Atmospheric Rivers: West-WRF, Forecast Evaluations and AR Summaries

F. Martin Ralph

Center for Western Weather and Water Extremes

UC San Diego/Scripps Institution of Oceanography

S2S Workshop

WSWC

San Diego, CA 18 May 2017

Center for Western Weather and Water Extremes

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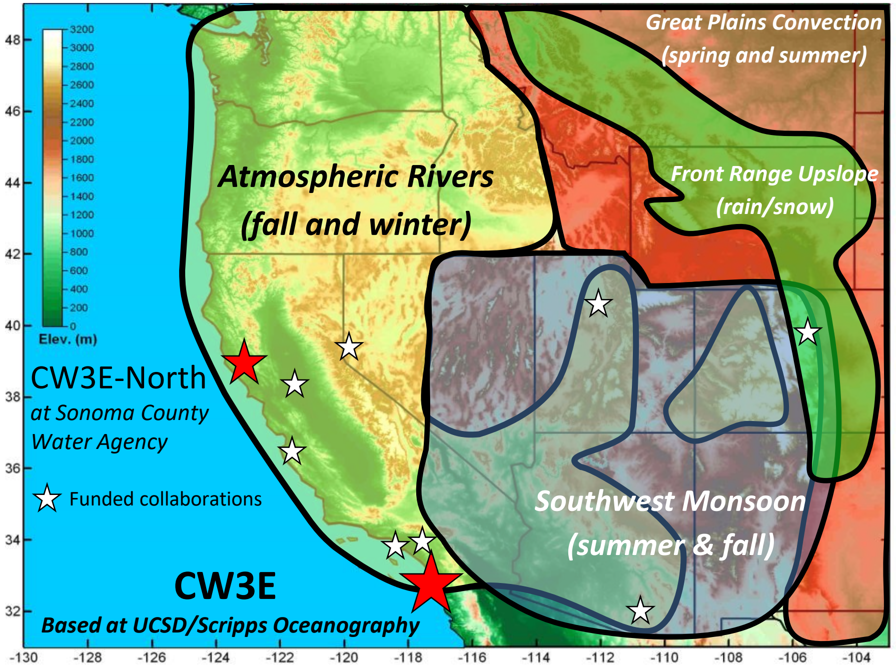


Key Phenomena Causing Extreme Precipitation in the Western U.S. (Ralph et al. 2014)

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

Partners: California DWR, Sonoma County Water Agency, CNAP, USGS
San Diego Supercomputing Center

Sponsors: CA DWR, USACE/ERDC, NOAA, SCWA, NASA, USBR

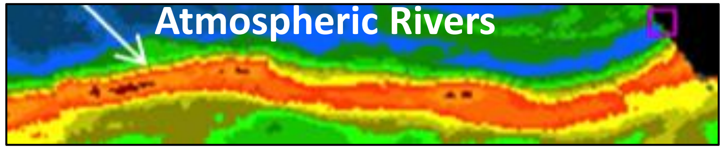
Mission

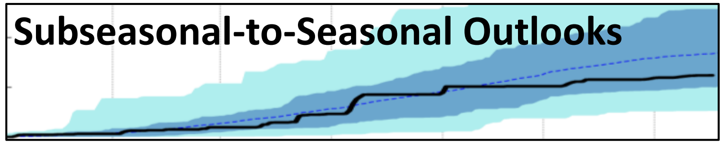
Provide 21st Century water cycle science, technology and outreach to support effective policies and practices that address the impacts of extreme weather and water events on the environment, people and the economy of Western North America

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





Develop a weather model tailored to Western U.S. Extreme precipitation

- West-WRF

Train and evaluate it against unique measurements

- Ground-based
- Airborne

Assimilate regional observations

tools

- Create educational opportunities
- Tap the benefits of diversity in disciplines, methods and people

applications and decision makers

- Transfer knowledge, information and tools to "operations"
- Utilize outreach to connect science to the public

CW3E's West-WRF Model Development Strategy

F.M. Ralph (PI)
CW3E Director

A. Martin, J. Helly, B. Cornuelle, S. Gershunov, J. Norris

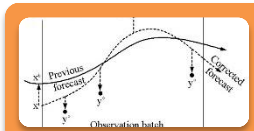
Steering Committee

Reporting Layer:

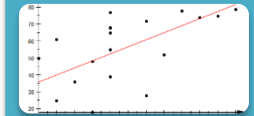
Development Tasks

West-WRF Development Strategy designed to:

- Ground new capabilities in deliverable commitments
- Build organizational knowledge
- Keep West-WRF up-to-date with latest technical developments
- Ensure balanced growth so that operational and research goals continue to support one another.



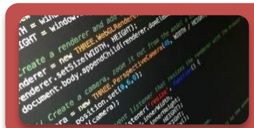
DA / Ensembles: Increase accuracy through data assimilation, devlop probabilistic forecasts, work with Verification to apportion forecast error.



Verification: Measure and report forecast accuracy and work with DA to apportion forecast error.

NRT and Data Management: Create specialized forecast products on a regular duty cycle and manage I/O streams and data storage

Physical Process Studies: Investigate realism of subgrid-scale processes and use numerical experimentation to address basic science questions



Code Curation: Keep West-WRF up to date, work with all other tasks to develop new code according to modern open-source practices, publish tutorials and technical descriptions.

Data Assimilation / Ensembles	Verification	NRT and Data Management	Physical Process Studies	Code Curation
Bruce Cornuelle	Andrew Martin	John Helly	Anna Wilson	Rachel Weihs

Andrew Martin – lead on West-WRF

Future West-WRF Development

A. Martin, F. M. Ralph, J. Helly, R. Weihs, B. Cornuelle, A. Wilson

Weather Modeling CW3E-SDSC Partnership

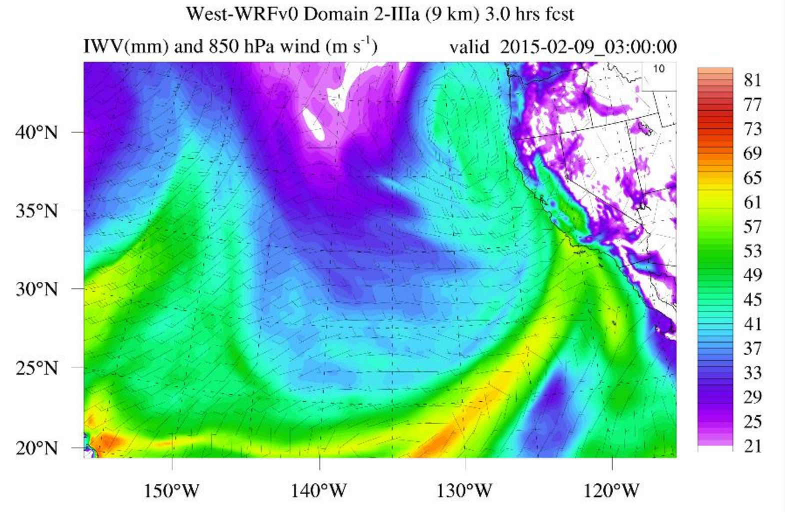
✓ SDSC Director and UCSD Physics Professor Mike Norman is fully-supportive of CW3E

✓ Contributing Staff time, computer time and disk storage on SDSC supercomputers

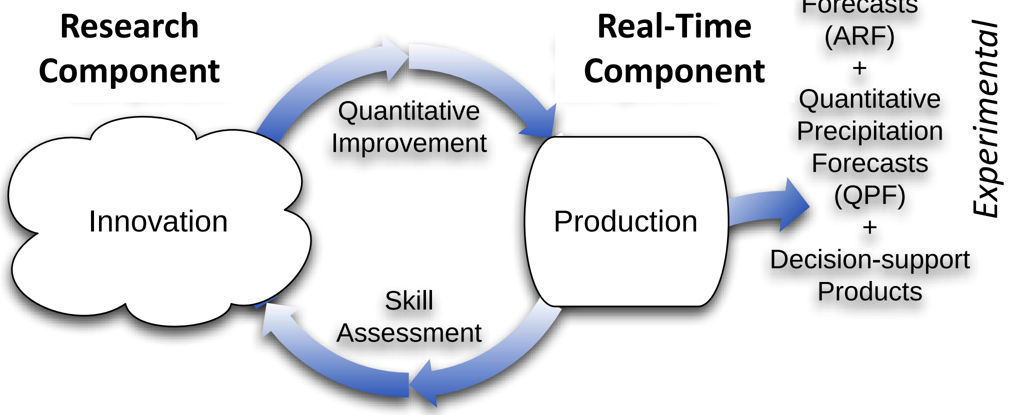
"West-WRF" Weather Model to Focus on Western U.S. Extreme Events

- ✓ 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
- ✓ Supporting CalWater2, DWR, FIRO

First Real-Time West-WRF runs

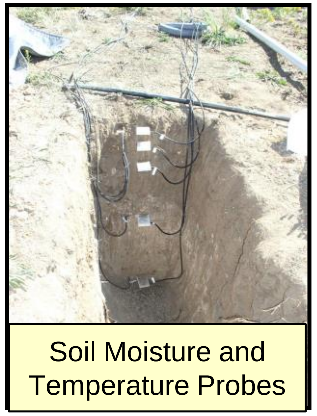


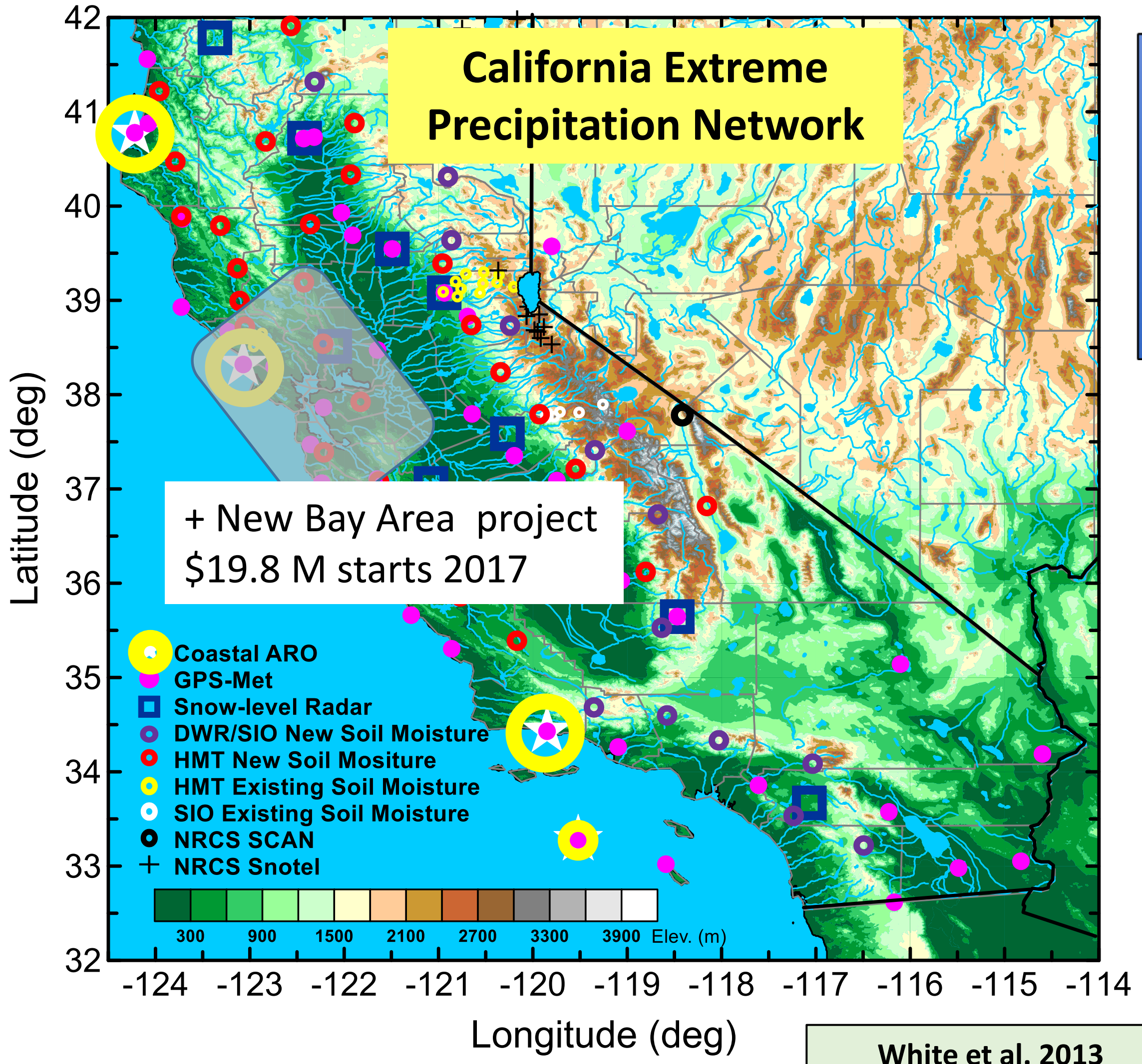
CW3E Modeling and Cyber-Infrastructure



Unique Observational Network in California

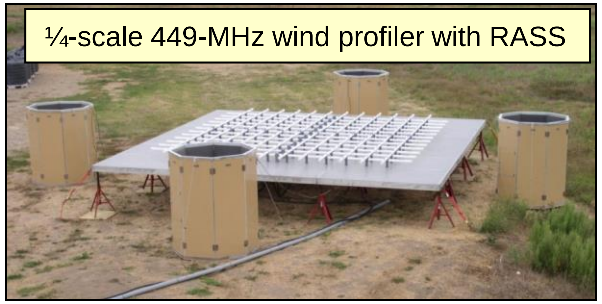
($20 M investment by CA Dept. of Water Resources)

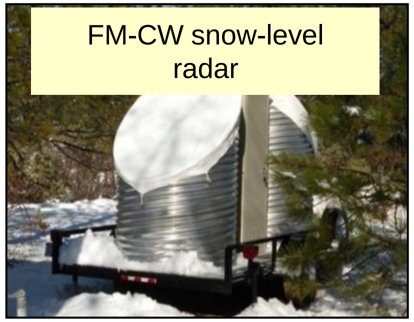




An Atmospheric River-focused long-term observing network is being installed in CA as part of a 5-year project between CA Dept. of Water Resources (DWR), NOAA and Scripps Inst. Of Oceanography

- Installed 2008-2014
- >100 field sites





White et al. 2013
(J. Atmos. Oceanic Tech.)

CalWater Field Studies Designed to Quantify the Roles of Atmospheric Rivers and Aerosols in Modulating U.S. West Coast Precipitation in a Changing Climate

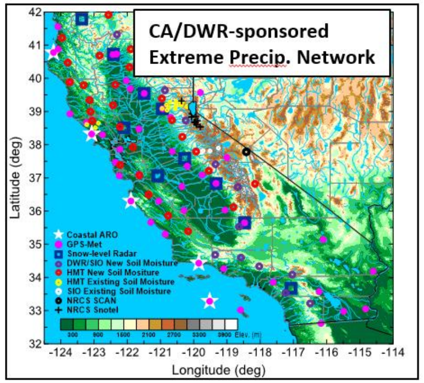
Ralph F.M., K. A. Prather, D. Cayan, J.R. Spackman, P. DeMott, M. Dettinger, C. Fairall, R. Leung, D. Rosenfeld, S. Rutledge, D. Waliser, A. B. White, J. Cordeira, A. Martin, J. Helly, and J. Intrieri, 2016, ***Bull. Amer. Meteor. Soc.***

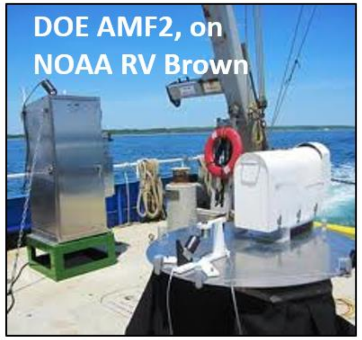
"CalWater – 2015" Field Experiment on Atmospheric Rivers & Aerosols

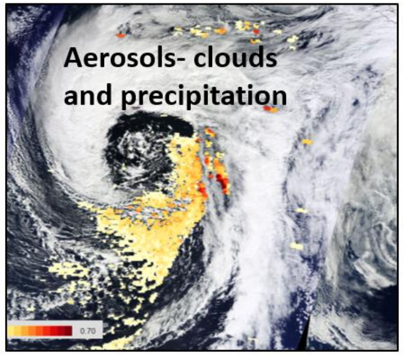
Steering Committee
Co-Chairs: F.M. Ralph
K. Prather, D. Cayan of USCD
+ NOAA, DOE, USGS, NASA
and other Univ. members

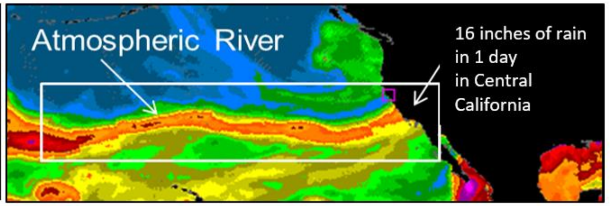
Atmospheric Sci., Chemistry, Hydrology, Oceanography

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









Field seasons

CalWater-1: 2009-2011
CalWater-2: 2014-2016

Locations

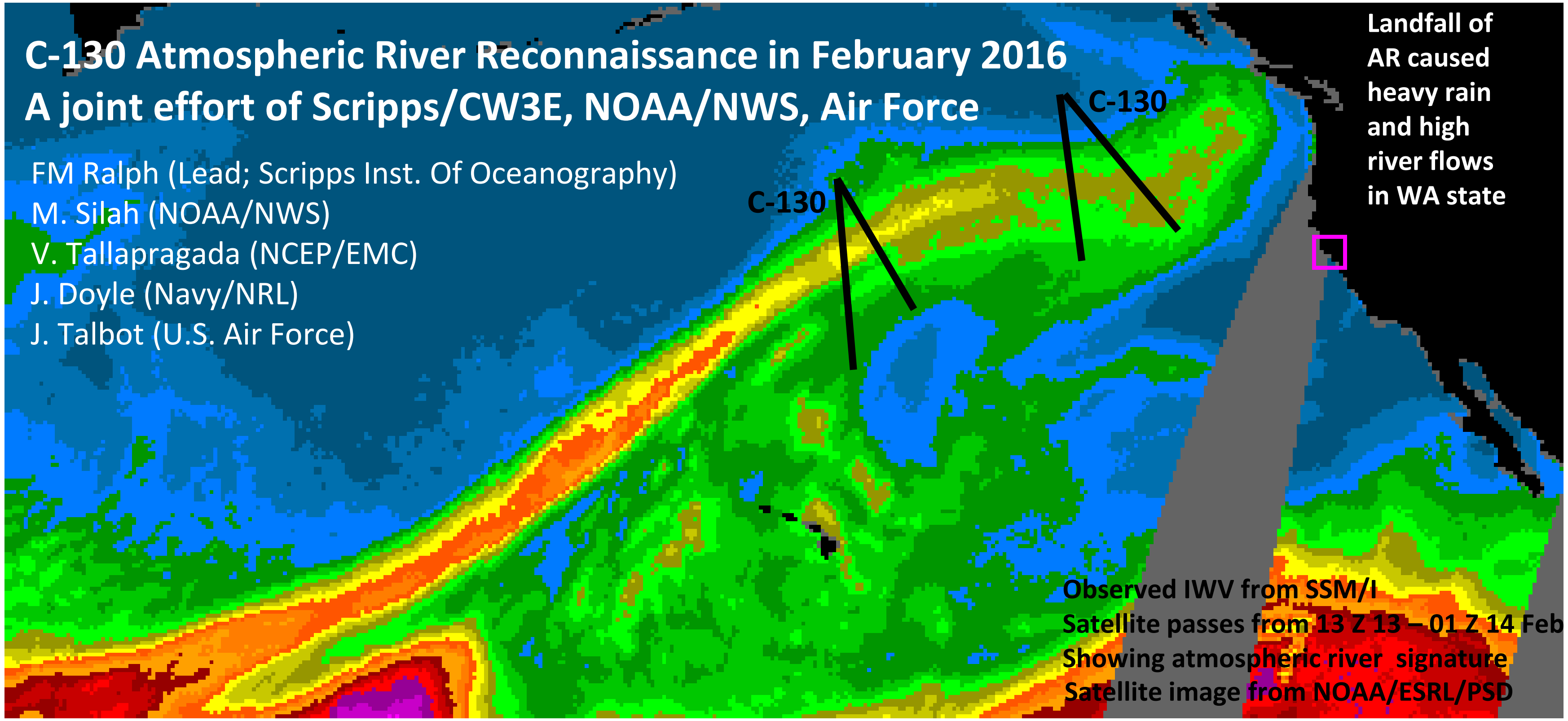
California
Eastern Pacific Ocean

Sponsors

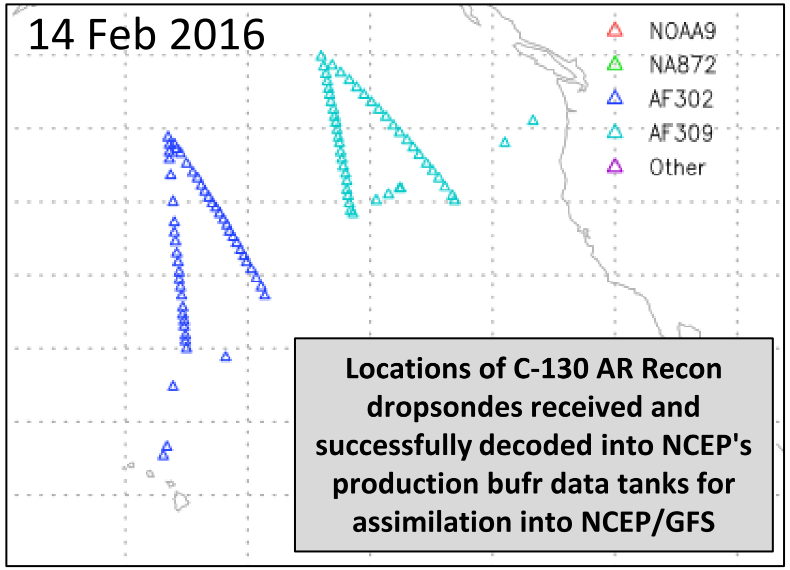
DOE, NOAA
California Energy Commission
California Dept. of Water Resources
NSF, NASA, ONR
(Total >$20 M investment)

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)
V. Tallapragada (NCEP/EMC)
J. Doyle (Navy/NRL)
J. Talbot (U.S. Air Force)



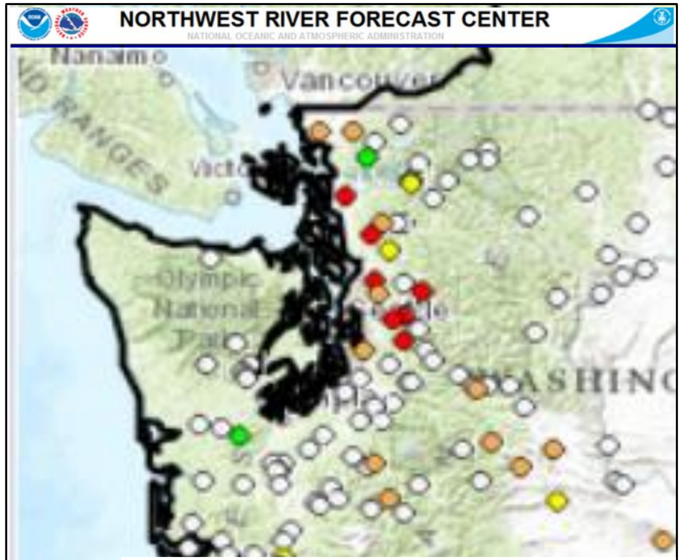
1st C-130 AR Recon Mission
13-14 Feb 2016
Dropsondes released for the 0000 UTC 14 Feb 2016 GFS data assimilation window



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

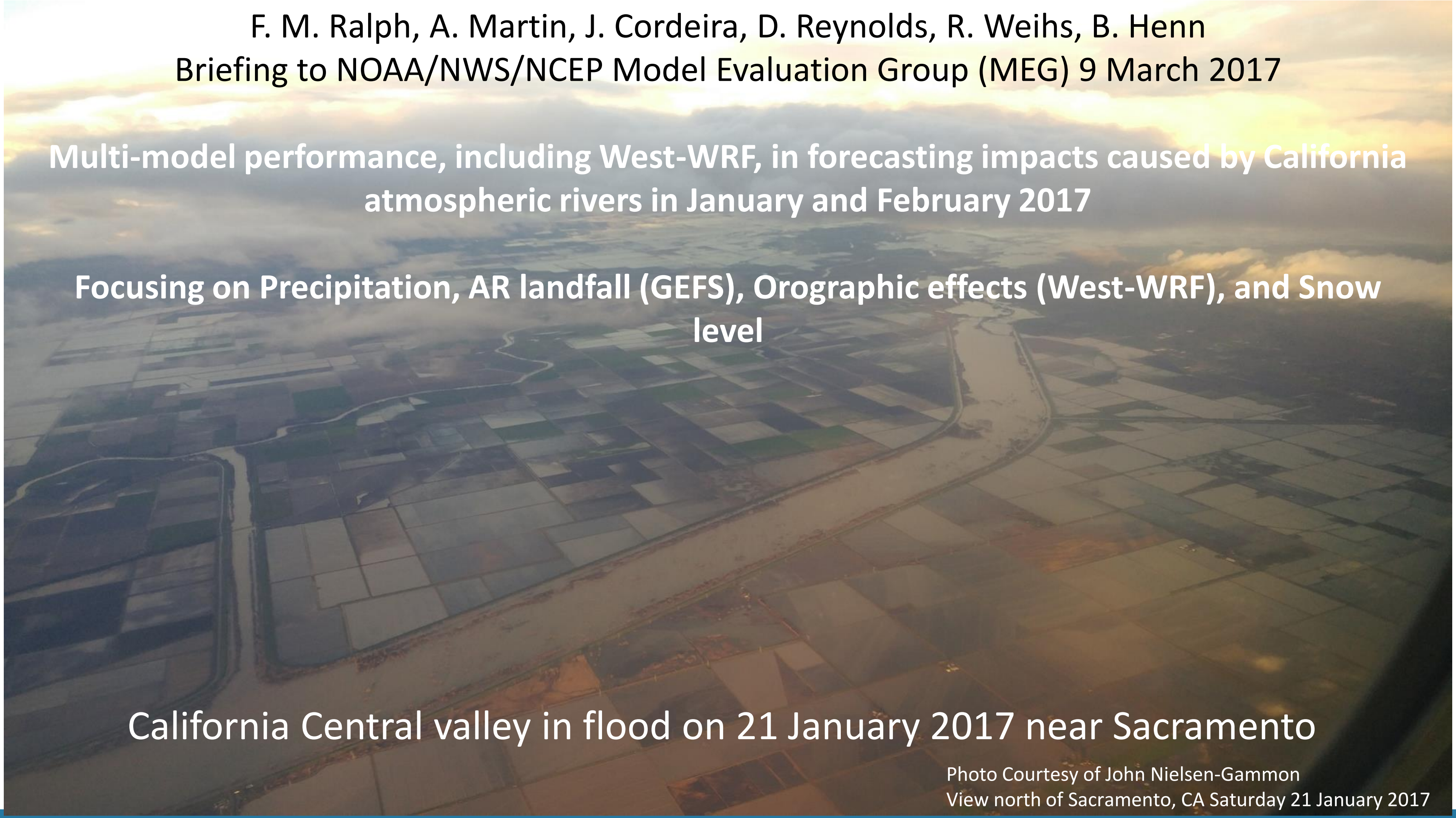
Air Force C-130 Aircraft – Weather Recon' Squadron

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)

CW3E West Coast Storms Overview and Examination of Forecasts



F. M. Ralph, A. Martin, J. Cordeira, D. Reynolds, R. Weihs, B. Henn

Briefing to NOAA/NWS/NCEP Model Evaluation Group (MEG) 9 March 2017

Multi-model performance, including West-WRF, in forecasting impacts caused by California atmospheric rivers in January and February 2017

Focusing on Precipitation, AR landfall (GEFS), Orographic effects (West-WRF), and Snow level

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

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QPF Skill by NWP Models During January and February Strong ARs

Including Floods on the Russian and Feather Rivers

Contact: D. Reynolds (david.reynolds@noaa.gov) for any questions

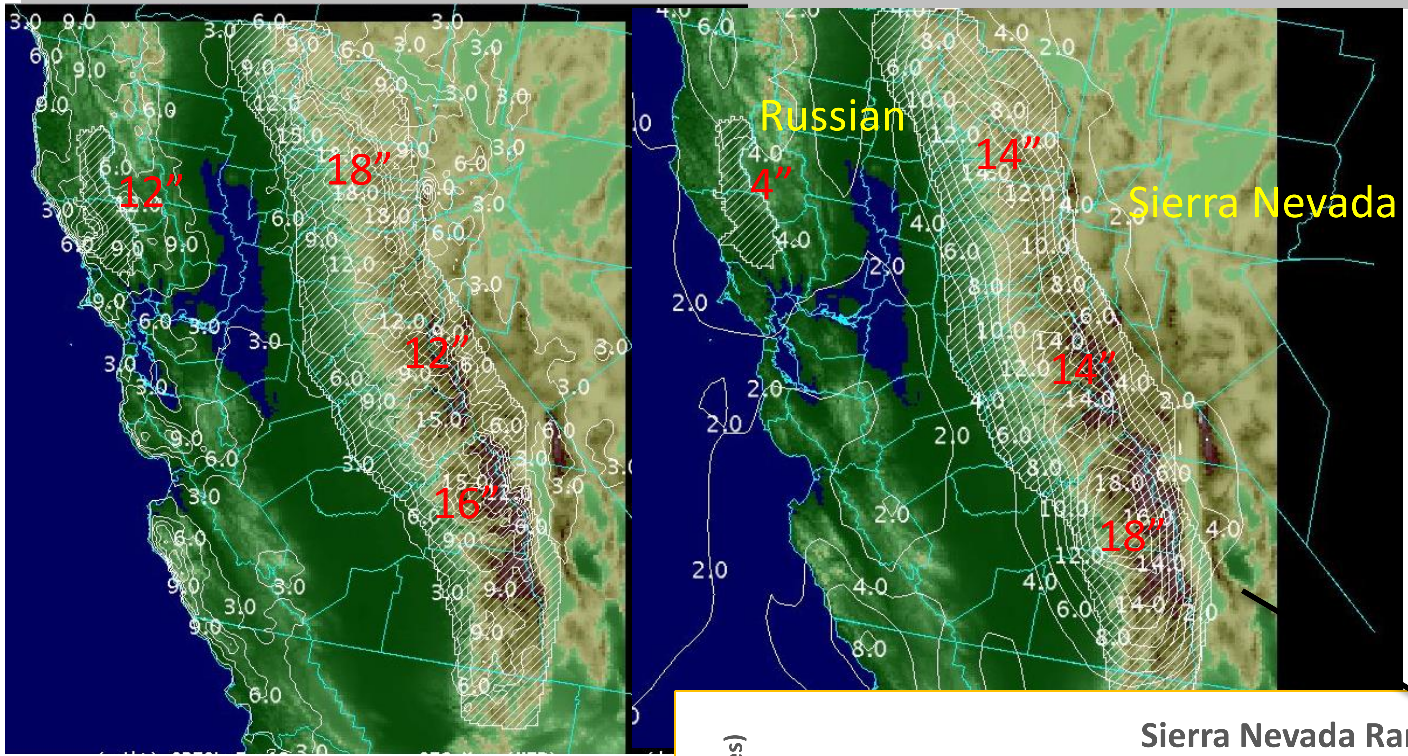
Produced by David Reynolds and Rachel Weihs

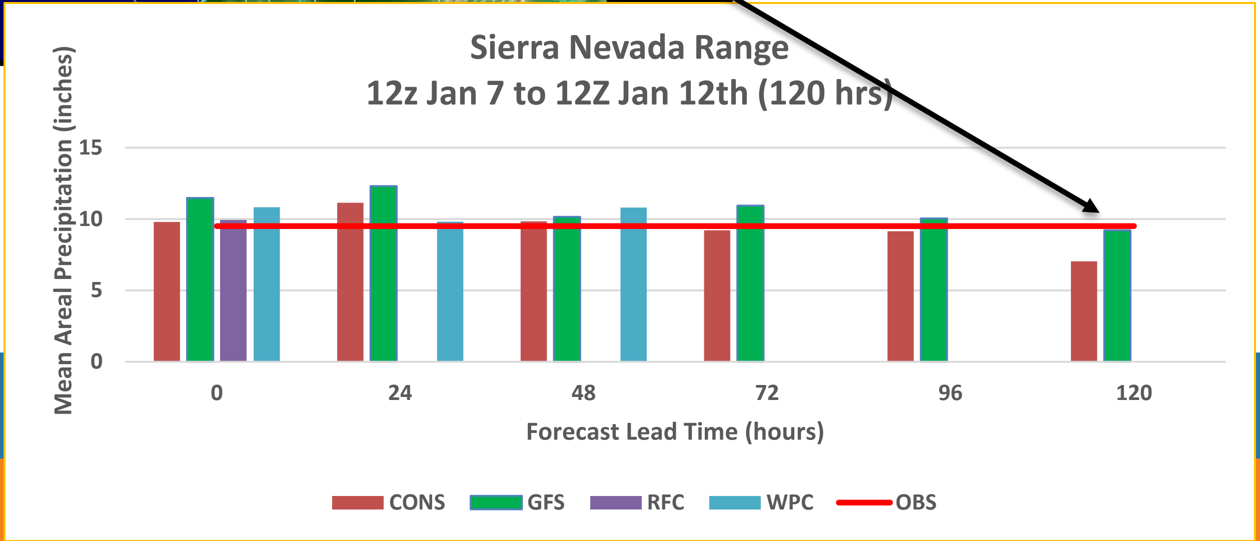
Outline

5-day Periods: 7 - 12 January 2017, 5 - 10 February 2017

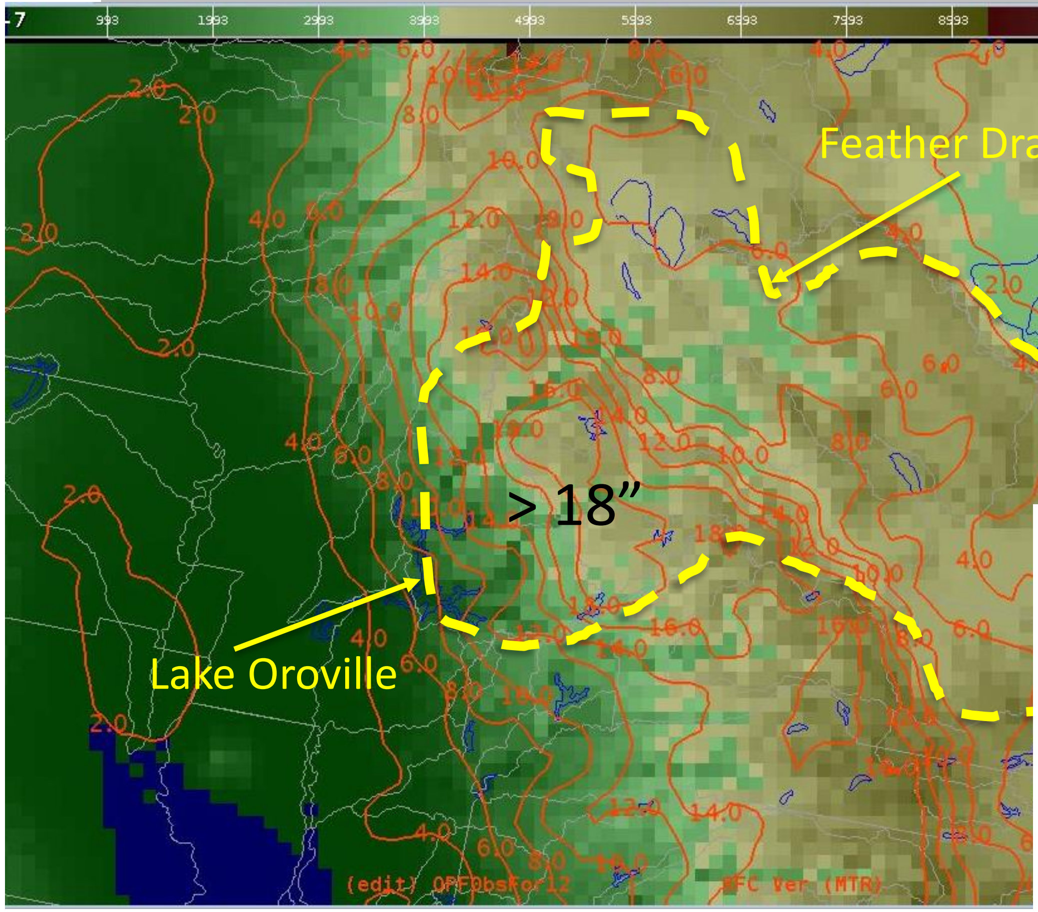
a) Multi-model mean areal QPF vs. mean-areal QPE
b) RFC Forecast vs. observed hydrographs

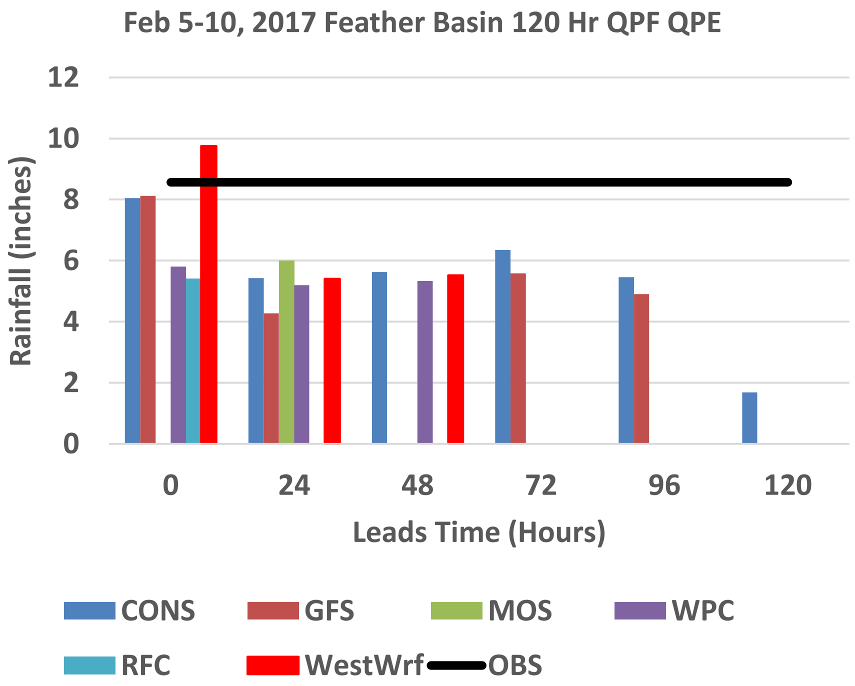
120 Hr Rainfall Sierra Nevada Jan 7-12, 2017
OBS GFS Day 5-10 Forecast





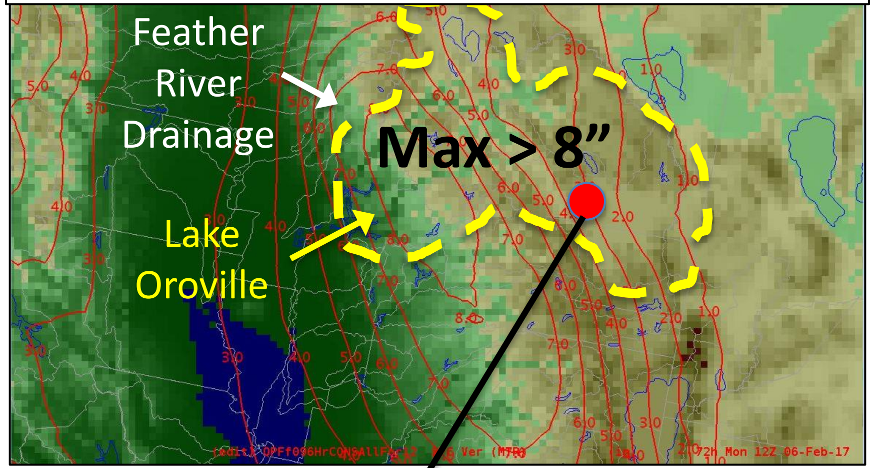
Feather River Drainage
5-day Observed QPE 5-10 Feb, 2017



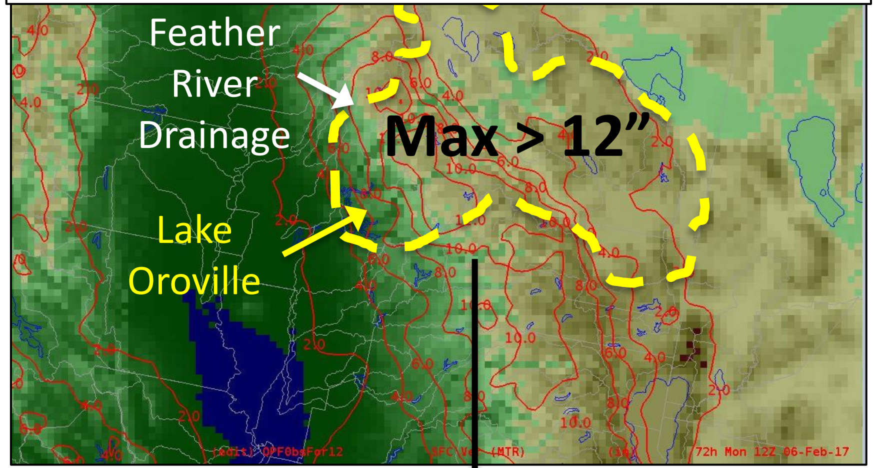


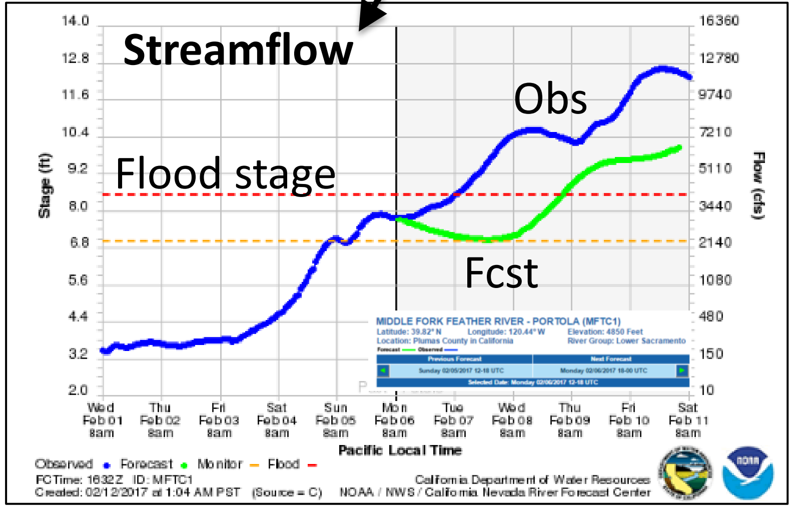
Observed Vs Predicted Precipitation over Feather River Basin for 6-9 Feb 2017

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

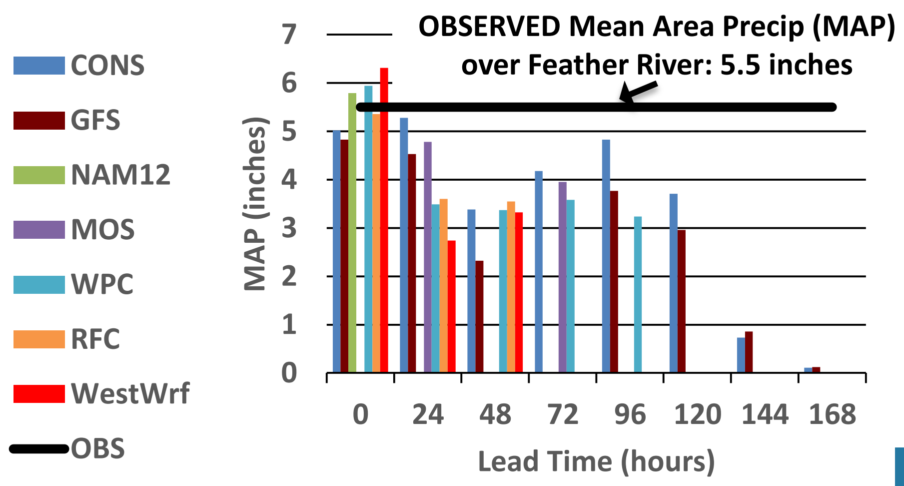


Observed Precipitation over 3 days ending 1200 UTC 9 Feb





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



Examples of dProg/dt from NCEP GFS Ensemble Forecast System graphics

Images generated at CW3E in collaboration with
J. Cordeira at Plymouth State University

For use during CW3E NCEP MEG Telecon meeting 9 March 2017

Contact: J. Cordeira at j_cordeira@plymouth.edu for any questions

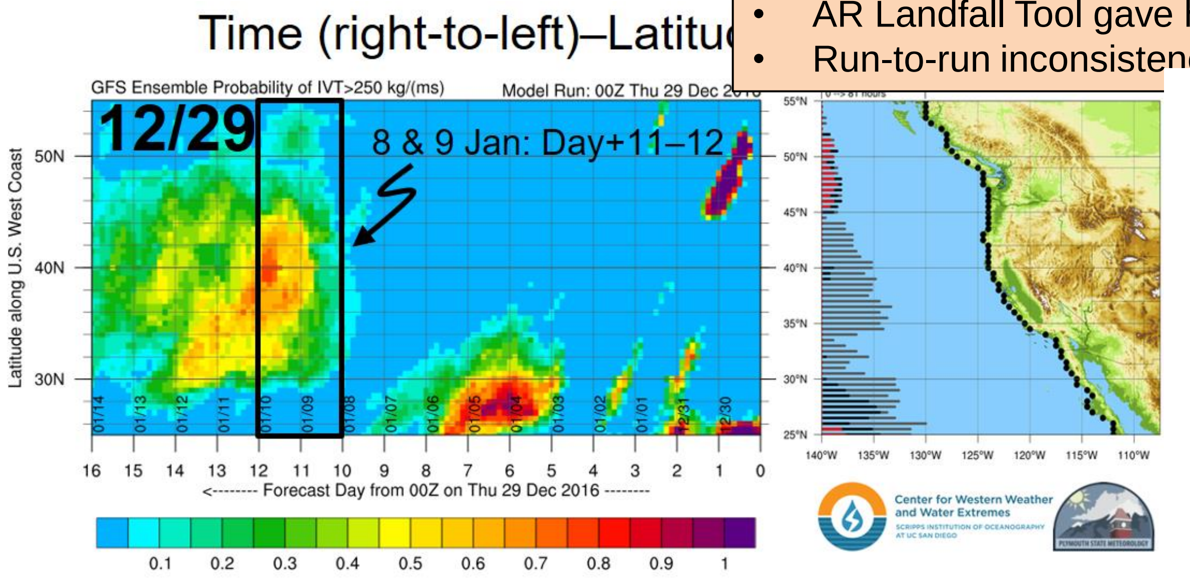
Outline

Cases: 8 January 2017, 6 February 2017

Images per case: (1) AR Landfall Tool – GEFS Probability IVT >250 kg m^{-1} s^{-1}
(2) GEFS IVT Plume Diagrams

GFS Forecast Model Performance

Take-Away:
- AR Landfall Tool gave heads up probability of at least weak landfalling AR 11–12 days in advance
- Run-to-run inconsistencies limited confidence in location/duration until 4–5 days in advance



NCEP GEFS dProg/dt Examples from January and February 2017

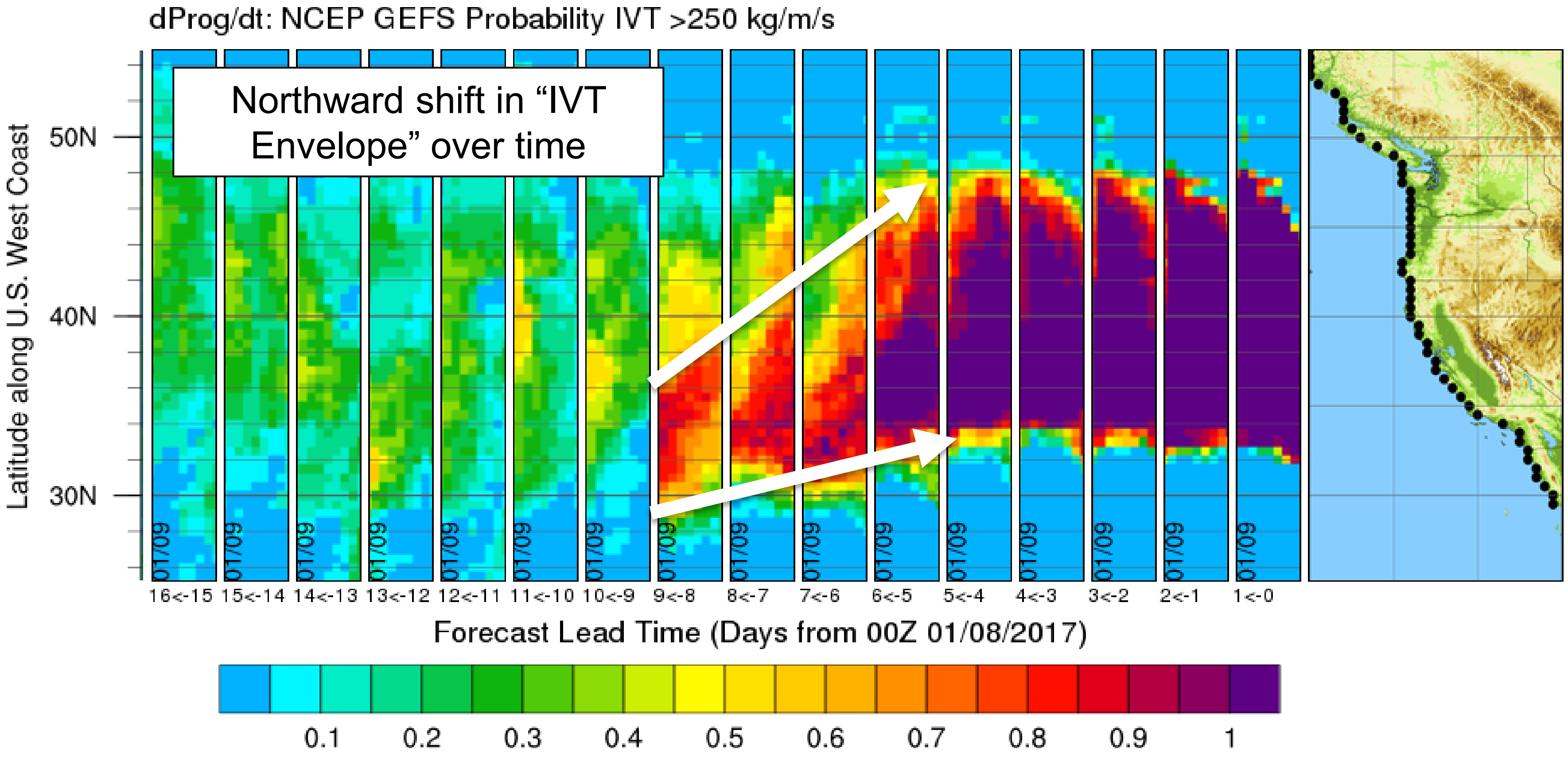
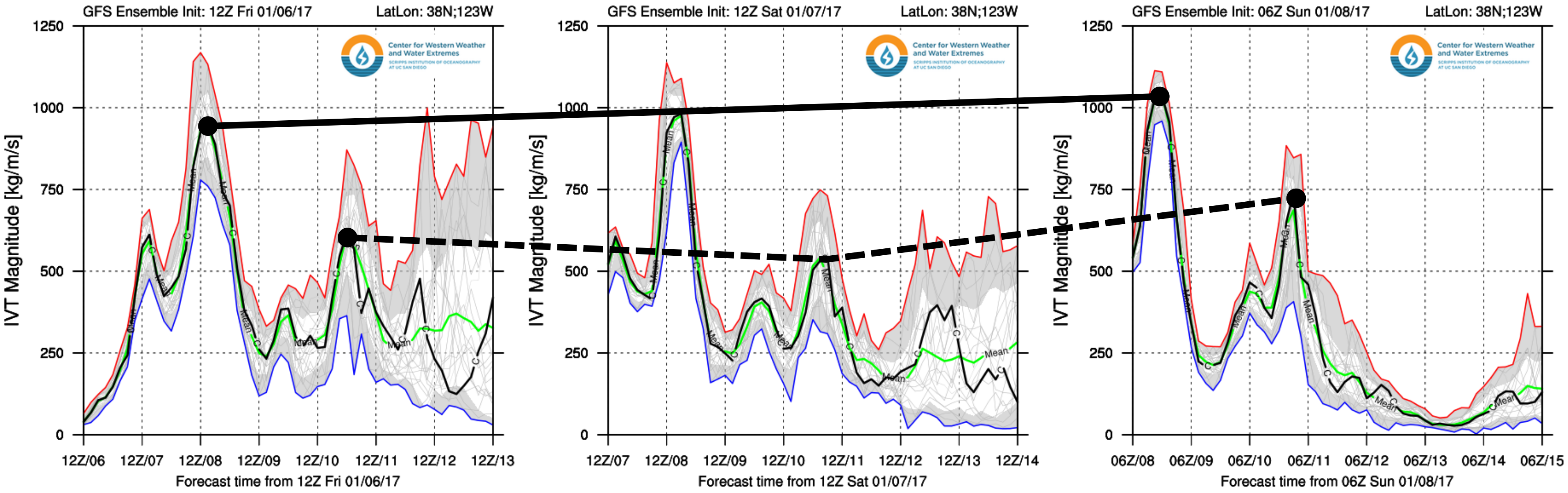


Image Description: Shading represents the NCEP GEFS probability that IVT will exceed 250 kg m^{-1} s^{-1} at 0.5-degree grid locations along the U.S. West Coast (dots). Each panel represents a 24-h forecast that verifies during the 24-h period starting at the time listed above the color bar. The lead 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.

NCEP GEFS dProg/dt Examples from January and February 2017



Init: 12Z/6 Jan

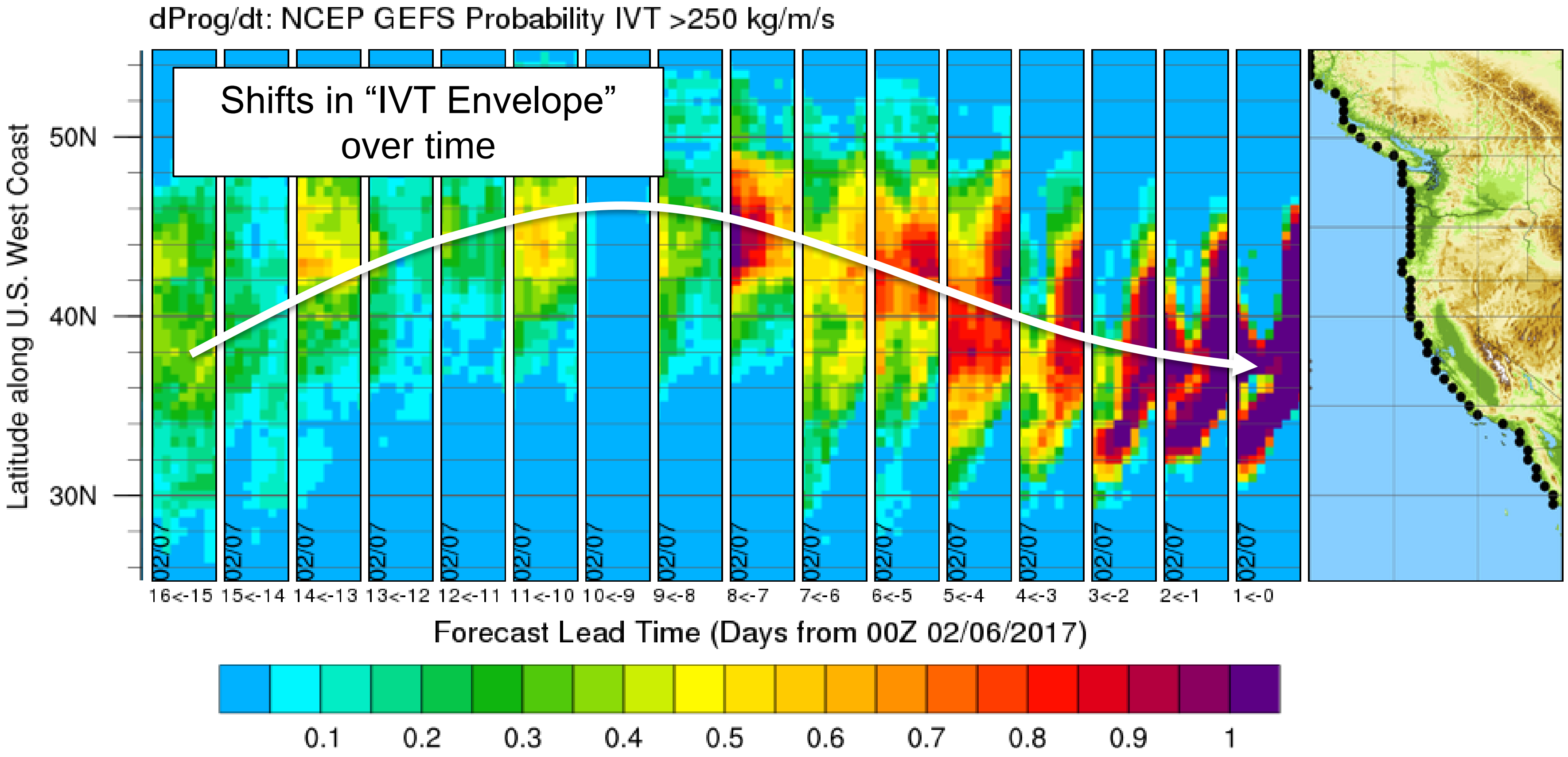
Init: 12Z/7 Jan

Init: 12Z/8 Jan

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



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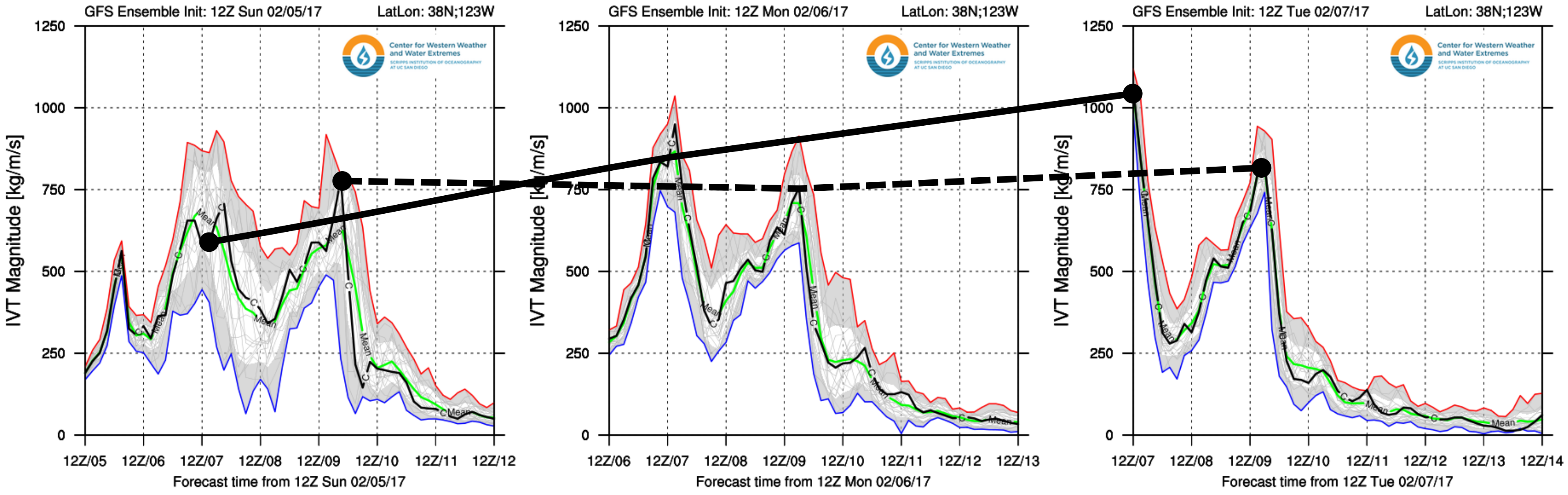


Init: 12Z/5 Feb
Init: 12Z/6 Feb
Init: 12Z/7 Feb

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**.

Model Accuracy in Simulating Orographic Precipitation
For CA's Russian River Watershed

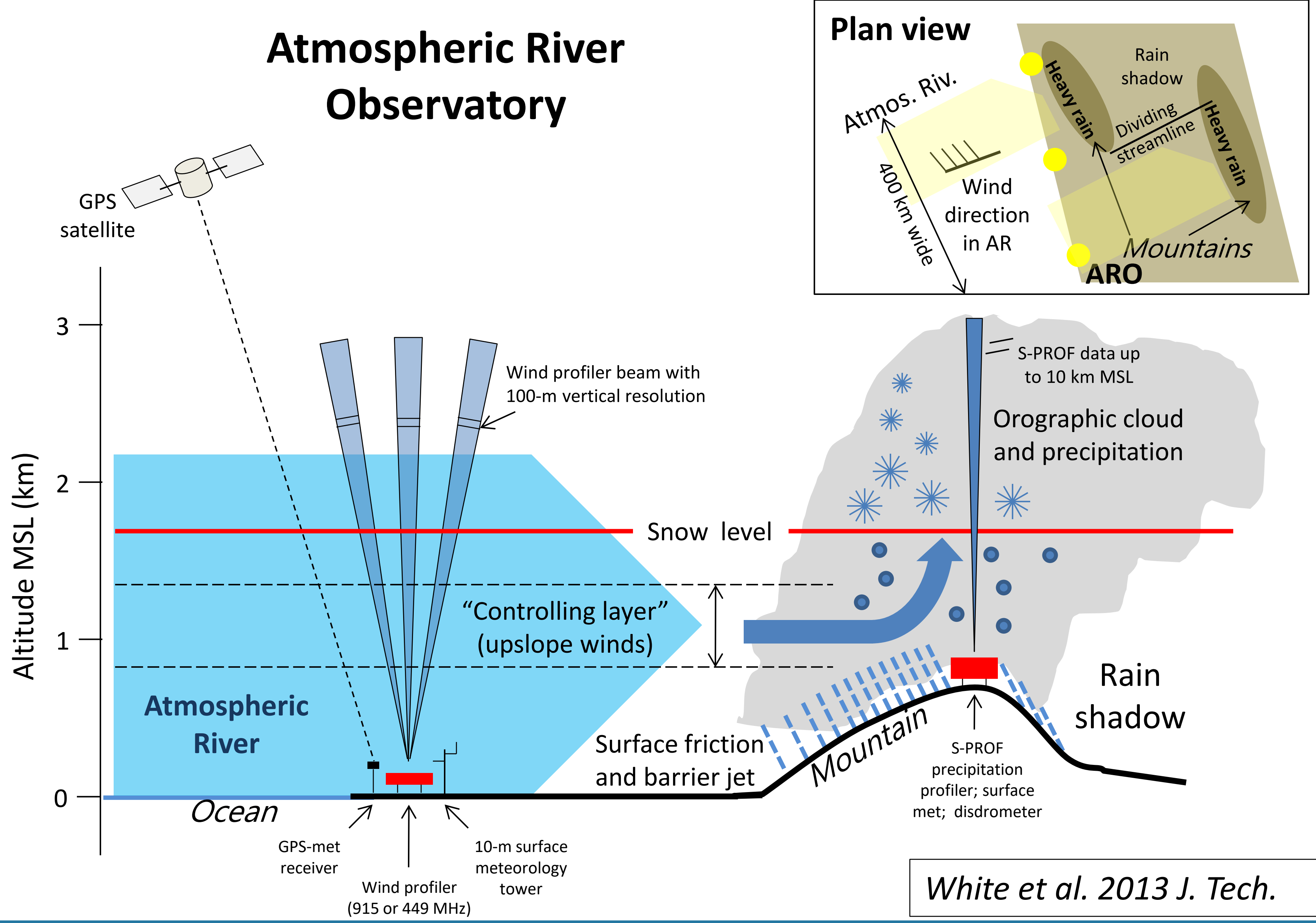
Contact: A. Martin (mc@ucsd.edu) for any questions

Produced by Andrew Martin and F. Martin Ralph

Outline

- An "Atmospheric River Observatory" to record orographic rainfall processes
- How can the ARO be used to measure NWP skill in orographic rain?
- How accurately did 3 NWP models of varying resolution predict orographic precipitation in early February AR?

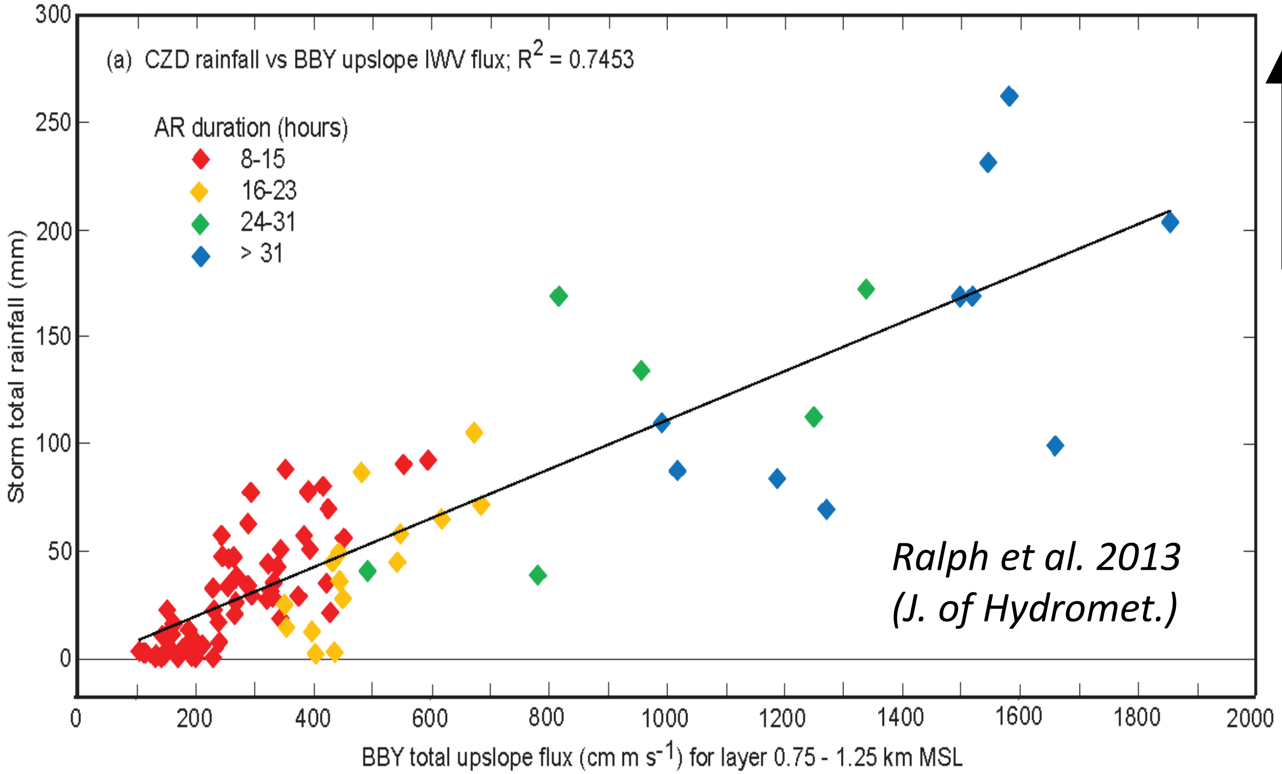
Atmospheric River Observatory



White et al. 2013 J. Tech.

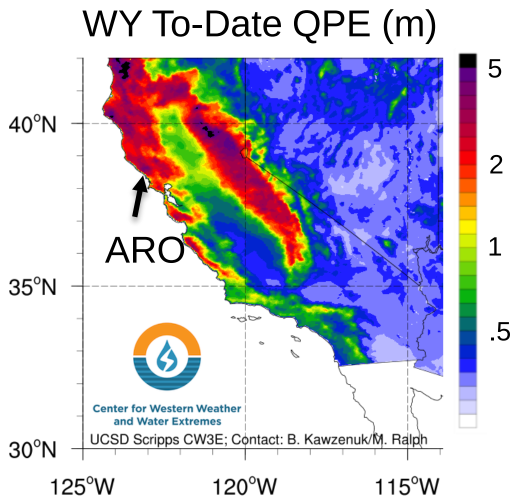
A Decade of ARO Observations Show that BUF is linearly related to Mountaintop Precipitation

Relationship between coast storm-total bulk upslope flux (BUF – x axis) and mountaintop storm-total precipitation (y axis).



The greater the AR strength and duration

The greater the precipitation

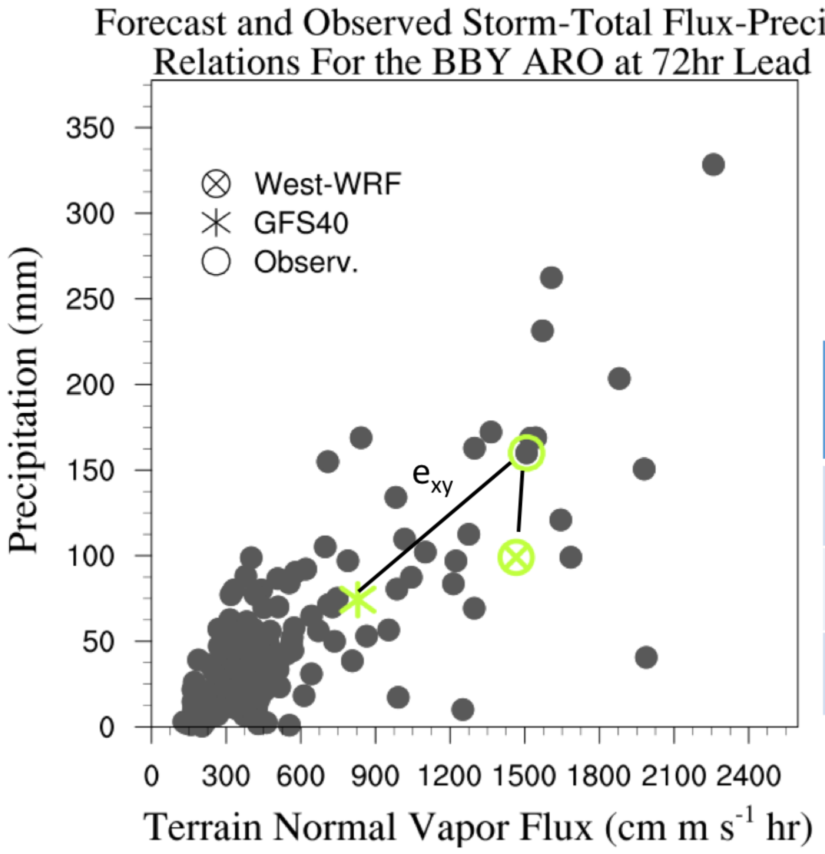


ARO Mountaintop < 500m MSL

A. Martin, F. M. Ralph

How Accurate Have NWP Models Been in Capturing This Relationship?

To answer this, we created a diagnostic (e_{xy}) that measures the normalized combined error in time-integrated BUF (x) and precip. (y) valid at the ARO.



- We evaluated West-WRF and GFS 0.5 degree e_{xy}
- For 10 Moderate to Strong AR 2014 – 2016
- For lead times 1-7 days.
- The following table summarizes the result

Normalized 2-dim. Error e_{xy}: Model - ARO

Lead Time (days)	West-WRF	GFS
1 - 2	0.82	4.29
3 - 4	2.25	4.53
5 - 6	4.65	7.37

Result is part of a study submitted to *J. Hydromet (Martin et al.)*

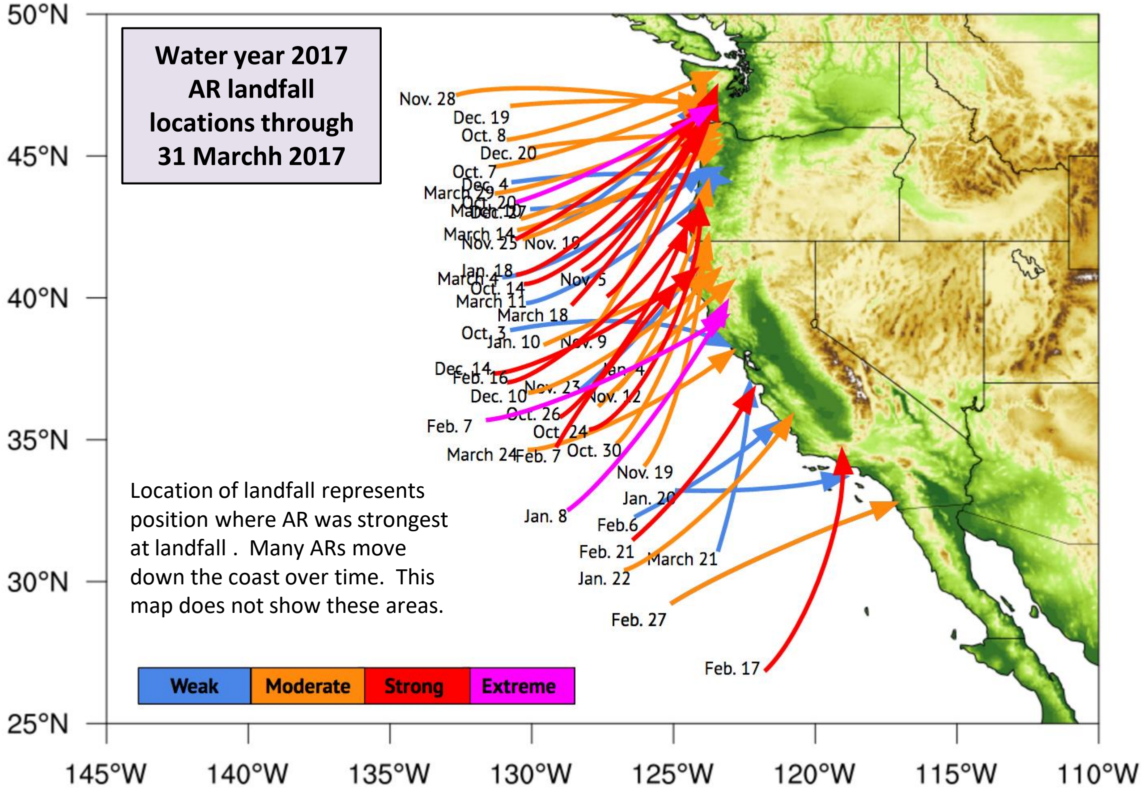
Distribution of Landfalling Atmospheric Rivers on the U.S. West Coast
(From 1 Oct 2016 to 31 March 2017)

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}

- 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"



*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)

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

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

Experimental

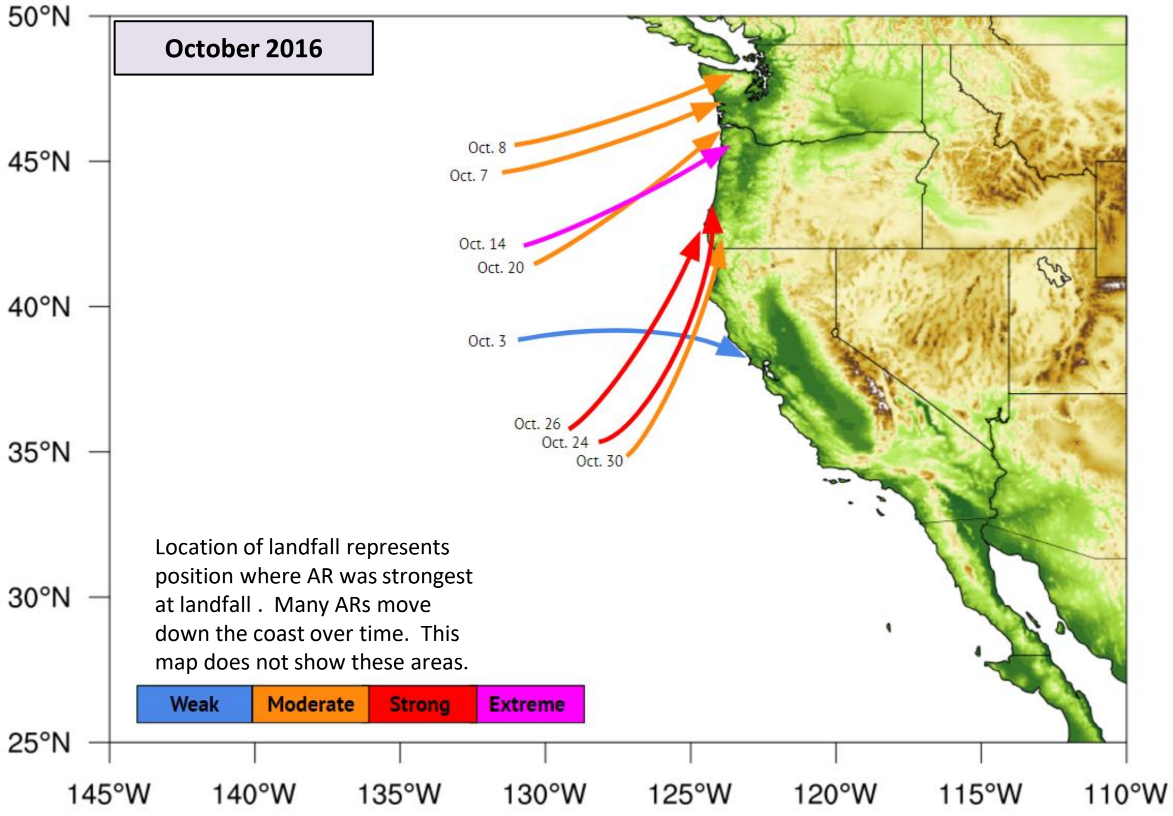
Distribution of Landfalling Atmospheric Rivers on the U.S. West Coast During October

- 8 atmospheric rivers made landfall over the U.S. West Coast during October 2016

AR Strength	AR Count*
Weak	1
Moderate	4
Strong	2
Extreme	1

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}



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

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

Experimental

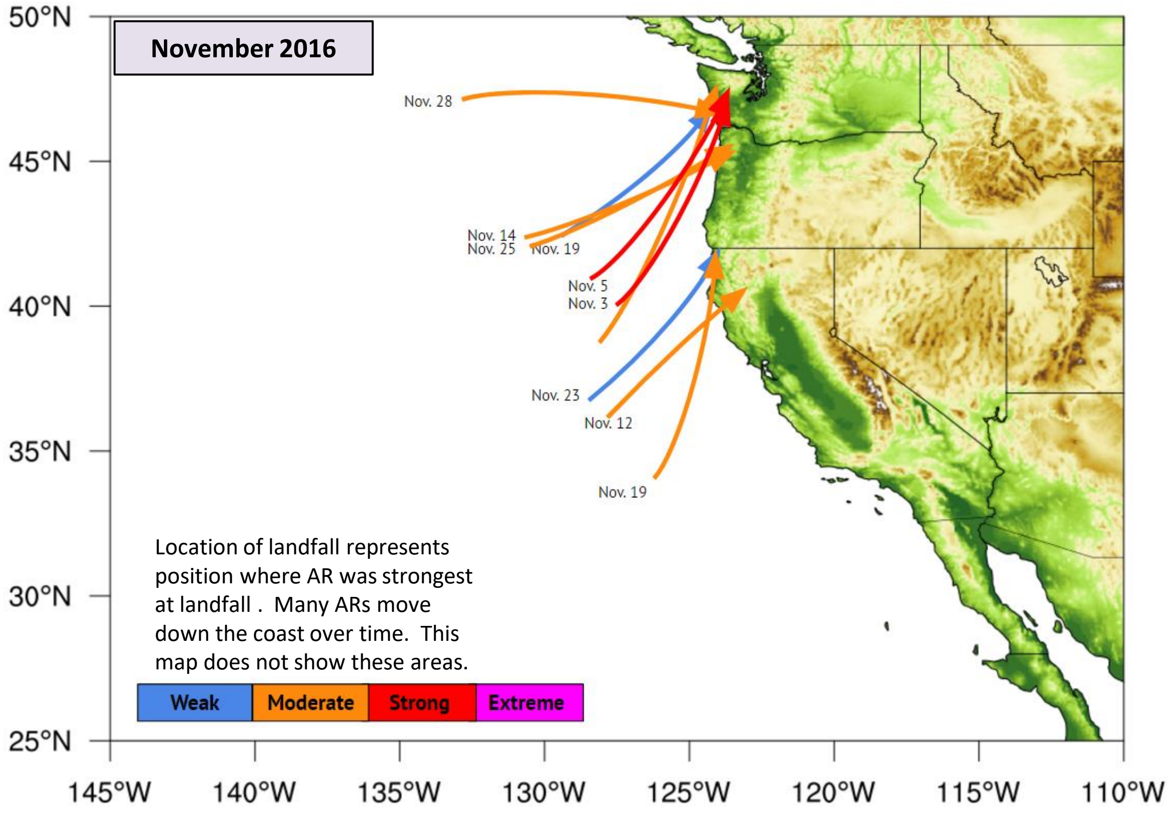
Distribution of Landfalling Atmospheric Rivers on the U.S. West Coast During November

- 10 atmospheric rivers made landfall over the U.S. West Coast during November 2016

AR Strength	AR Count*
Weak	2
Moderate	6
Strong	2
Extreme	0

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}



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

Experimental

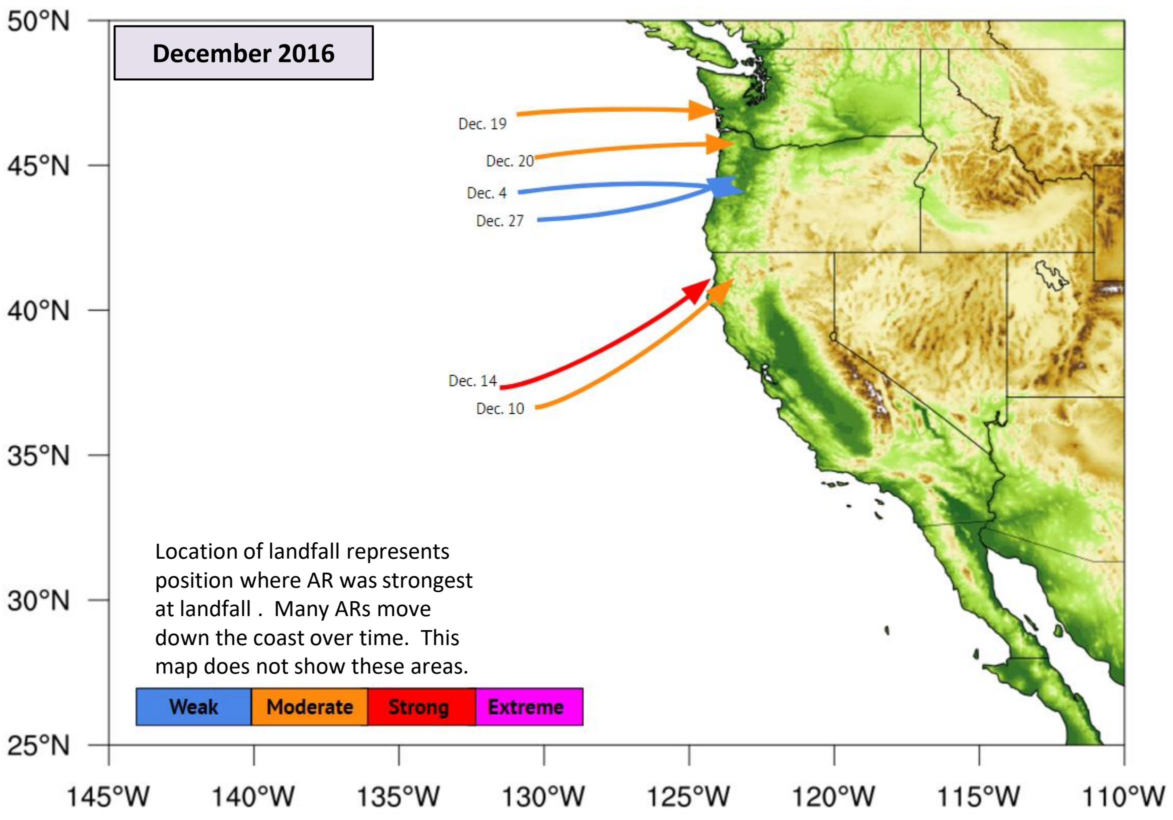
Distribution of Landfalling Atmospheric Rivers on the U.S. West Coast During December

- 6 atmospheric rivers made landfall over the U.S. West Coast during December 2016

AR Strength	AR Count*
Weak	2
Moderate	3
Strong	1
Extreme	0

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}



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

Experimental

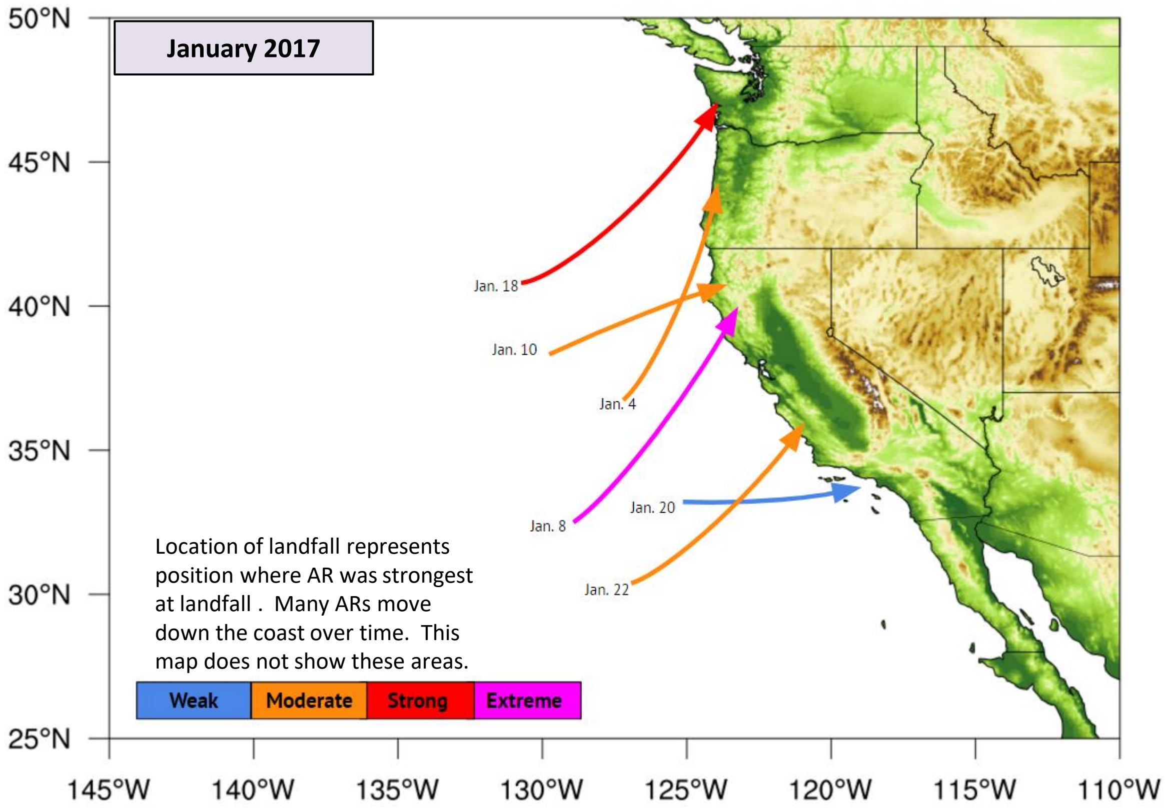
Distribution of Landfalling Atmospheric Rivers on the U.S. West Coast During January

- 6 atmospheric rivers made landfall over the U.S. West Coast during January 2016

AR Strength	AR Count*
Weak	1
Moderate	3
Strong	1
Extreme	1

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}



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Experimental

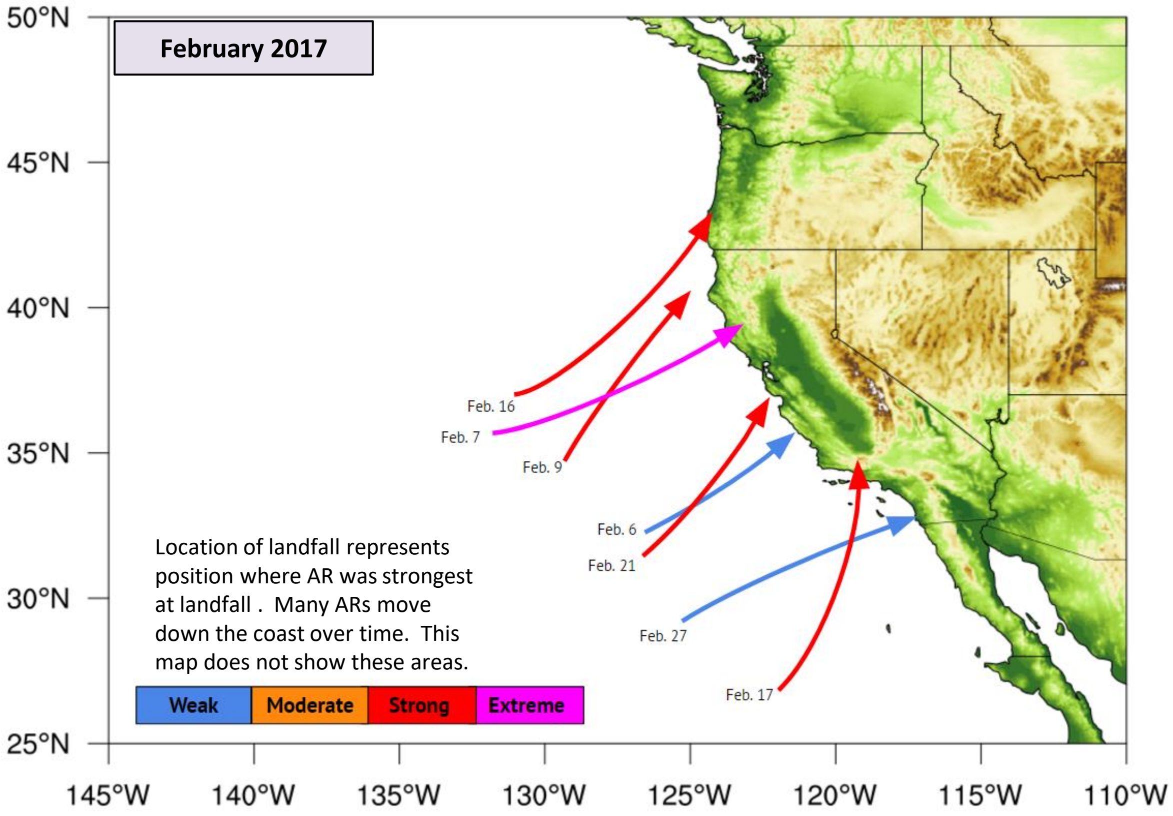
Distribution of Landfalling Atmospheric Rivers on the U.S. West Coast During February

- 7 atmospheric rivers made landfall over the U.S. West Coast during February 2016

AR Strength	AR Count*
Weak	2
Moderate	0
Strong	4
Extreme	1

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}



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Experimental

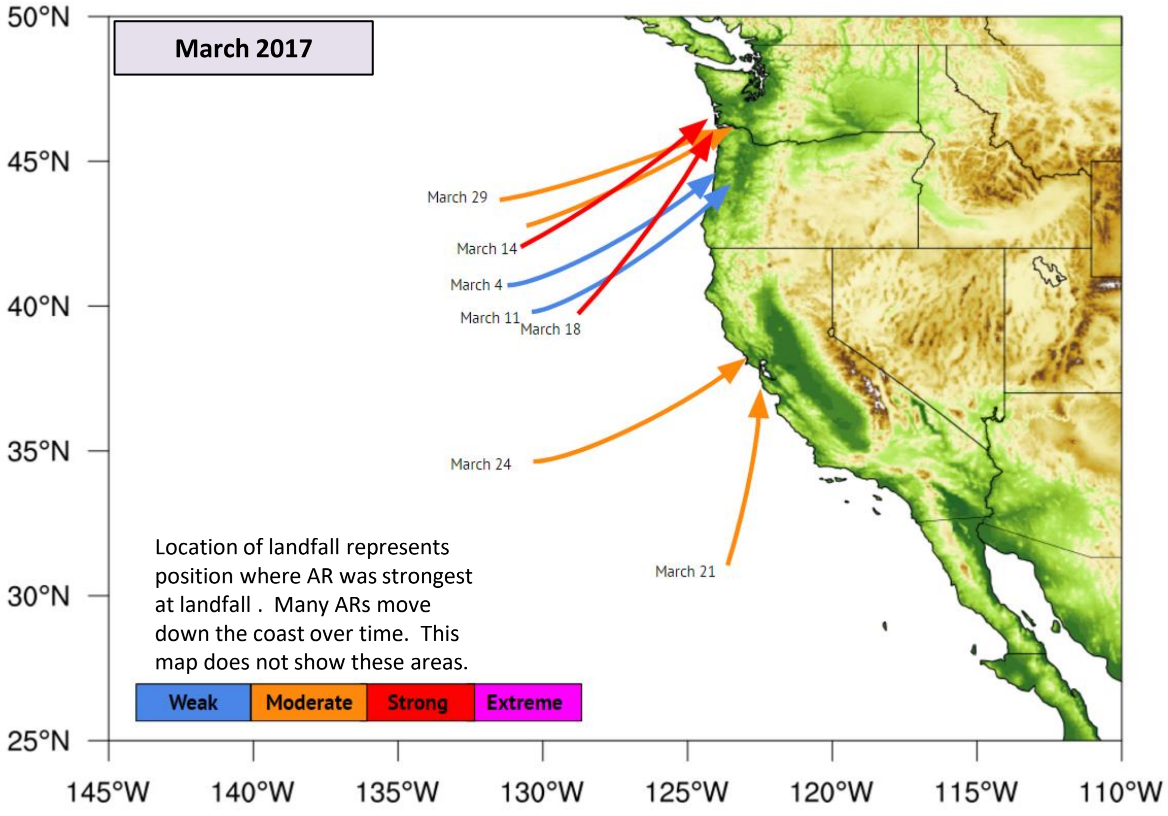
Distribution of Landfalling Atmospheric Rivers on the U.S. West Coast During March

- 8 atmospheric rivers made landfall over the U.S. West Coast during March 2016

AR Strength	AR Count*
Weak	2
Moderate	4
Strong	2
Extreme	0

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}



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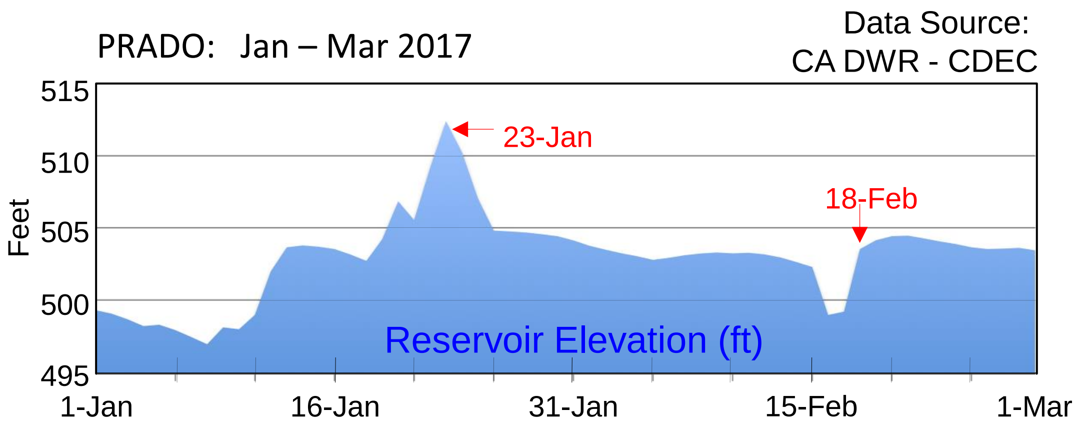
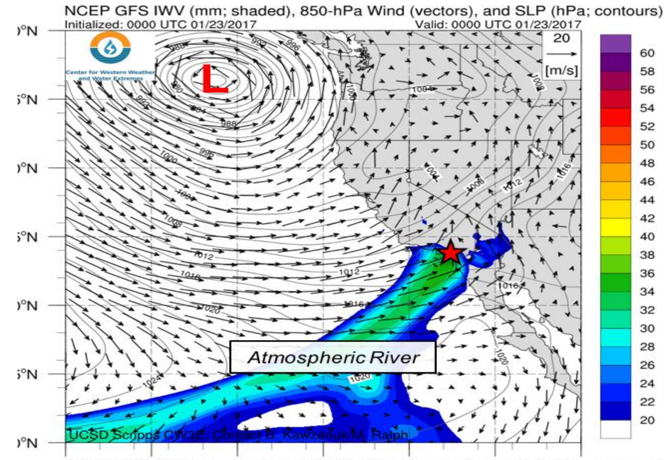
Experimental

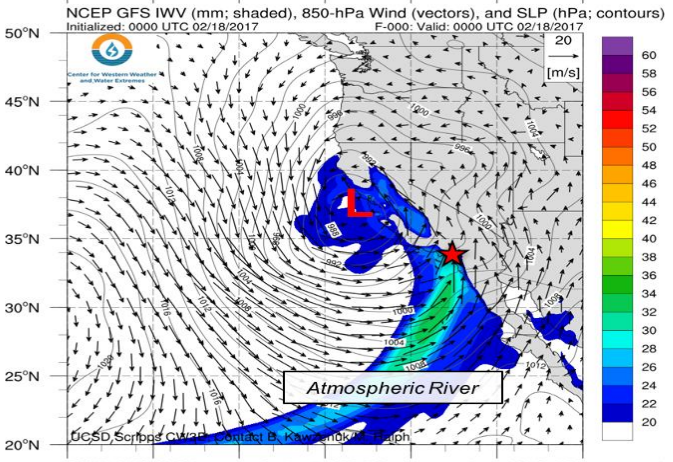
Variation in Atmospheric Rivers That Struck Santa Ana River Watershed in 2017

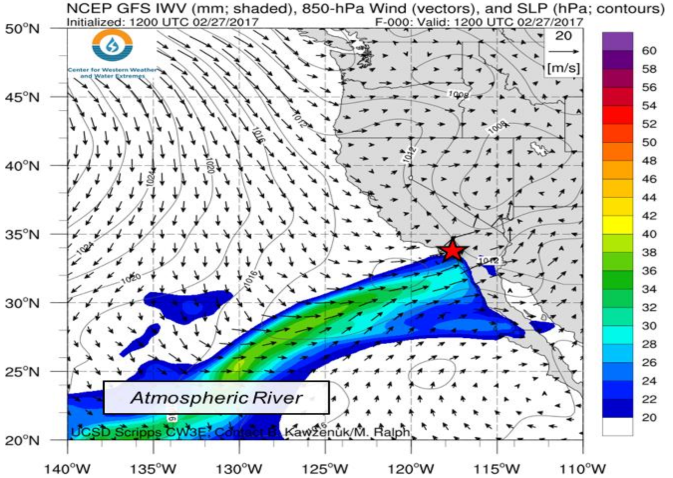


Large differences in synoptic condiitions

F. Cannon
F.M. Ralph
CW3E







AR Update: 4 April 2017

For California DWR's AR Program

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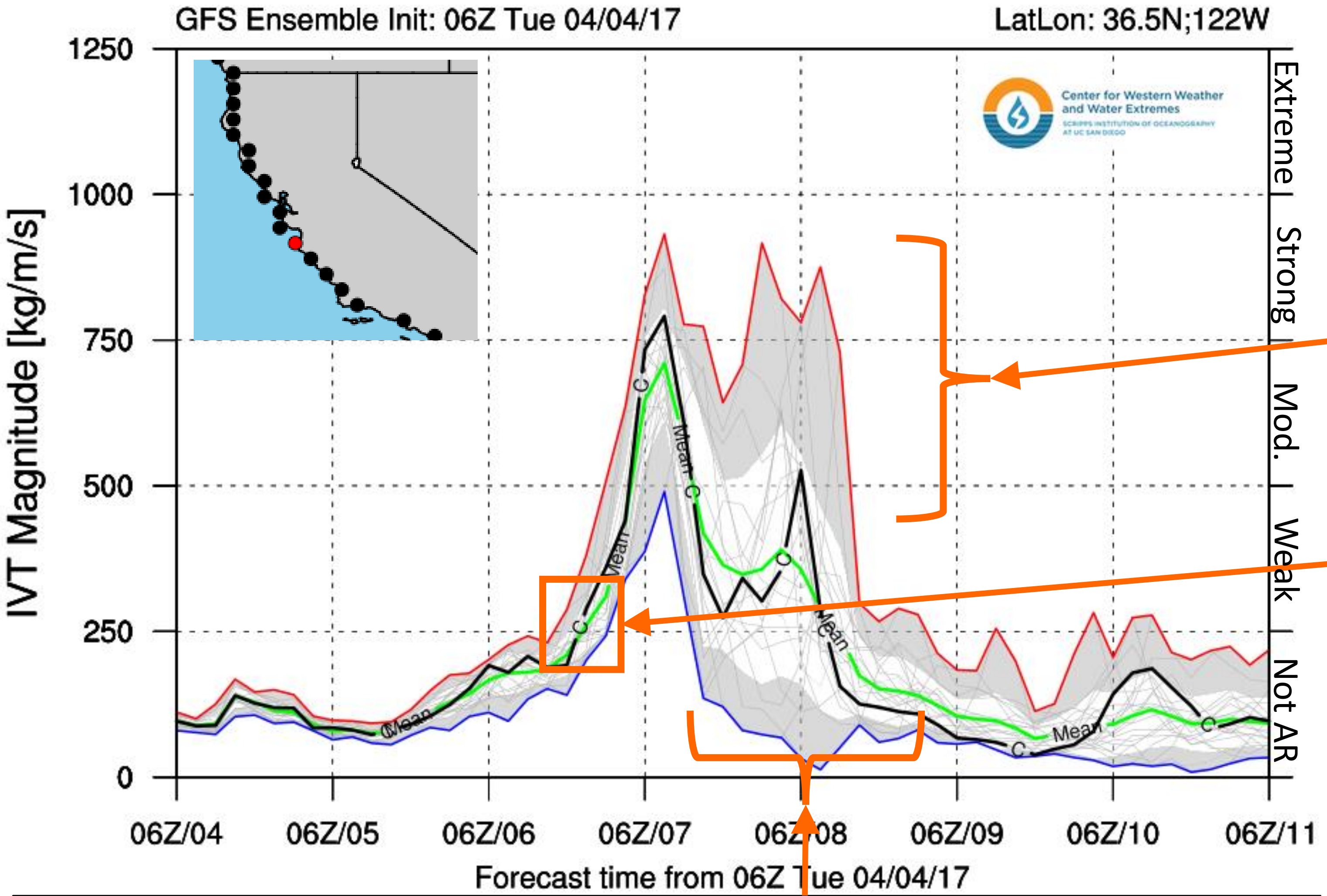


Monterey, CA could experience strong AR conditions IVT> 750 kg m^{-1} s^{-1}

Magnitude of AR over Monterey

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

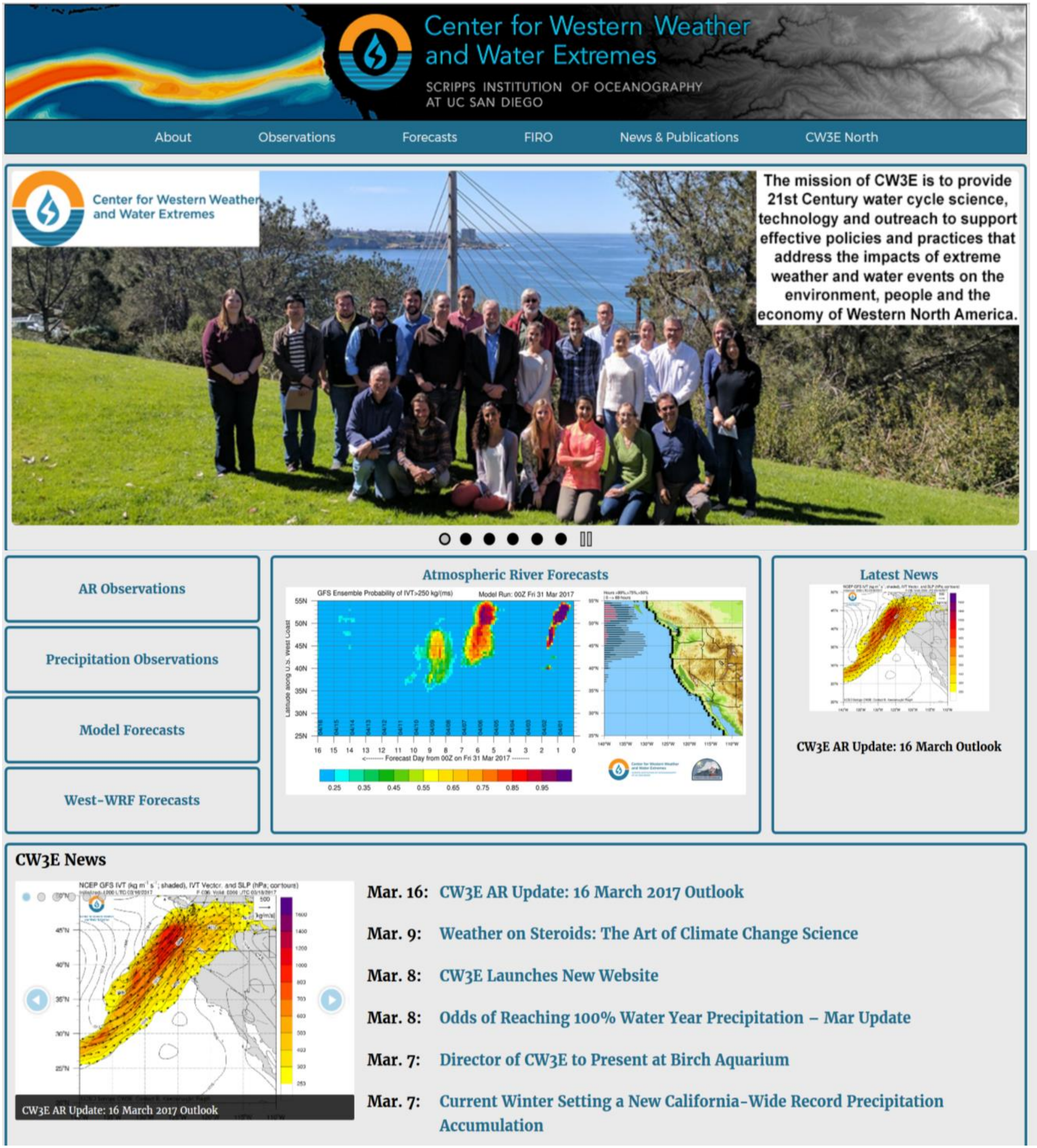
High Confidence in onset of AR conditions:

- 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



AR Forecast Tools

Extreme Event Summaries

Lake Mendocino FIRO summary information

Are available at

CW3E.UCSD.EDU

Contact: mralph@ucsd.edu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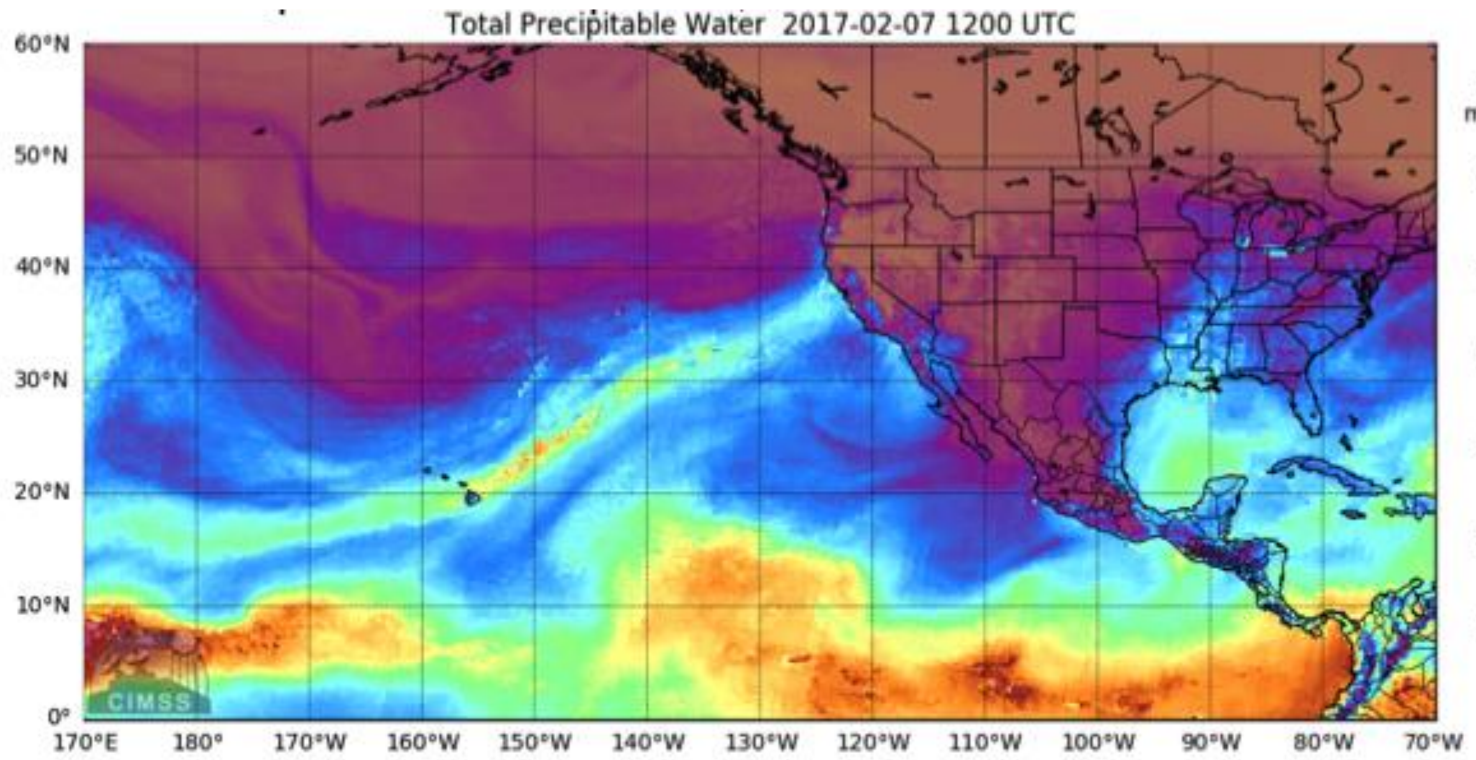
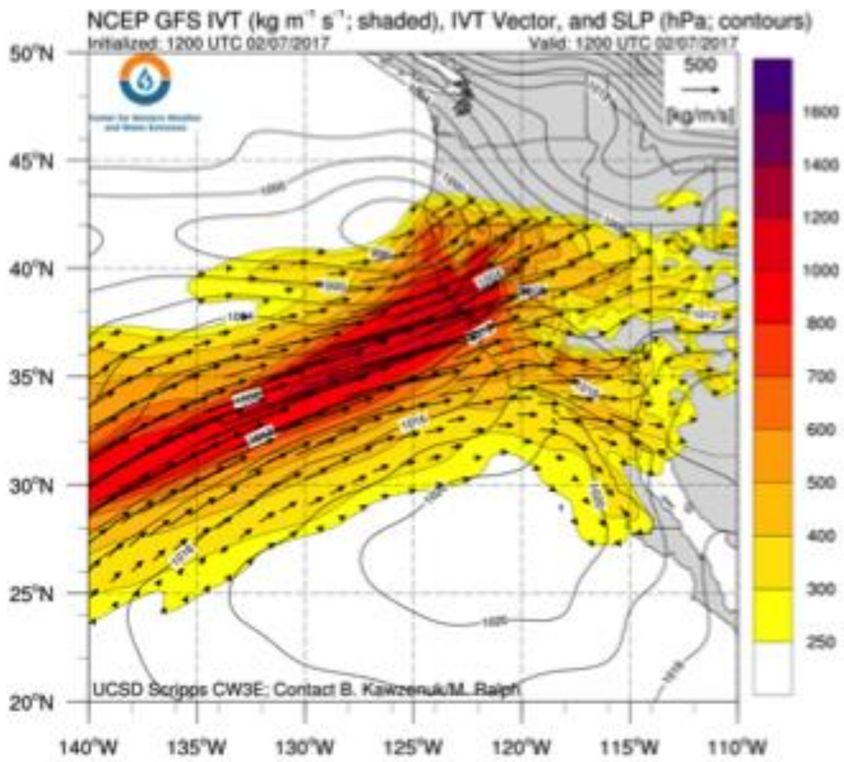
UCSD
2 March 2017

Was the Oroville Incident Related to an AR?

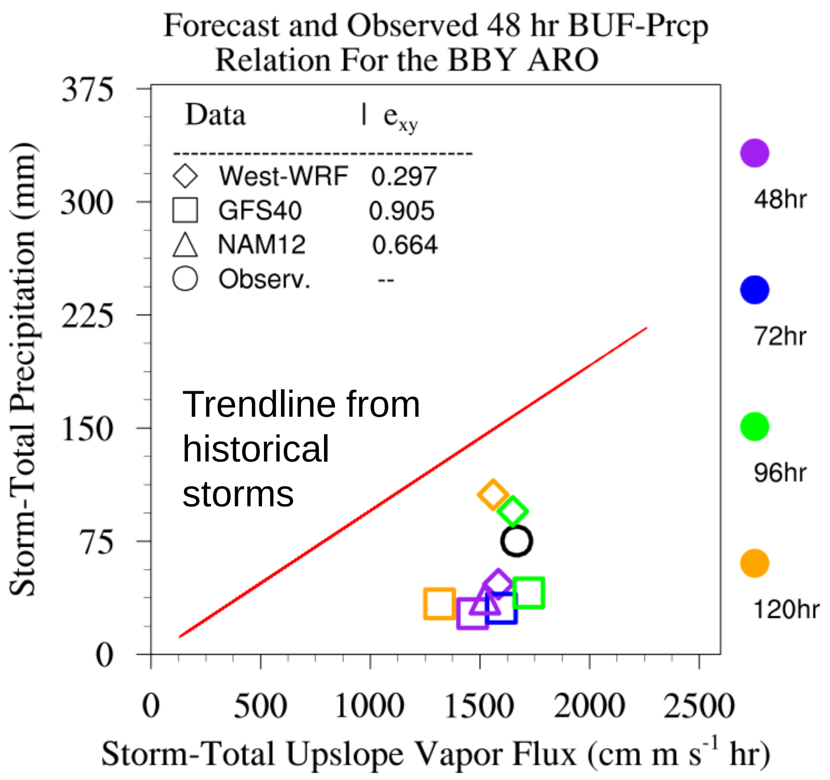




Yes. An "extreme" AR hit the area.

What was the Skill (e_{xy}) by NAM, GFS and West-WRF for Early Feb. AR?

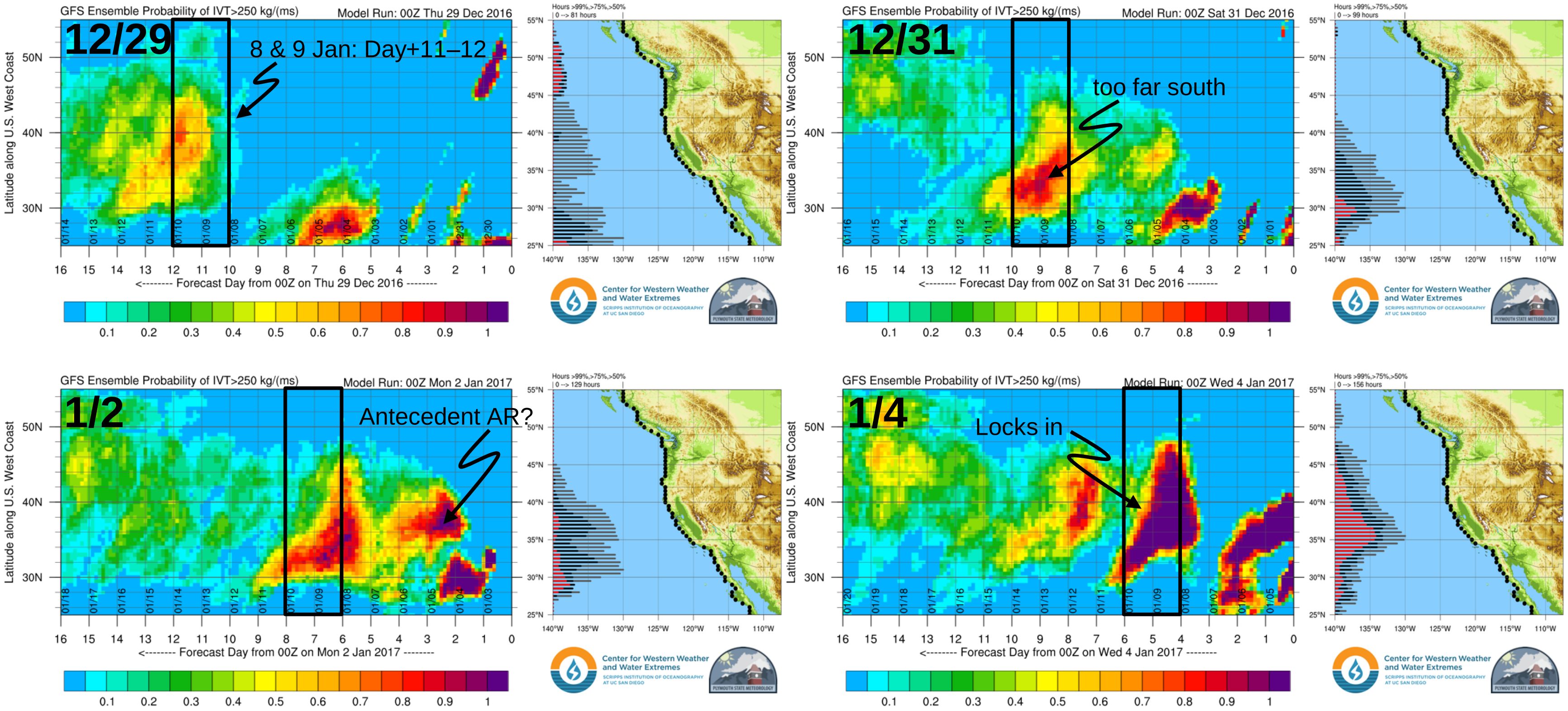
We'll Examine the 48 hour Period Feb 7 @ 12 UTC to Feb 9 @ 12 UTC. Other periods produced more rain, but ARO coverage was inconsistent.



- e_{xy} shown is mean value over lead times 48 to 120 hr.
- West-WRF shows greatest improvement over it's parent model (GFS40) at longer lead times.
- For 48 hr lead time, horizontal resolution (40 km – 12 km – 3 km) makes quasi-linear and incremental improvement.
- Impact of forecast AR timing on result unknown.

GFS Forecast Model Performance

Time (right-to-left)–Latitude Ensemble Forecast Probability of **IVT>250 kg/m/s** at the Coast



Take-Away:

- AR Landfall Tool gave heads up probability of at least weak landfalling AR 11–12 days in advance
- Run-to-run inconsistencies limited confidence in location/duration until 4–5 days in advance

AR summary for Pt Reyes, CA area, including Russian River

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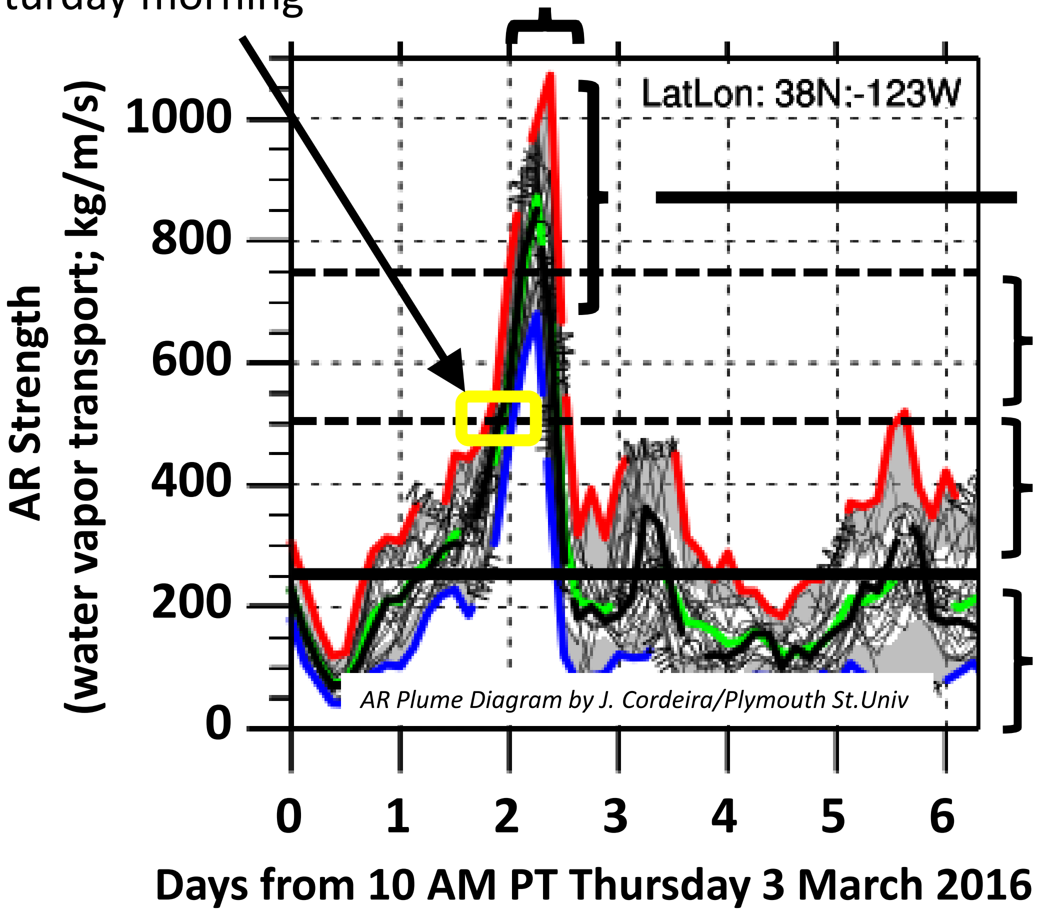
Onset of moderate-strength AR conditions Saturday morning

Normal-duration AR landfall (12-24 hours)

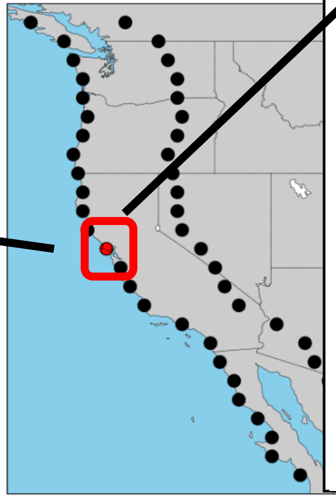


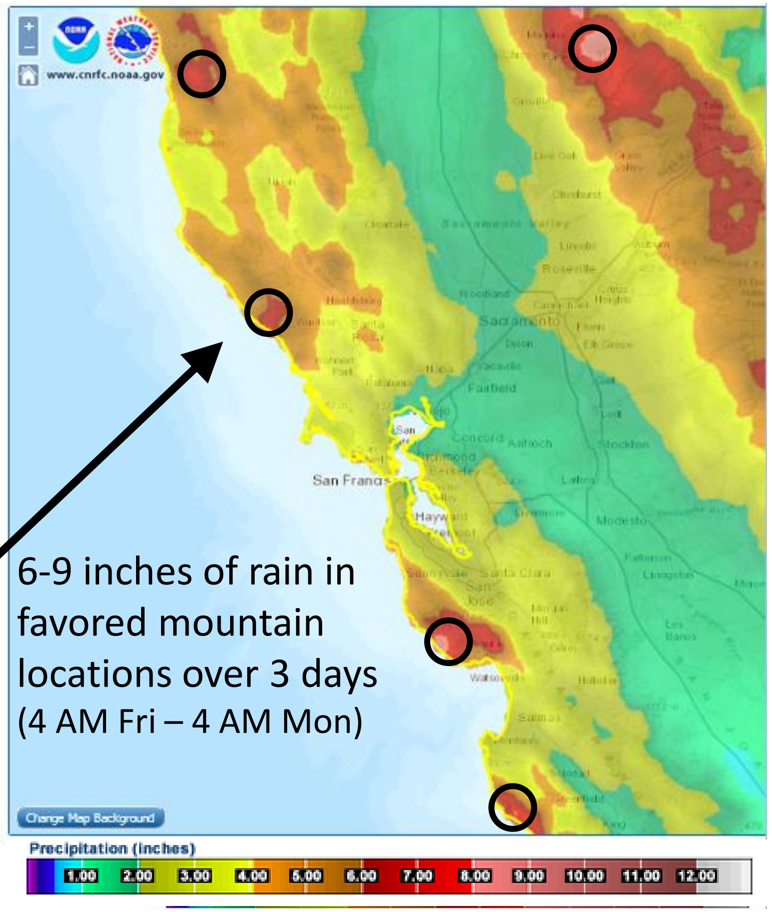
Max AR strength is uncertain by +/- 20%

Moderate strength AR

Minimal strength AR

Not an AR





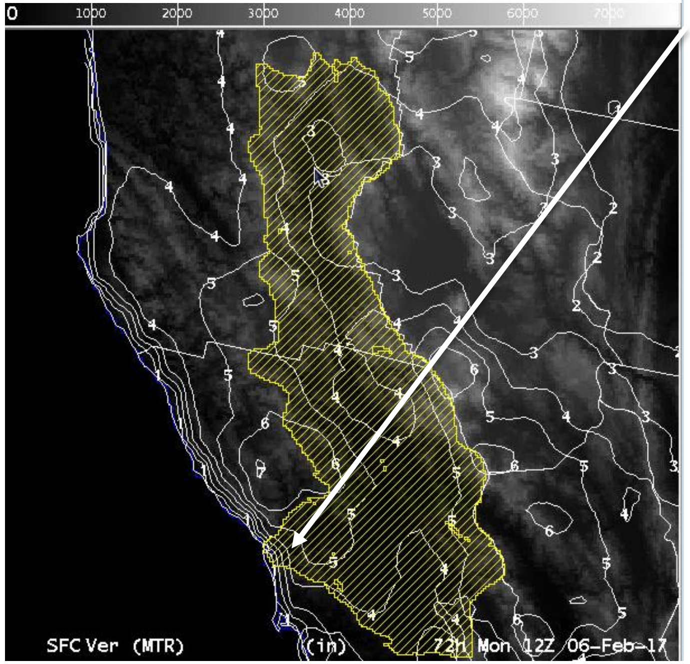
6-9 inches of rain in favored mountain locations over 3 days
(4 AM Fri – 4 AM Mon)

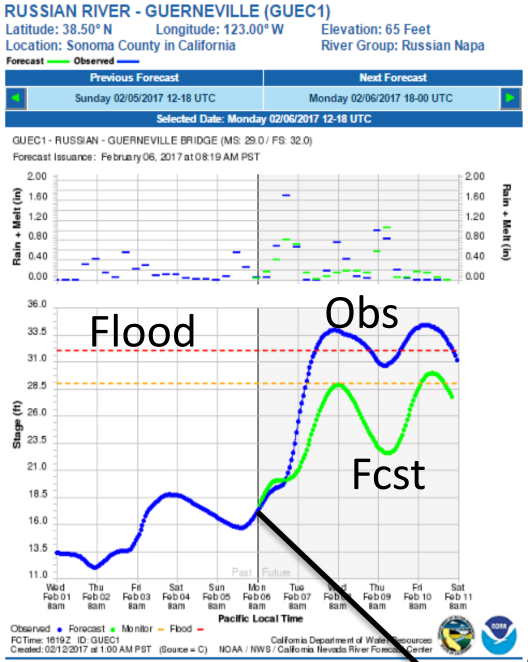
Precipitation forecast from NOAA/NWS California/Nevada River Forecast Center

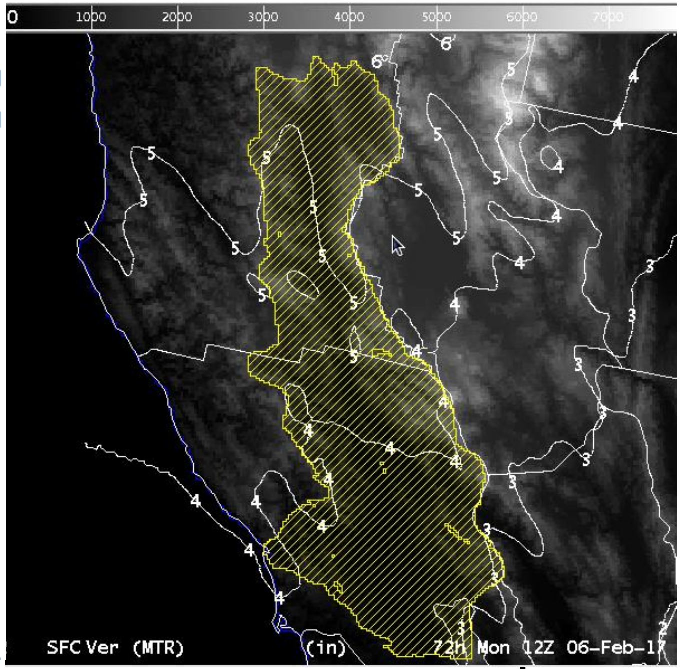
Summary by F.M. Ralph 8 AM PT Fri 4 March 2016

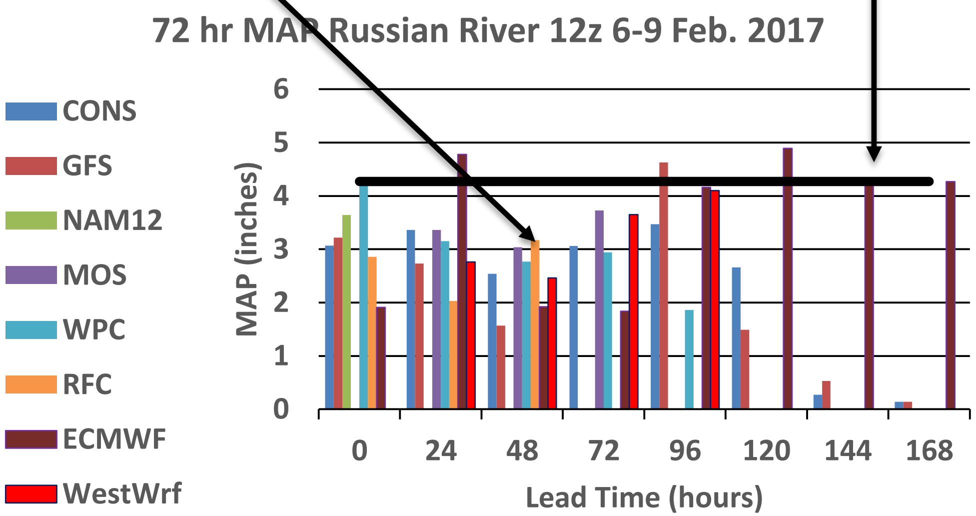
Feb 6-9, 2017 72 Hr QPE QPF

CNRFC 3 day Obs 144hr ECMWF 3 Day QPF









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AR Update: 4 April 2017

Center for Western Weather and Water Extremes
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<u>AR conditions Forecast for Entire U.S. West Coast</u>

- 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[redacted]vada