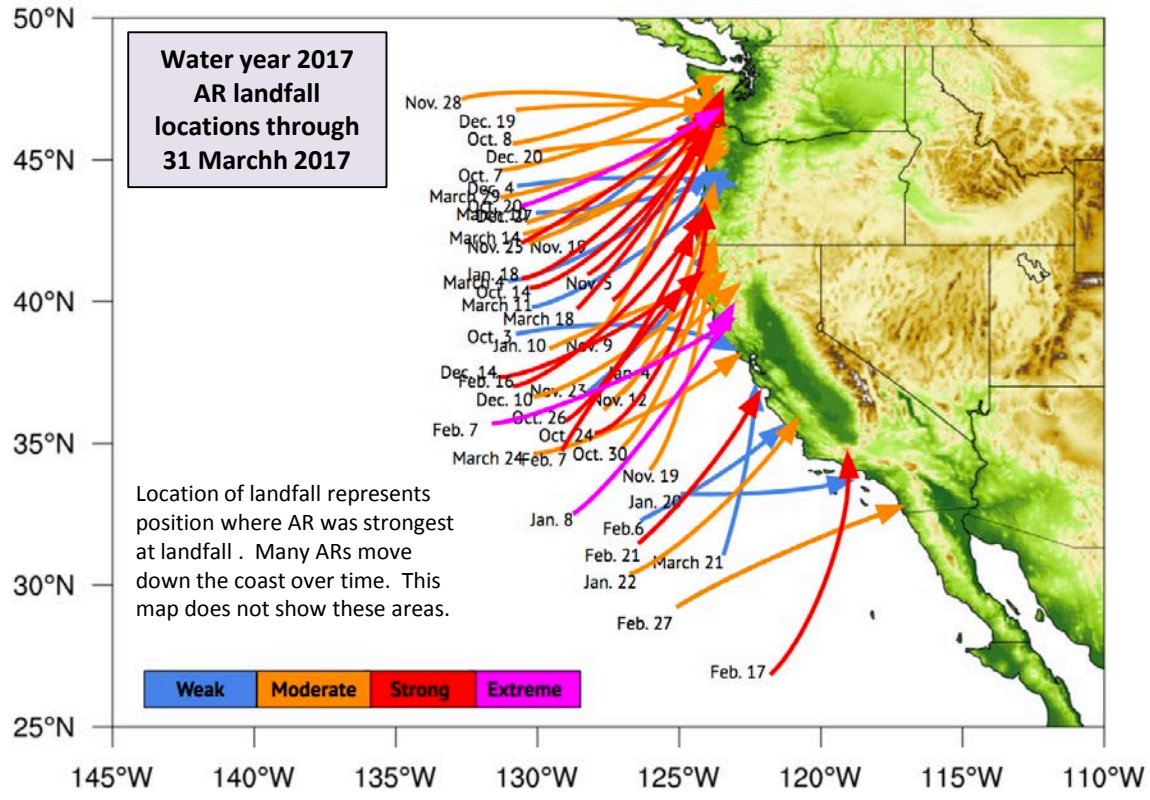
AR Strength	AR Count*
Weak	11
Moderate	19
Strong	13
Extreme	3

Ralph/CW3E AR Strength Scale

- Weak: IVT=250–500 kg m^{-1} s^{-1}
- Moderate: IVT=500–750 kg m^{-1} s^{-1}
- Strong: IVT=750–1000 kg m^{-1} s^{-1}
- Extreme: IVT>1000 kg m^{-1} s^{-1}

*Radiosondes at Bodega Bay, CA indicated the 10–11 Jan AR was strong (noted as moderate based on GFS analysis data) and 7–8 Feb AR was extreme (noted as strong)

- 46 Atmospheric Rivers have made landfall on the West Coast thus far during the 2017 water year (1 Oct. – 31 March 2017)
- This is much greater than normal
- 1/3 of the landfalling ARs have been “strong” or “extreme”



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By F.M. Ralph, B. Kawzenuk, C. Hecht, J. Kalansky

Atmospheric River Forecast Example

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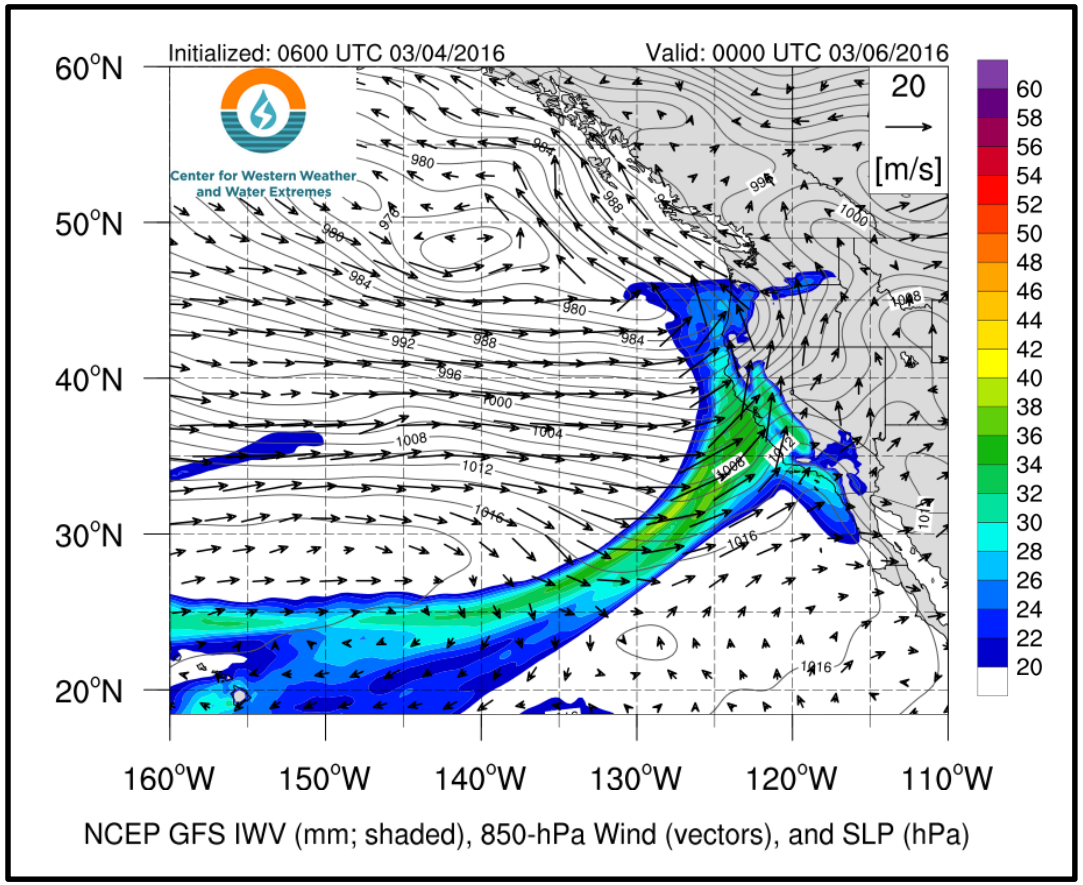
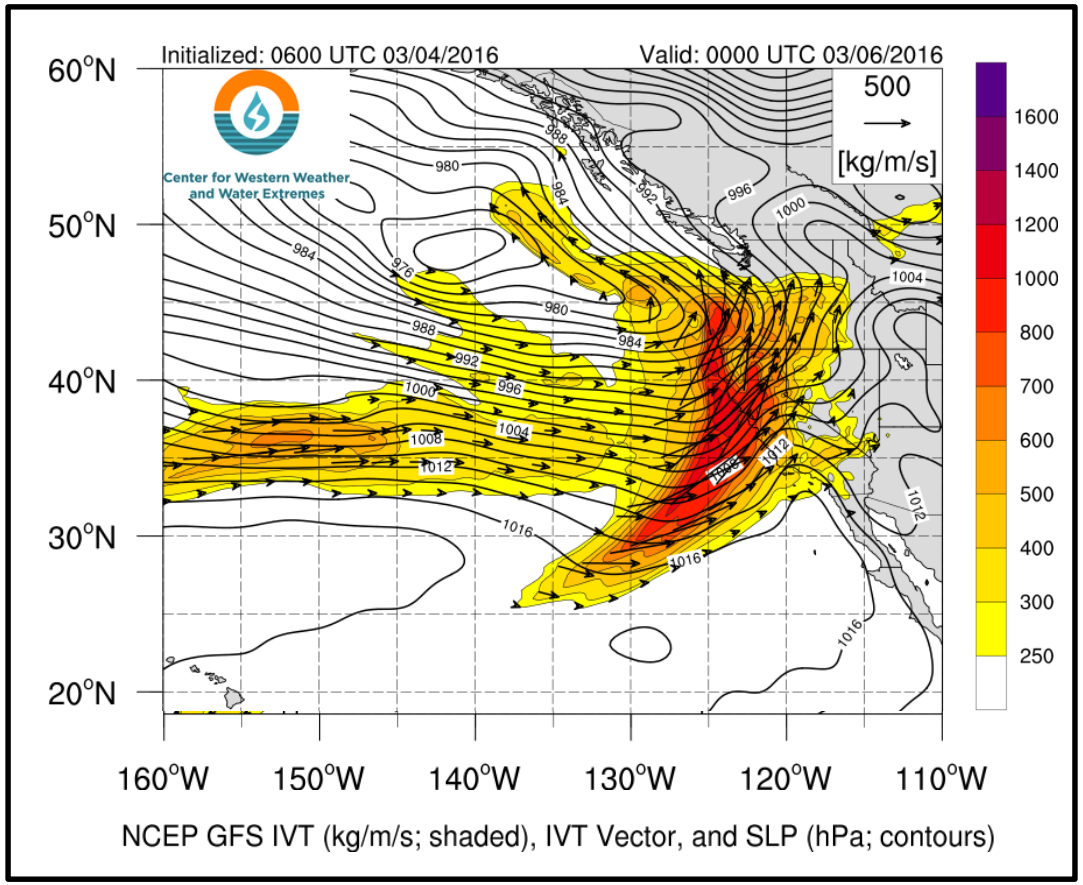
Incoming storm of 5-7 March 2016 has characteristics of an atmospheric river

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

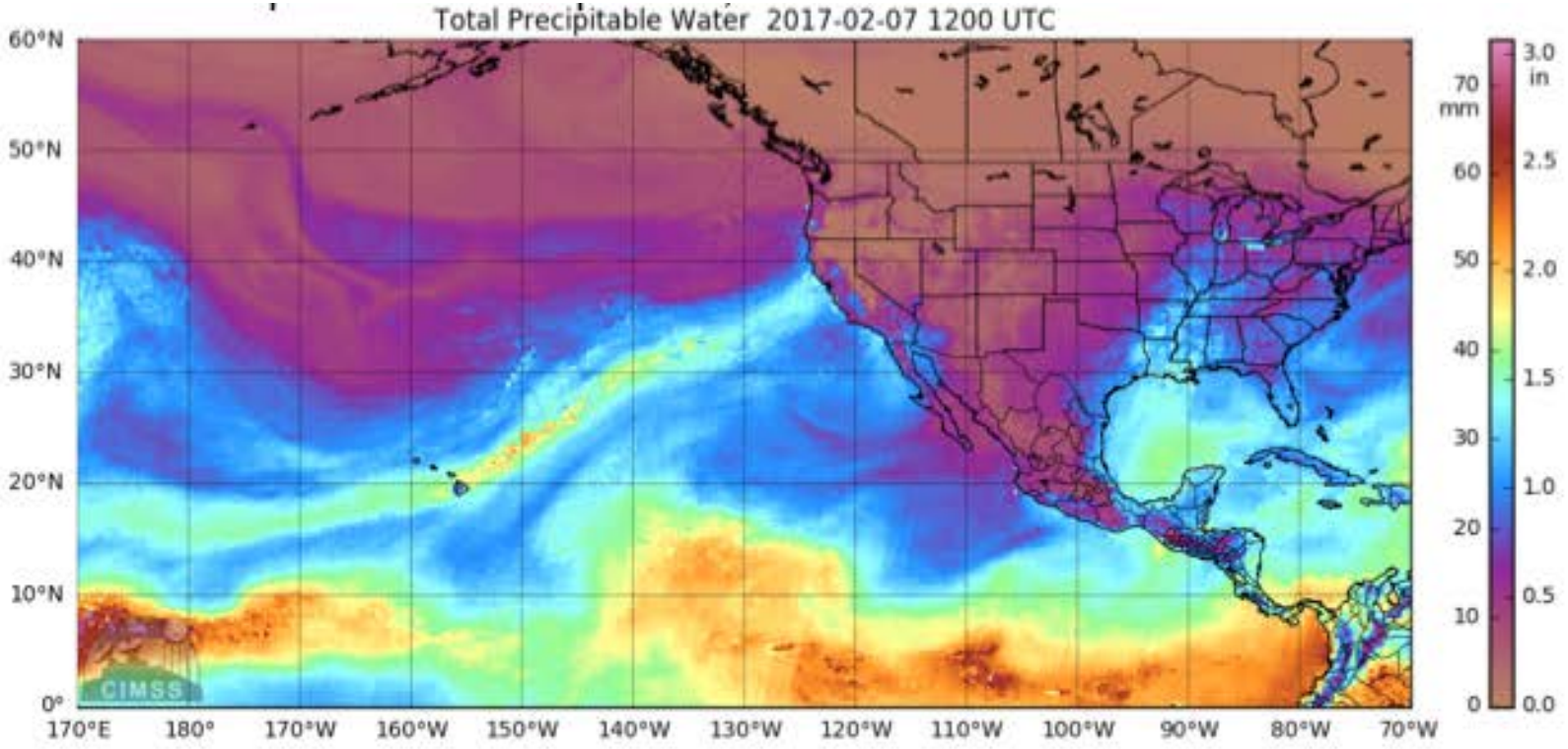
Example of a 2 day lead-time forecast

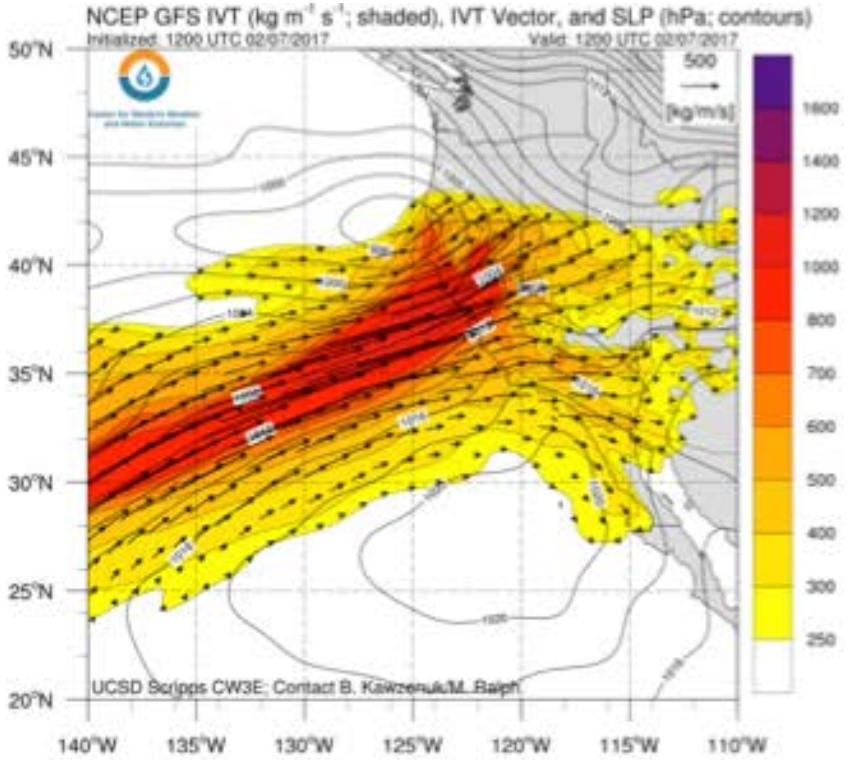




Summary by F.M. Ralph 8 AM PT Fri 4 March 2016

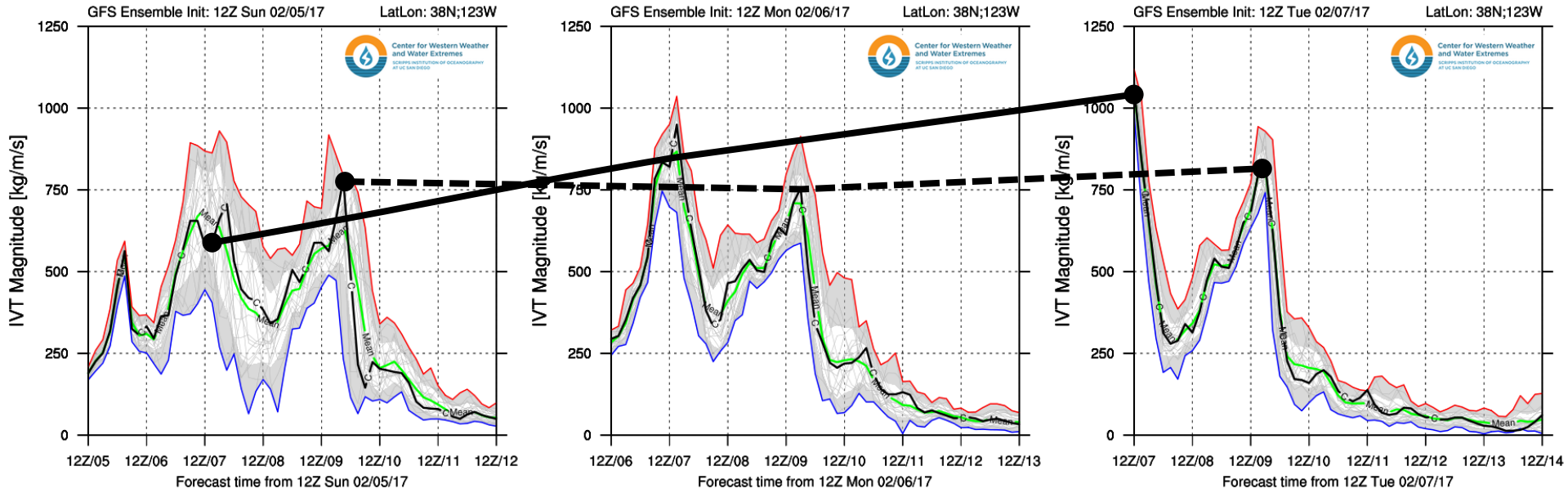
Was the Oroville Incident Related to an AR?





Yes. An “extreme” AR hit the area.

NCEP GEFS dProg/dt Examples from January and February 2017



Init: 12Z/5 Feb

Init: 12Z/6 Feb

Init: 12Z/7 Feb

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.**

NCEP GEFS dProg/dt Examples from January and February 2017

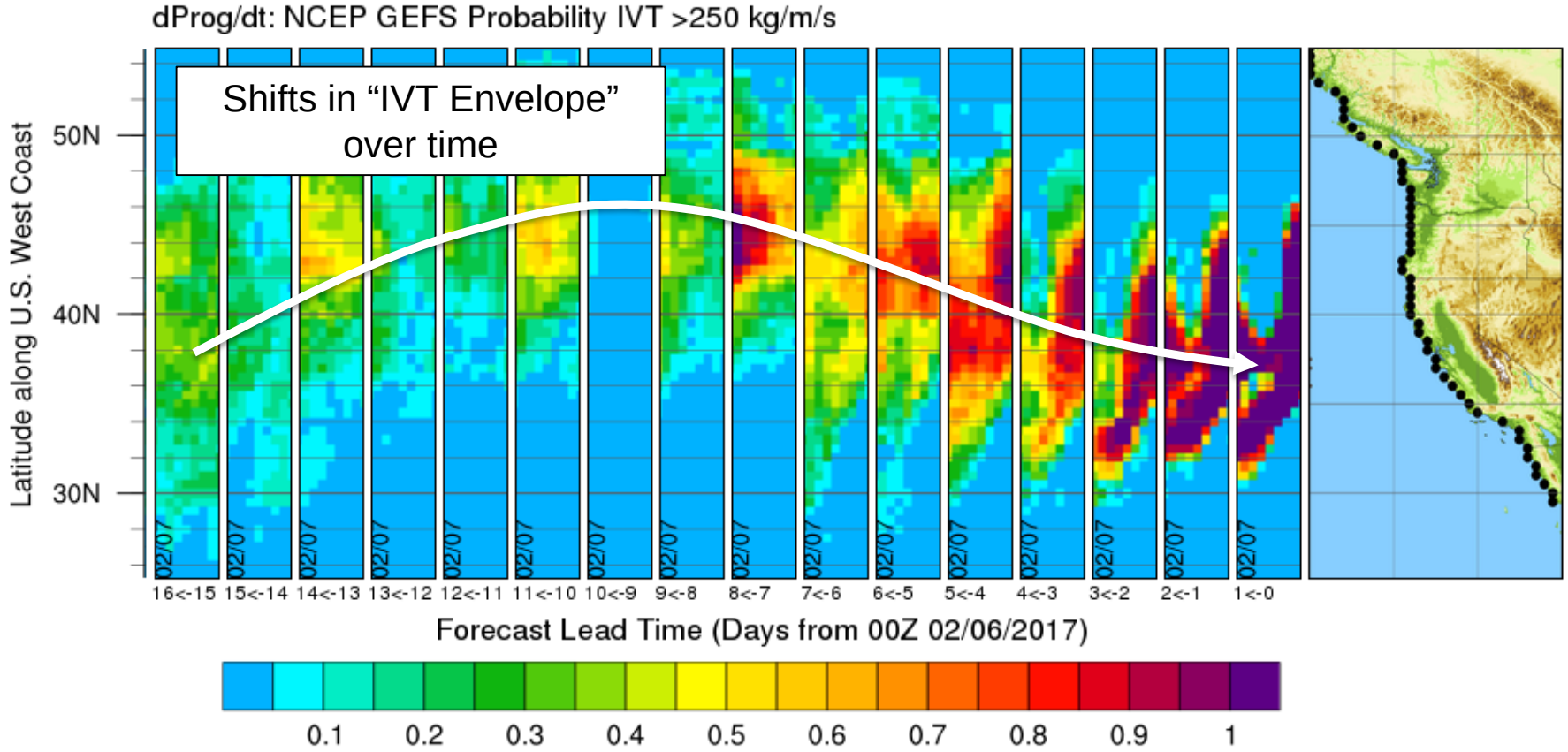
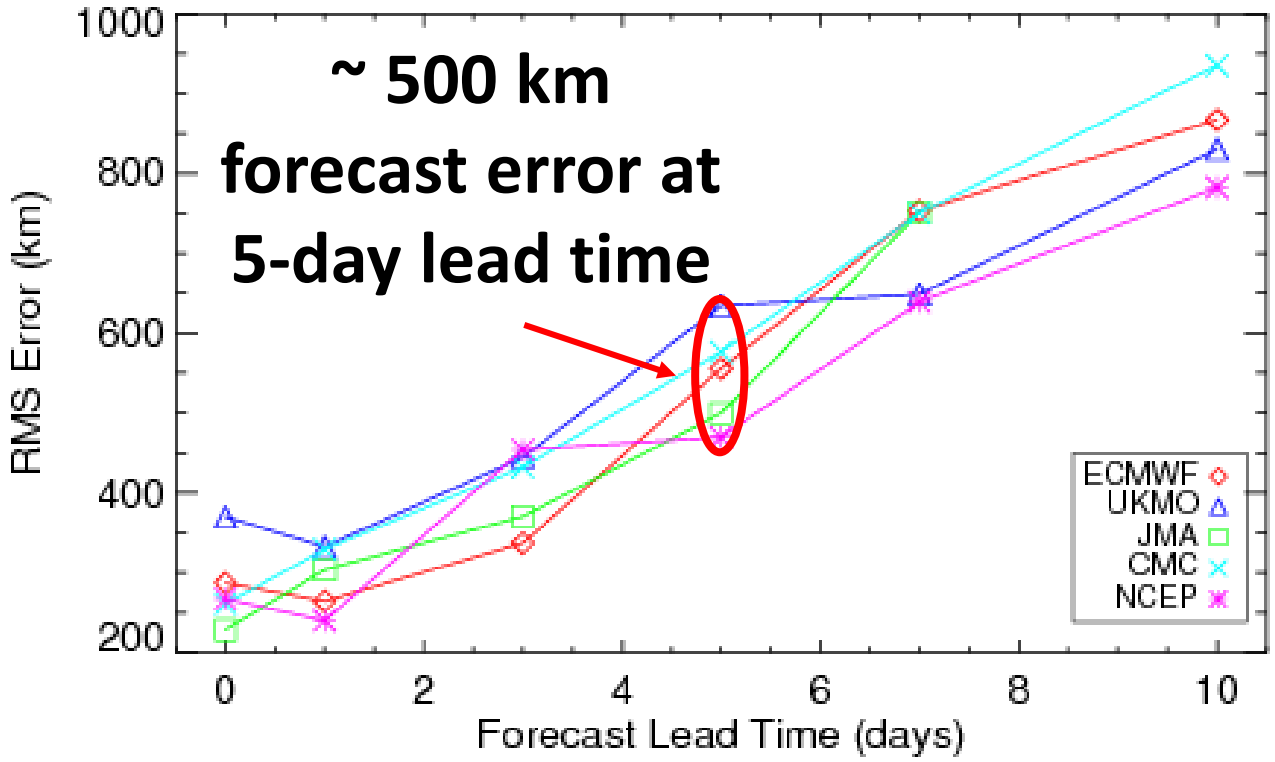


Image Description: Shading represents the NCEP GEFS probability that IVT will exceed 250 kg m^{-1} s^{-1} at 0.5-degree grid locations along the U.S. West Coast (dots). Each panel represents a 24-h forecast that verifies during the 24-h period starting at the time listed above the color bar. The lead time of that forecast period increases from right-to-left. For example, the left-most panel is a 15-to-16-day forecast whereas the right-most panel is the 0-to-1-day forecast.

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



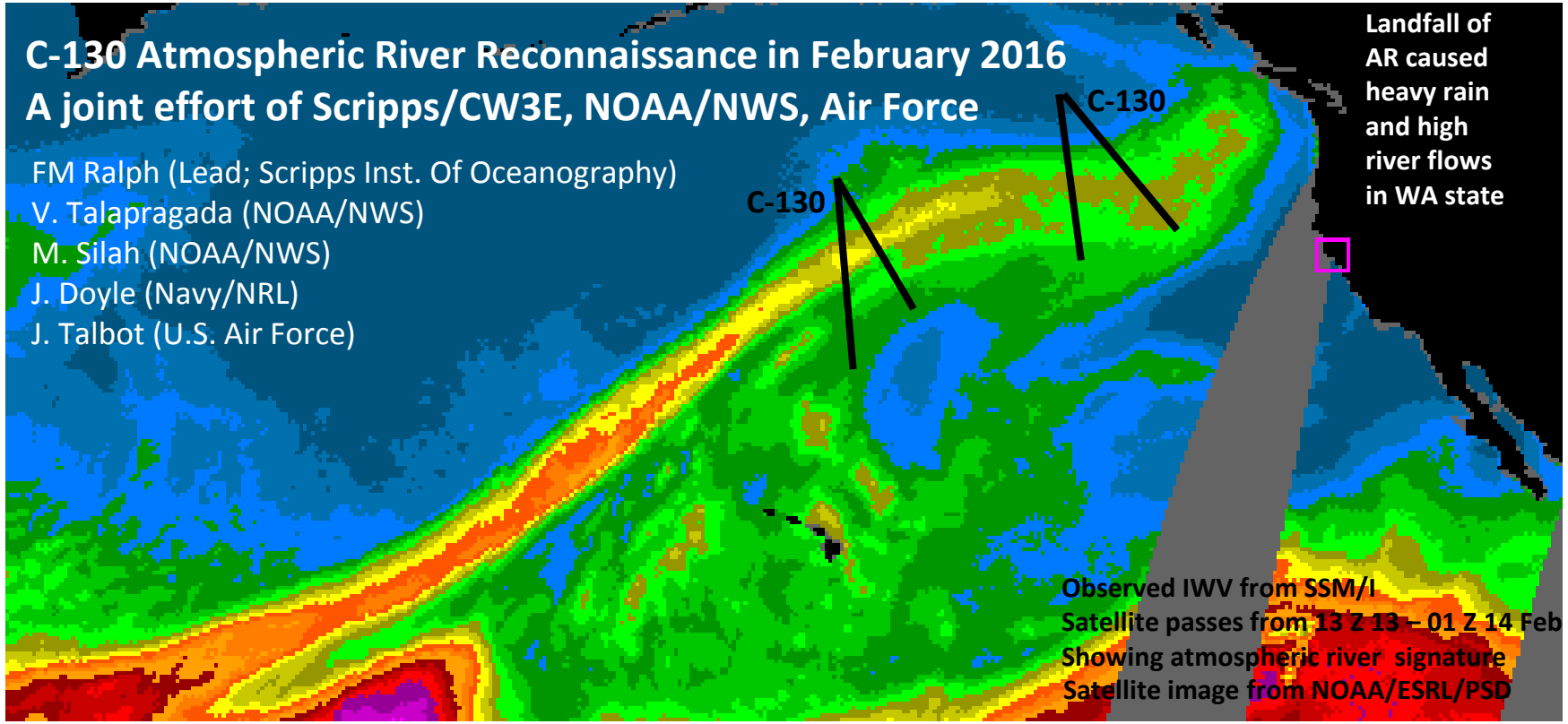
- Errors in location increase to over 800 km at 10-day lead
- Errors in 3-5 day forecasts comparable with current hurricane track errors
- Model resolution a key factor

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

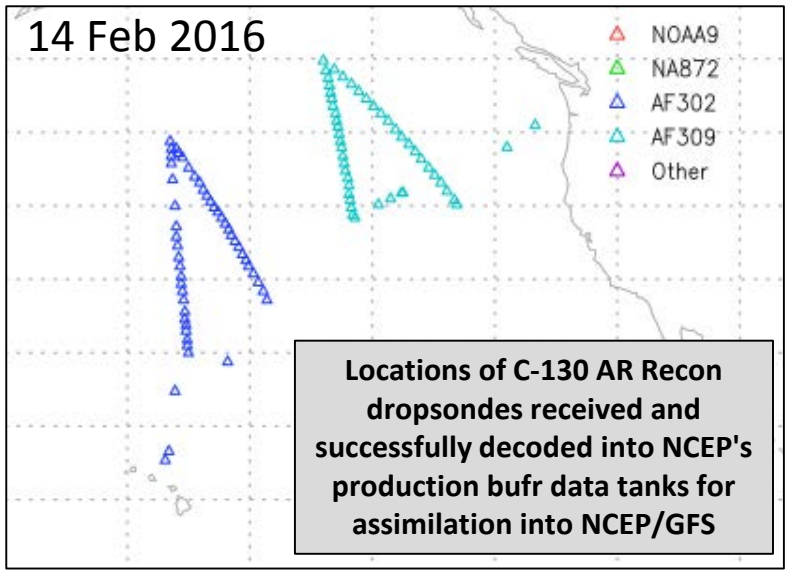
- **Models provide useful heads-up for AR impact and IWV content, but location highly uncertain**
- **Location uncertainty highlights limitations in ability to predict extreme precipitation and flooding**
- **Improvements in predictions clearly desirable**

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)
V. Talapragada (NOAA/NWS)
M. Silah (NOAA/NWS)
J. Doyle (Navy/NRL)
J. Talbot (U.S. Air Force)



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

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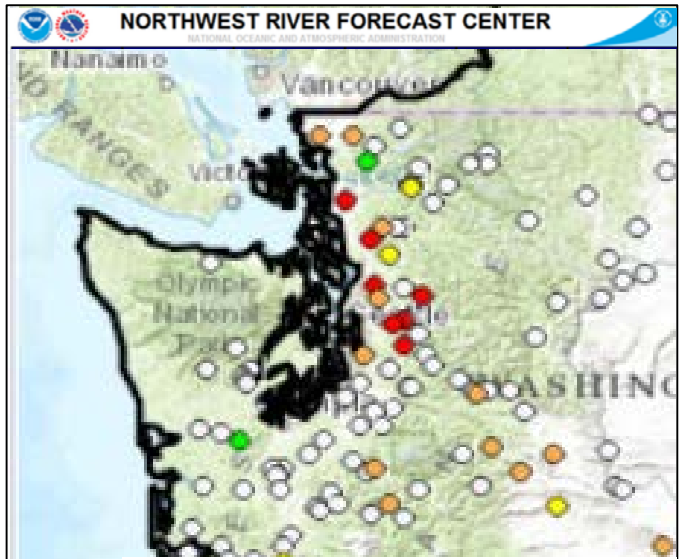
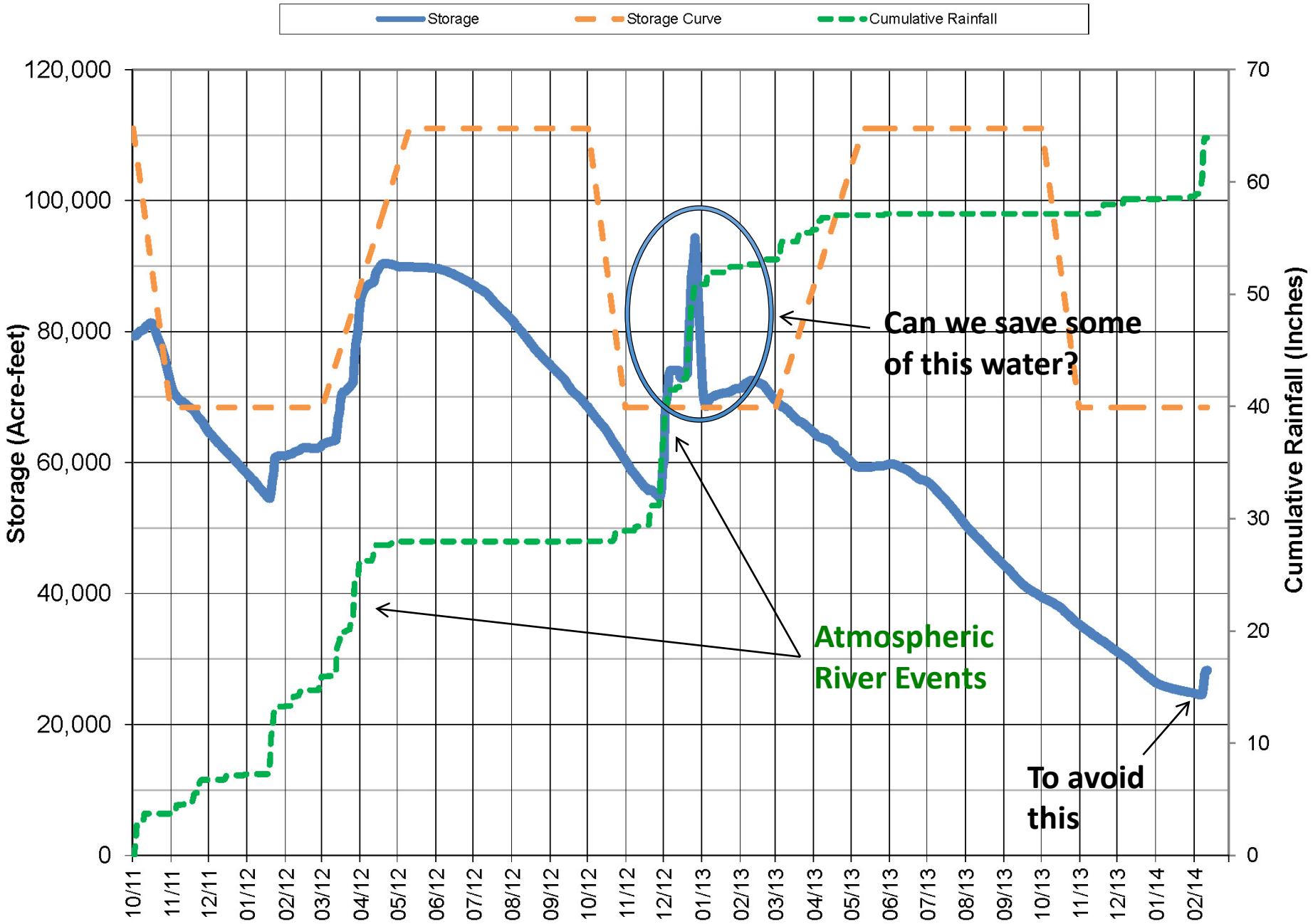


NWRFC flood forecast map as of 1500 UTC 15 Feb showing several rivers predicted to reach flood stage on 15-16 Feb (red dots)

Lake Mendocino Water Years 2012 - 2014



FACT SHEET: Lake Mendocino Forecast Informed Reservoir Operations Preliminary Viability Assessment Work Plan

PURPOSE: The Lake Mendocino Forecast Informed Reservoir Operations (FIRO) Preliminary Viability Assessment Work Plan (Work Plan) describes an approach for using modeling, forecasting tools and improved information to determine whether the Lake Mendocino Water Control Manual can be adjusted to improve flood-control and water supply operations. This proof-of-concept FIRO viability assessment uses Lake Mendocino as a model that could have applicability to other reservoirs.

*STEERING COMMITTEE CO-CHAIRS

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Sonoma County Water Agency

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David Ford Consulting Engineers

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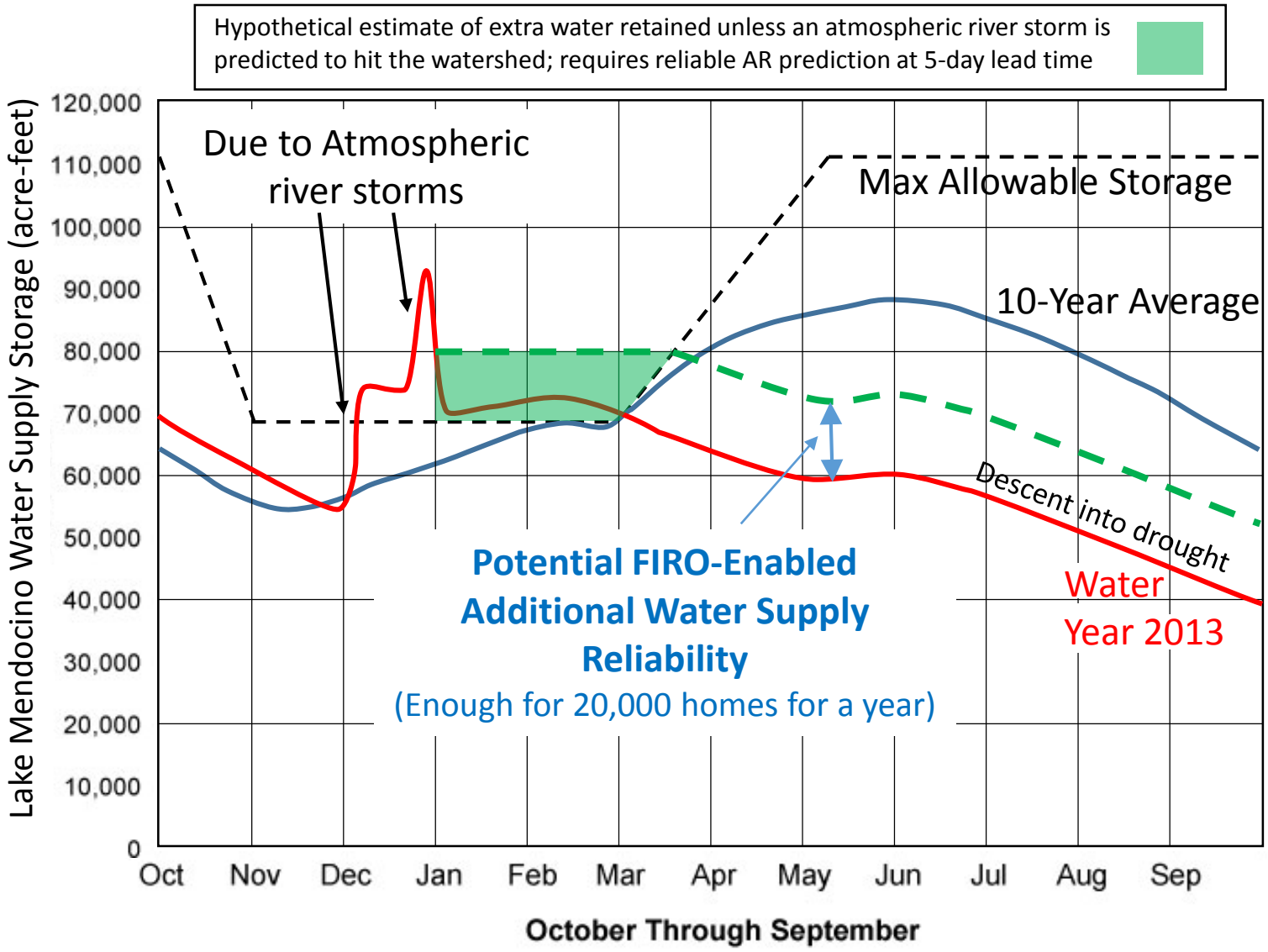
Sonoma County Water Agency

September 2015

Lake Mendocino Forecast-Informed Reservoir Operations Concept



AR Update: 4 April 2017

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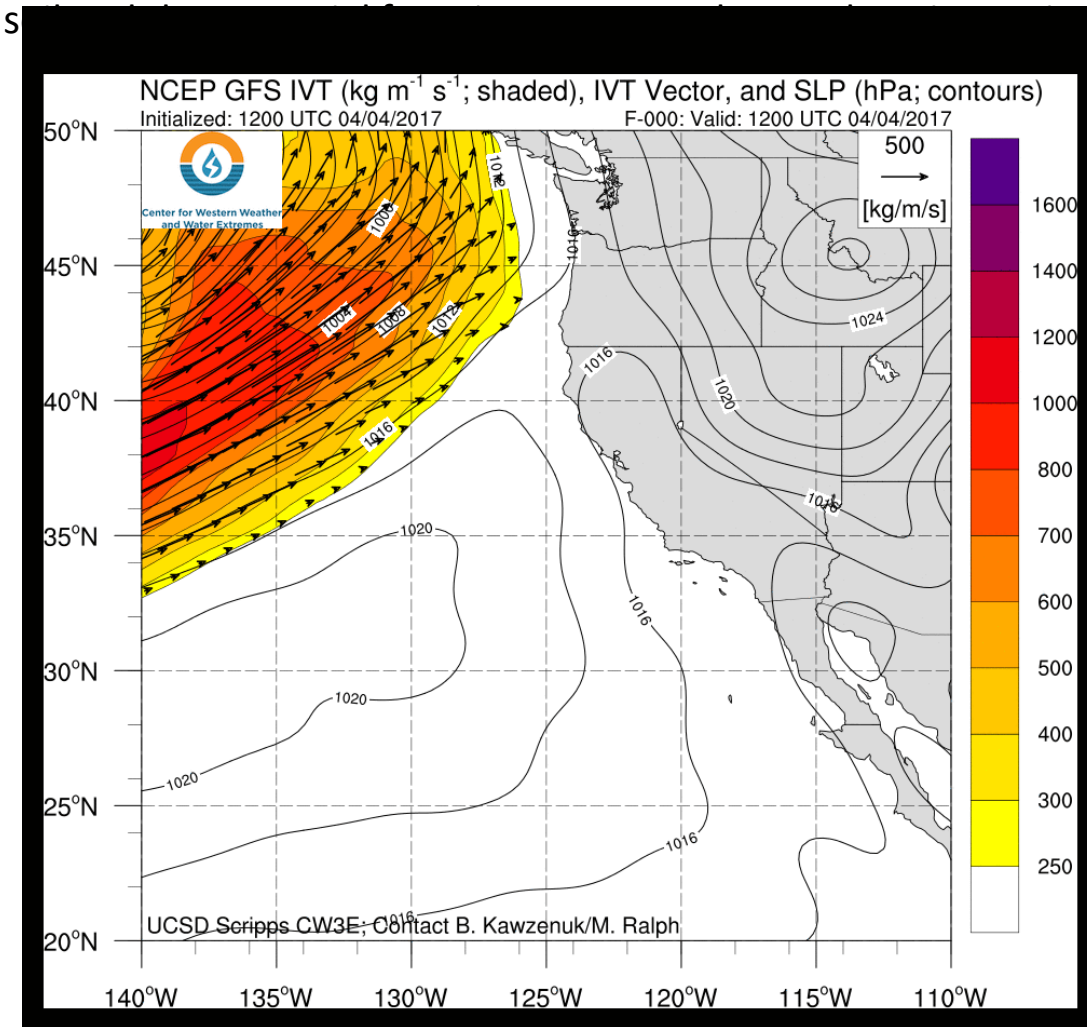
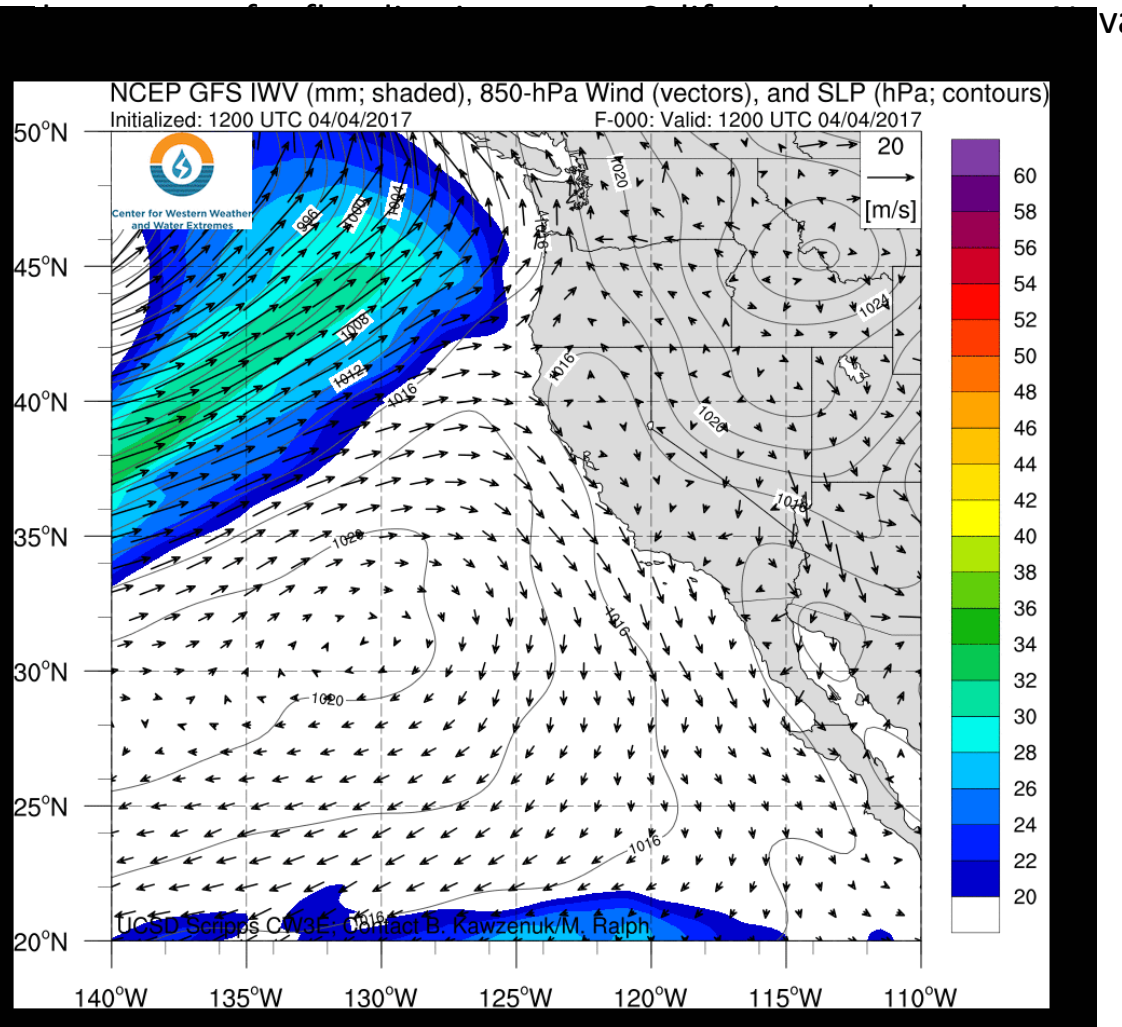
AR conditions Forecast for Entire U.S. West Coast

- An AR is currently impacting the Pacific Northwest while another AR is forecast to make landfall over Northern CA on Thursday
- A mesoscale frontal wave that develops during the second AR could prolong the duration of AR conditions but uncertainty is currently high
- 1–5 day precipitation forecasts are >6 inches over the high elevations of the Coastal Mts., Northern Sierra Mts., and Trinity Alps
- Freezing levels are forecast to start at ~7,000 feet before dropping to ~3,000 feet, causing this to be a snow event for higher elevations
- Wet s[illegible]vada





AR Update: 4 April 2017

For California DWR's AR Program

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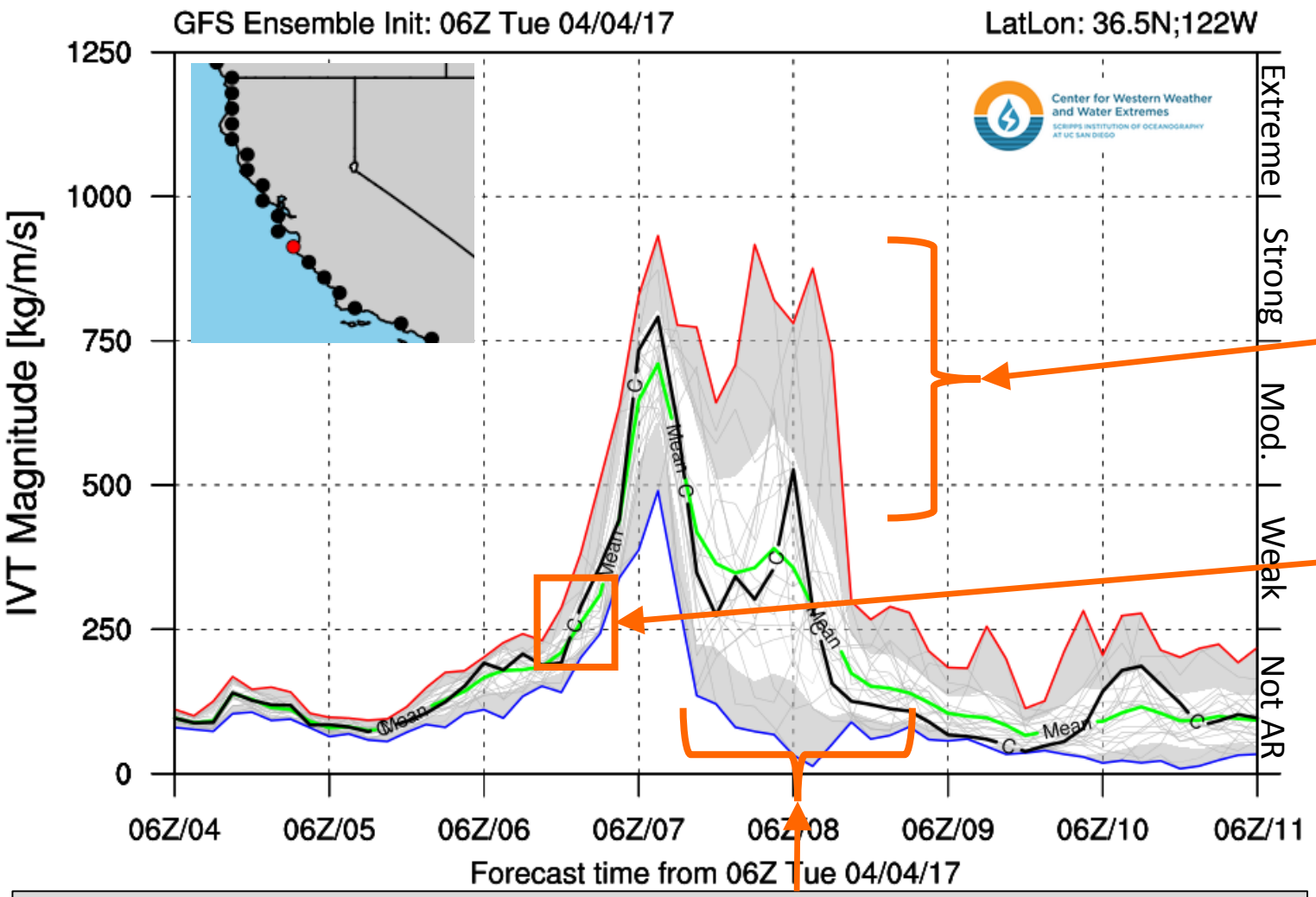


Monterey, CA could experience strong AR conditions IVT> 750 kg m^{-1} s^{-1}

Magnitude of AR over Monterey

- Maximum possible IVT ~ 900 kg m^{-1} s^{-1}
- Mean IVT ~ 800 kg m^{-1} s^{-1}
- Uncertainty ~ +/– 12%

High Confidence in onset of AR conditions:

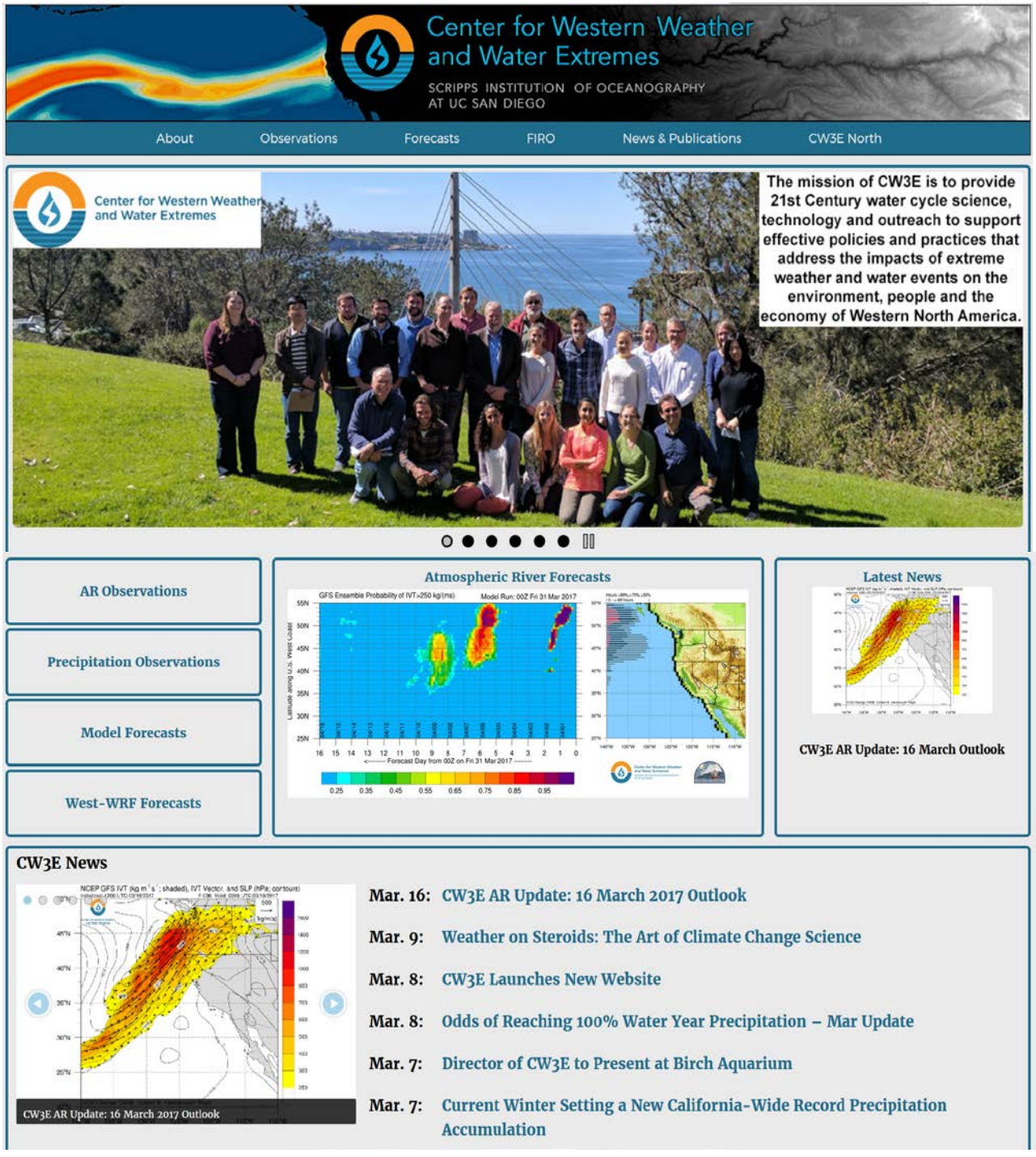
- 1 PM PT Thursday 06 April +/– 4 h

Duration of AR conditions

- Weak: ~36 hours +/– 20 h
- Moderate: ~10 hours +/– 20 h
- Strong ~3 hours +/– 3 h

There is more uncertainty in IVT magnitude associated with the development of the mesoscale frontal wave, which creates large uncertainty in the duration of AR conditions over Monterey

Summary by C. Hecht 1 PM PT Tuesday 04 April 2017



AR Forecast Tools

Extreme Event Summaries

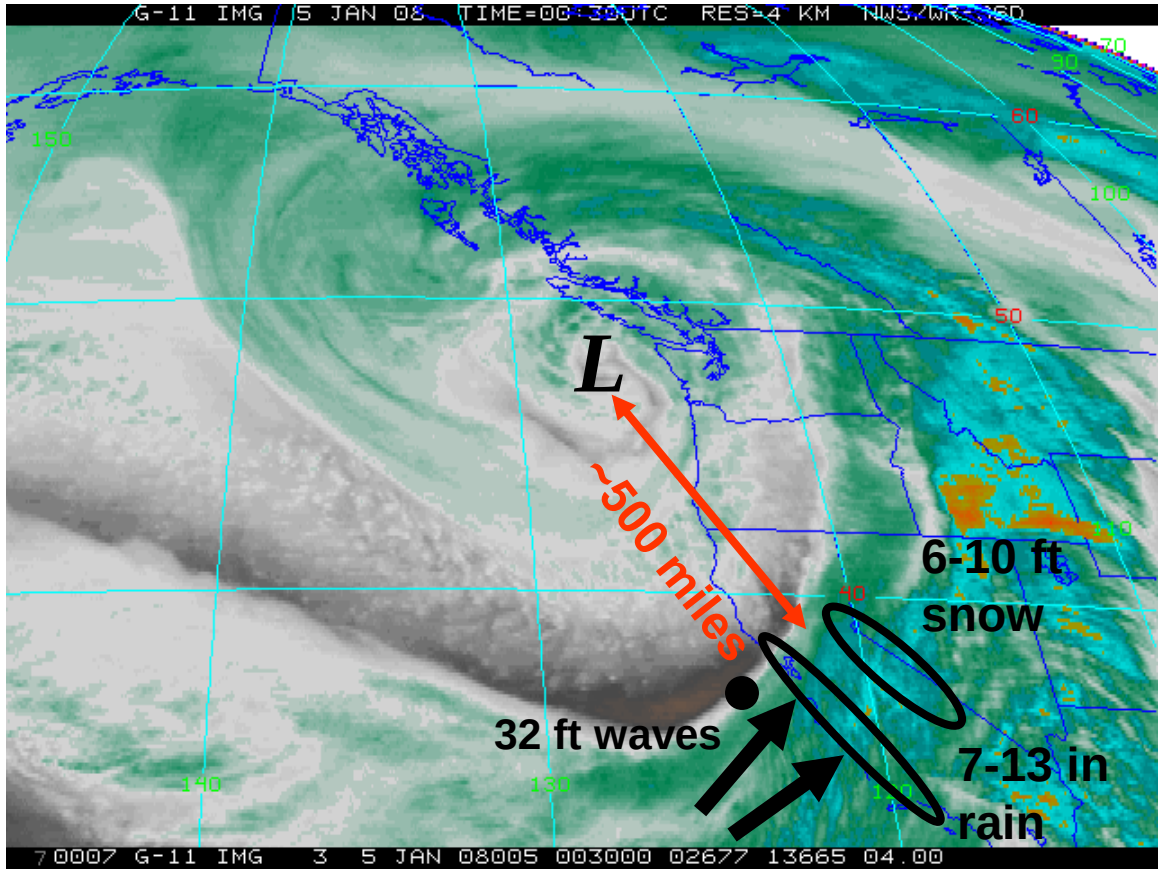
Lake Mendocino FIRO summary information

Are available at

CW3E.UCSD.EDU

Contact: mralph@ucsd.edu

The Storm of 4-5 Jan 2008



Atmospheric river

GOES IR image of major West Coast storm

- Time = 0030 UTC 5 January 2008
- Low pressure center is off WA coast

Note that major impacts were focused >500 miles south of the Low pressure center in this storm.

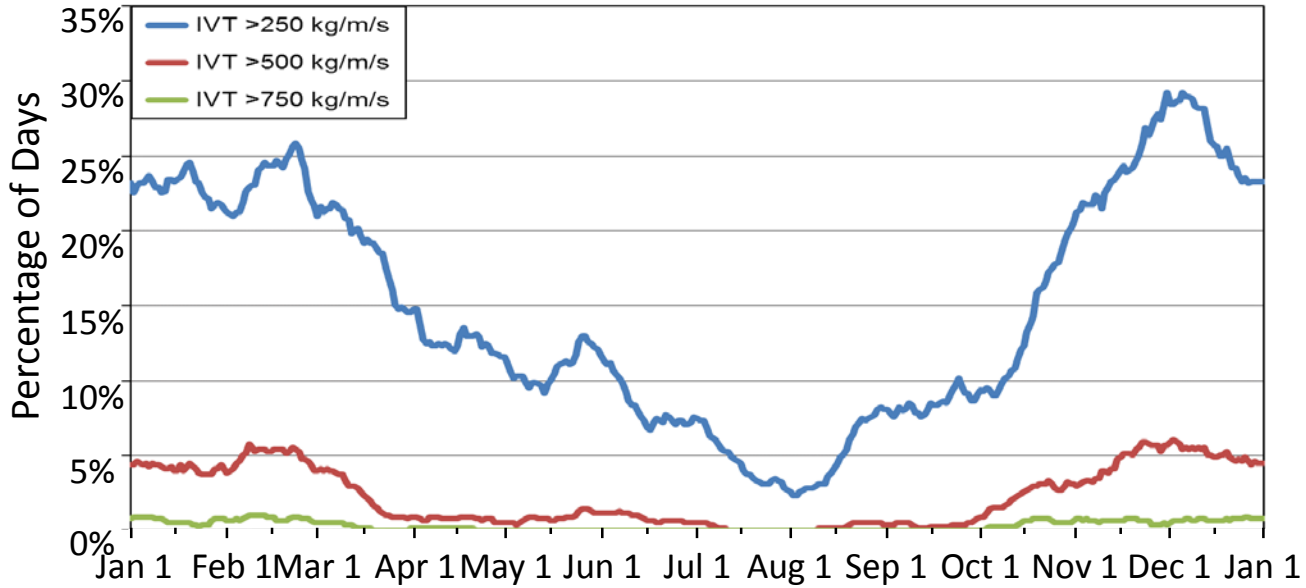
This differs significantly from hurricanes, but the impacts are enormous and spread over a large area

Many major impacts are associated with the landfall of the "atmospheric river" element of the storm, the precise characteristics of which are not operationally monitored offshore or onshore.

Annual Cycle of AR Conditions Near Lake Oroville, California Based on Daily Maximum IVT Magnitude

Provided to Mike Anderson (DWR State Climatologist) For consideration by Oroville Spillway Incident Unified Command From F. M. Ralph, J. Cordeira, C. Hecht, B. Kawzenuk of CW3E

Climatological probability of daily maximum IVT > Various Thresholds
39°N, 121.25°W | 1980–2016



- Frequency of Atmospheric River related conditions striking a location near Oroville Dam based on 37 years of past analyses of vertically integrated water vapor transport (IVT; the key defining characteristic of ARs)
- The frequency of daily max IVT>250 kg m^{-1} s^{-1} and 500 and 750 kg m^{-1} s^{-1} on any given calendar day is shown
- Table: average number of days per month with IVT >250 kg m^{-1} s^{-1} , 500 and 750
- Dec–Feb contain, on average, ~0.20-to-0.25 days/mon with IVT>750 kg m^{-1} s^{-1}: IVT magnitudes >750 kg m^{-1} s^{-1} were not observed during May-Sep

Ralph/CW3E AR Strength Scale

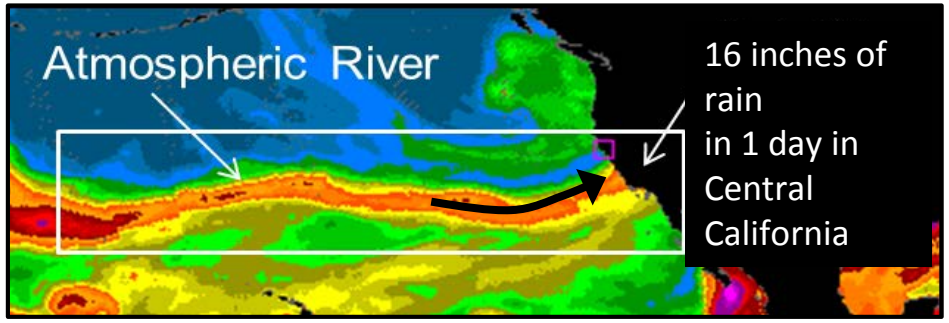
Weak: IVT=250 – 500 kg m^{-1} s^{-1}

Moderate: IVT=500 – 750 kg m^{-1} s^{-1}

Strong: IVT=750–1000 kg m^{-1} s^{-1}

Extreme: IVT>1000 kg m^{-1} s^{-1}

Month	IVT > 250	IVT > 500	IVT >750
	Avg number of days	Avg number of days	Avg number of days
Jan	7.2	1.32	0.19
Feb	6.4	1.35	0.24
Mar	6.1	0.81	0.08
Apr	3.8	0.22	0.03
May	3.4	0.24	0.00
Jun	2.6	0.30	0.00
Jul	1.4	0.03	0.00
Aug	1.6	0.11	0.00
Sep	2.4	0.05	0.00
Oct	4.4	0.78	0.16
Nov	7.0	1.35	0.16
Dec	8.4	1.59	0.22

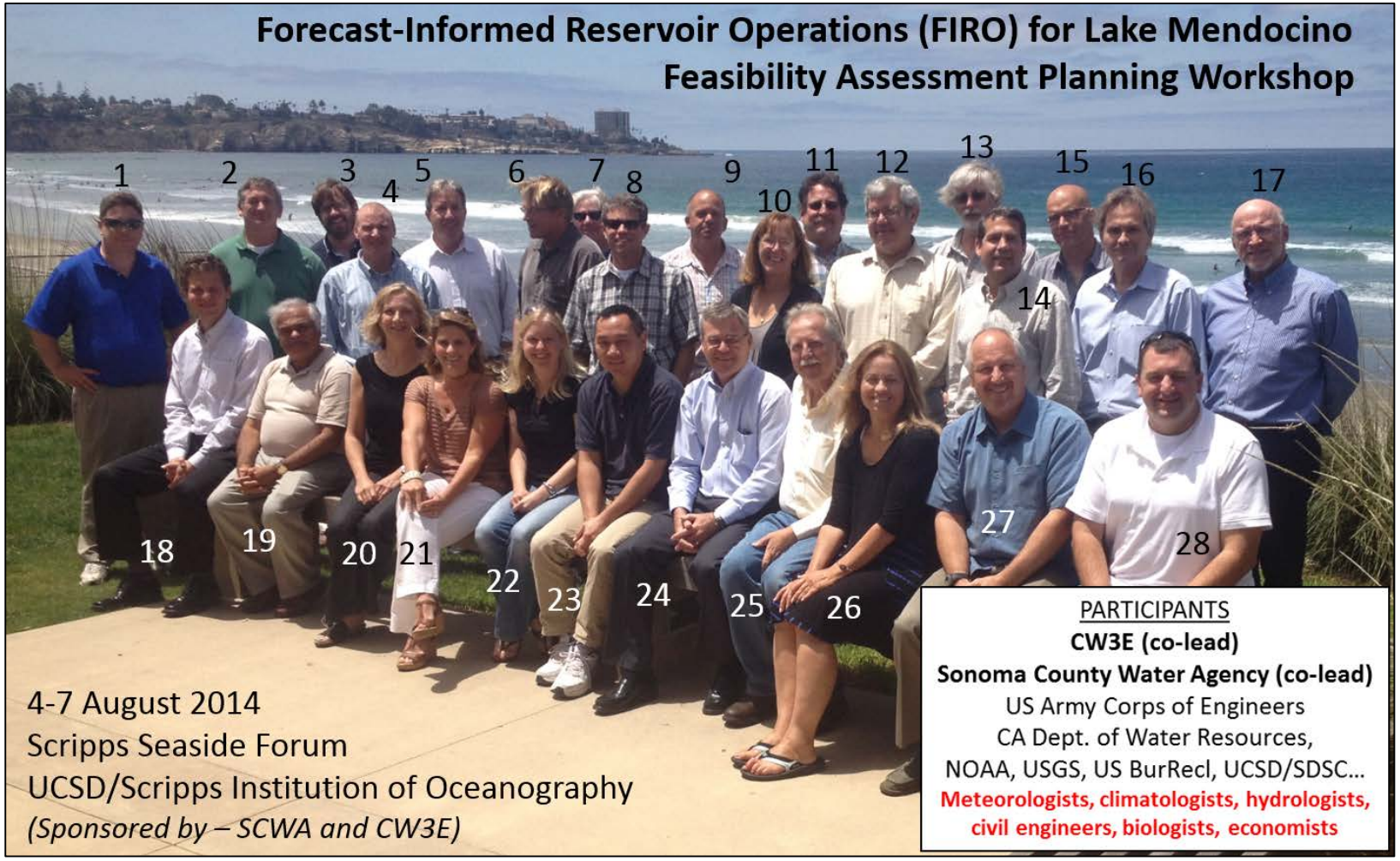


Forecast-Informed Reservoir Operations*: A Concept Supporting Water Security, Flood Control, Ecosystems

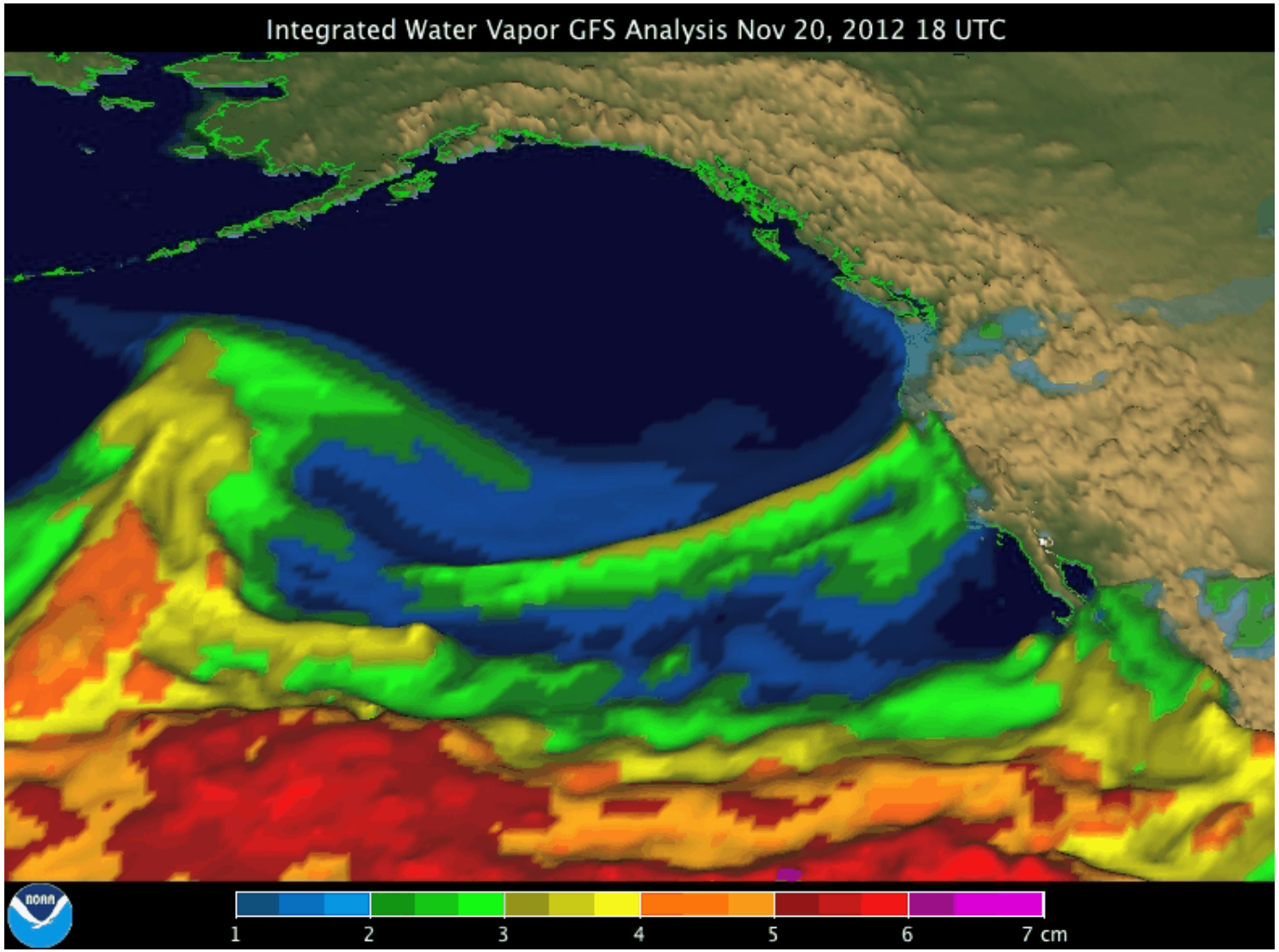
FIRO Steering Committee:
Co-Chairs Jasperse & Ralph

Local, State, Federal and University weather and water experts working to evaluate the potential viability of using forecasts of atmospheric rivers, rain and streamflow to enable safe retention of extra water if major storms are not predicted over the watershed in the coming days, or to enhance flood control if strong storms *are* predicted.

***http://cw3e.ucsd.edu/FIRO/**



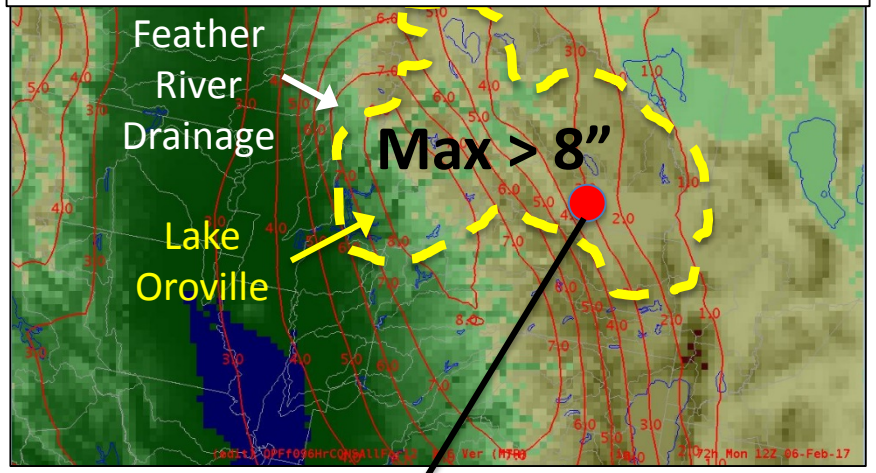
Atmospheric River Events 20 Nov-3 Dec 2012

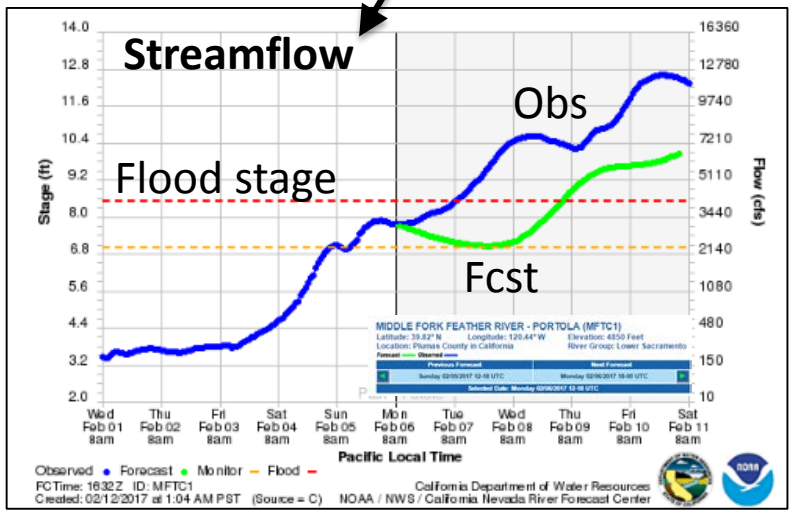


Animation courtesy of Don Murray (NOAA/ESRL/PSD)

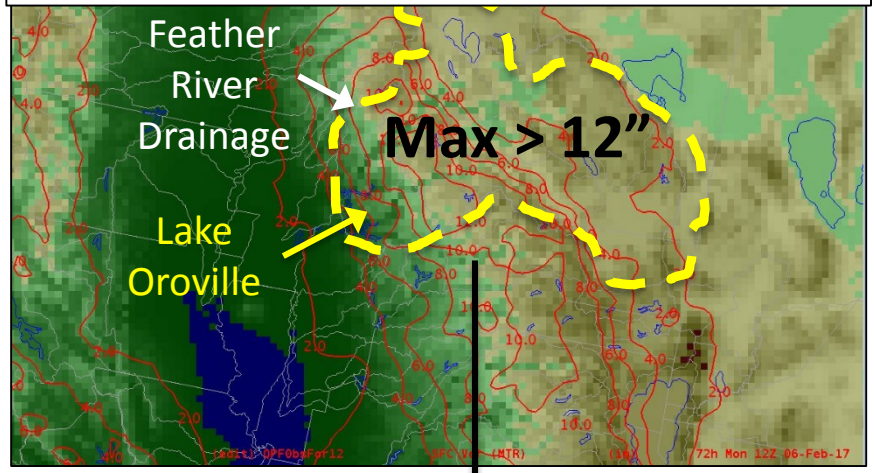
Observed Vs Predicted Precipitation over Feather River Basin for 6-9 Feb 2017

Predicted (CNS) Precipitation over 3 days at 4-day lead time

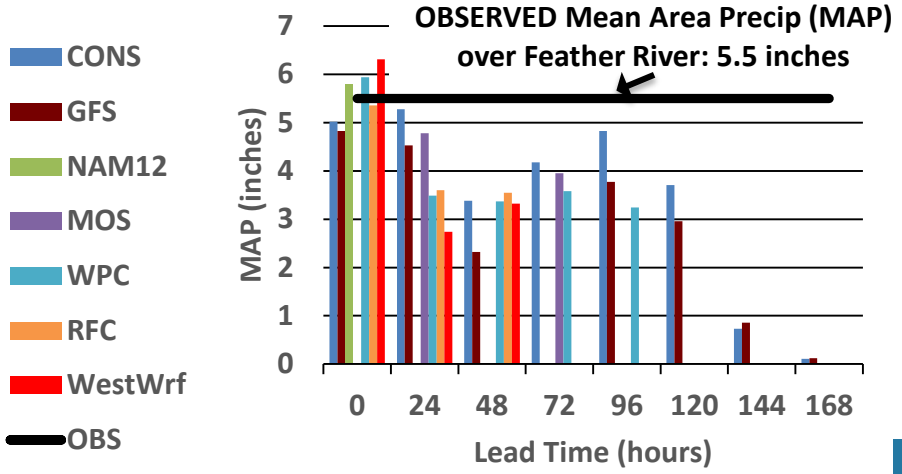


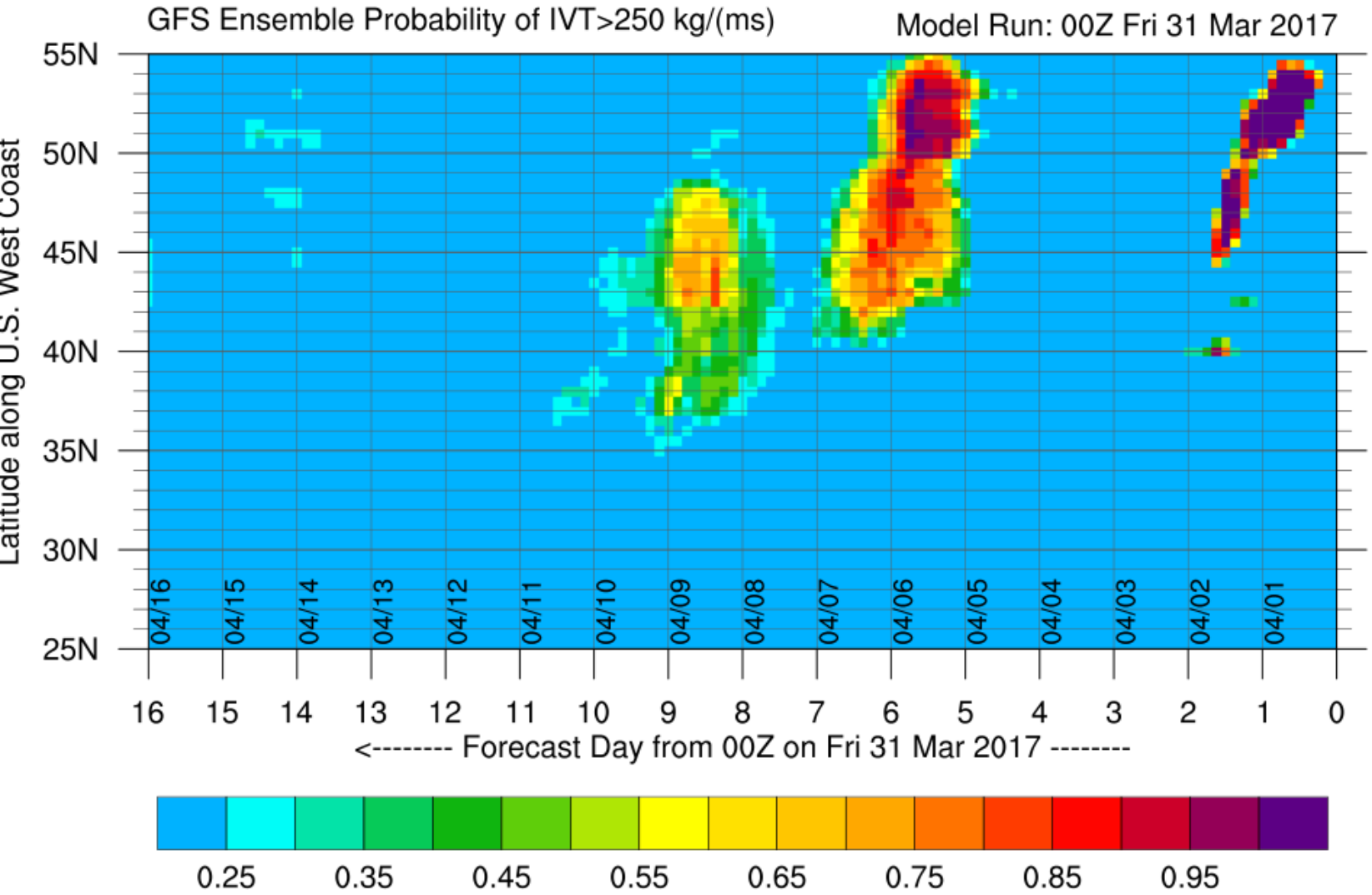


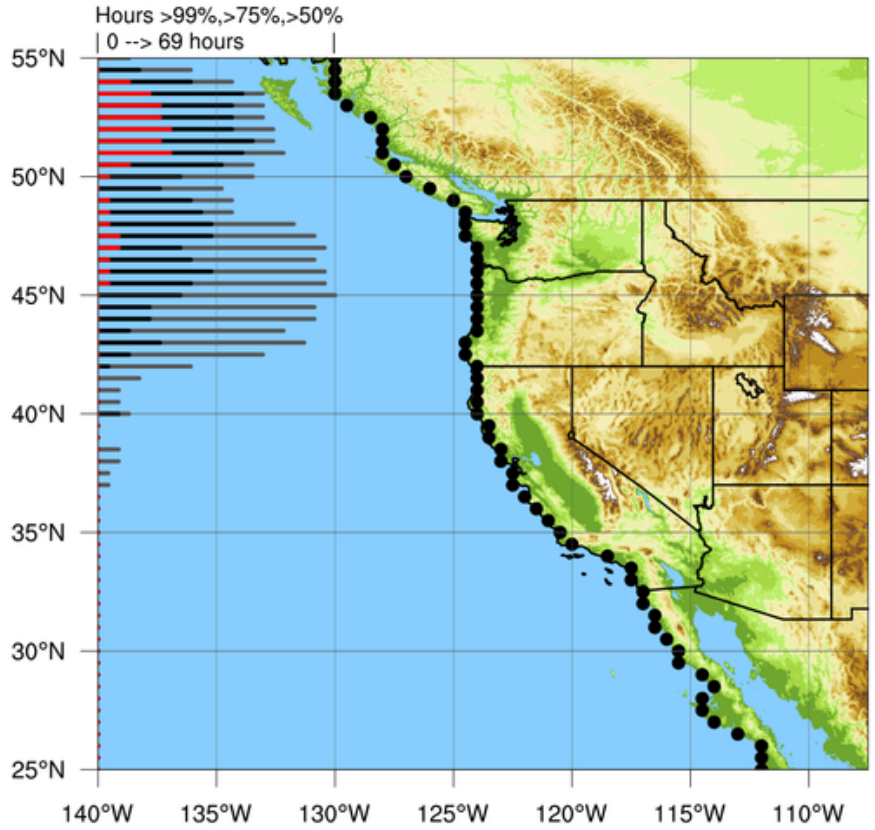
Observed Precipitation over 3 days ending 1200 UTC 9 Feb



72 hr MAP Feather Basin 12z 6-9 Feb. 2017







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SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

PLYMOUTH STATE METEOROLOGY

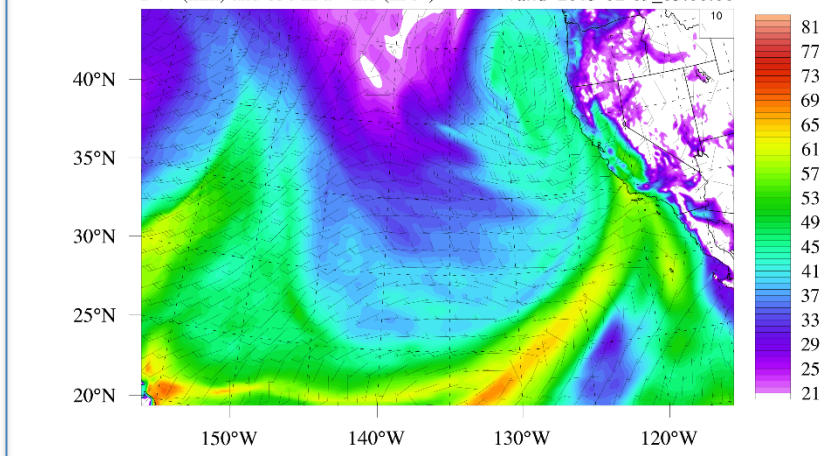
CW3E-SDSC Partnership

"West-WRF" Weather Model to Focus on Western U.S. Extreme Events

- ✓ SDSC Director and UCSD Physics Professor Mike Norman is fully-supportive of CW3E
- ✓ Contributing Staff time (J. Helly), computer time and disk storage on the *Gordon* supercomputer

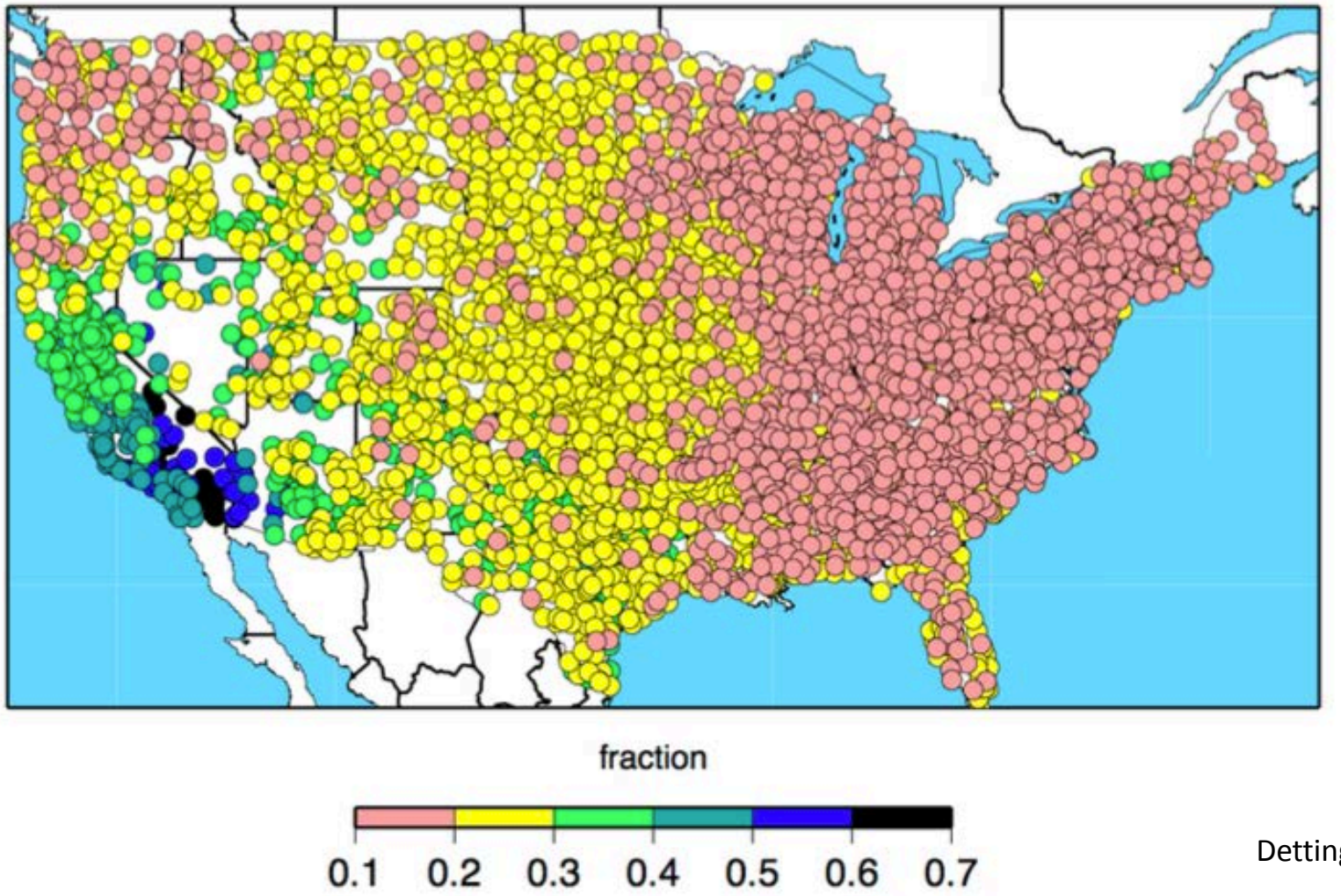
- ✓ Interdisciplinary team of SIO & SDSC Scientists, post-docs and grad students
- ✓ Working to an integrated *research* and *operations* plan
- ✓ *West-WRF* implemented in < 6 months now supporting Calwater2 mission planning

First Real-Time West-WRF runs



CalWater Observations will be used to evaluate, explore and improve the physics in CW3E's West-WRF Model from air-sea interaction, to mesoscale dynamics, aerosols and cloud microphysics and data assimilation.

Variability of Annual Precipitation



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).

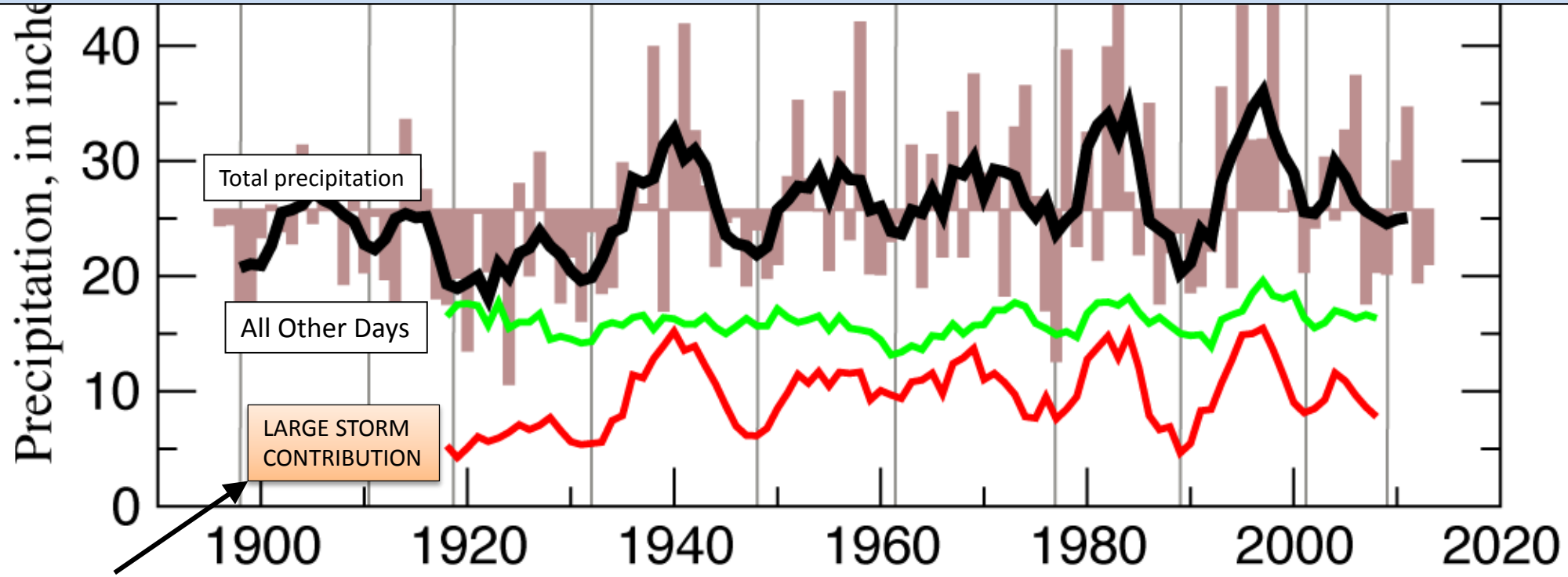
Dettinger, M.D., Ralph, F.M., Das, T., Neiman, P.J., and Cayan, D., 2011: **Atmospheric rivers, floods, and the water resources of California**. *Water*, **3**, 455-478.

A few large storms (or their absence)

account for a disproportionate amount of California's precipitation variability

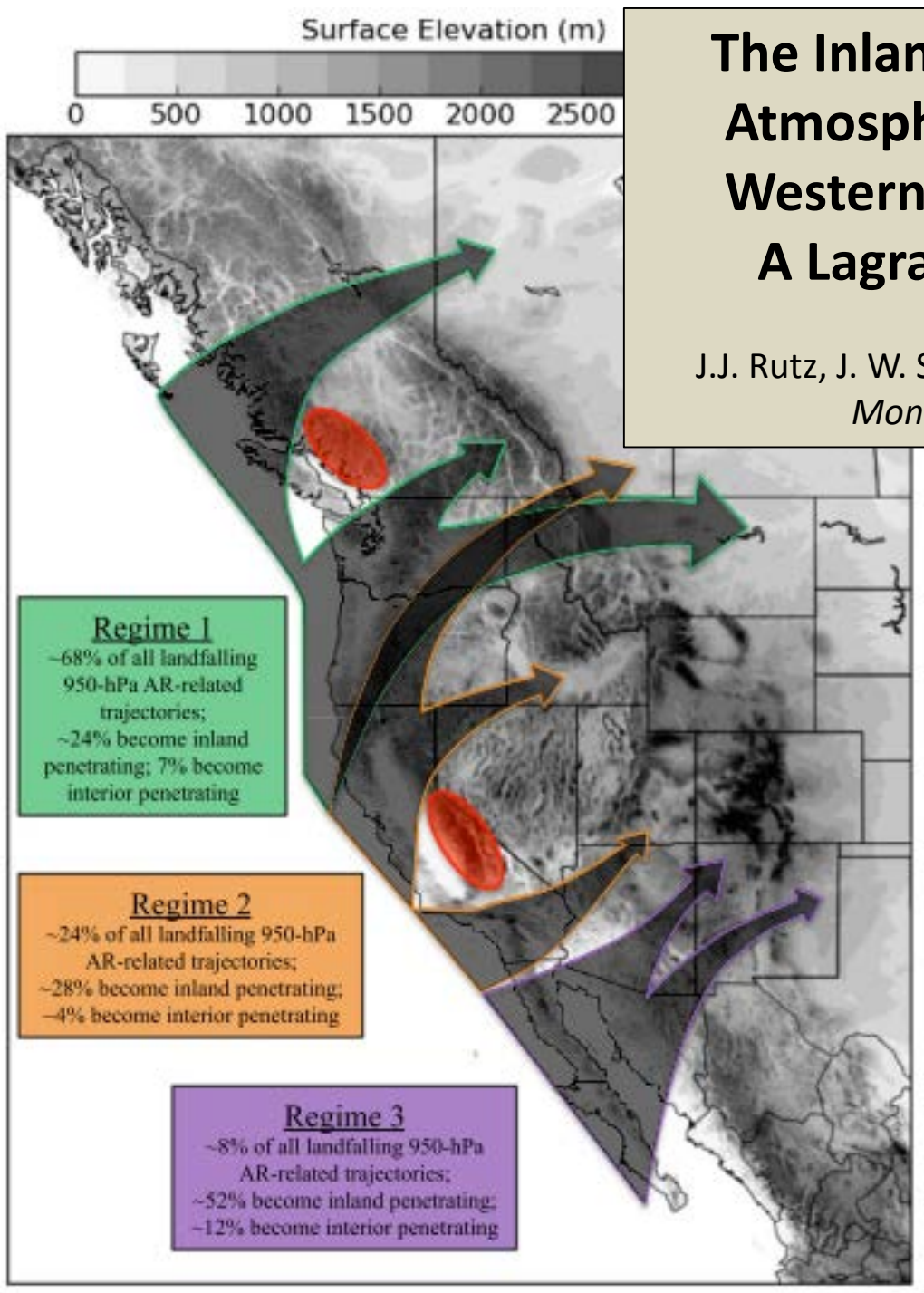
a) Water-Year Precipitation, Delta Catchment

WHETHER A YEAR WILL BE WET OR DRY IN CALIFORNIA IS MOSTLY DETERMINED BY THE NUMBER AND STRENGTH OF ATMOSPHERIC RIVERS STRIKING THE STATE.



- 85% of interannual variability results from how wet the 5% wettest days are each year.
- These days are mostly atmospheric river events.

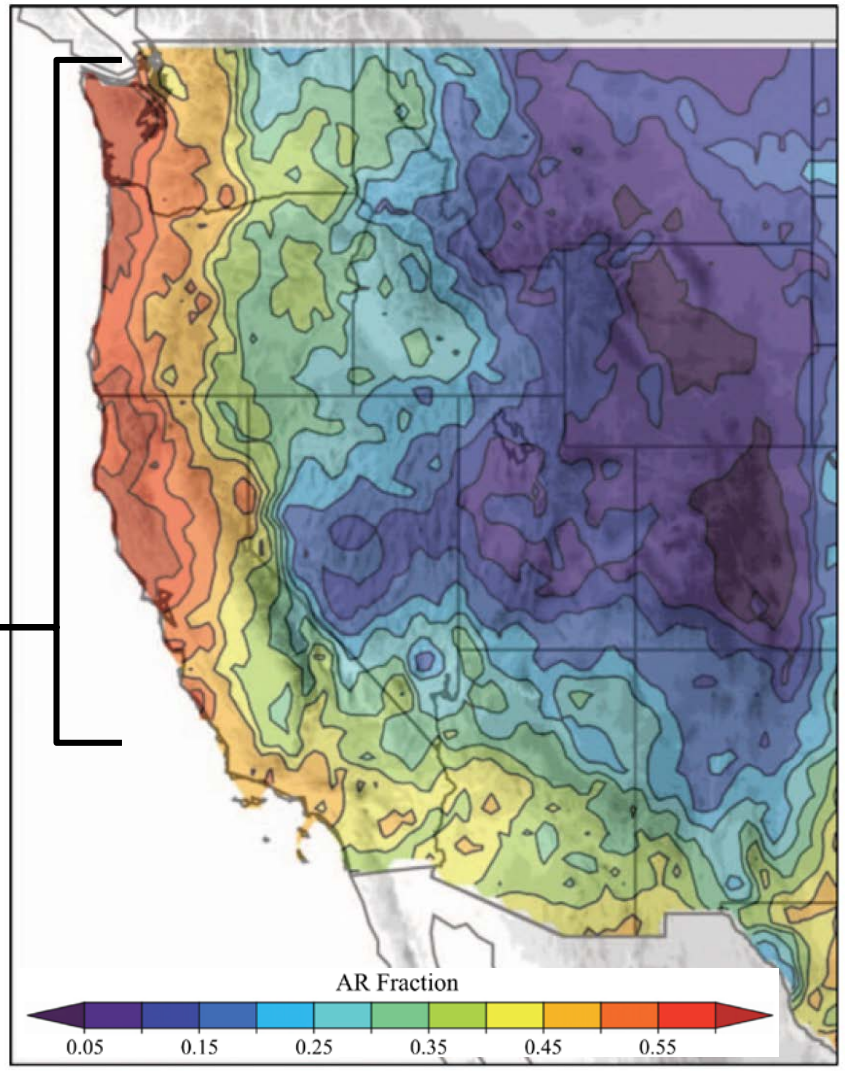
Dettinger and Cayan Drought and the Delta—A Matter of Extremes
San Francisco Estuary and Watershed Science, April 2014



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

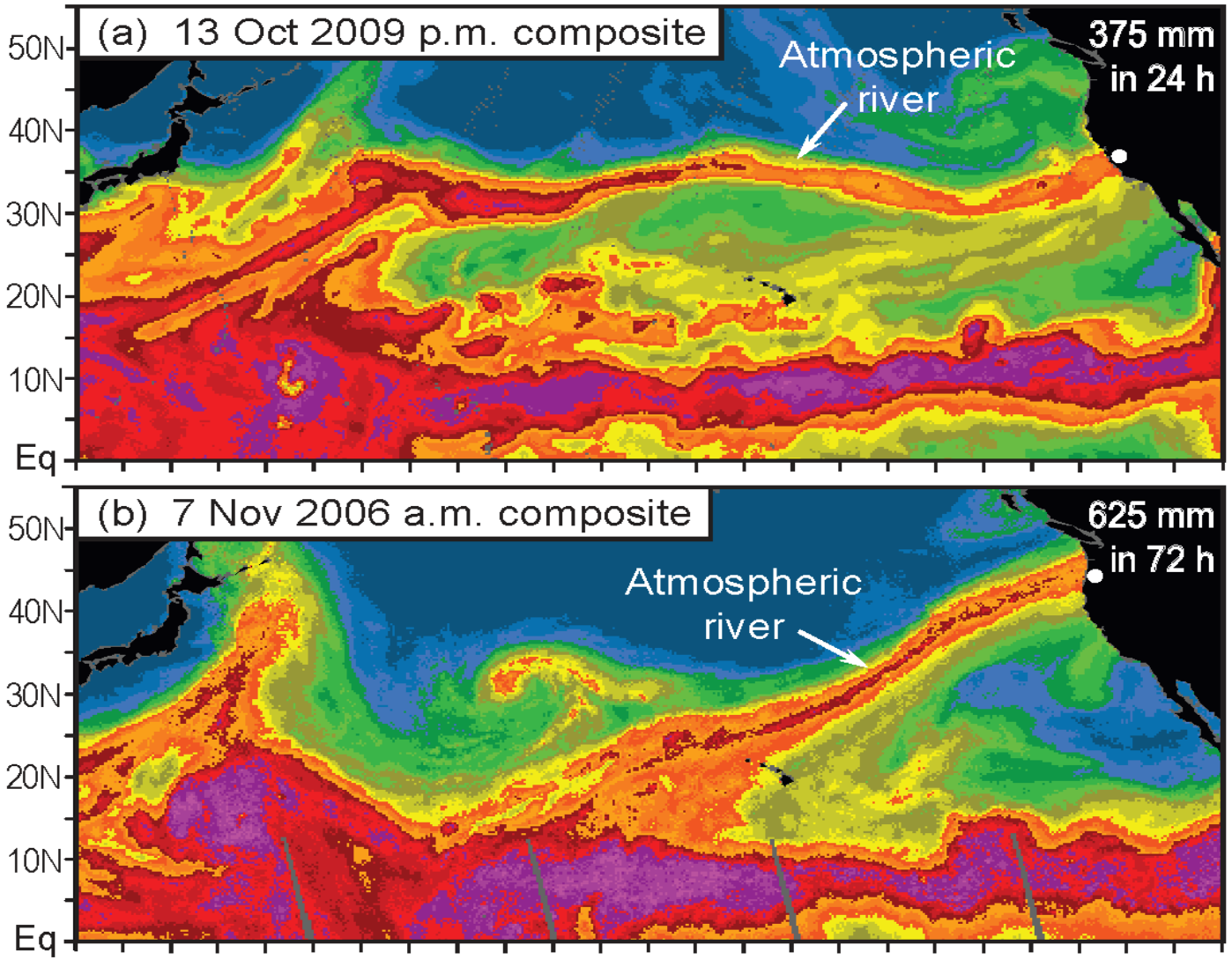
40-50% of annual precipitation falls during AR events in key areas



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

Atmospheric rivers: SSM/I Satellite data for two recent examples that produced extreme rainfall and flooding



From Ralph et al. 2011, Mon. Wea. Rev.

These color images represent satellite observations of atmospheric water vapor over the oceans.

Warm colors = moist air
Cool colors = dry air

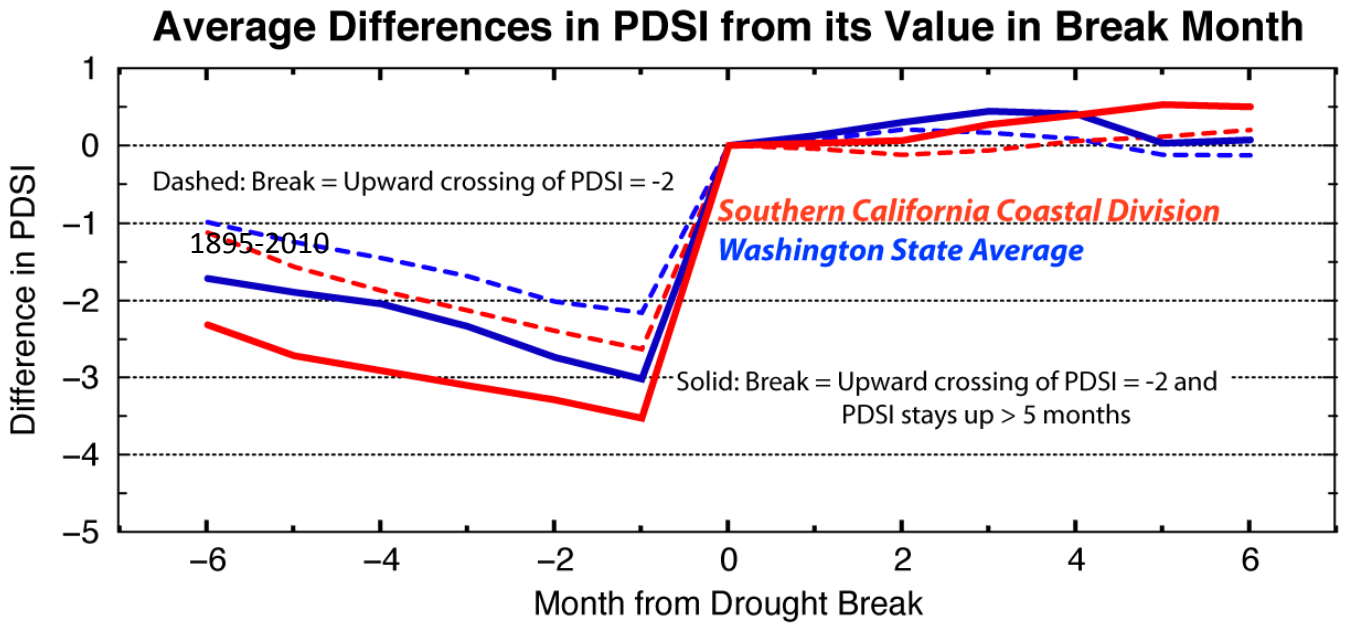
ARs can be detected with these data due to their distinctive spatial pattern.

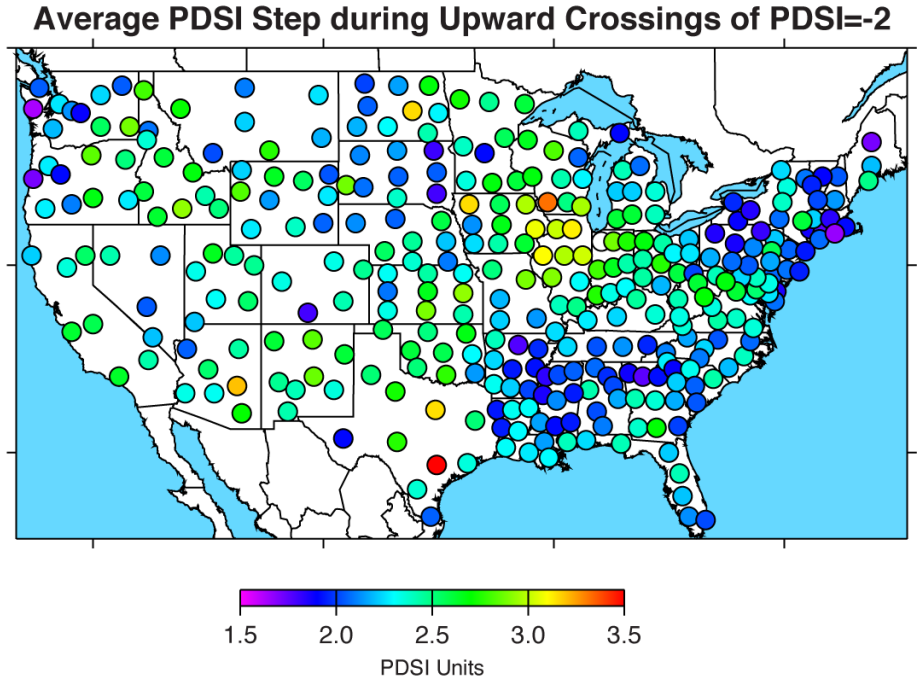
In the top panel, the AR hit central California and produced 18 inches of rain in 24 hours.

In the bottom panel, the AR hit the Pacific Northwest and stalled, creating over 25 inches of rain in 3 days.

Droughts, on average, end with a bang (and begin with a whimper) all over the U.S.

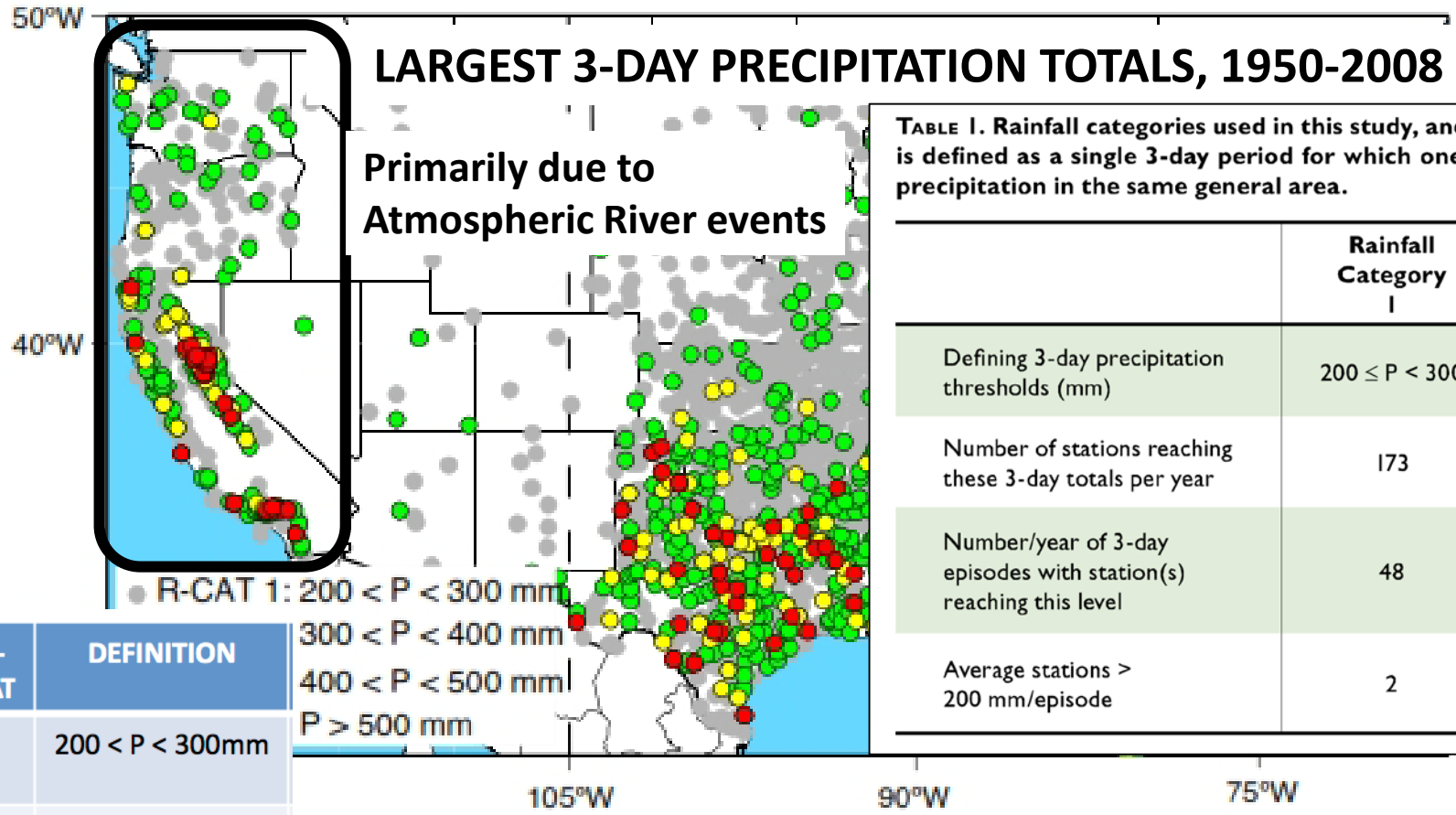
- **Atmospheric rivers provide the bang** in a large fraction of the west coast drought breaks, especially in winters





Dettinger, Michael D., 2013: Atmospheric Rivers as Drought Busters on the U.S. West Coast. *J. Hydrometeor*, **14**, 1721–1732.

R-Cat Precipitation Scale: 3-day total rainfall

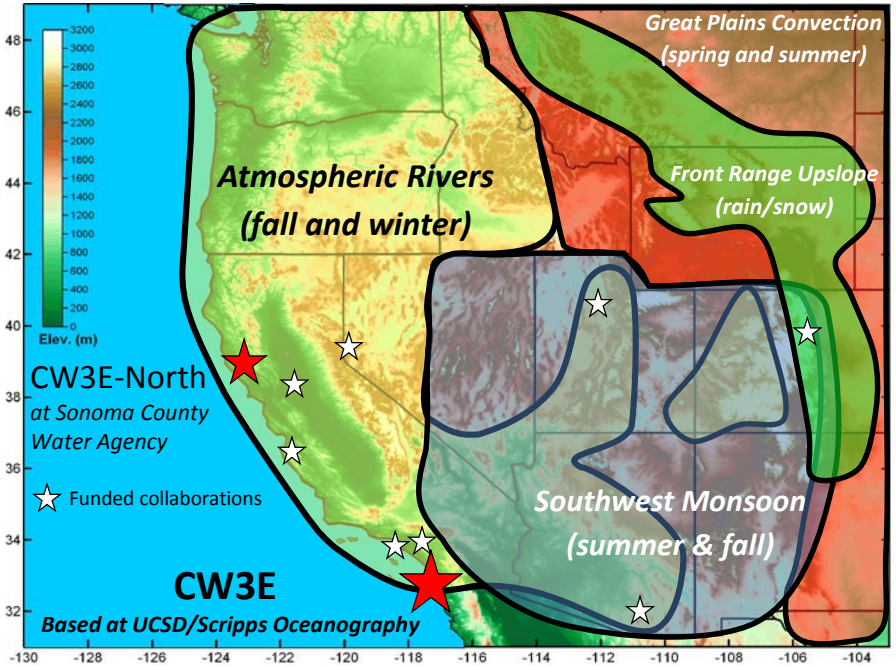


R-CAT	DEFINITION
1	200 < P < 300mm
2	300 < P < 400mm
3	400 < P < 500mm
4	P > 500mm

Table 1. Rainfall categories used in this study, and national frequencies of occurrence. Note that an "episode" is defined as a single 3-day period for which one or more stations observed at least 200 mm (~ 8 inches) of precipitation in the same general area.

	Rainfall Category 1	Rainfall Category 2	Rainfall Category 3	Rainfall Category 4
Defining 3-day precipitation thresholds (mm)	200 ≤ P < 300	300 ≤ P < 400	400 ≤ P < 500	500 ≥ P
Number of stations reaching these 3-day totals per year	173	23	4	2
Number/year of 3-day episodes with station(s) reaching this level	48	9	2	1
Average stations > 200 mm/episode	2	7	13	15

Ralph, F.M., and Dettinger, M.D. 2012, Historical and national perspectives on extreme west-coast precipitation associated with atmospheric rivers during December 2010: *Bulletin of the American Meteorological Society,* (2012)



Key Phenomena Causing Extreme Precipitation in the Western U.S. (Ralph et al. 2014)

Center for Western Weather and Water Extremes

SCRIPPS INSTITUTION OF OCEANOGRAPHY
AT UC SAN DIEGO

Director: F. Martin Ralph, Ph.D. **Website: cw3e.ucsd.edu**

Strategies: Observations, physical processes, modeling, decision support
Scope: A group of roughly 40 people with 10 major projects
Partners: California DWR, Sonoma County Water Agency, CNAP, USGS
San Diego Supercomputing Center
Sponsors: CA DWR, USACE/ERDC, NOAA, SCWA, NASA, USBR

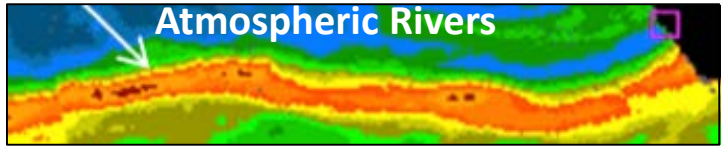
Mission

Provide 21st Century water cycle science, technology and outreach to support effective policies and practices that address the impacts of extreme weather and water events on the environment, people and the economy of Western North America

Goal

Revolutionize the physical understanding, observations, weather predictions and climate projections of extreme events in Western North America, including atmospheric rivers and the North American summer monsoon as well as their impacts on floods, droughts, hydropower, ecosystems and the economy

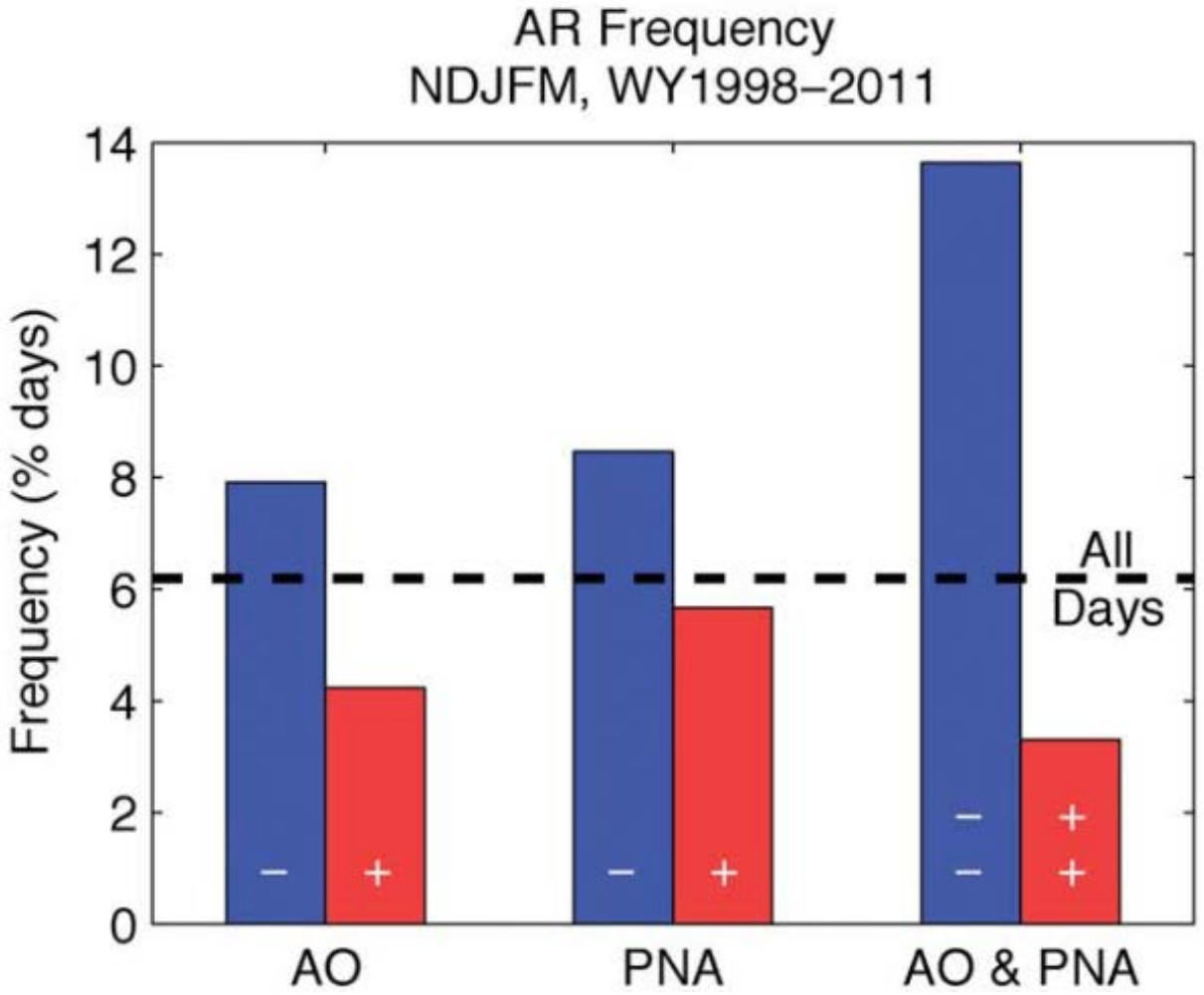
CW3E's Core Efforts




Center for Western Weather
and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY
AT UC SAN DIEGO
2 March 2017

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

Thursday 930-1100 AM: Exhibitor Technical Presentation I
"Actions to Improve the Skill of Long-term Precipitation Forecasting"
Panelists from WSWC, NOAA/NWS, and NASA/JPL
Location: "Grand Ballroom G"