Recent Developments in Atmospheric River Science, Prediction and Applications

F. Martin Ralph
Center for Western Weather and Water Extremes
UC San Diego/Scripps Institution of Oceanography

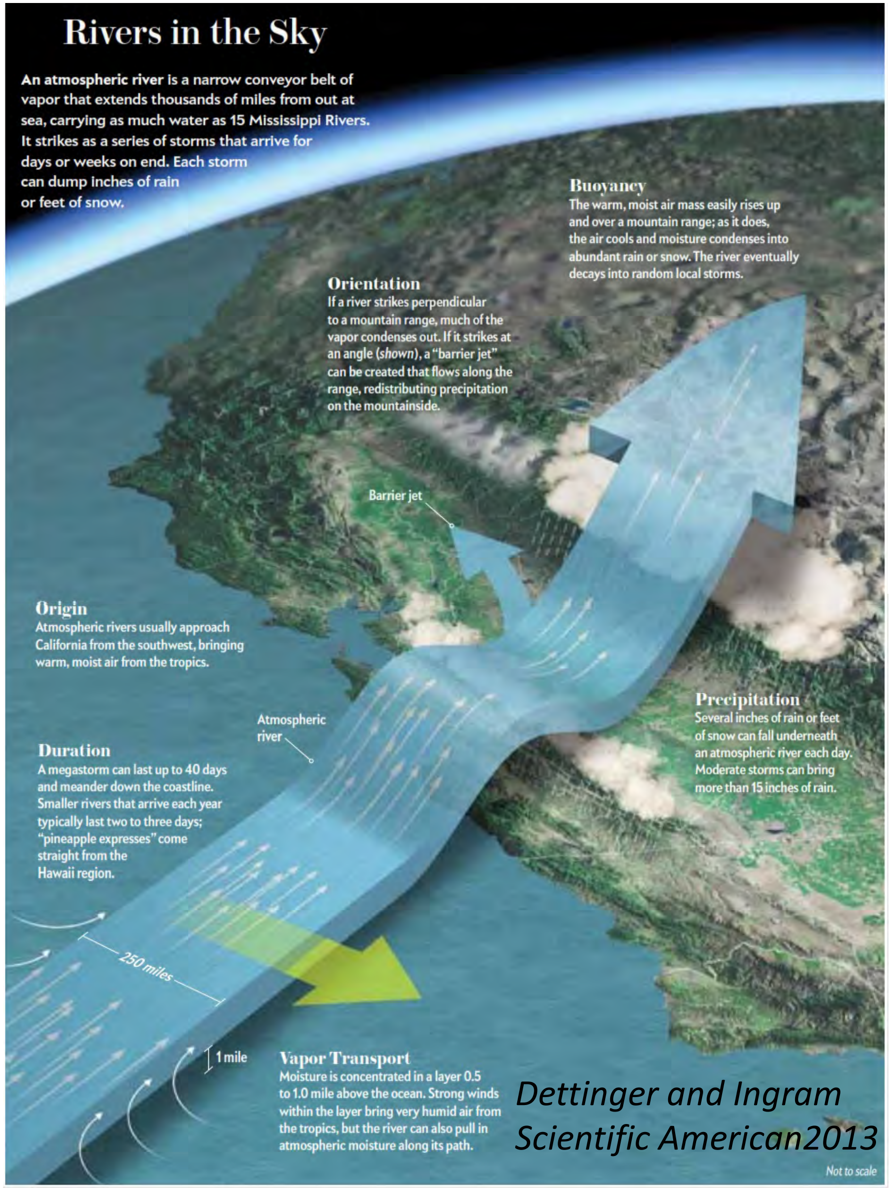
Research Aircraft at McClellan Airfield, Sacramento, CA
For the CalWater-2015 Interagency Field Campaign
25 January 2015

Photo by Marty Ralph (UCSD/Scripps/CW3E)

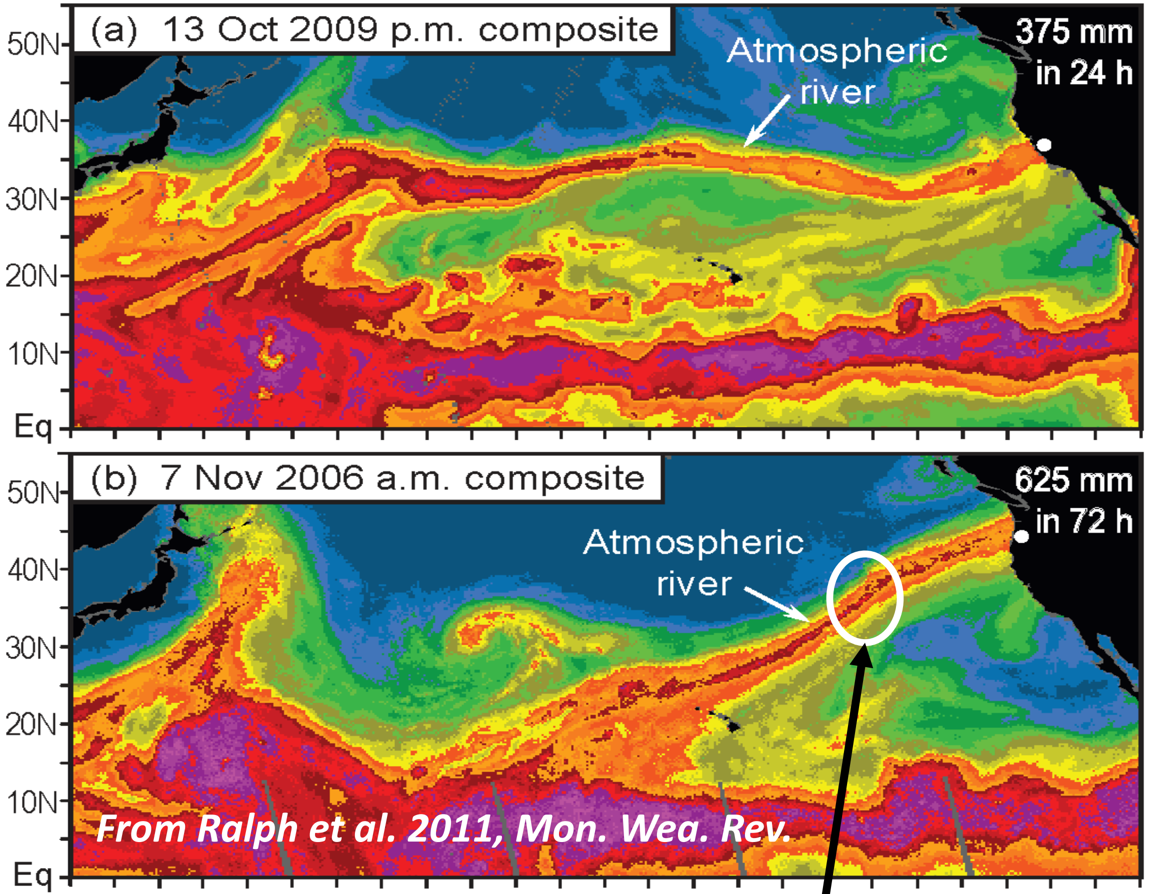
Seminar at the Water Resources Research Center (WRRC)
Tucson, Arizona, 12 February 2018

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

Atmospheric Rivers are like rivers in the sky – Rivers of water vapor



Dettinger and Ingram Scientific American2013



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.

One AR transports as much water as 25 Mississippi Rivers, but as vapor rather than liquid
(from Ralph et al. 2017)

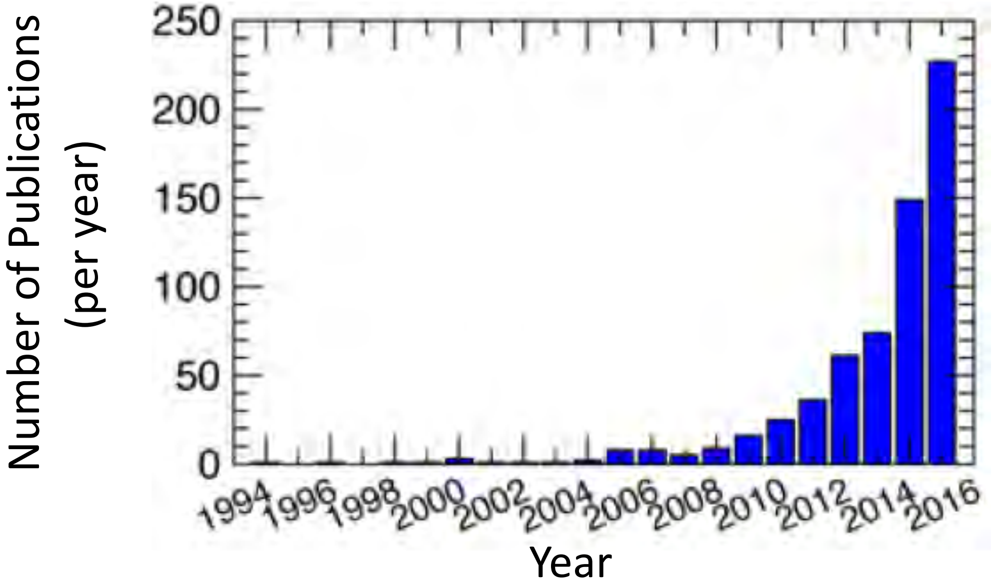
Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

Atmospheric Rivers Emerge as a Global Science and Applications Focus

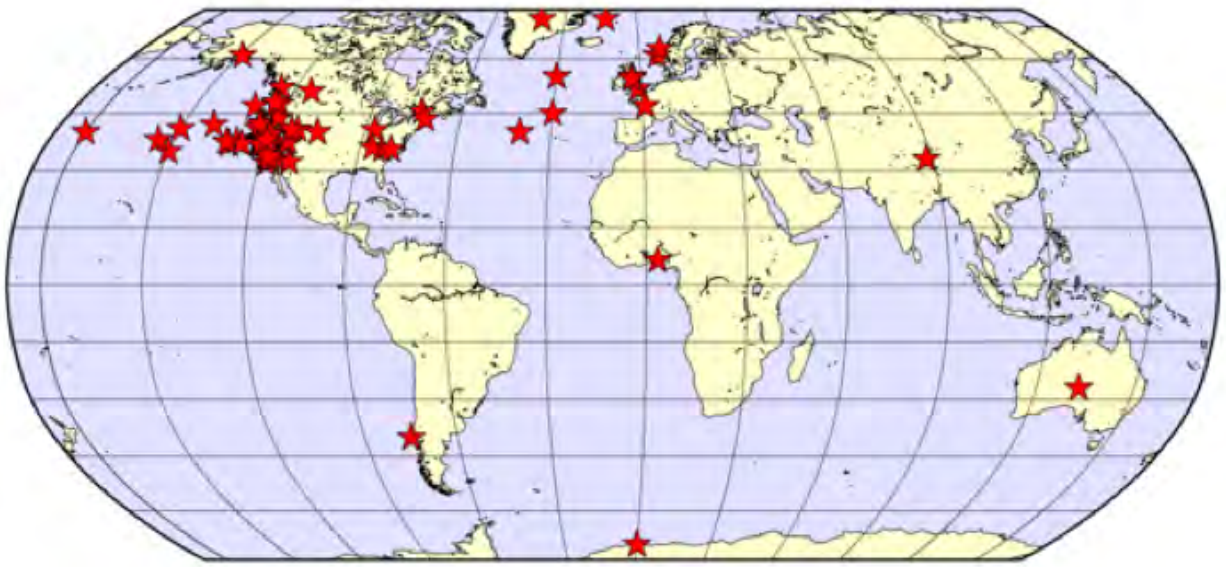
A Summary of the 1st International Atmospheric Rivers Conference

F. M. Ralph, M. Dettinger, D. Lavers, I. V. Gorodetskaya, A. Martin, M. Viale, A. B. White, N. Oakley, J. Rutz, J. R. Spackman, H. Wernli and J. Cordeira, *Bull. Amer. Meteorol. Soc. 2017 (in press)*

a) Scientific literature discussing ARs



b) Locations of studies and scientists at IARC



Center for Western Weather and Water Extremes

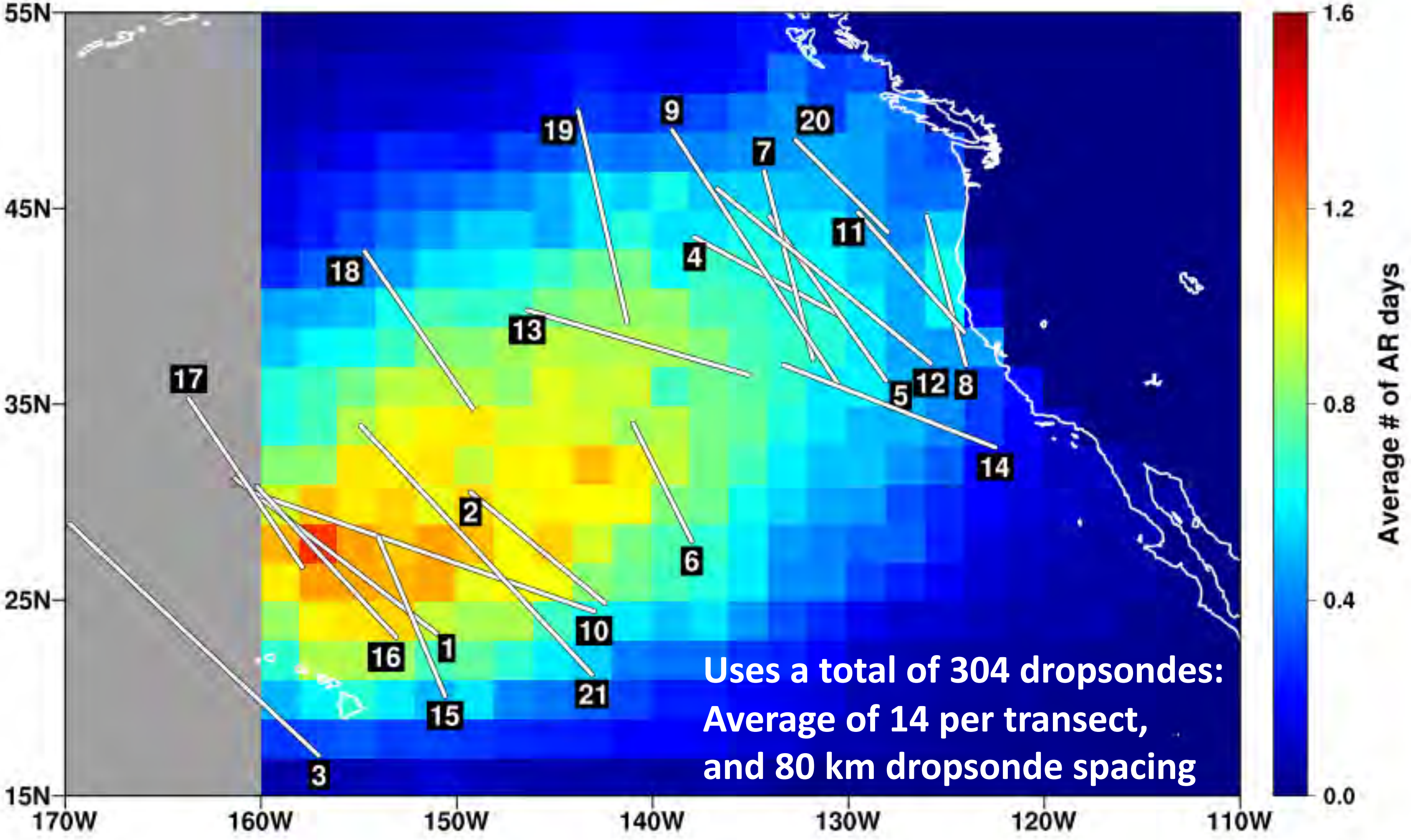
Dropsonde Observations of Total Integrated Water Vapor Transport within North Pacific Atmospheric Rivers

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

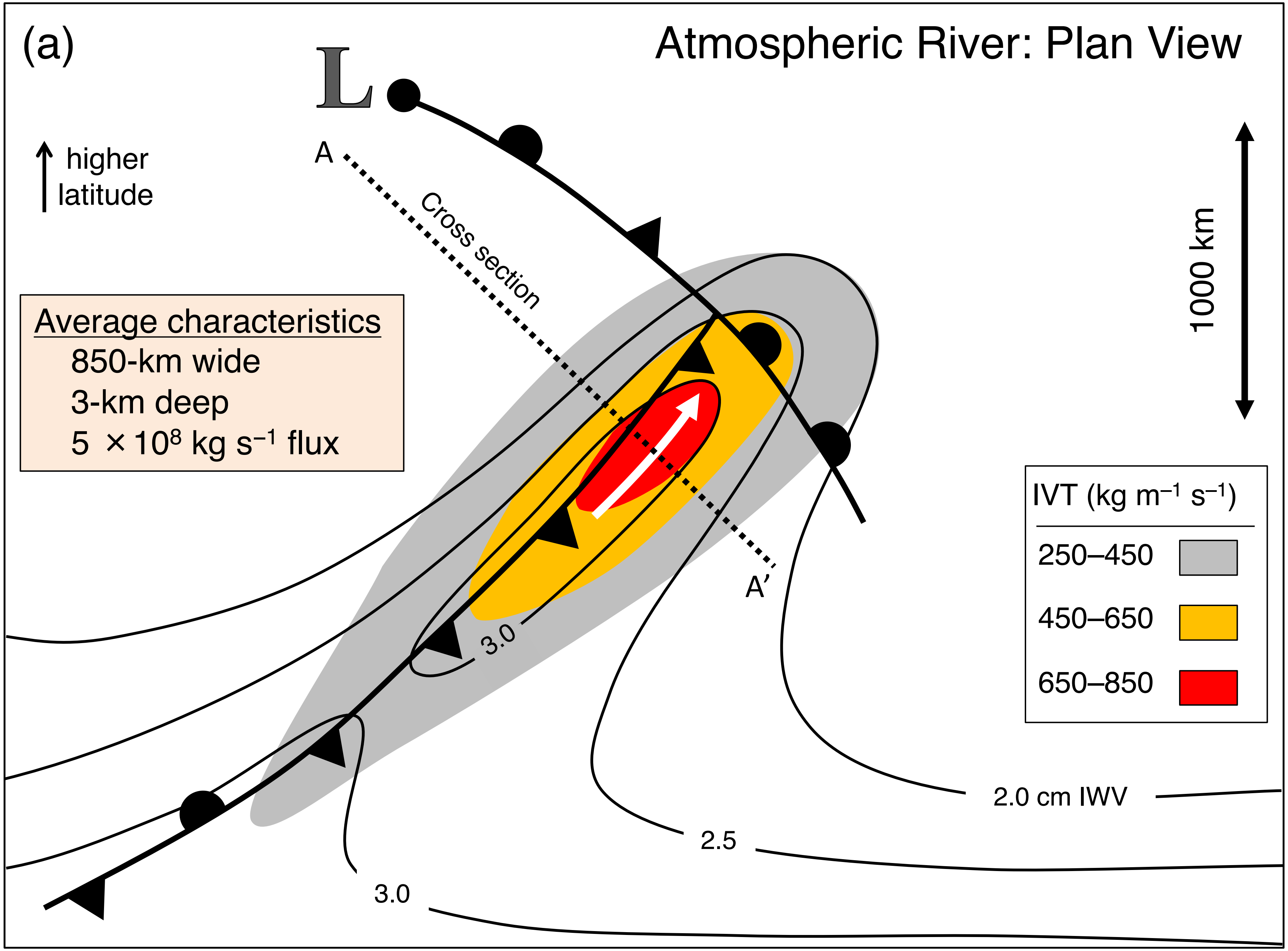
J. Hydrometeor., 2017
July 2017

This study uses 21 AR cases observed in 2005 - 2016 with full dropsonde transects

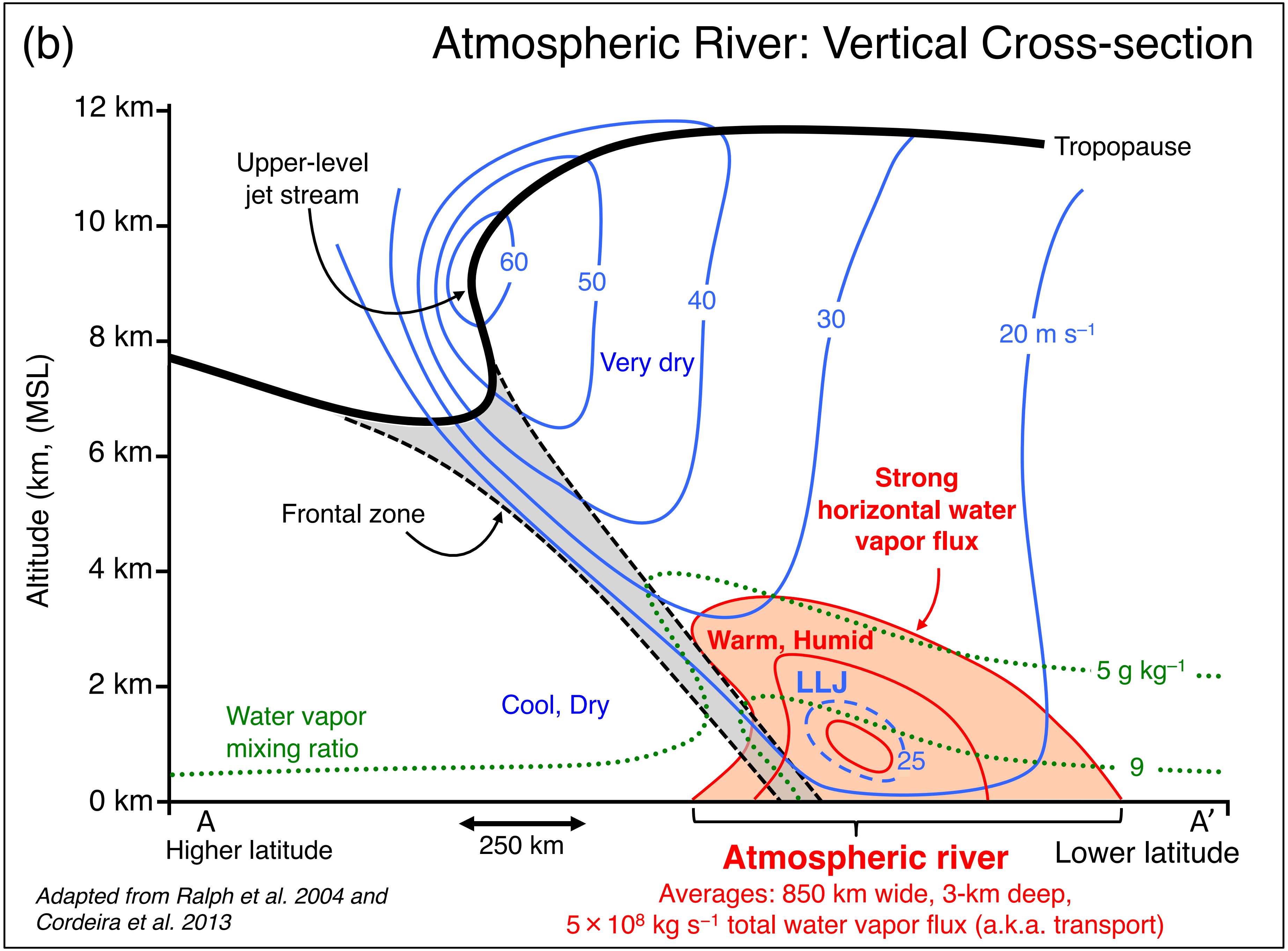
1 from Ghostnets (2005), 4 from WISPAR (2011), 12 from CalWater (2014, 2015), 4 from AR Recon (2016)



Location of the dropsonde transects listed in Table 1. The background image denotes weekly AR frequency calculated using the AR Detection Tool of Wick et al (2013) applied during the 2003-2012 cool seasons (November-February). AR frequency data west of 160°W was not available.



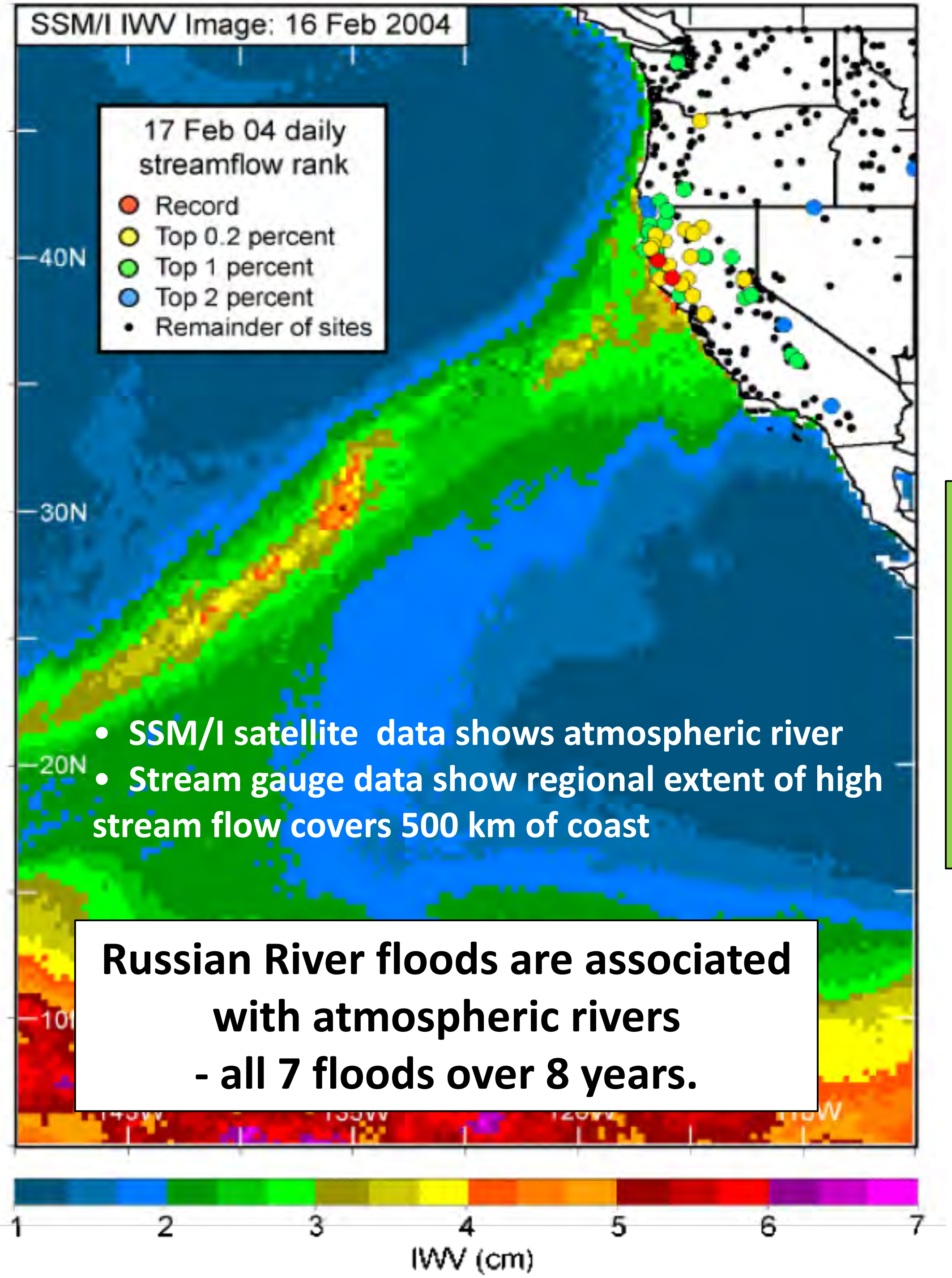
From Ralph et al. 2017, *J. Hydrometeor.*



From Ralph et al. 2017,
J. Hydrometeor.

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)*



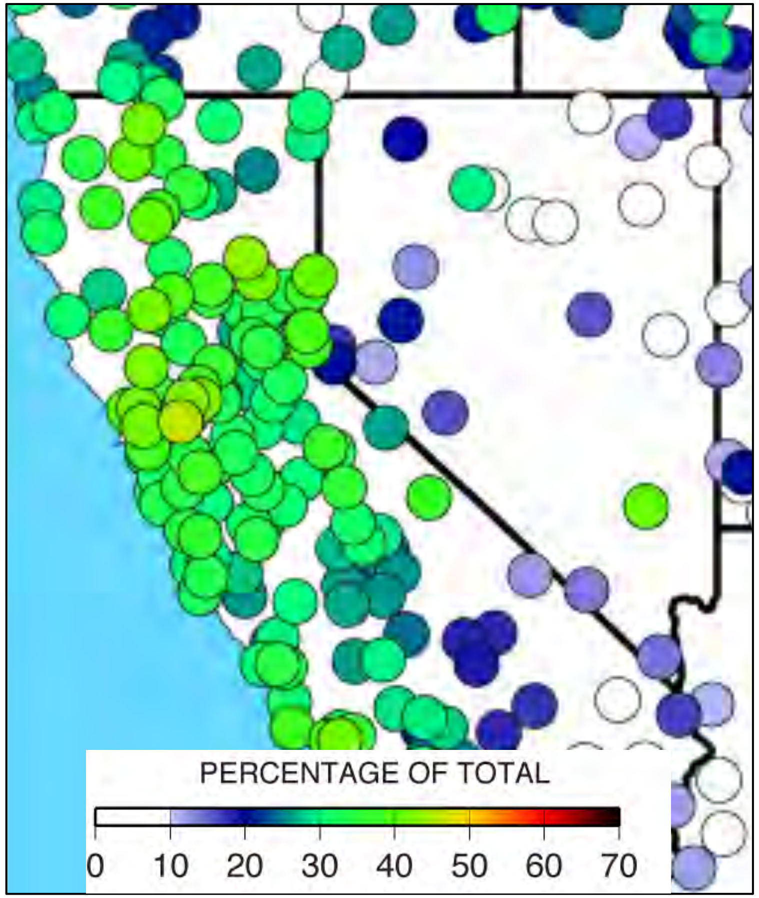
- SSM/I satellite data shows atmospheric river
- Stream gauge data show regional extent of high stream flow covers 500 km of coast

Russian River floods are associated with atmospheric rivers - all 7 floods over 8 years.

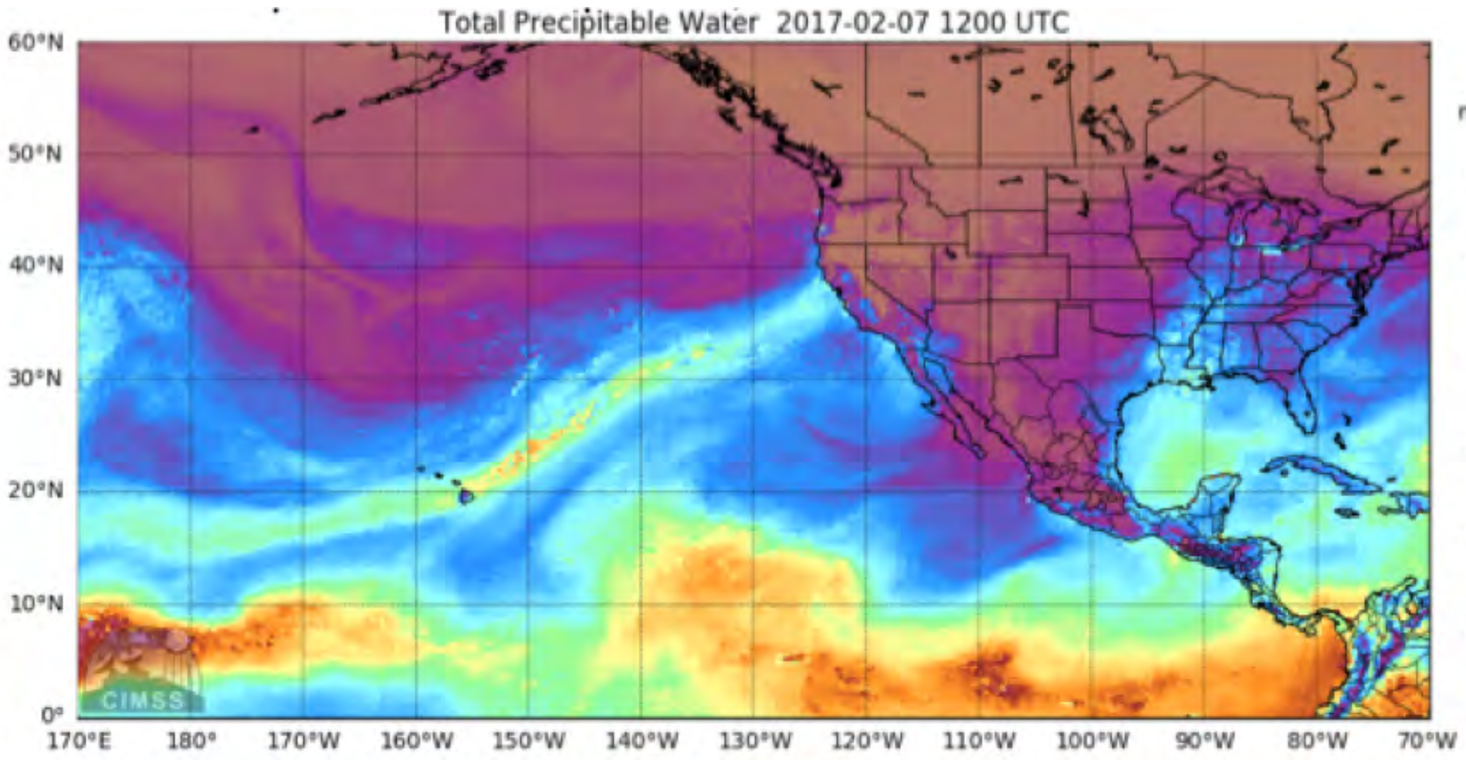
ARs can CAUSE FLOODS and PROVIDE WATER SUPPLY

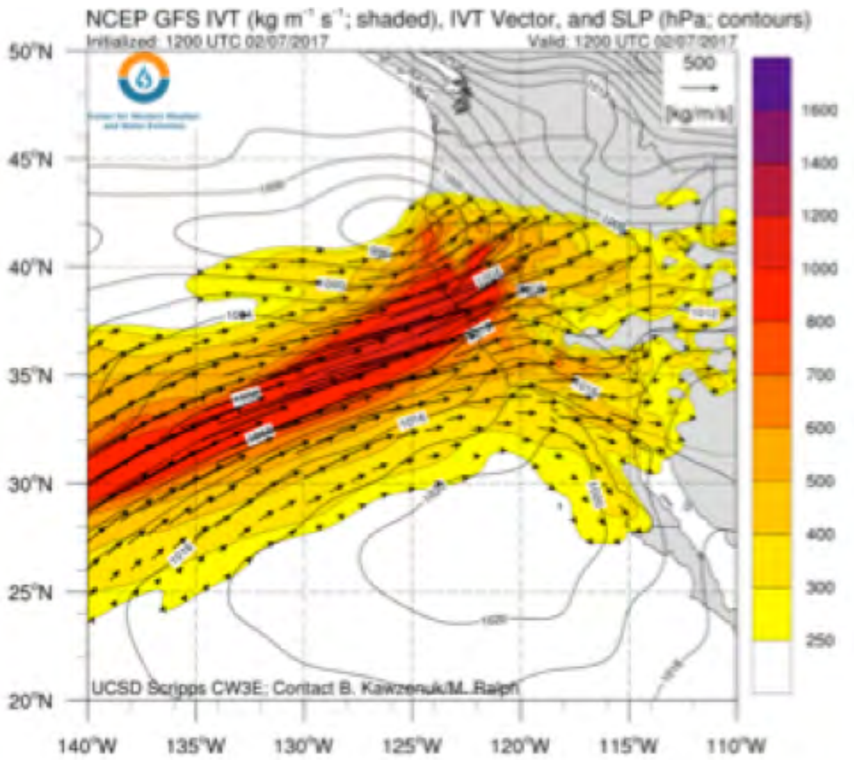
Atmospheric Rivers, Floods and the Water Resources of California

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



Was the Oroville Incident Related to an AR?

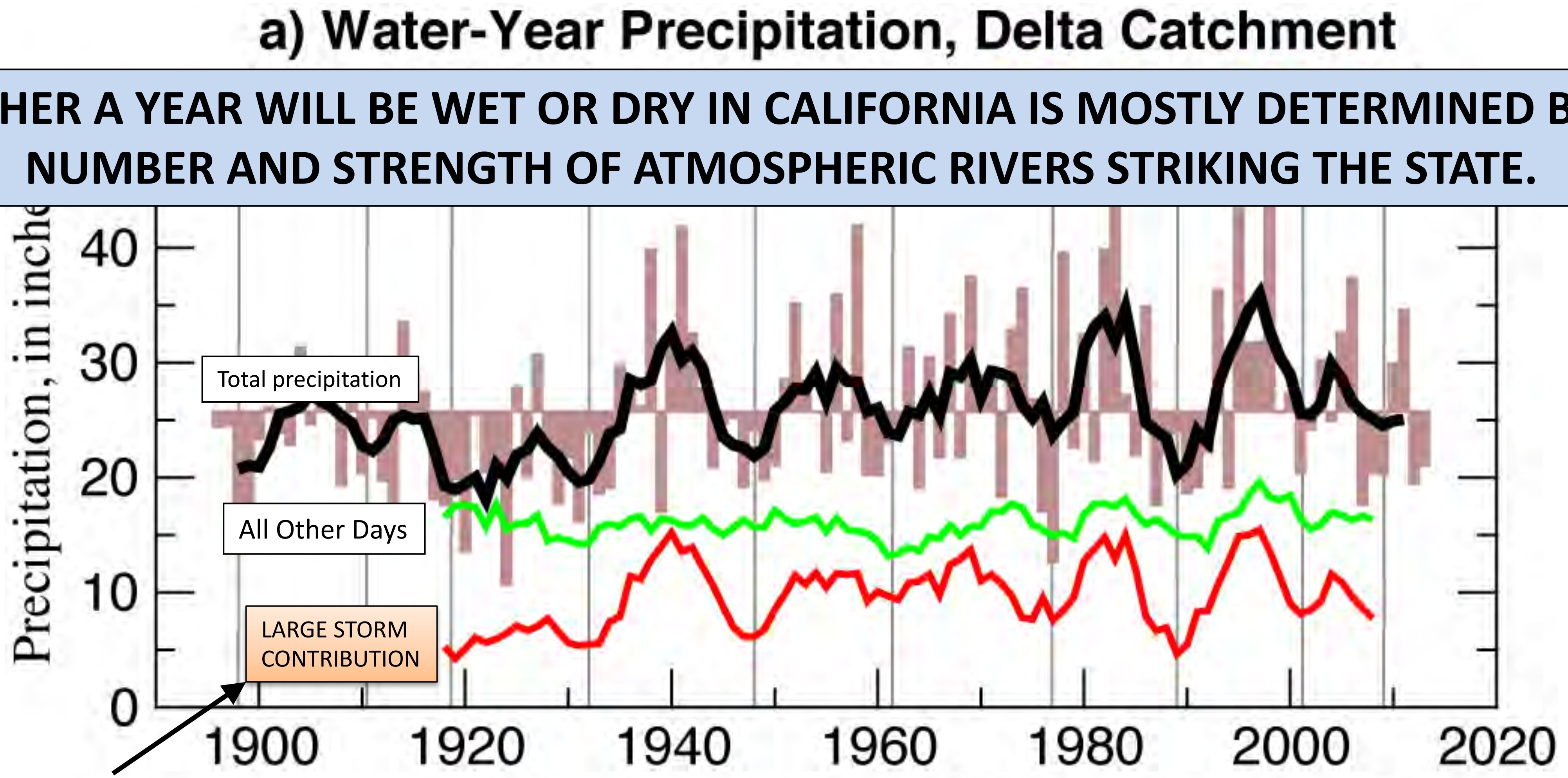




Yes. An “extreme” AR hit the area.

A few large storms (or their absence)

account for a disproportionate amount of California's precipitation variability

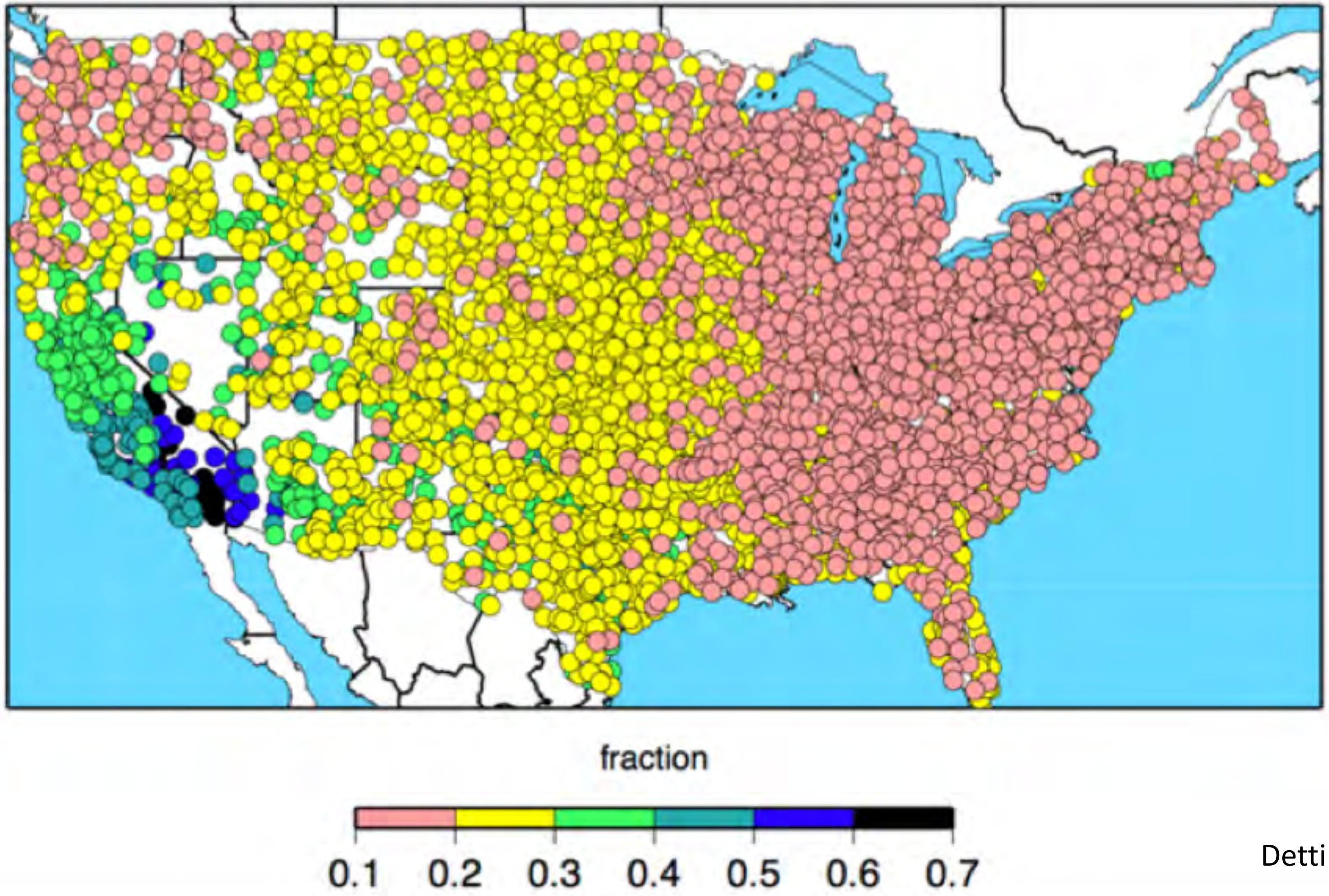


WHETHER A YEAR WILL BE WET OR DRY IN CALIFORNIA IS MOSTLY DETERMINED BY THE NUMBER AND STRENGTH OF ATMOSPHERIC RIVERS STRIKING THE STATE.

- 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

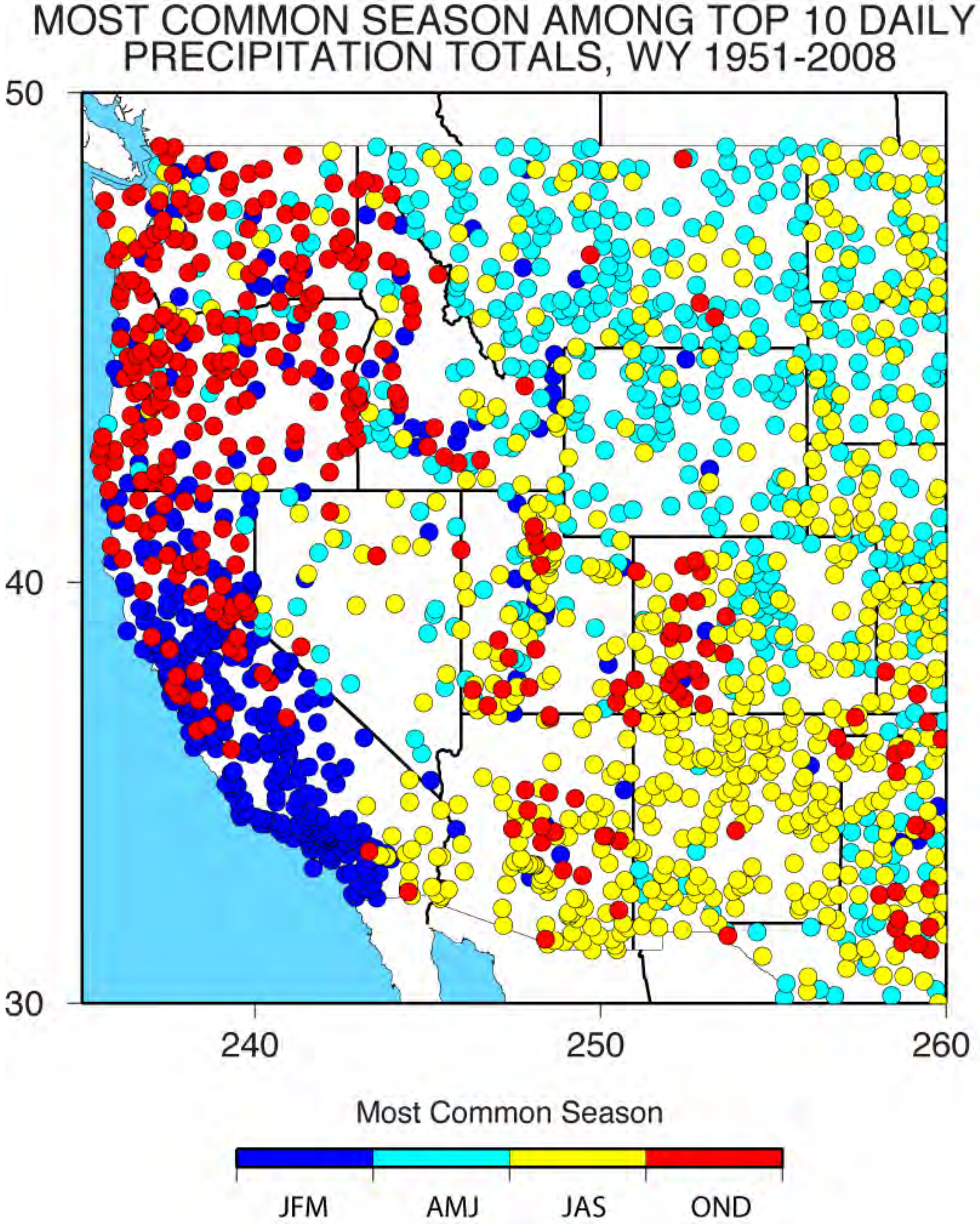
Variability of Annual Precipitation



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.



Ralph et al, 2014, UCOWR

Analysis from COOP daily precipitation observations.

-Each site uses at least 30 years of data

-The top 10 daily precip dates are found

-The season for which most of these top-10 dates occurred at that site is color coded.

-The affect of the southwest Monsoon is seen in yellow dots in AZ, CA, UT, NM, and CO (yellow sites in the Great Plains are not monsoon dominated)

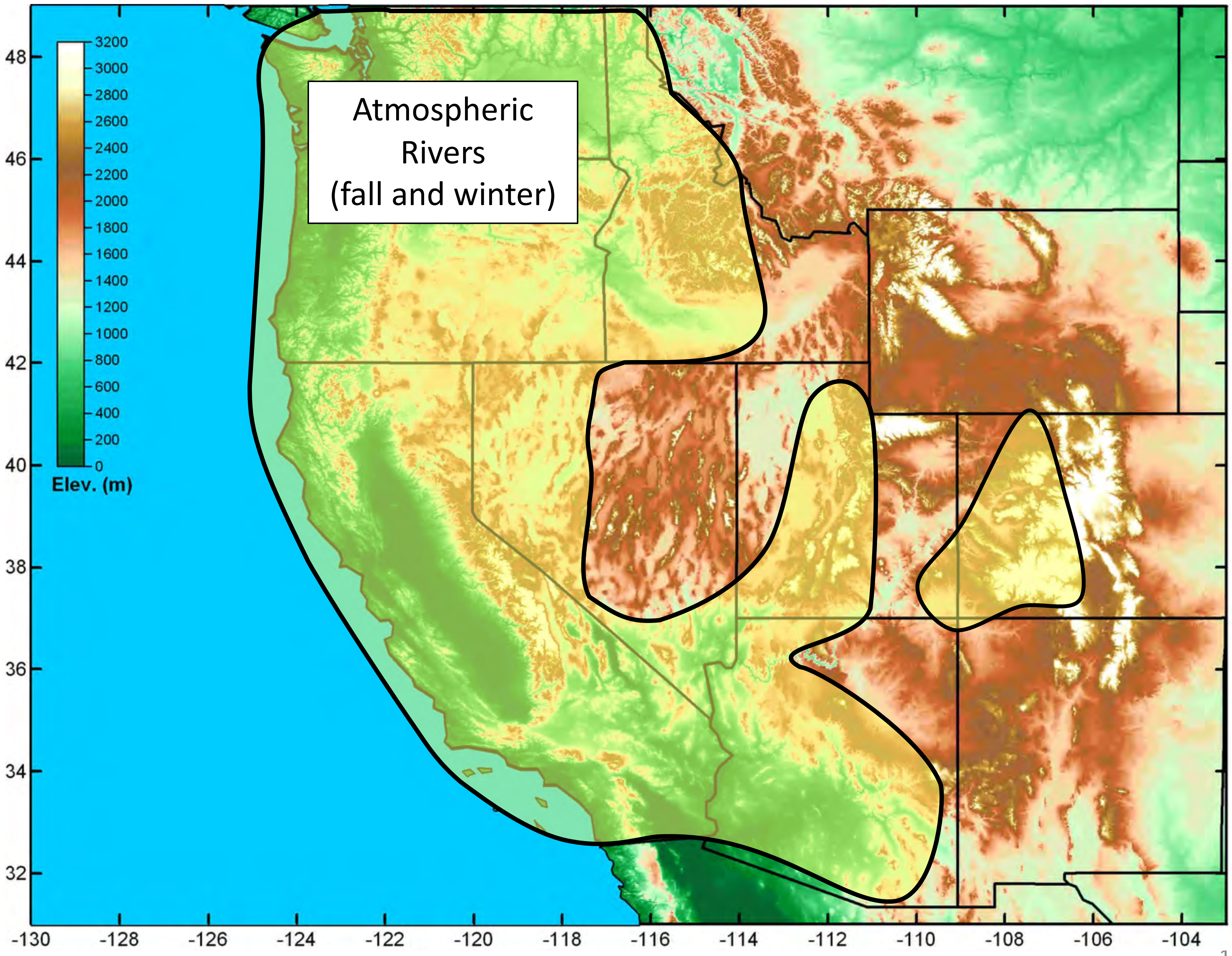
-The affect of atmospheric rivers is highlighted by blue and red dots, including almost all of each coastal state, plus inland penetration of AR impacts into AZ, Western CO, SW and Central UT, and ID.

-Great Plains convective events focus in spring (light blue dots) and summer (yellow).

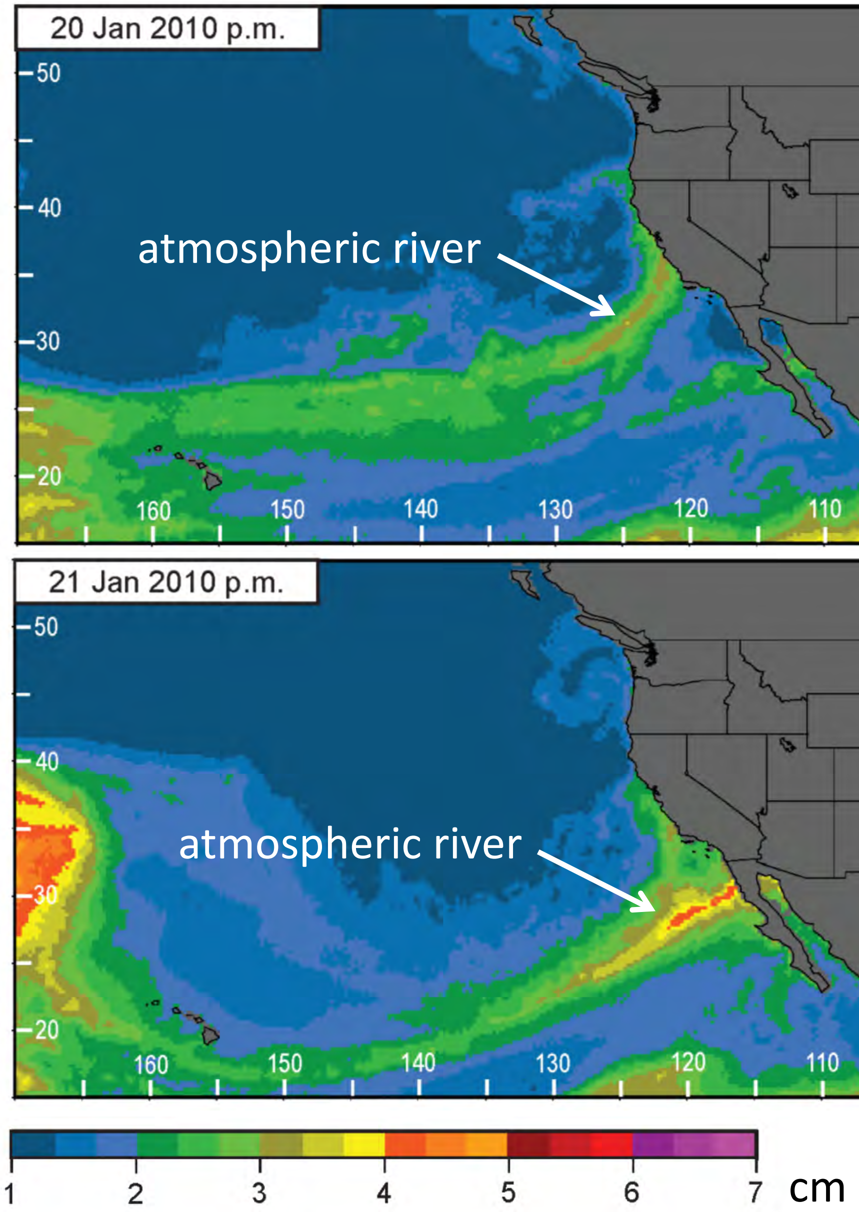
-Colorado front range is mostly spring.

-Nevada is a mixture.

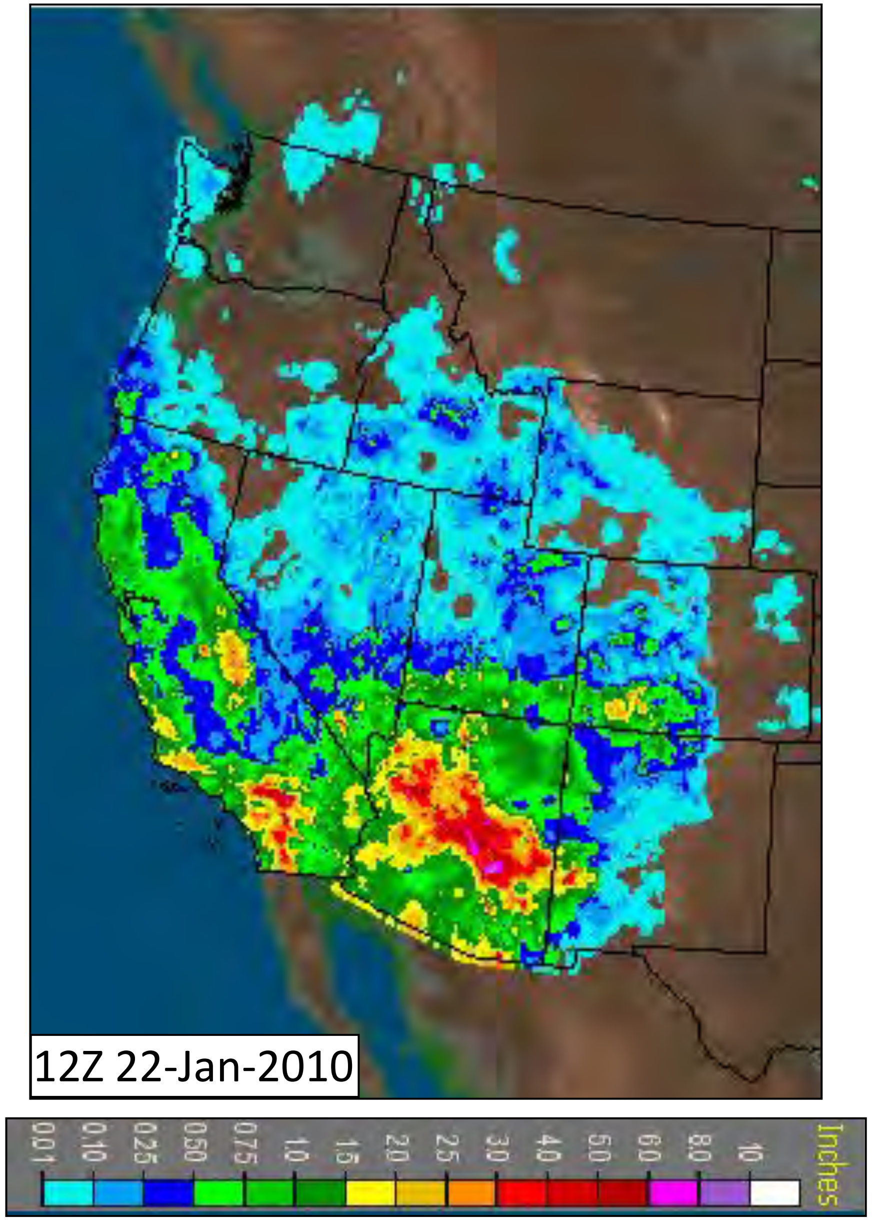
Schematic illustration of regional variations in the primary weather phenomena that lead to extreme precipitation, flooding and contribute to water supply in the Western U.S.



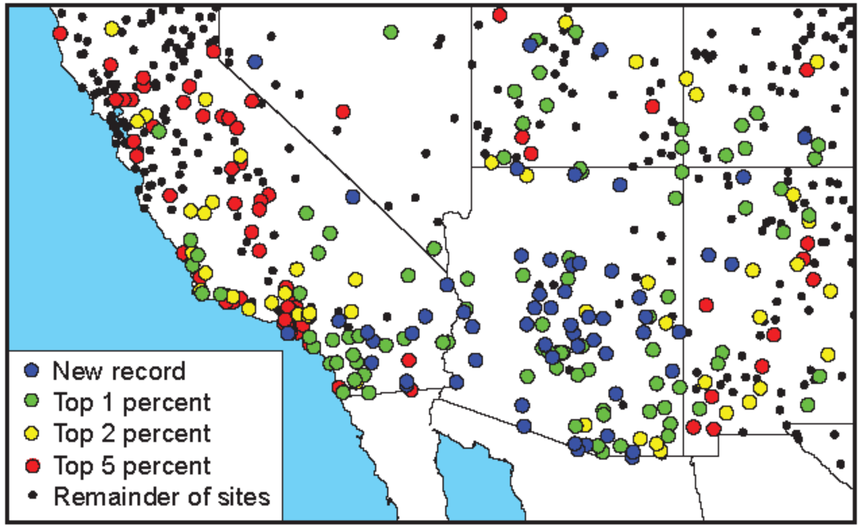
SSM/I IWV satellite imagery 20-21 Jan. 2010 depicts a strengthening AR making landfall



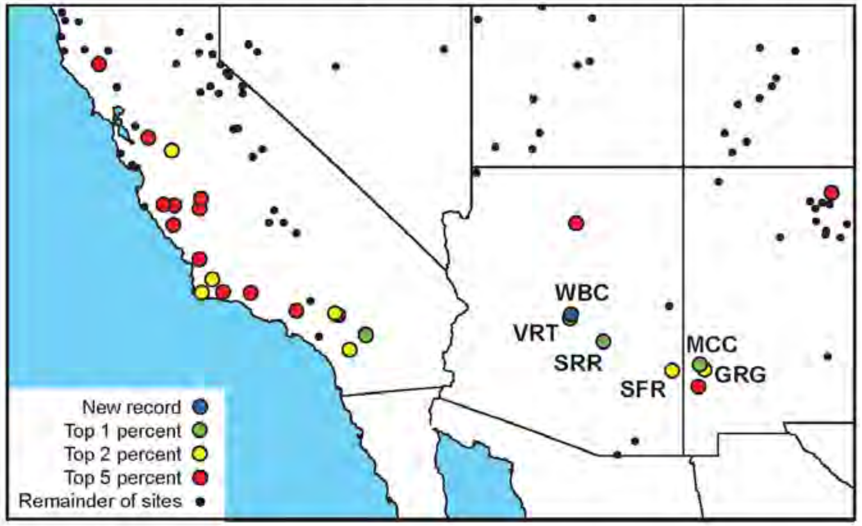
24-h precip ending 12Z 22 Jan. 2010: Advanced Hydrological Prediction Services



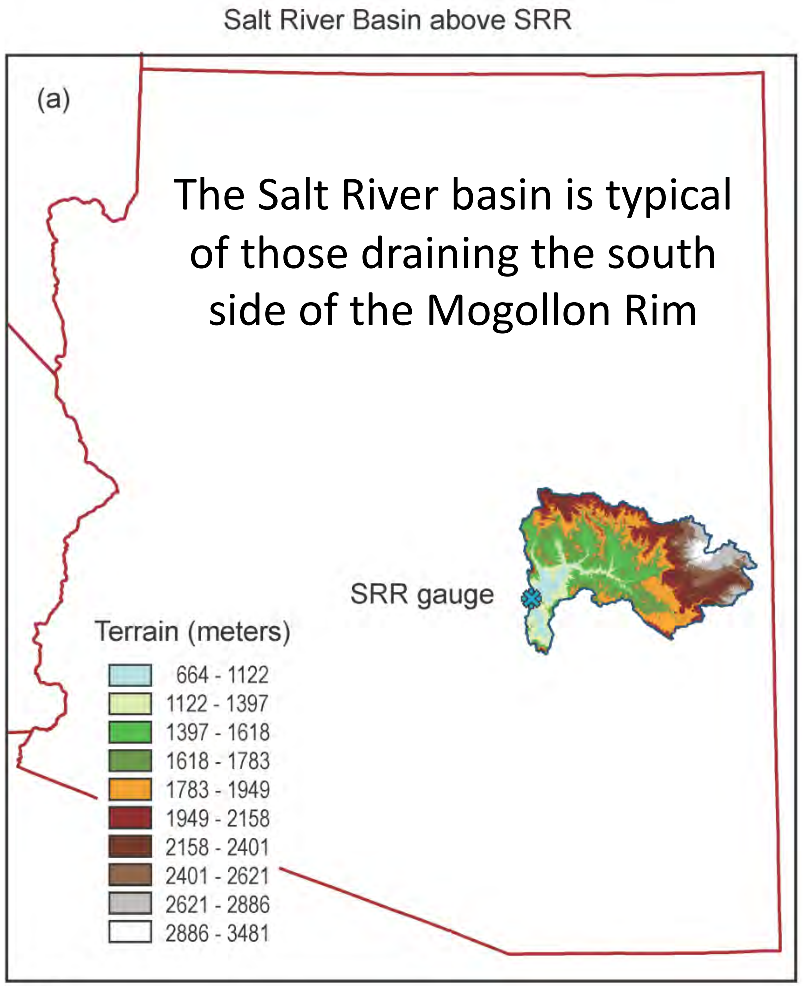
COOP precip on 21-22 Jan. 2010: Rank relative to all January pairs of days between 1950-2009 for gauges with >25 Januarys of data.



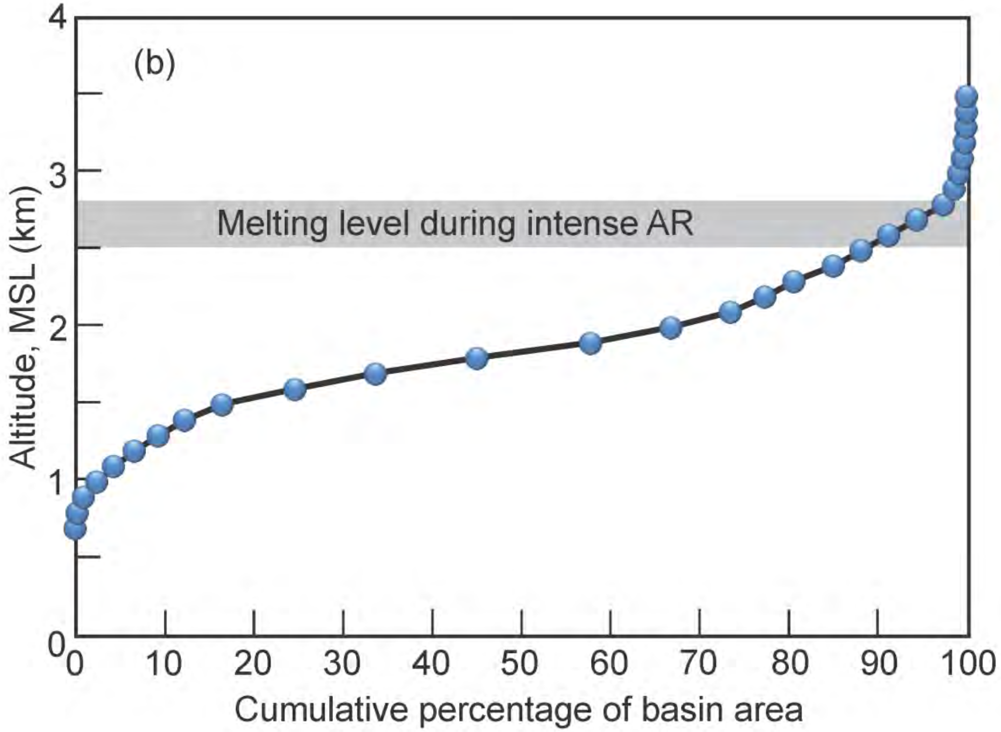
USGS streamflow on 21-22 Jan. 2010 for unregulated channels: Rank relative to all January pairs of days between 1901-2009 for gauges with >25 Januarys of data.

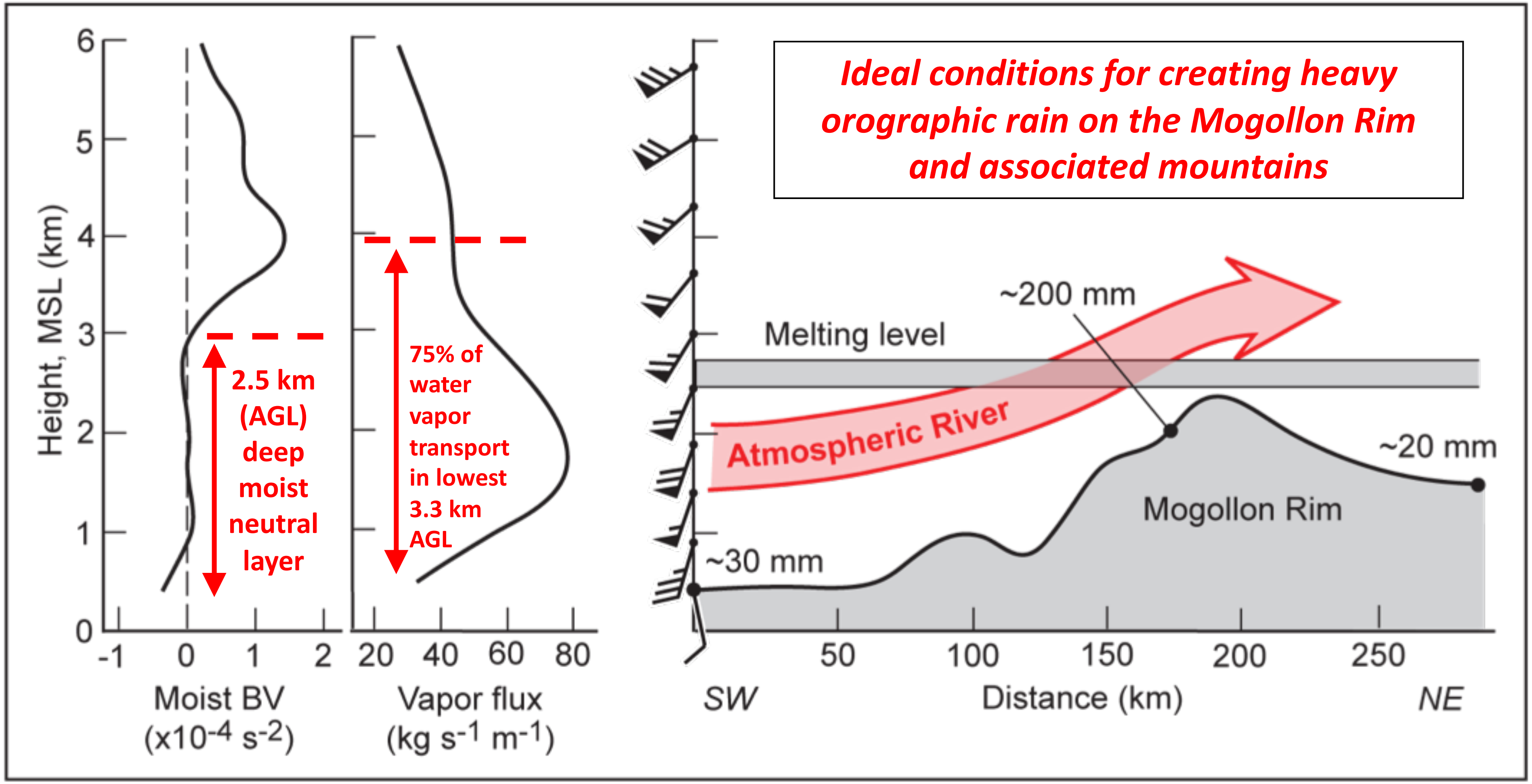


Catchment basin characteristics, local meteorology, and implications for flooding

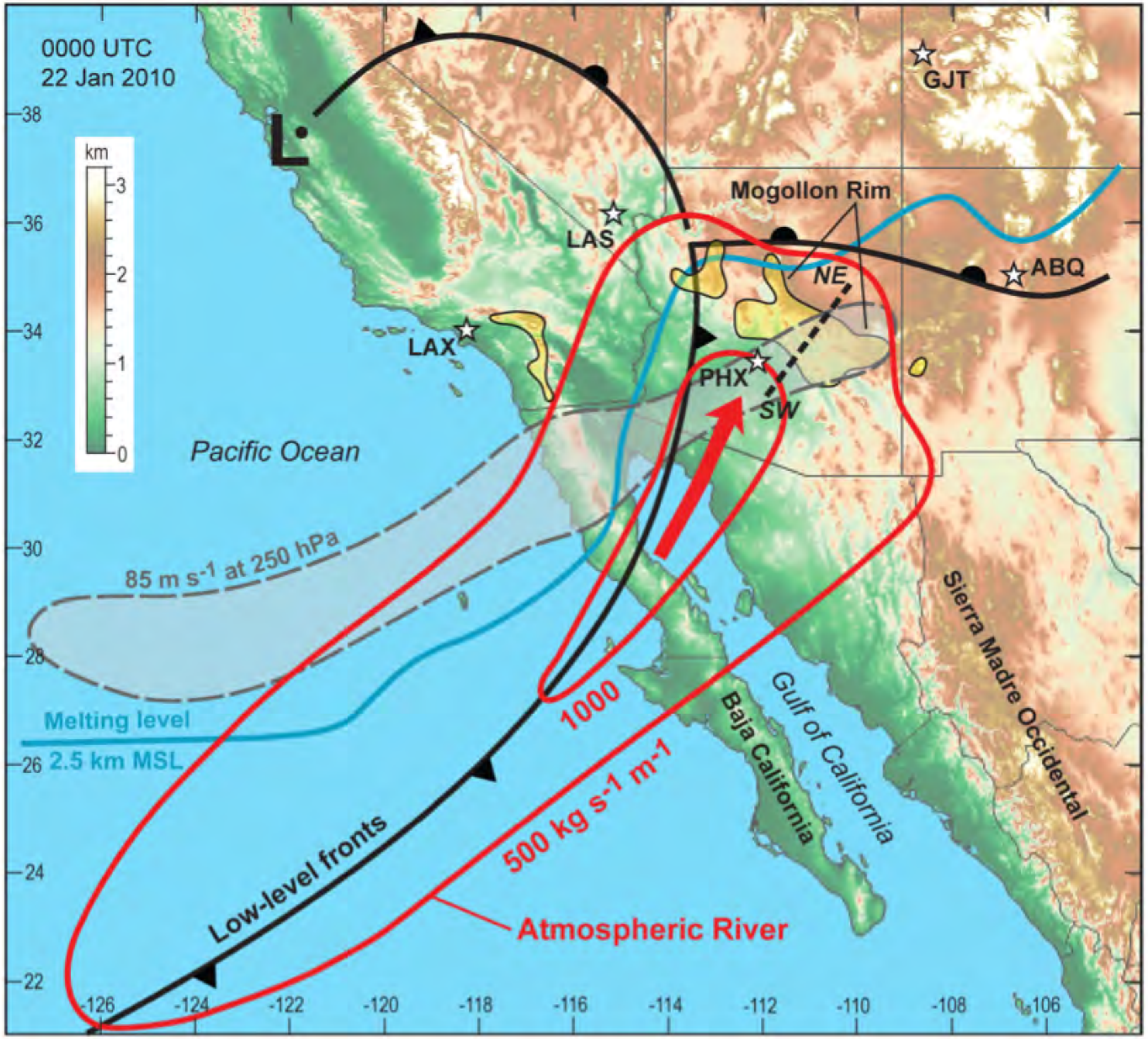


The Salt River basin is typical of those draining the south side of the Mogollon Rim





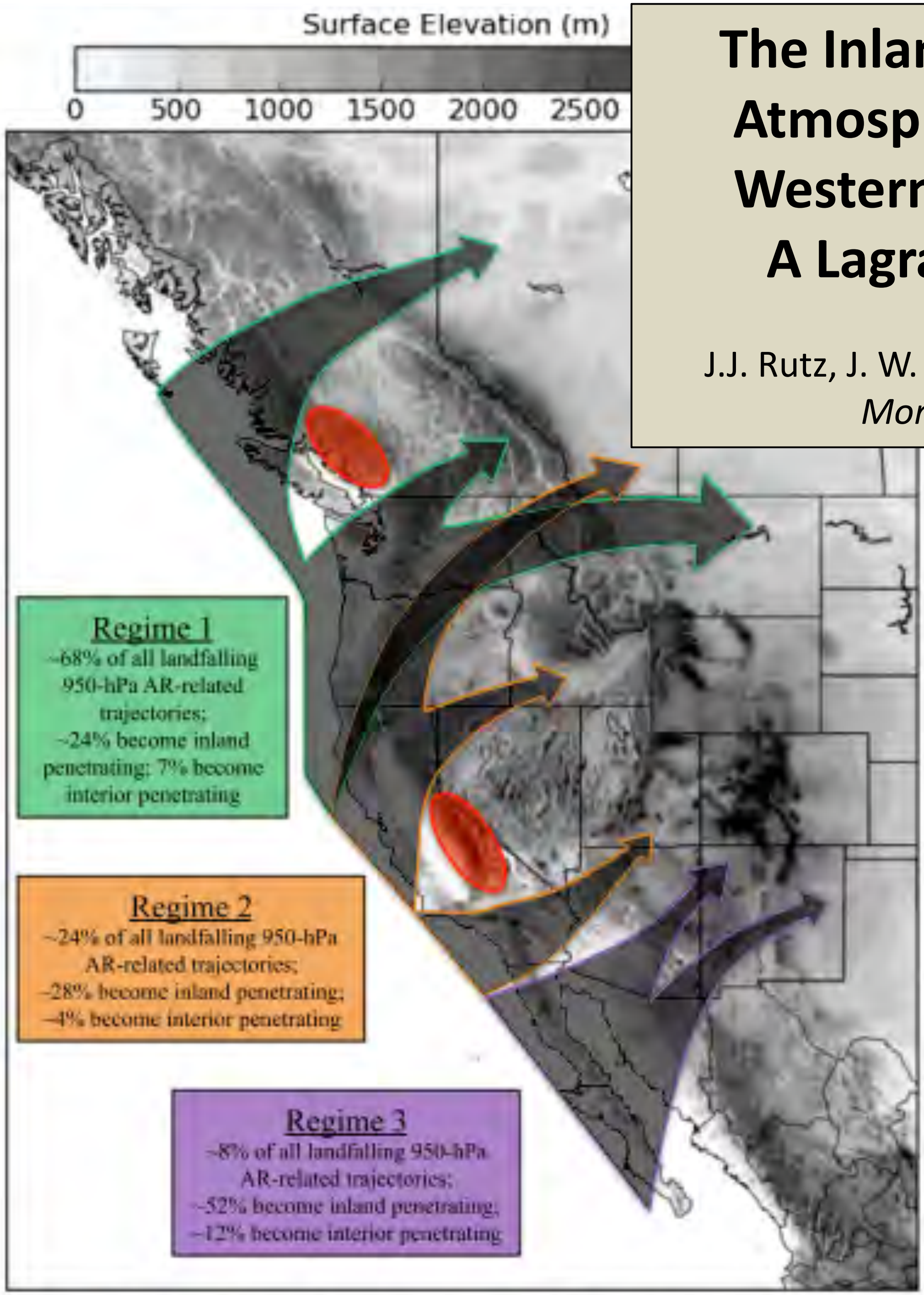
Summary schematic for Jan 2010 case presented by Neiman et al. (in preparation)

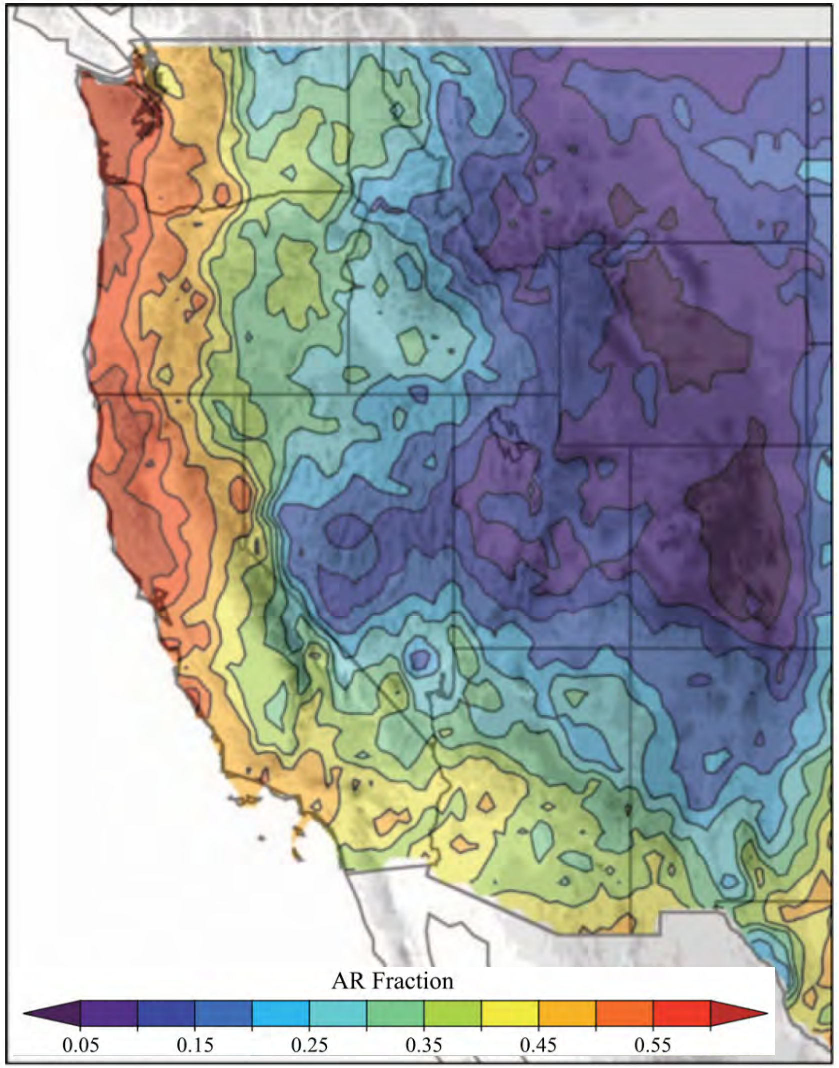


0000 UTC
22 Jan 2010
km
3
2
1
0
L
GJT
LAS
LAX
PHX
ABQ
Mogollon Rim
NE
SW
Pacific Ocean
85 m s-1 at 250 hPa
Melting level
2.5 km MSL
1000
500 kg s-1 m-1
Low-level fronts
Atmospheric River
Baja California
Gulf of California
Sierra Madre Occidental
38
36
34
32
30
28
26
24
22
-126
-124
-122
-120
-118
-116
-114
-112
-110
-108
-106

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

Forecast Informed Reservoir Operations: Bringing Science and Decision-Makers Together to Explore Use of Hydrometeorological Forecasts to Support Future Reservoir Operations

F. Martin Ralph (Presenter)
Center for Western Weather and Water Extremes
UC San Diego/Scripps Institution of Oceanography

Jay Jasperse
Sonoma County Water Agency

Acknowledgments to the FIRO Steering Committee
US Army Corps of Engineers/ERDC and CA DWR AR Programs

Science to Action: Towards More Effective Decision Maker – Scientist Partnerships
AGU Fall 2017, New Orleans, LA

Russian River Reservoirs are Dual Purpose

Flood protection in a flood-prone watershed
(US Army Corp of Engineers)

Water supply for 600,000 people and agriculture
(Sonoma County Water Agency)

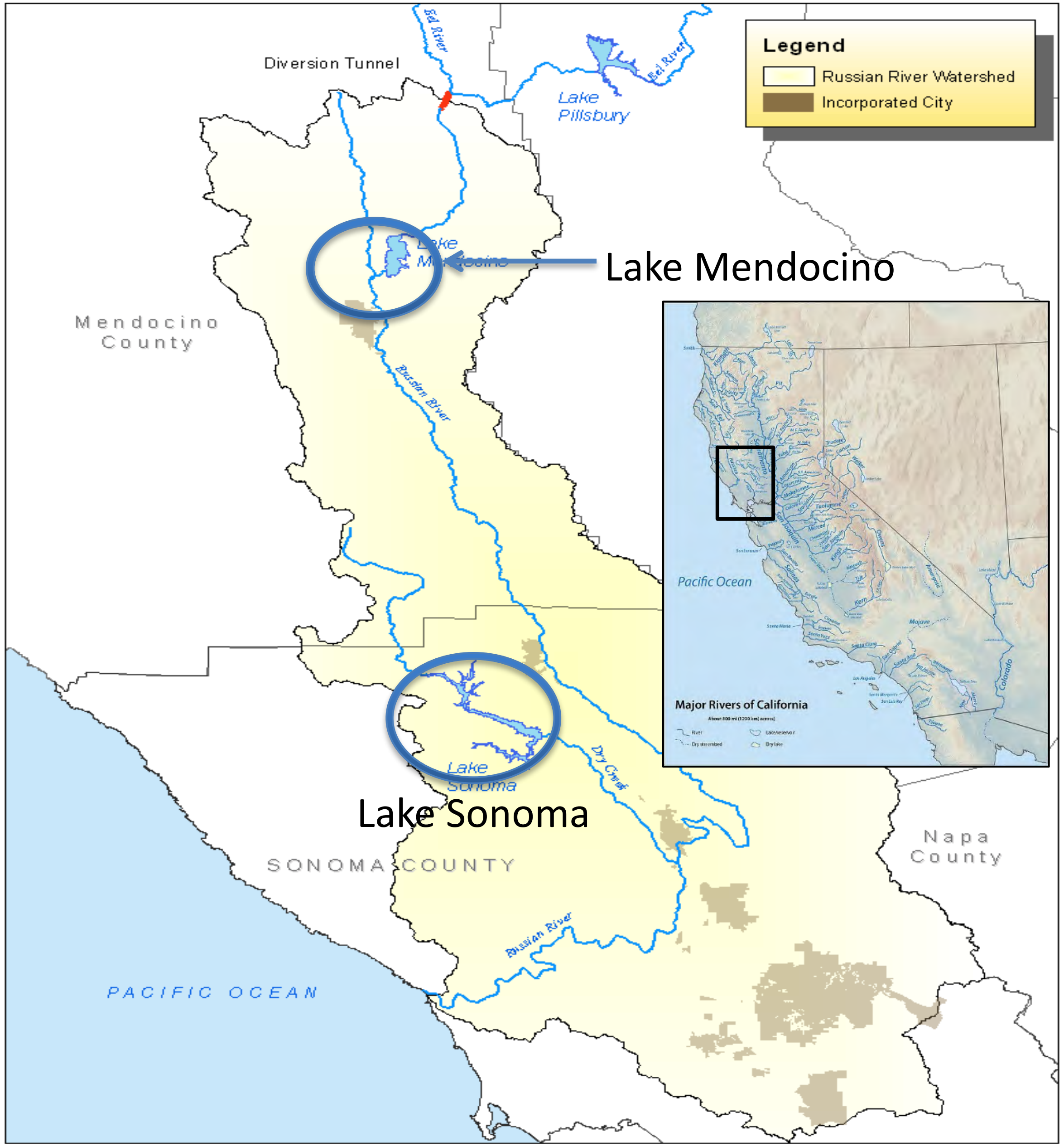
Operations Dictated by
Storage Levels Relative to "Rule Curve"

Lake Mendocino (Coyote Valley Dam)

Flood Control Pool (empty space): 48,100 AF
Water Supply Pool: 68,400 A

Lake Sonoma (Warm Springs Dam)

Flood Control Pool:136,000 AF
Water Supply Pool: 245,000 AFF (Nov. 1 – March 1)



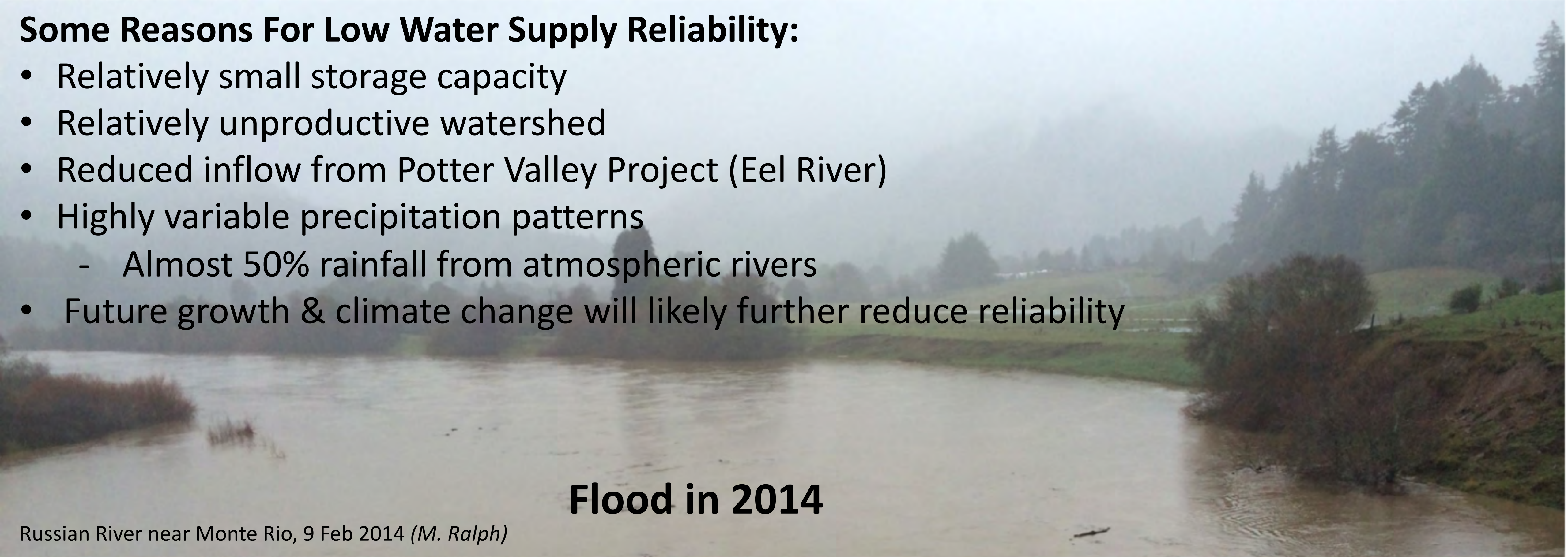
The Issue: Lake Mendocino's Water Supply Is Not Reliable

Drought in 2014

Lake Mendocino, July 2014

Some Reasons For Low Water Supply Reliability:

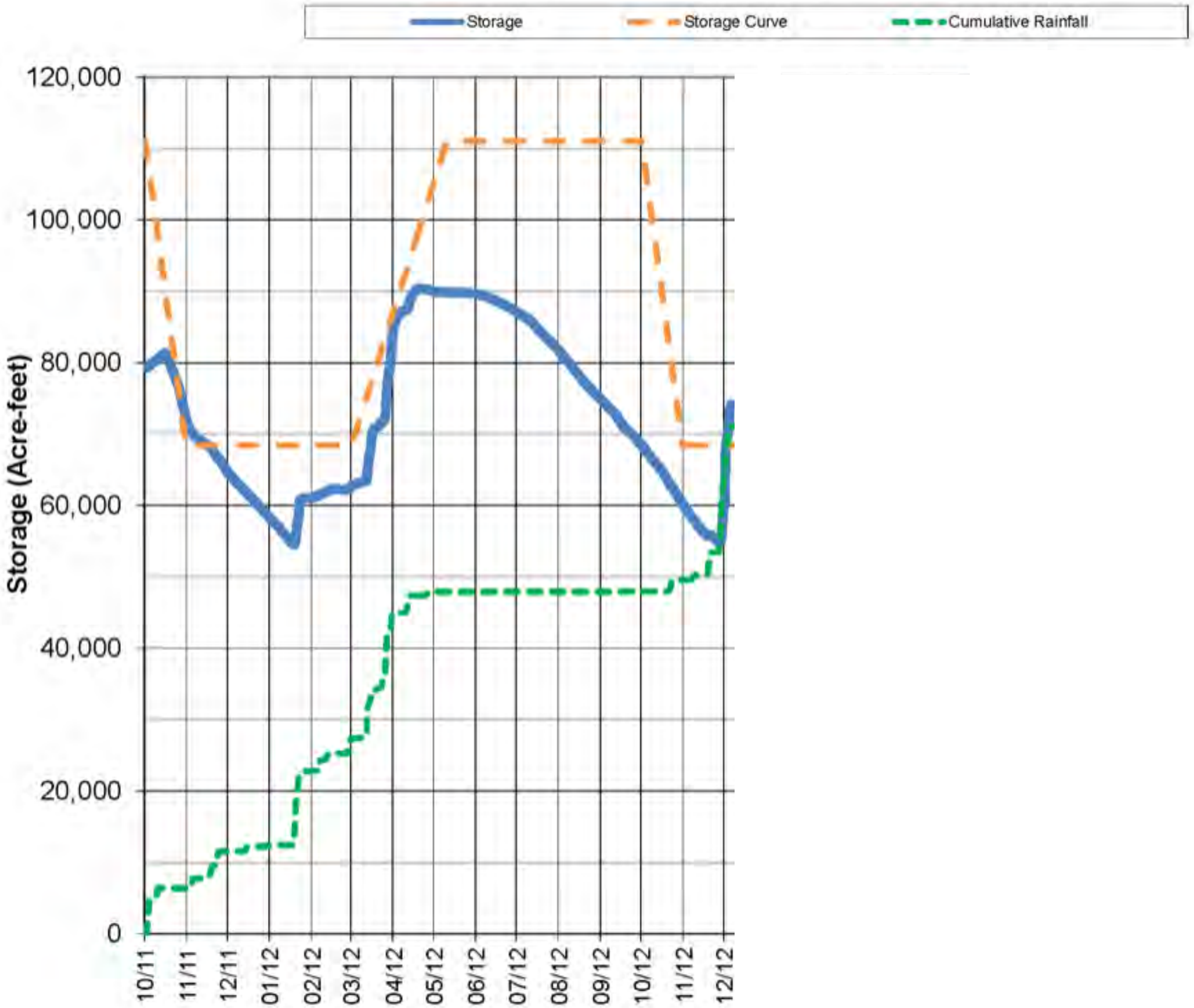
- Relatively small storage capacity
- Relatively unproductive watershed
- Reduced inflow from Potter Valley Project (Eel River)
- Highly variable precipitation patterns
    - Almost 50% rainfall from atmospheric rivers
- Future growth & climate change will likely further reduce reliability



Flood in 2014

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

Lake Mendocino Water Years 2012 - 2014



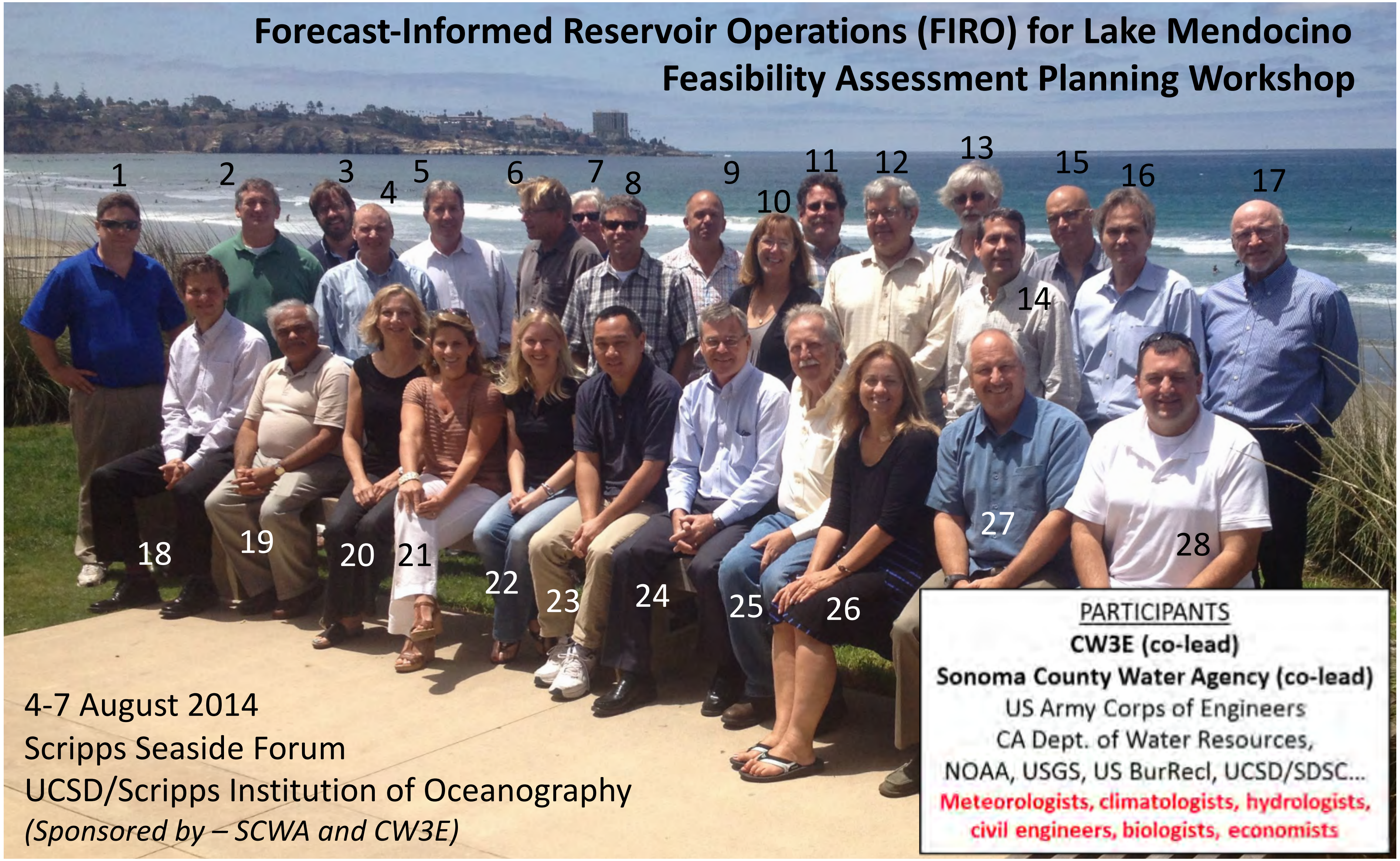
Lake Mendocino FIRO Steering Committee

- **Co-Chairs**
  Jay Jasperse – Sonoma County Water Agency
  F. Martin Ralph – UCSD / SIO / CW3E
- **Members**
  Michael Anderson – California DWR
  Levi Brekke – USBR
  Mike Dillabough – USACE / SPN
  Michael Dettinger – USGS
  Joe Forbis – USACE / SPK
  Alan Haynes – NOAA / NWS
  Patrick Rutten – NOAA / NMFS
  Cary Talbot – USACE / ERDC
  Robert Webb – NOAA / OAR

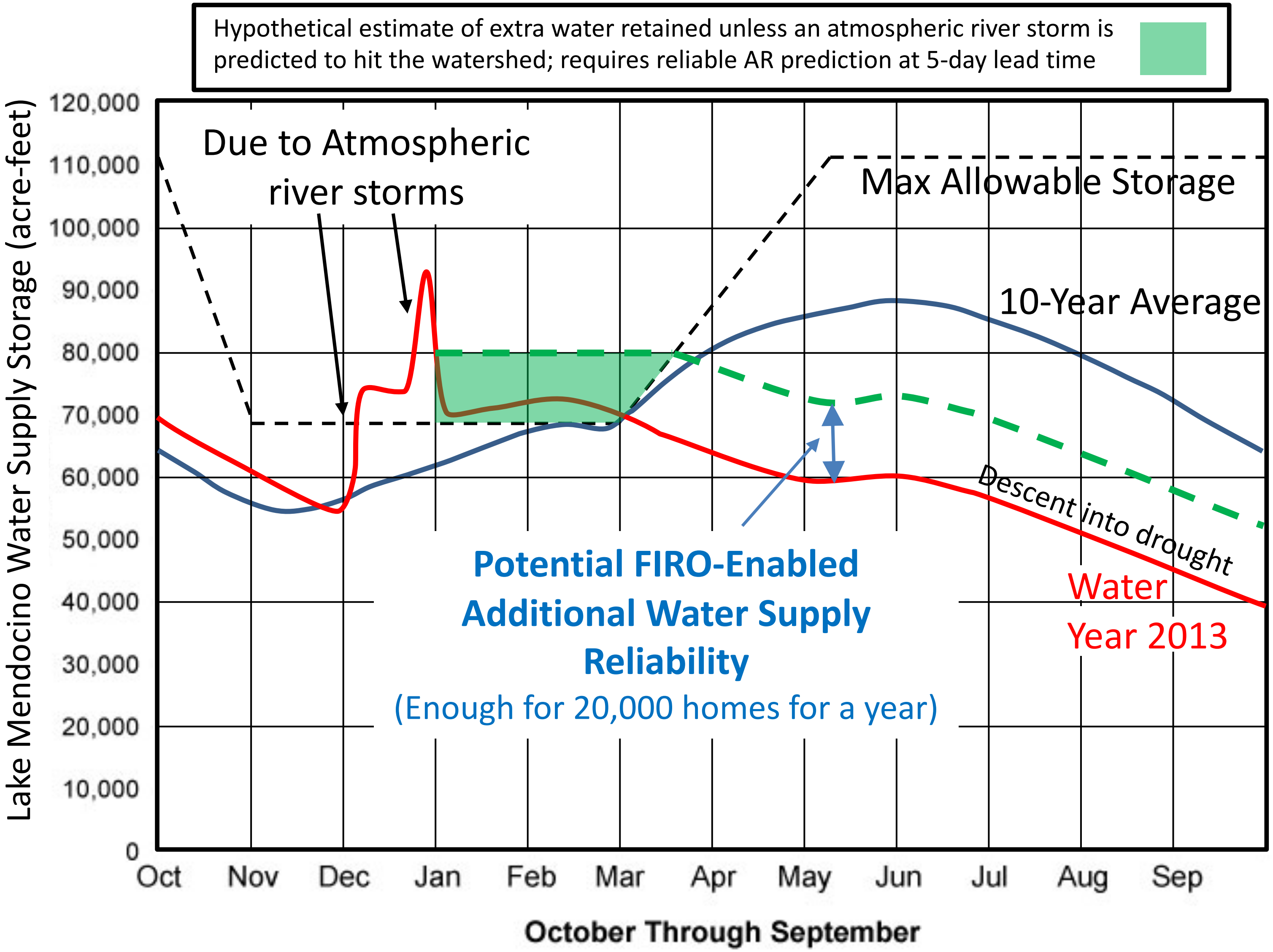
Project Partners

A Comprehensive **Work Plan** to Evaluate FIRO for Lake Mendocino

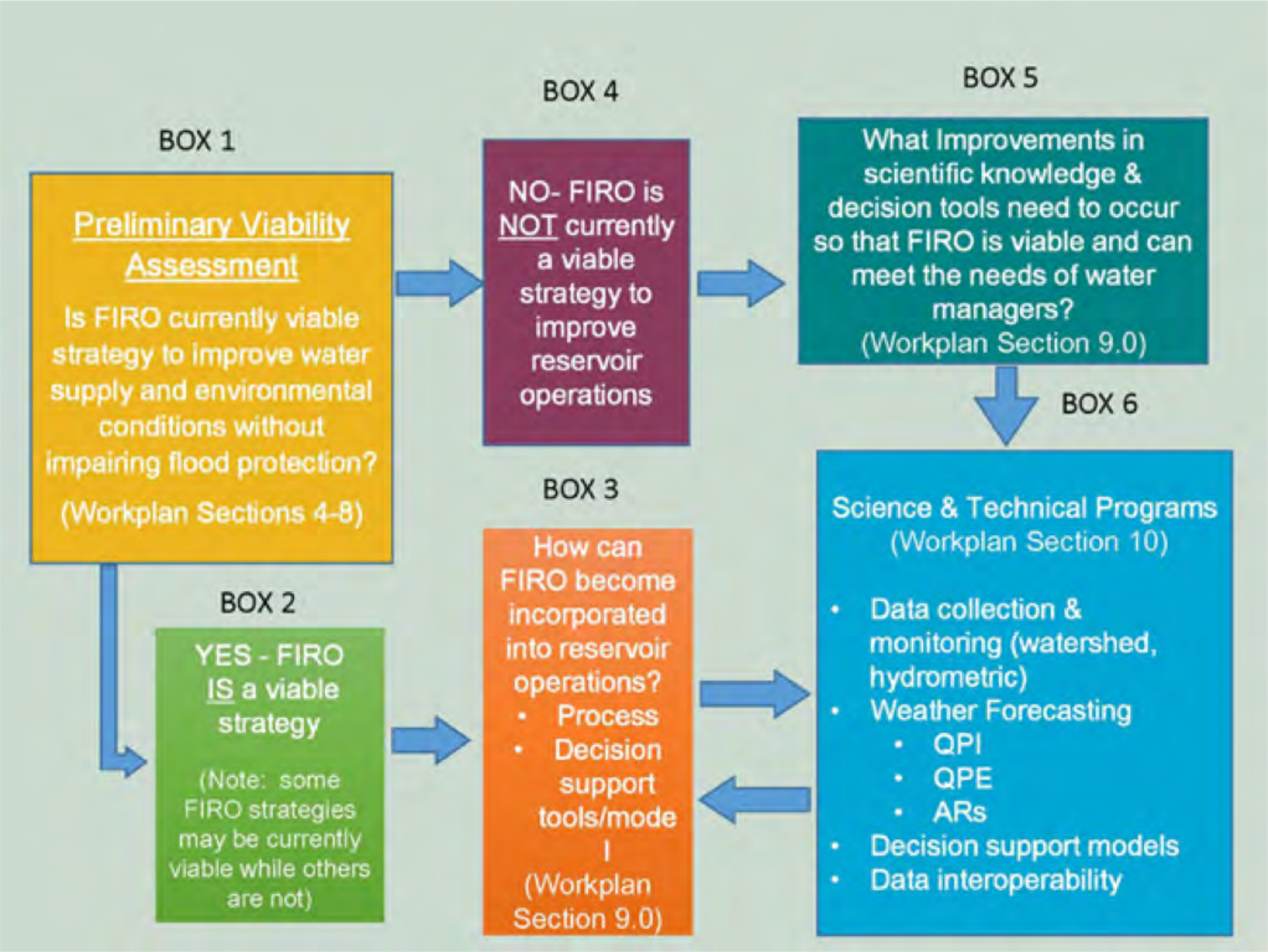
- Viability Assessment Process
- Evaluation Framework
- Benefits Assessment
- Implementation Strategies
- Technical and Scientific Support


Forecast-Informed Reservoir Operations (FIRO) for Lake Mendocino
Feasibility Assessment Planning Workshop
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
18 19 20 21 22 23 24 25 26 27 28
4-7 August 2014
Scripps Seaside Forum
UCSD/Scripps Institution of Oceanography
(Sponsored by – SCWA and CW3E)
PARTICIPANTS
CW3E (co-lead)
Sonoma County Water Agency (co-lead)
US Army Corps of Engineers
CA Dept. of Water Resources,
NOAA, USGS, US BurRecl, UCSD/SDSC...
Meteorologists, climatologists, hydrologists,
civil engineers, biologists, economists

Lake Mendocino Forecast-Informed Reservoir Operations Concept



FIRO Viability Assessment Process

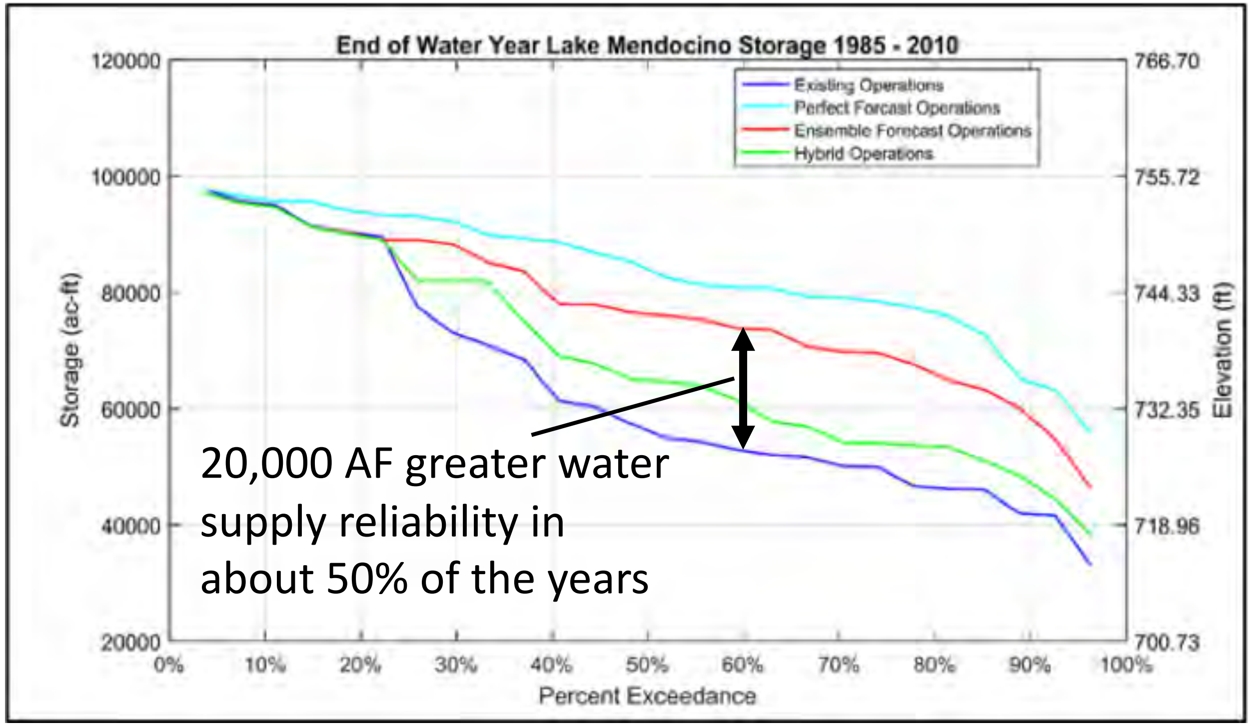


Selected results of FIRO-motivated science

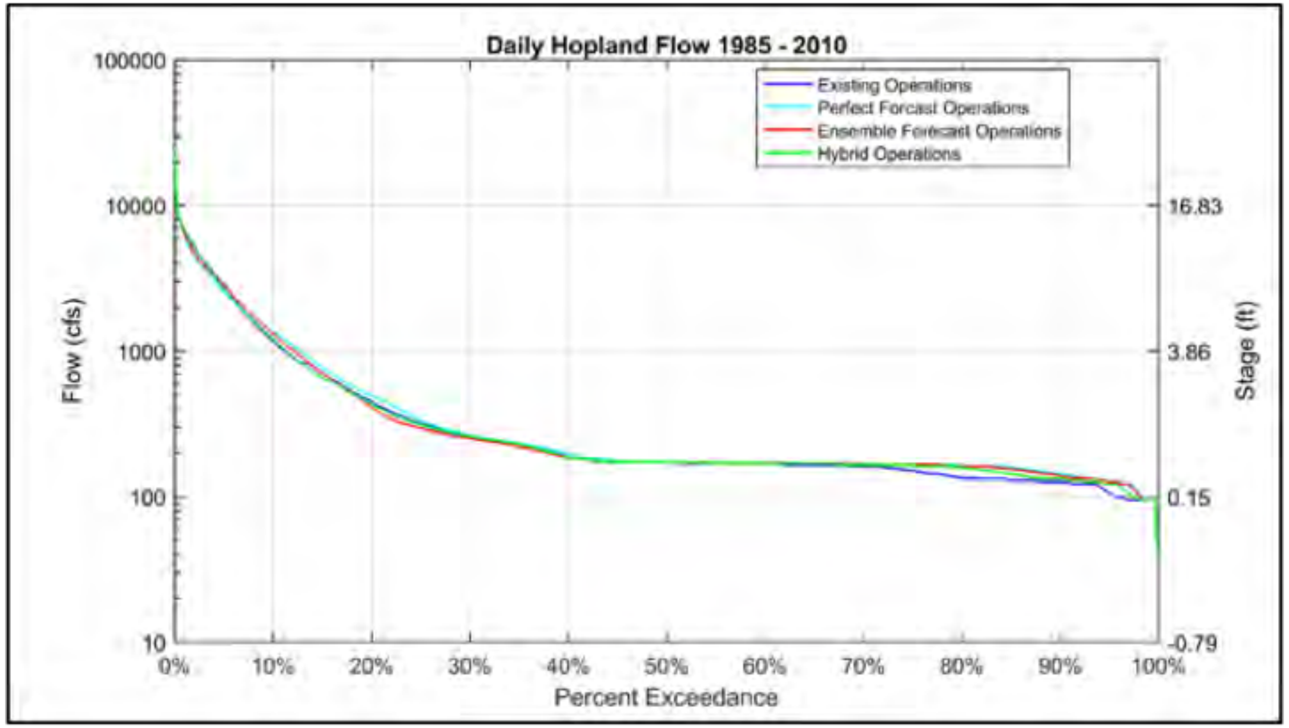
- Established forecast skill requirements, e.g., 3-5 day lead time on heavy precipitation and runoff forecasts
- ARs are the main weather phenomenon that causes extremes
- AR landfall forecasts have useful skill out to a few days
- Mesoscale frontal waves are key source of forecast busts
- AR Recon offers potential to improve AR landfall prediction
- Prediction of no AR landfall has skill beyond 1 week
- Probabilistic streamflow predictions are key; developing thresholds based on ensemble methods
- Exploring roles of distributed, physics-based steamflow models

Hypothetical Impacts of FIRO on Water Supply and Flood Risk

Water Supply



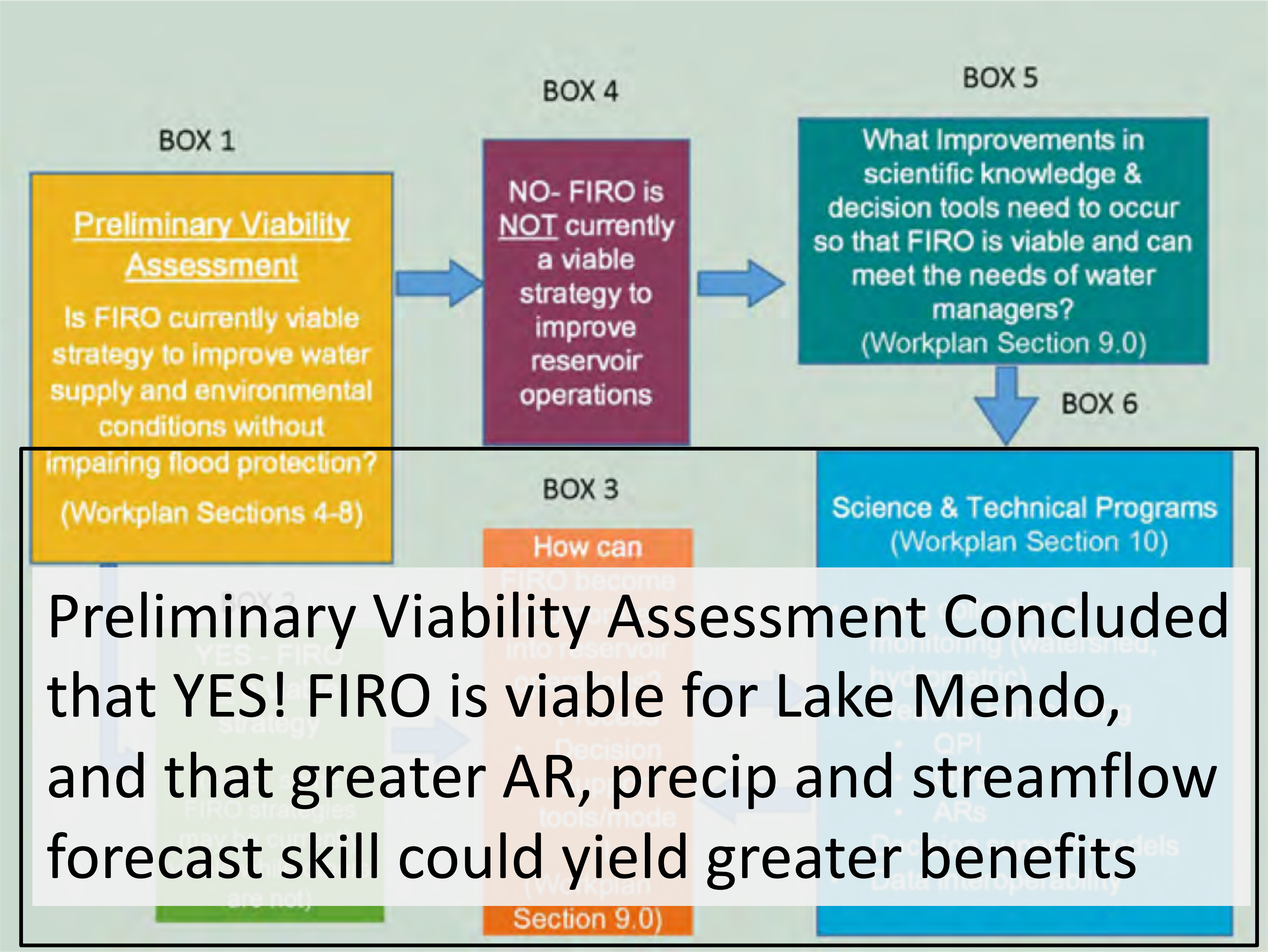
Flood Risk



- ✓ Substantial gains in water storage over existing operations by leveraging information in streamflow forecasts

- ✓ Downstream flood control benefits are not impacted

FIRO Viability Assessment Process



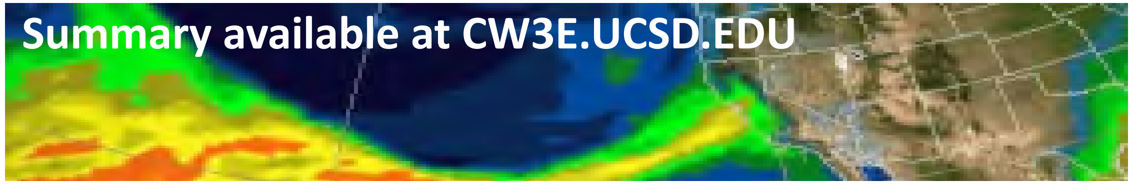
Preliminary Viability Assessment Concluded that YES! FIRO is viable for Lake Mendo, and that greater AR, precip and streamflow forecast skill could yield greater benefits

Steering Committee report finalized July 2017

Congressional Staff Briefing on July 13, 2016

"A New Frontier in Water Operations: Atmospheric Rivers, Subseasonal-to-Seasonal Predictions and Weather Forecasting Technology"

An interagency, cross-disciplinary team of experts convened in Washington to provide Congressional staff with a briefing on atmospheric rivers, subseasonal-to-seasonal precipitation prediction needs, and the benefits of enhanced predictive forecasting technology to the future of water management.



PANELISTS AND PRESENTATIONS

Dr. Louis W. Uccellini is Assistant Administrator for Weather Services, National Oceanic and Atmospheric Administration (NOAA), and Director, National Weather Service. His presentation may be found [HERE].

Dr. Cary Talbot is the Program Manager, Engineer Research and Development Center, U.S. Army Corps of Engineers. His presentation may be found [HERE].

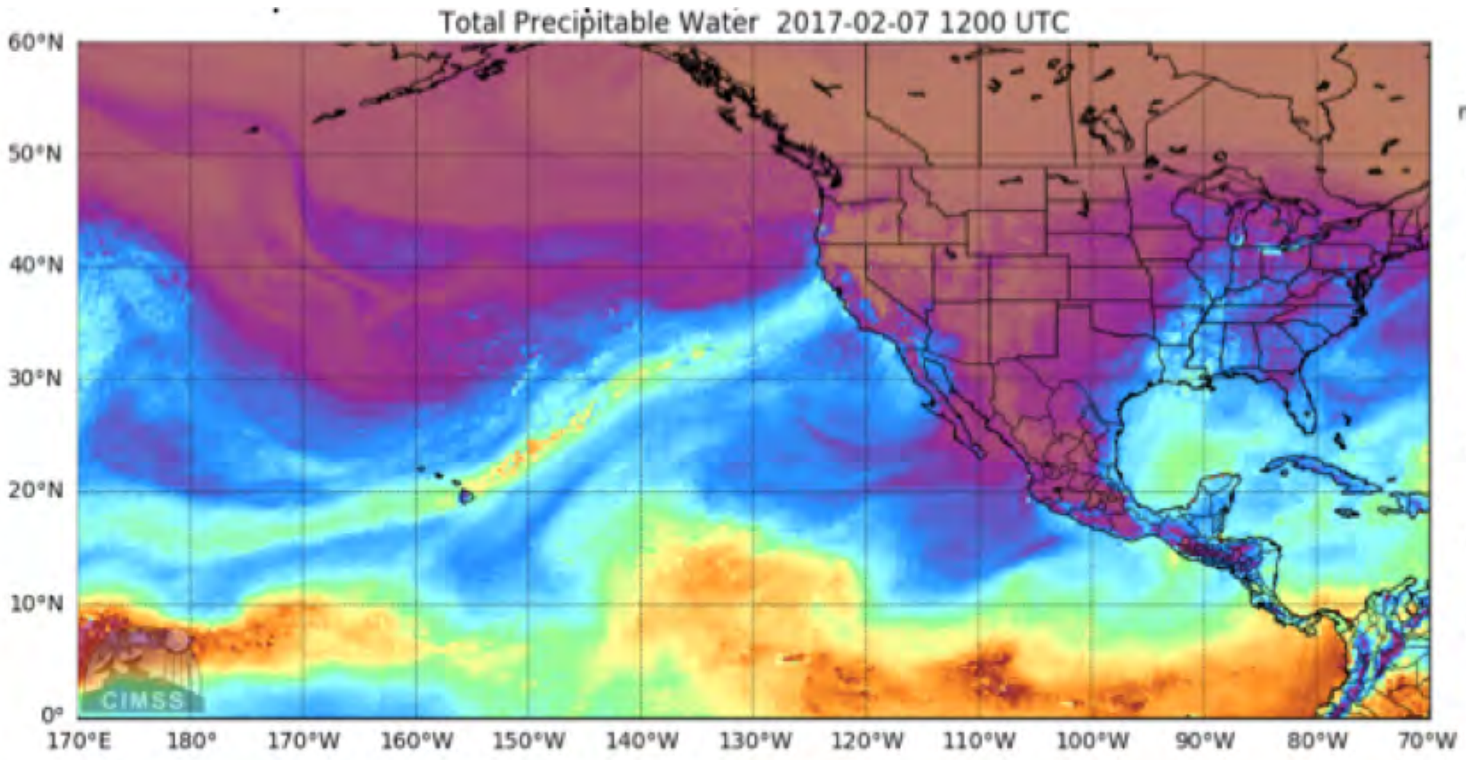
Ms. Jeanine Jones serves as the Secretary-Treasurer of the Western States Water Council. Her presentation may be found [HERE] .

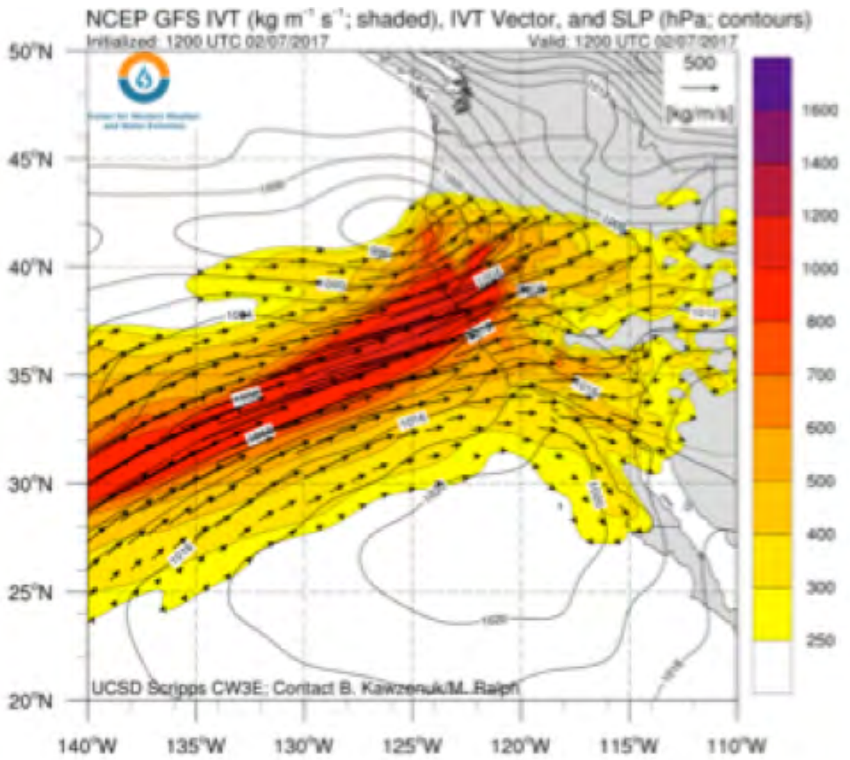
Dr. F. Martin Ralph, Director of the Center for Western Weather and Water Extremes, UCSD / Scripps Institution of Oceanography. His presentation may be found [HERE] .

MODERATOR: Ms. Shirlee Zane serves on the Sonoma County Board of Supervisors and is a Director of the Sonoma County Water Agency.

Wide range of water levels at Oroville Dam: From drought, to normal, to flood and damage

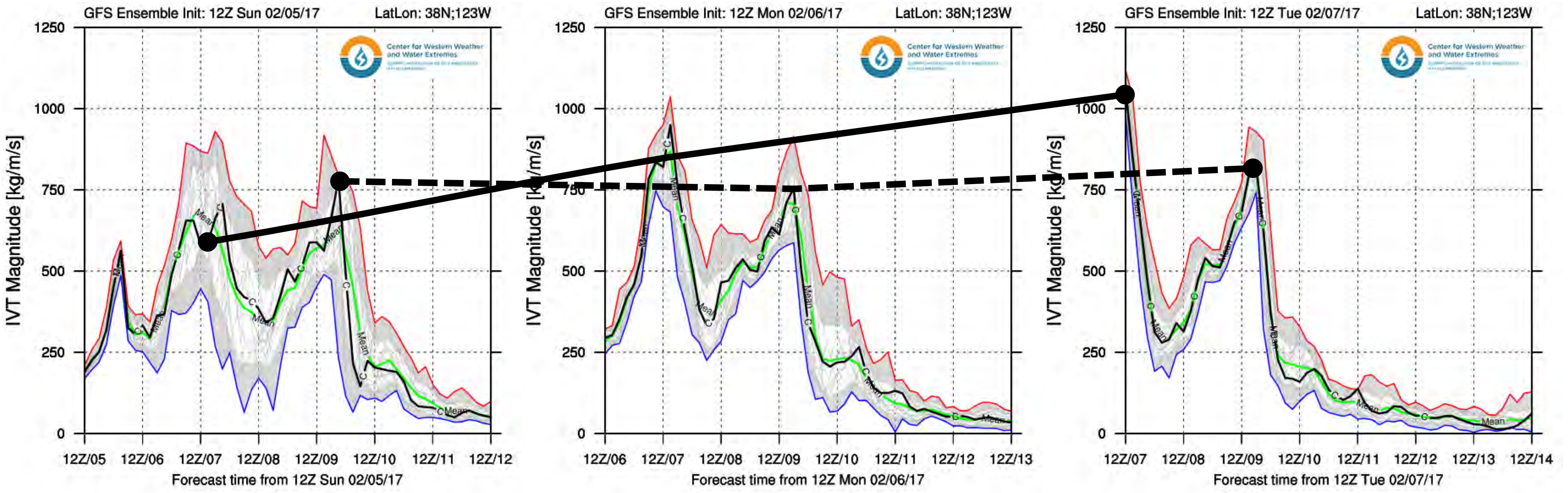
Was the Oroville Incident Related to an AR?





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.**

J. Cordeira/M. Ralph

NCEP GEFS dProg/dt Examples from January and February 2017

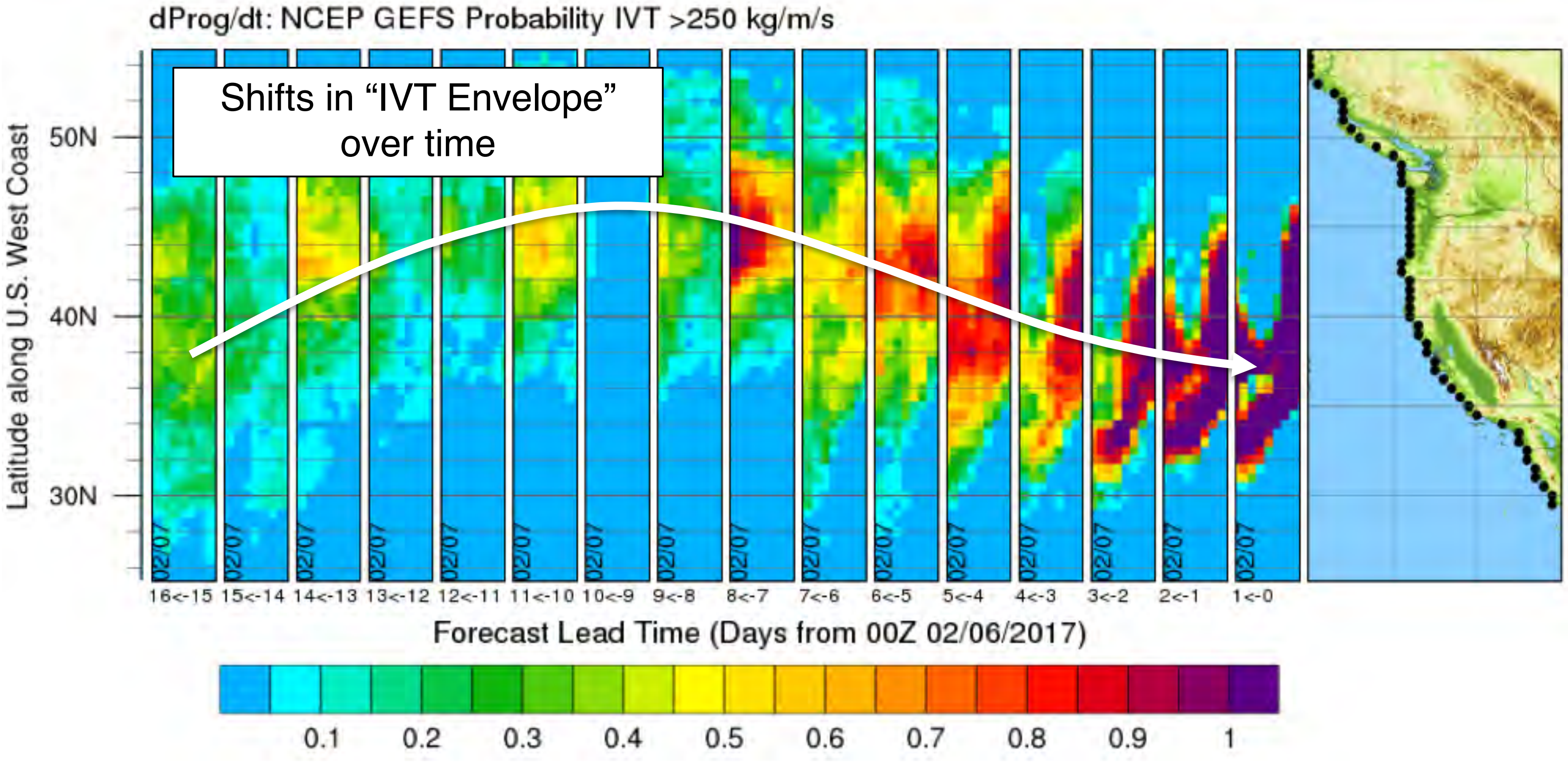
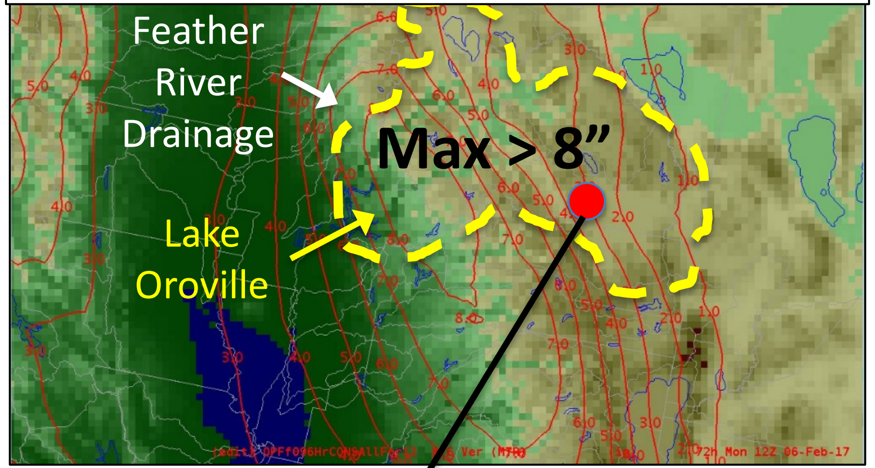


Image Description: Shading represents the NCEP GEFS probability that IVT will exceed 250 kg m^{-1} s^{-1} at 0.5-degree grid locations along the U.S. West Coast (dots). Each panel represents a 24-h forecast that verifies during the 24-h period starting at the time listed above the color bar. The lead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

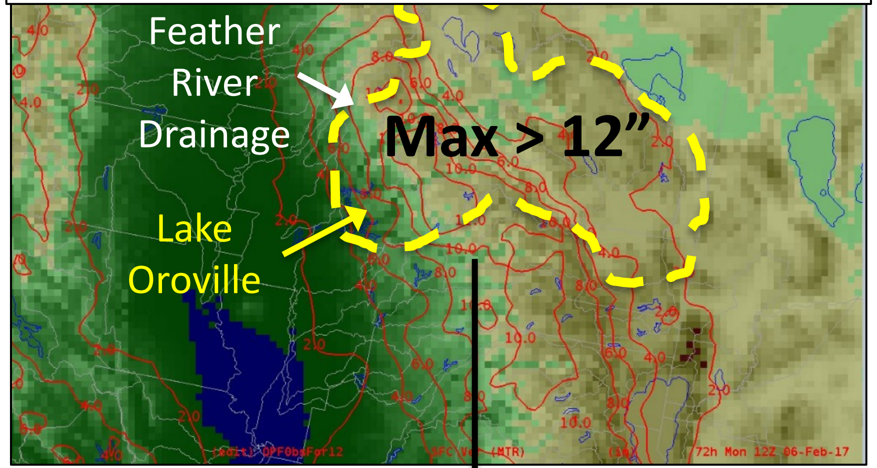
J. Cordeira

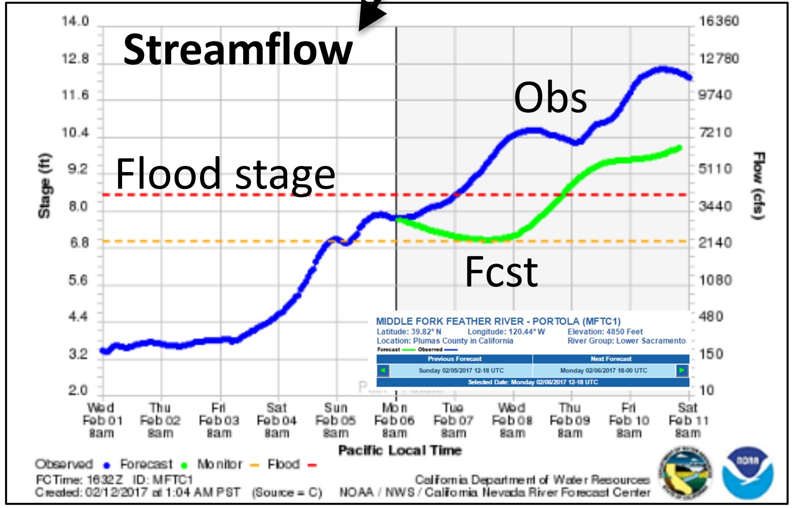
Observed Vs Predicted Precipitation over Feather River Basin for 6-9 Feb 2017

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

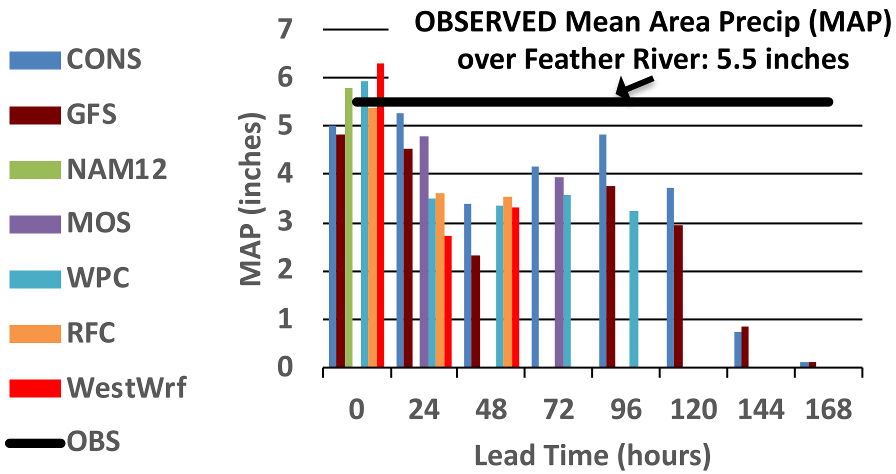


Observed Precipitation over 3 days ending 1200 UTC 9 Feb





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

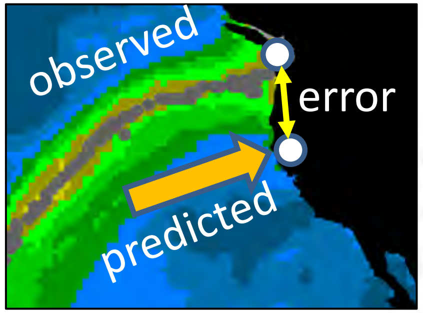


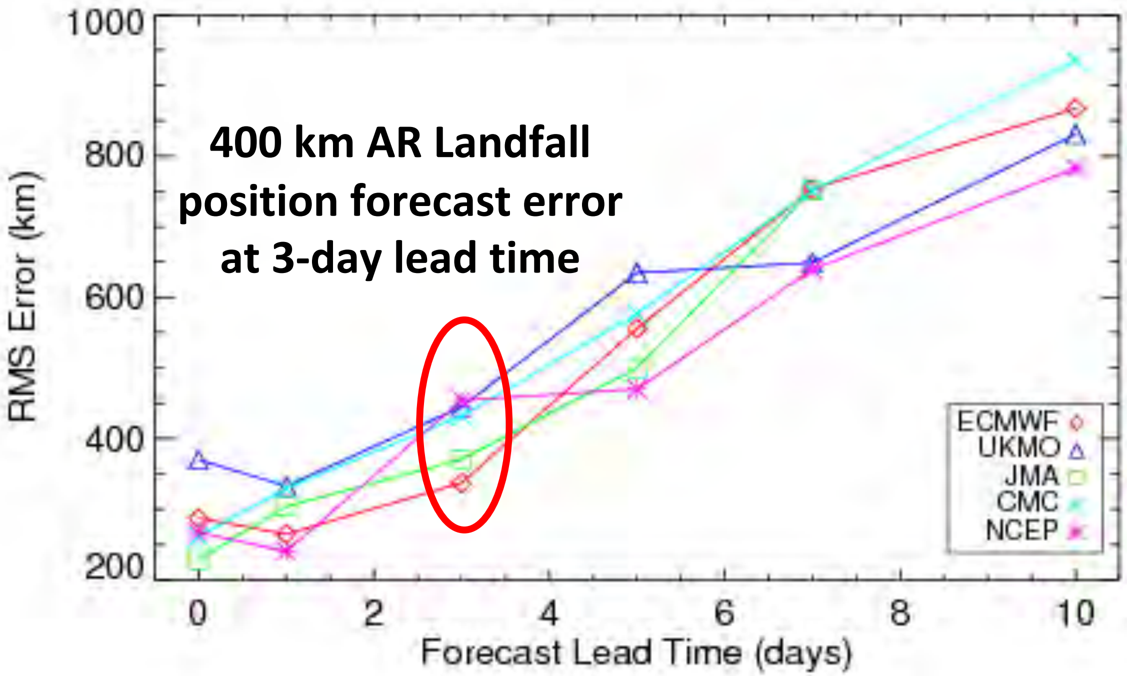
Atmospheric River Reconnaissance

FM Ralph (Scripps/CW3E), V Tallapragada (NWS/NCEP), J Doyle (NRL)

Water managers, transportation sector, agriculture, etc… require improved atmospheric river (AR) predictions

AR Forecast skill assessment establishes a performance baseline





Wick, G.A., P.J. Neiman, F.M. Ralph, and T.M. Hamill, 2013: Evaluation of forecasts of the water vapor signature of atmospheric rivers in operational numerical weather prediction models. *Wea. Forecasting*, **28**, 1337-1352.

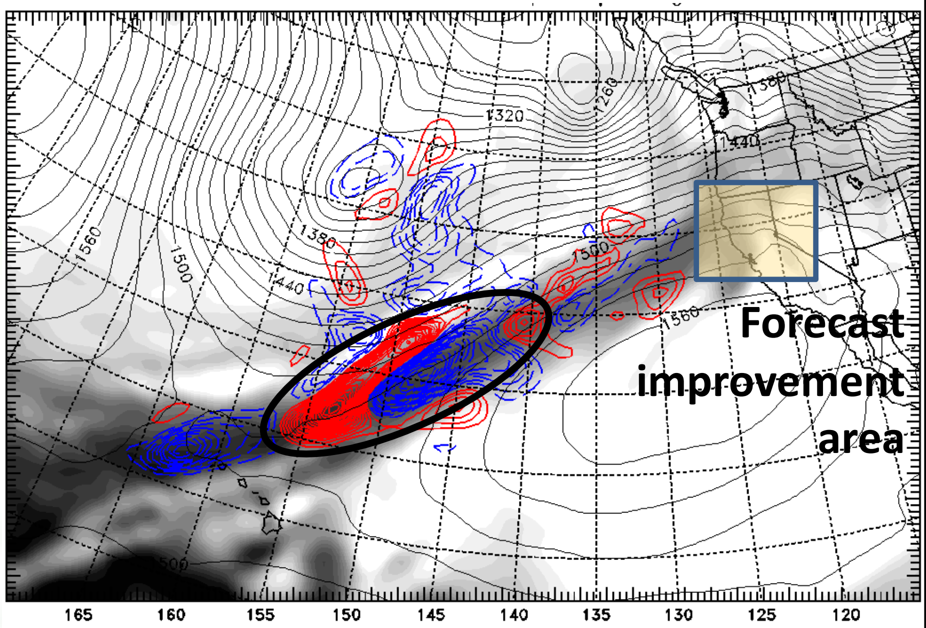
New Adjoint includes moisture – and finds AR is prime target

36-h Sensitivity (Analysis) 00Z 13 February (Final Time 12Z 14 February 2014)

J. Doyle, C. Reynolds, C. Amerault, F.M. Ralph

(International Atmospheric Rivers Conference 2016)

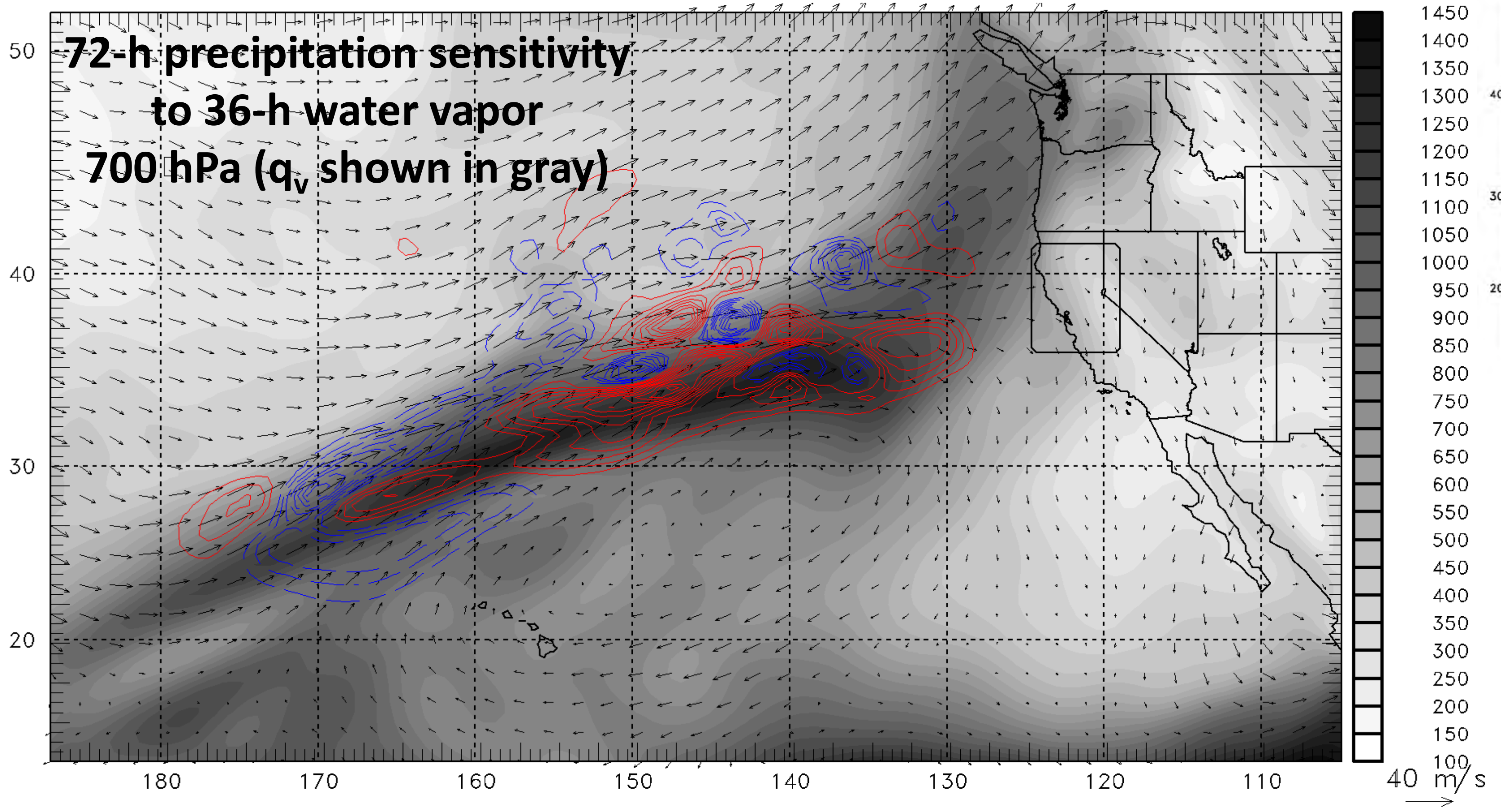
Color contours show the forecast sensitivity to 850 mb water vapor (grey shading) uncertainty at analysis time 00Z 13 Feb 2014 for a 36-h forecast over NorCal valid 12Z 14 Feb



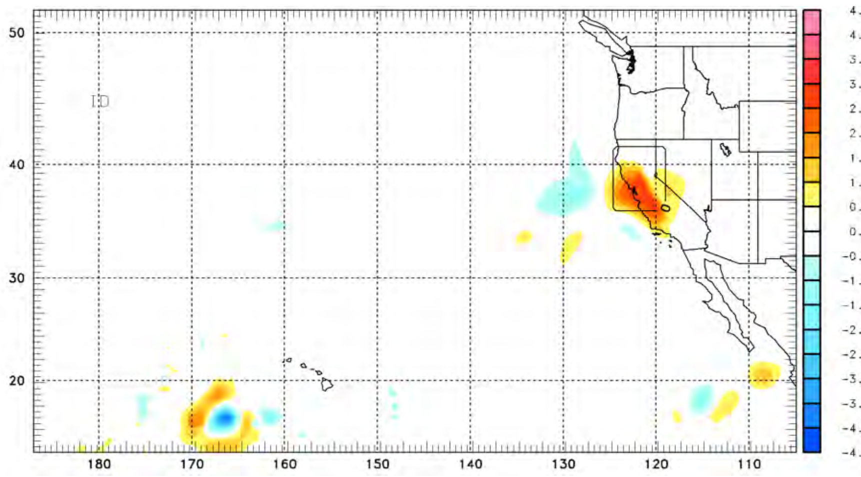
- Moisture sensitivity is strongest along AR axis; located > 2000 km upstream
- **Moisture sensitivity substantially larger than temp. or wind sensitivity.**

AR Recon – 2016 Using Two Air Force C-130s

COAMPS 36-h sensitivity with 36-h lead time
Target time 00Z 28 Jan 2016, Verification time 12Z 29 Jan.

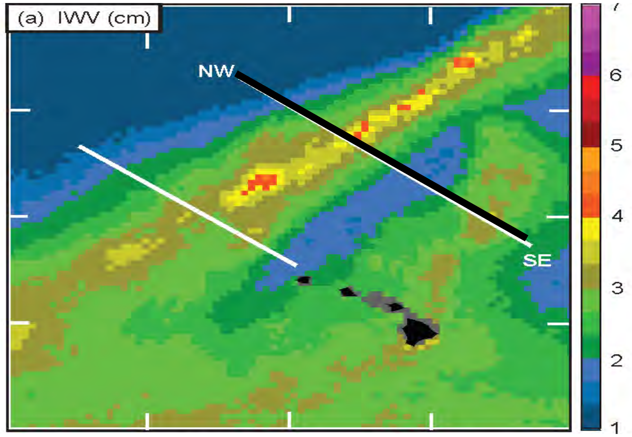


Moist adjoint product from J. Doyle, C. Reynolds of NRL-Monterey



Verification Time Optimal Water Vapor Perturbation valid at 12 Z 29 Jan.

Note large increase in water vapor available for precipitation at final time.

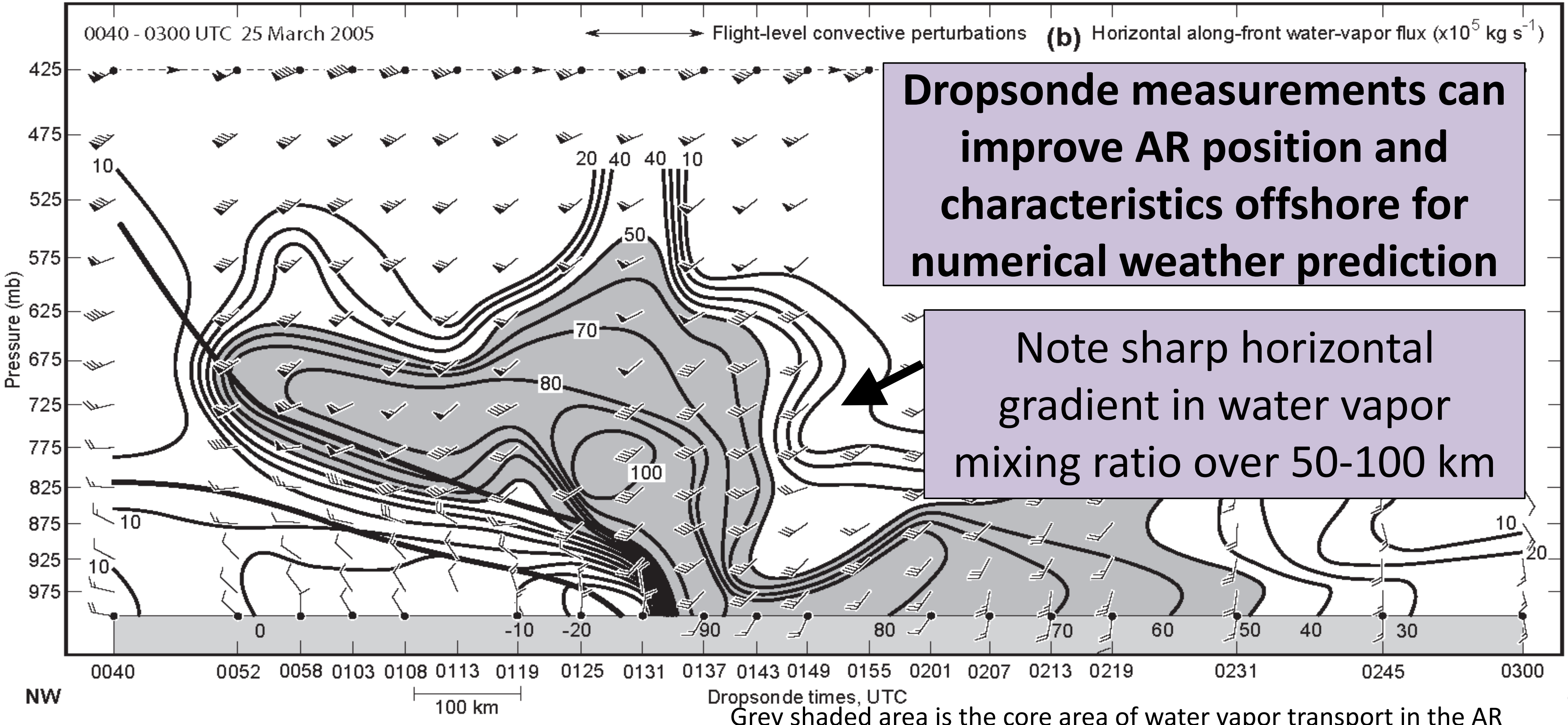


Cross-section of an AR observed using dropsondes

Ralph, F. M., P. J. Neiman, G. N. Kiladis, K. Weickman, and D. W. Reynolds, 2011, *Mon. Wea. Rev.*

The atmospheric river as seen in SSM/I integrated water vapor (IWV). Black line marks the cross-section baseline.

Horizontal along-front water vapor flux (×10^5 kg s^{-1}; shading: >50 ×10^5 kg s^{-1})



Dropsonde measurements can improve AR position and characteristics offshore for numerical weather prediction

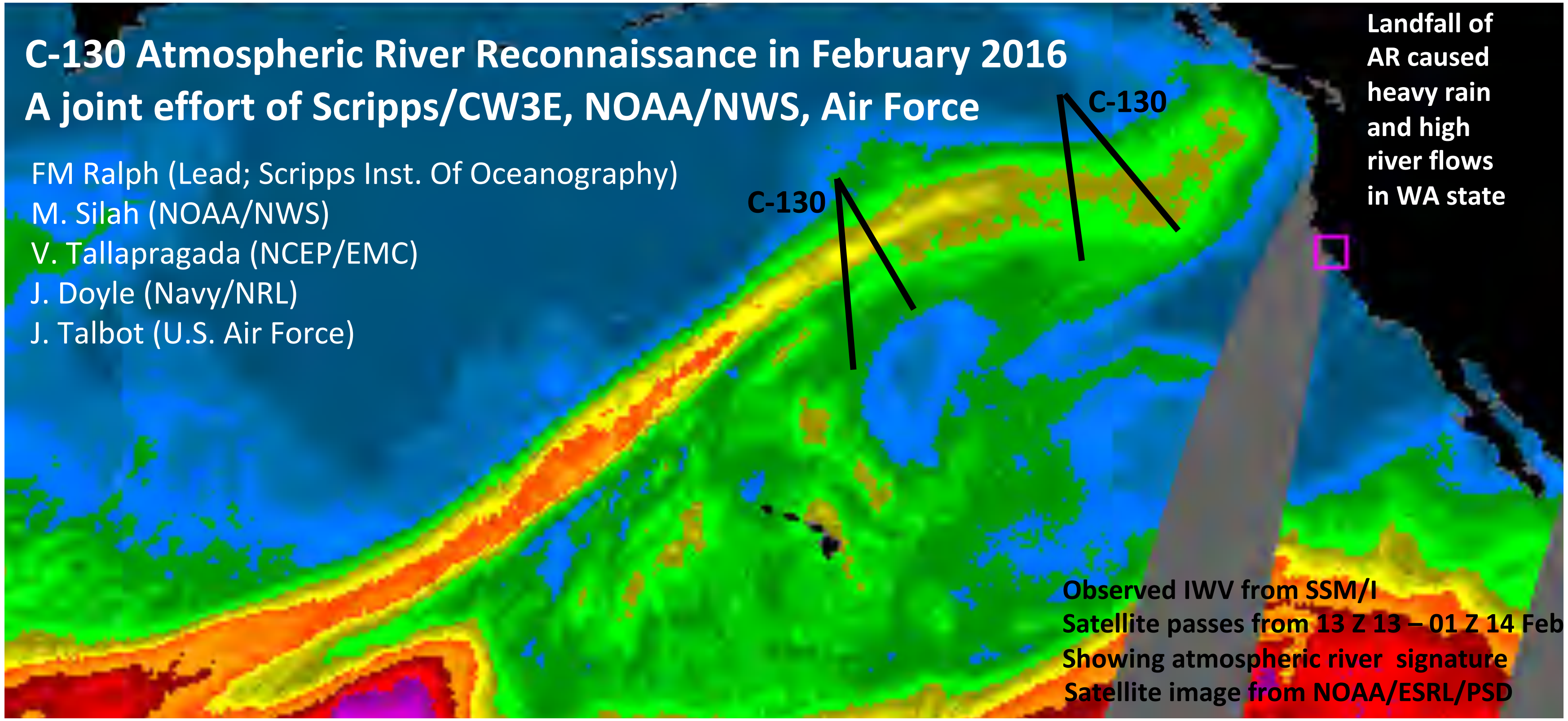
Note sharp horizontal gradient in water vapor mixing ratio over 50-100 km

Grey shaded area is the core area of water vapor transport in the AR

C-130 Atmospheric River Reconnaissance in February 2016

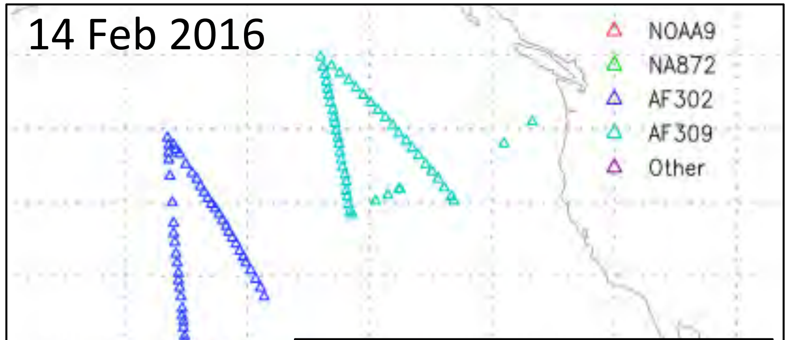
A joint effort of Scripps/CW3E, NOAA/NWS, Air Force

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

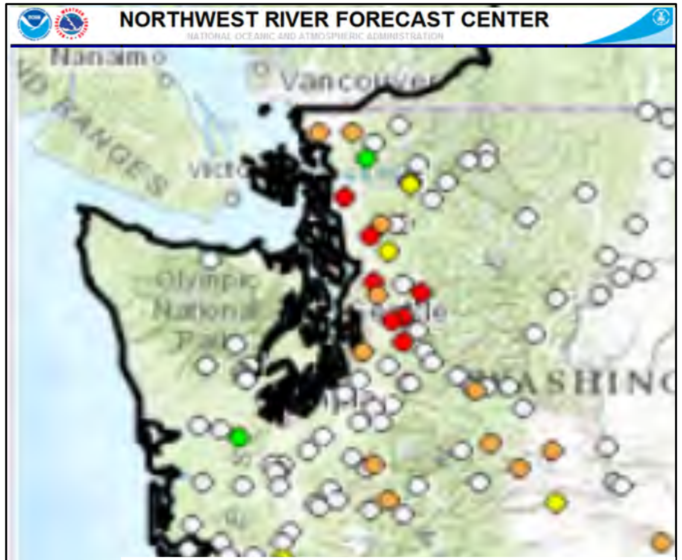
Dropsondes released for the 0000 UTC 14 Feb 2016 GFS data assimilation window



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

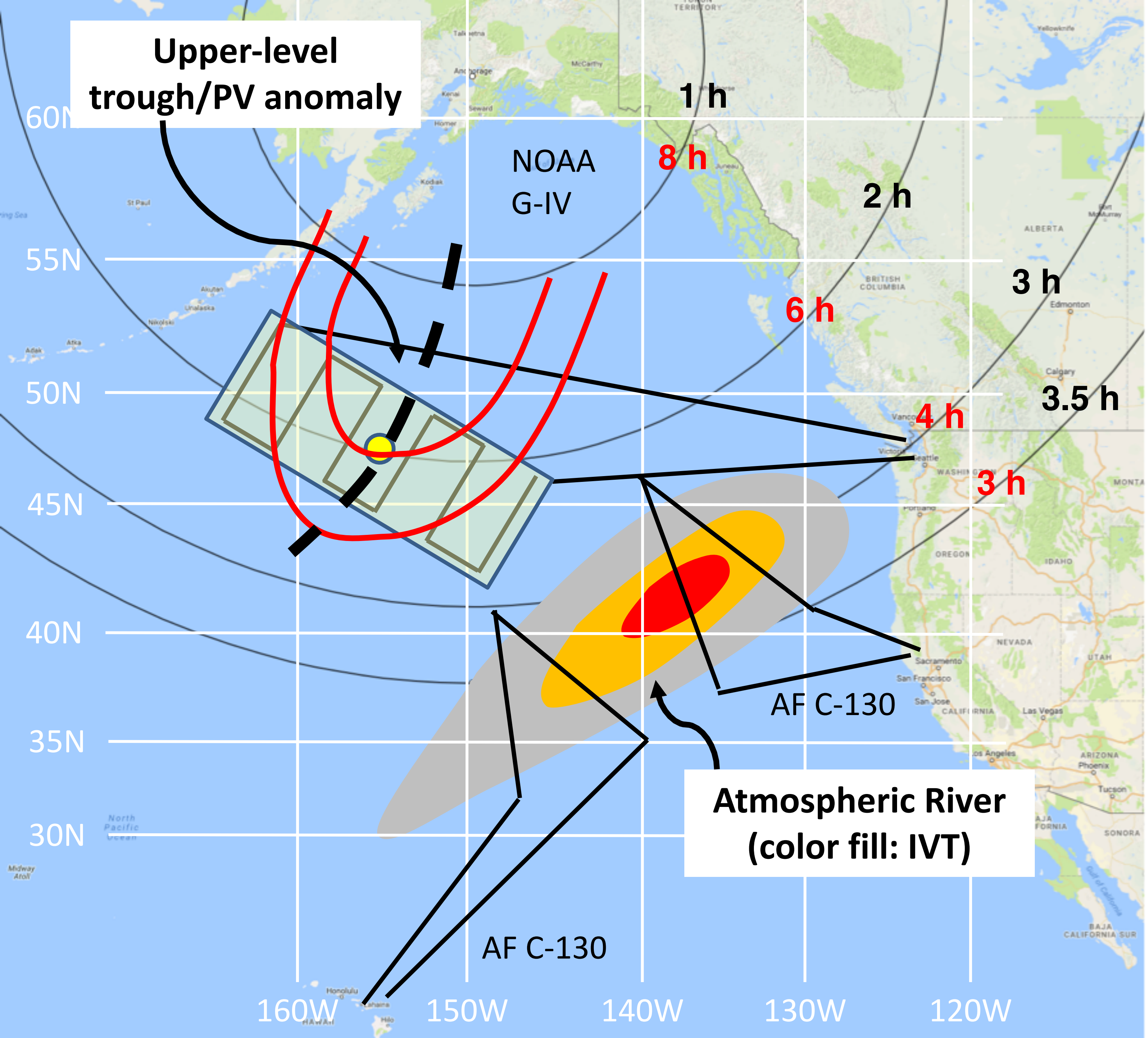


NWRFC flood forecast map as of 1500 UTC 15 Feb showing several rivers predicted to reach flood stage on 15-16 Feb (red dots)

AR Recon Field Campaigns and Modeling

- Year 1 (2016): 3 storms flown with 2 aircraft over 2 weeks
- Year 2 (2018): target 6 storms with two aircraft over 6 weeks
- Year 3 (2019): target 9 storms with three aircraft over 10 weeks
- Years 1-3: Data denial analyses of 18 storms at NCEP, NRL, CW3E

2018 Atmospheric River Reconnaissance Flight Strategies



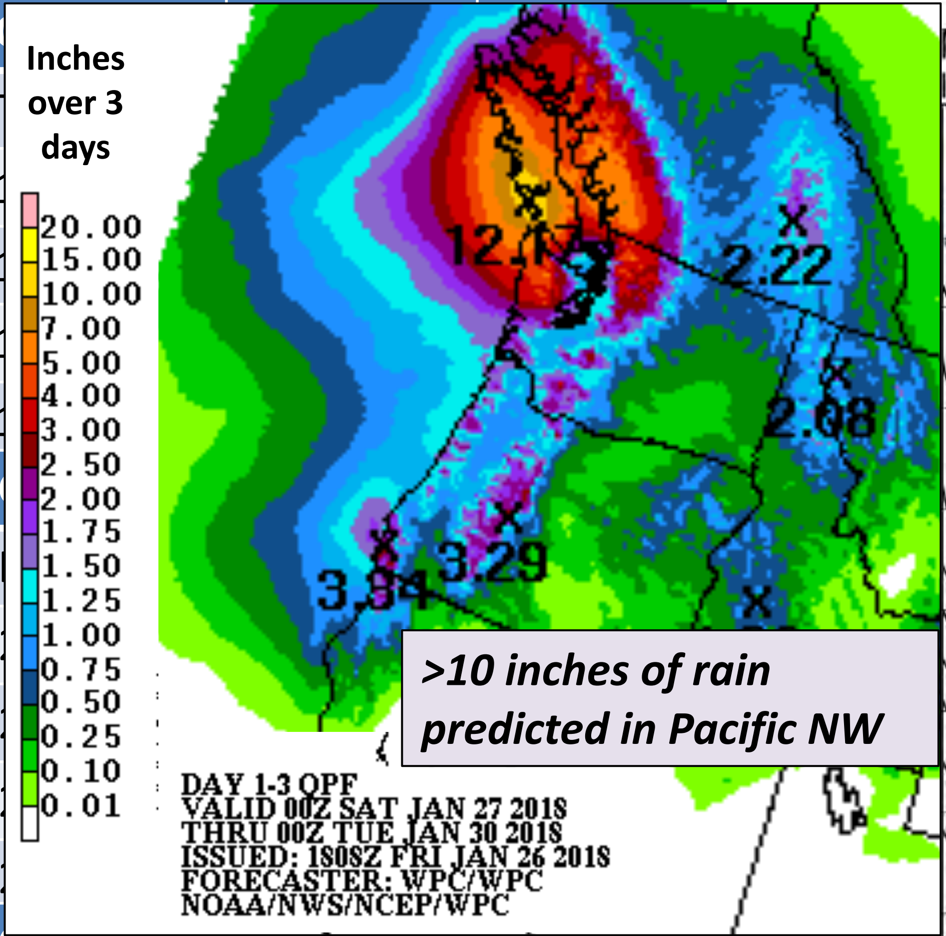
Center time: 0000 UTC

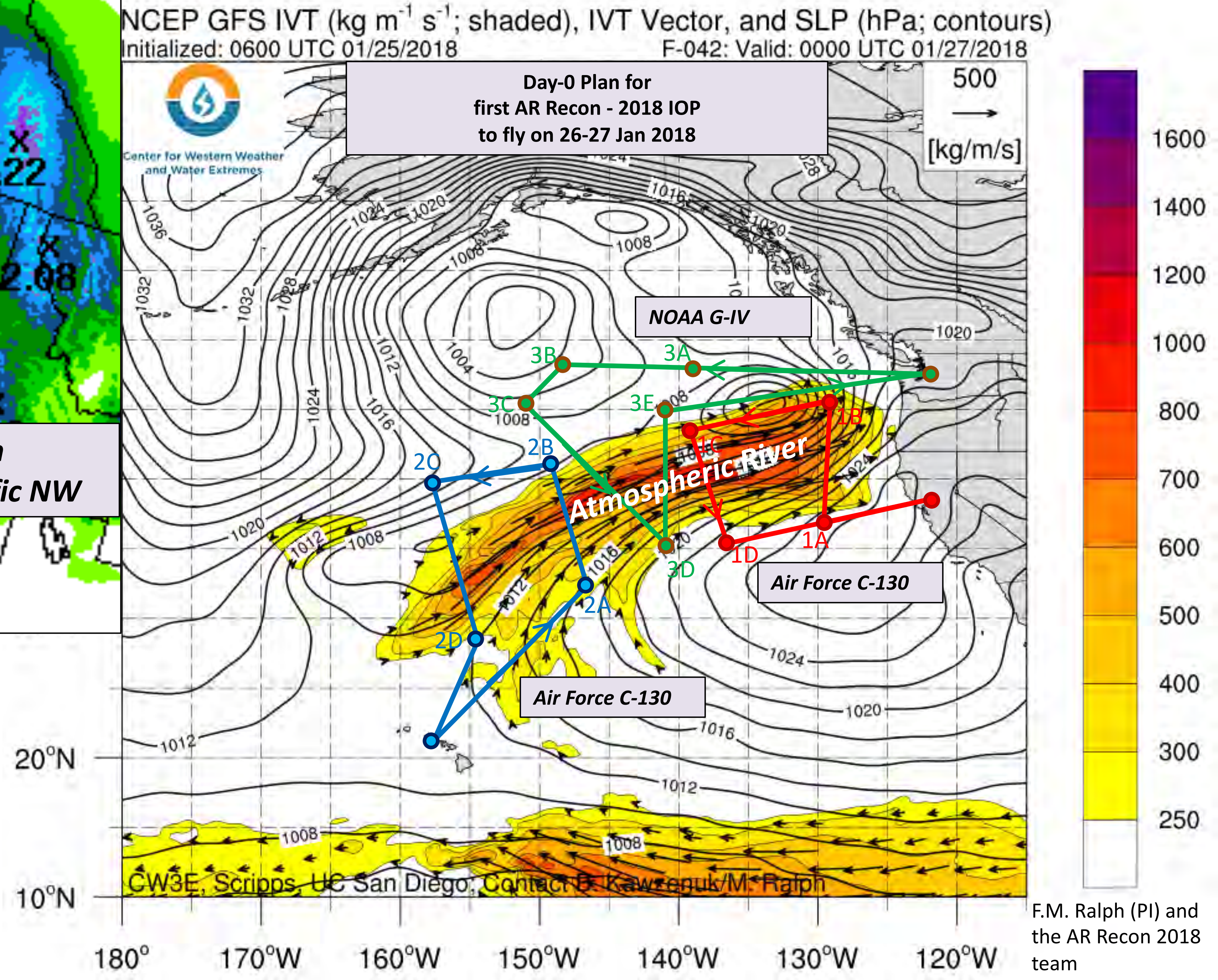
Dropsonde deployment window:

2100 – 0300 UTC

Each aircraft has a range of about 3500 nm

F.M. Ralph (AR Recon PI) and AR Recon Team

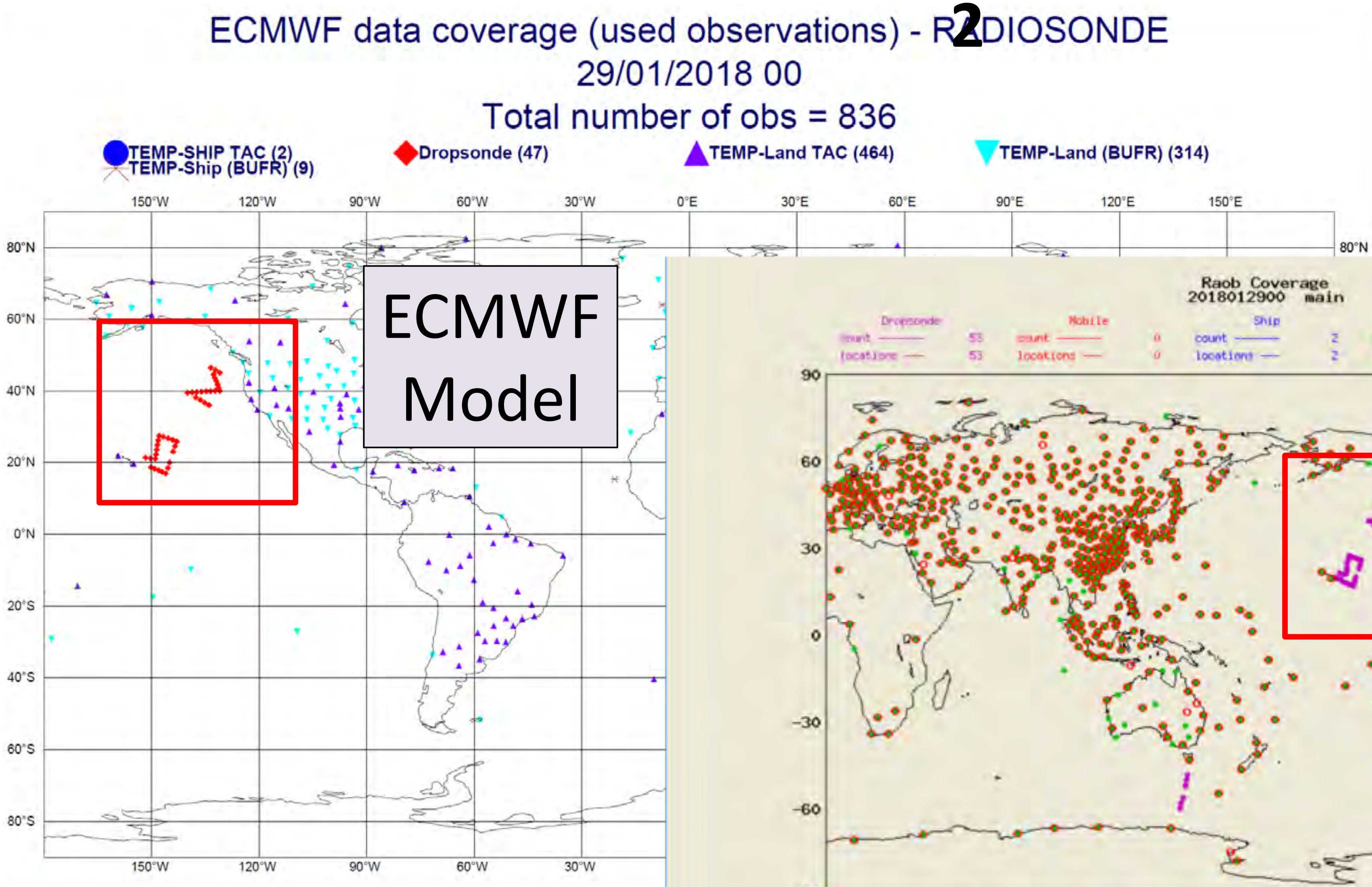


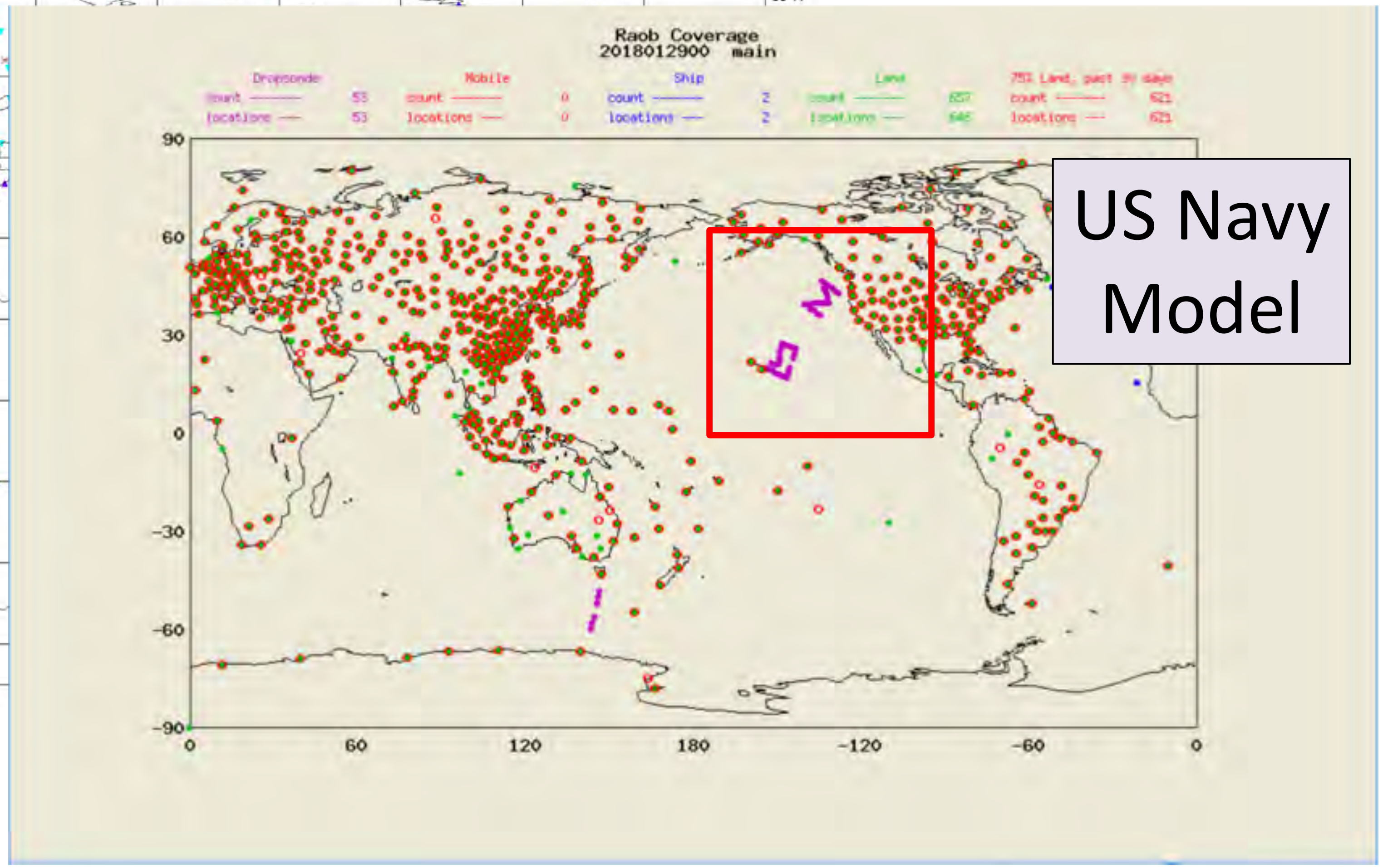


G-IV	Lat	Lon
SEA	47.91	-122.28
3A	50	-128
3B	49	-148
3C	46	-152
3D	36	-141
3E	45	-141

F.M. Ralph (PI) and the AR Recon 2018 team

Dropsondes Assimilated – AR Recon-2018, IOP-2





"Atomspheric River" drink created for season at Harrah's and Harveys

Submitted by paula on Wed, 02/22/2017 - 1:55pm

SouthTahoeNOW.com
Your One Stop for Lake Tahoe News & Information

NEWSROOM EVENTS BUSINESSES COMMUNITY SCHOOLS

Rivers have flooded, the lake is filling and snow is covering the slopes because of the several atmospheric rivers to hit Lake Tahoe this winter. To celebrate the epic season, the Beverage Department team at Harrah's and Harveys Lake Tahoe concocted a cocktail to honor and celebrate the winter.

The "Atmospheric River" drink "blends the frosty peaks of the Sierra Nevada with the stunning shades of blue found only at Lake Tahoe," said John Packer of Harrah's and Harveys Lake Tahoe.

Named for the climatic condition that has held sway in northern California and Nevada for the past few months, the "Atmospheric River" combines fruit juices, vodka, cognac and other ingredients to produce one of the most refreshing adult beverages of the season.

The festive cocktail is available exclusively at the two California Bars, located on the main floor of both casinos in Stateline, Nevada.

Their master mixologists combine Grey Goose Vodka, Hpnotiq Liqueur, Cointreau, Curacao, Sweet and Sour with Seven-Up, blend it with ice and serve it up in a chilled, sugar-rimmed martini glass.

It's a "drought-busting libation."

Tweets Tweets & replies Media

South Tahoe Now @SouthTahoeNow · 10m
Atmospheric River cocktail created @HarrahsTahoe and @harveystahoe to celebrate extra wet & snowy season #LakeTahoe southtahoenow.com/story/02/22/20...

1 oz Grey Goose Vodka + 1 oz Hpnotiq Liquer + 1 oz Cointreau, top off with Sweet and Sour with 7-Up; blend with ice and serve in sugar-rimmed, chilled martini glass.

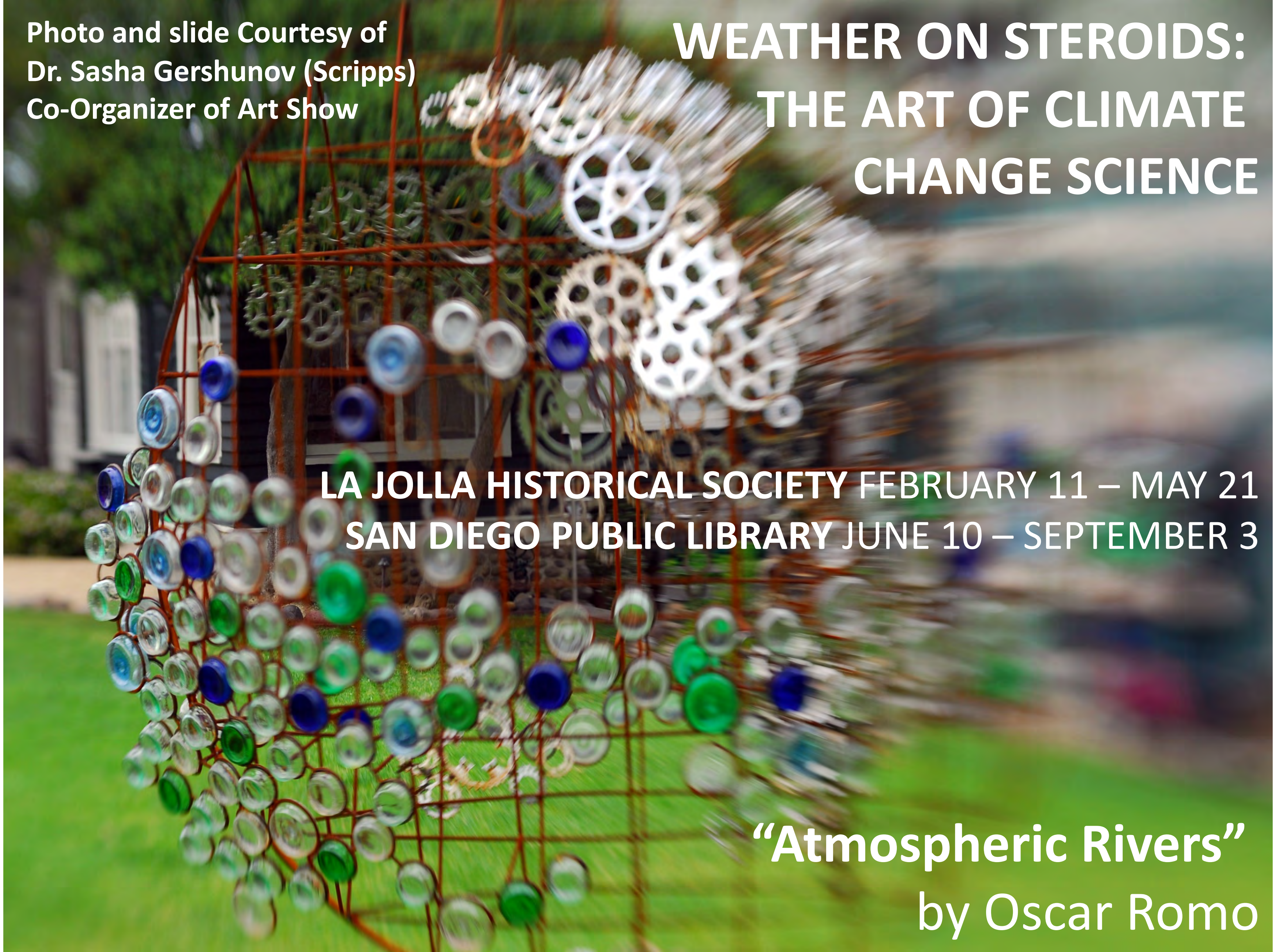


Photo and slide Courtesy of
Dr. Sasha Gershunov (Scripps)
Co-Organizer of Art Show
WEATHER ON STEROIDS:
THE ART OF CLIMATE
CHANGE SCIENCE
LA JOLLA HISTORICAL SOCIETY FEBRUARY 11 – MAY 21
SAN DIEGO PUBLIC LIBRARY JUNE 10 – SEPTEMBER 3
"Atmospheric Rivers"
by Oscar Romo


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

Updates on the 2018 CW3E Field Campaign Supporting FIRO

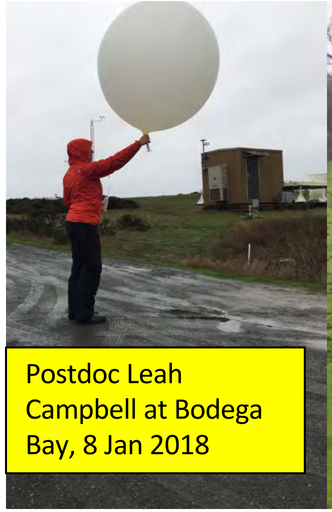
Anna Wilson

Marty Ralph, PI

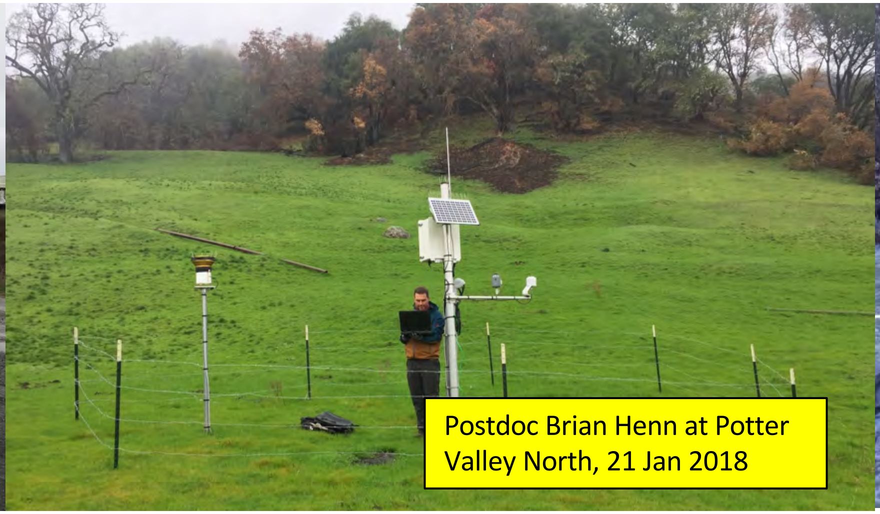
Brian Henn (CW3E), Douglas Alden (CW3E), Steve Turnbull (ERDC)

Maryam Lamjiri (CW3E), Leah Campbell (CW3E)

Primary sponsors: US Army Corps of Engineers, California Dept. of Water Resources, Sonoma County Water Agency



Postdoc Leah Campbell at Bodega Bay, 8 Jan 2018



Postdoc Brian Henn at Potter Valley North, 21 Jan 2018

Graduate student Will Chapman and postdoc Brian Henn at Perry Creek, 22 Jan 2018

31 January 2018 – FIRO Steering Committee Meeting

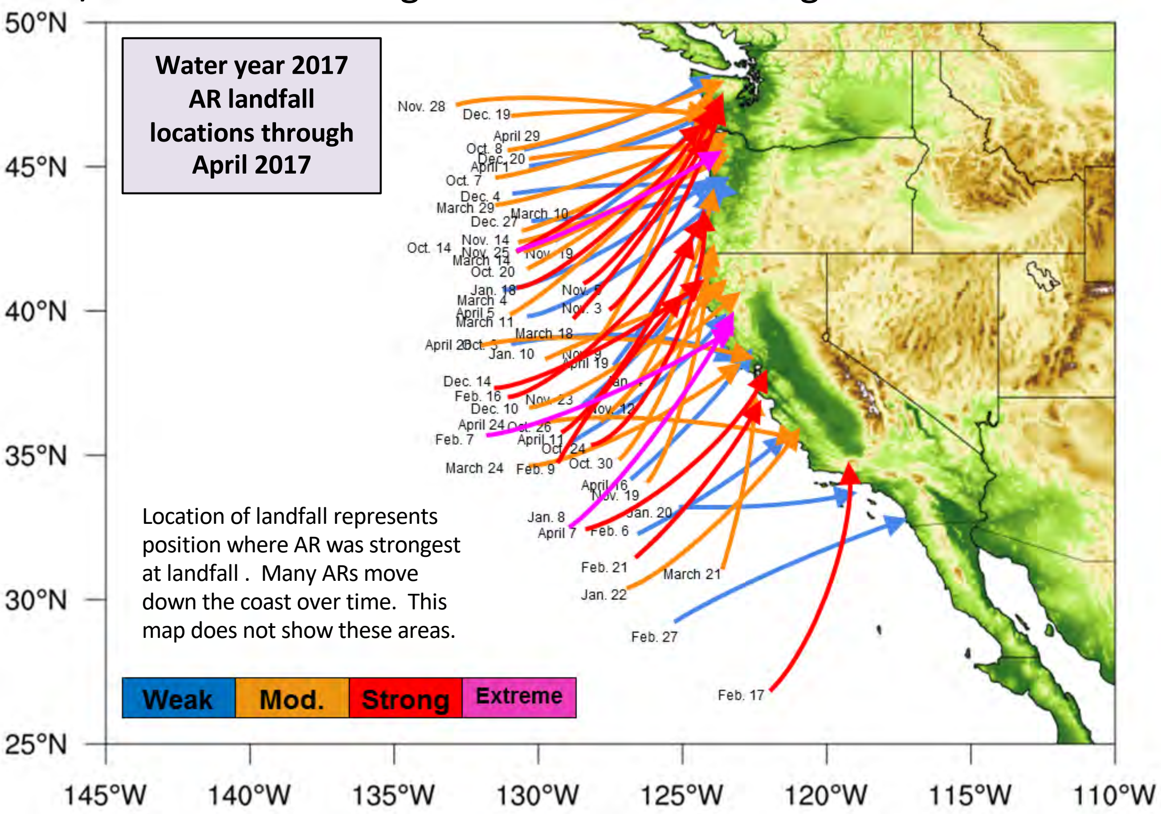
Distribution of Landfalling Atmospheric Rivers on the U.S. West Coast
(From 1 Oct 2016 to 1 May 2017)

AR Strength	AR Count*
Weak	15
Moderate	23
Strong	13
Extreme	3

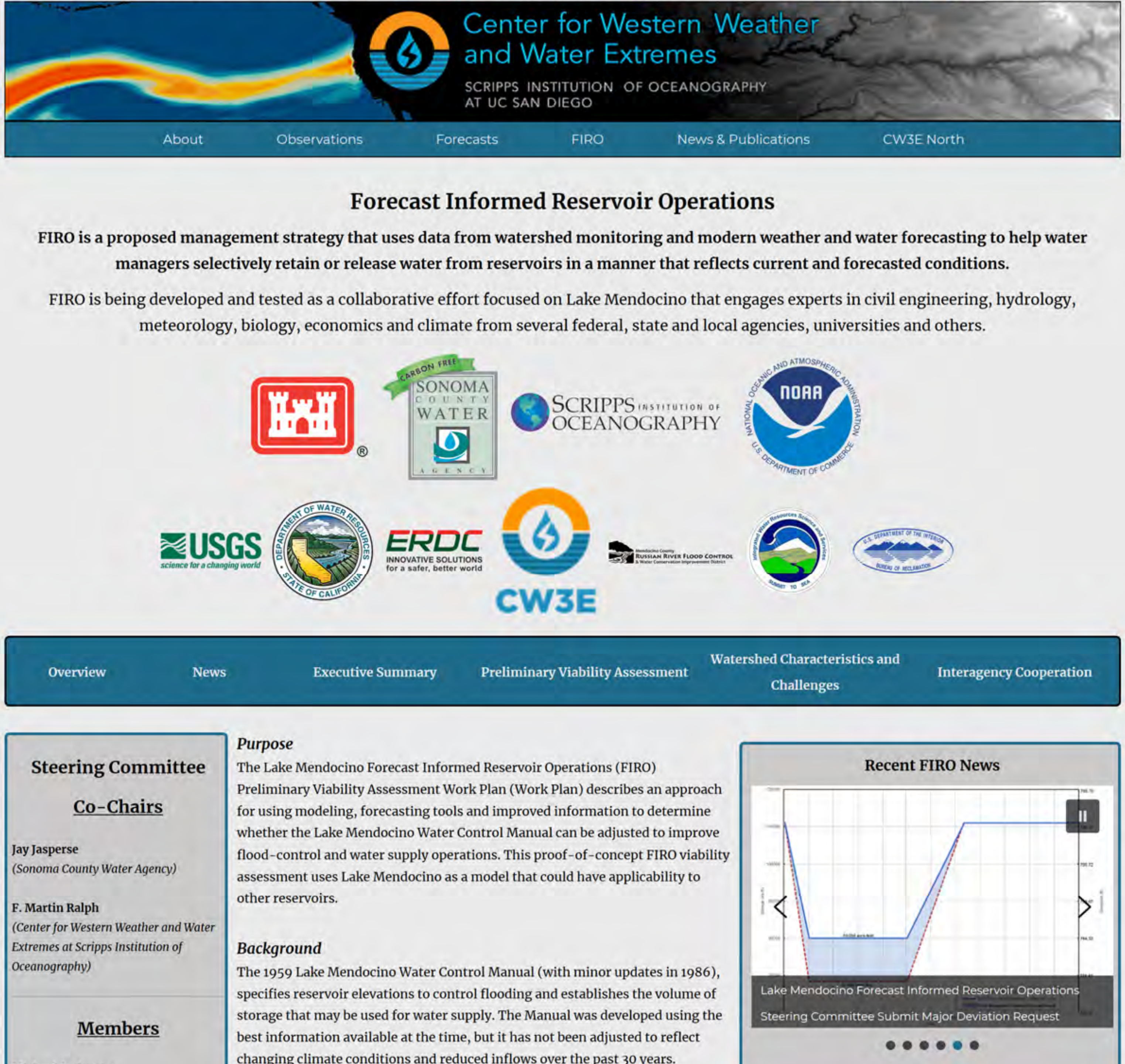
Ralph/CW3E AR Strength Scale
- Weak: IVT=250–500 kg m^{-1} s^{-1}
- Moderate: IVT=500–750 kg m^{-1} s^{-1}
- Strong: IVT=750–1000 kg m^{-1} s^{-1}
- Extreme: IVT>1000 kg m^{-1} s^{-1}

*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)

- 54 Atmospheric Rivers have made landfall on the West Coast thus far during the 2017 water year (1 Oct. – 12 April 2017)
- This is much greater than normal
- 1/3 of the landfalling ARs have been "strong" or "extreme"



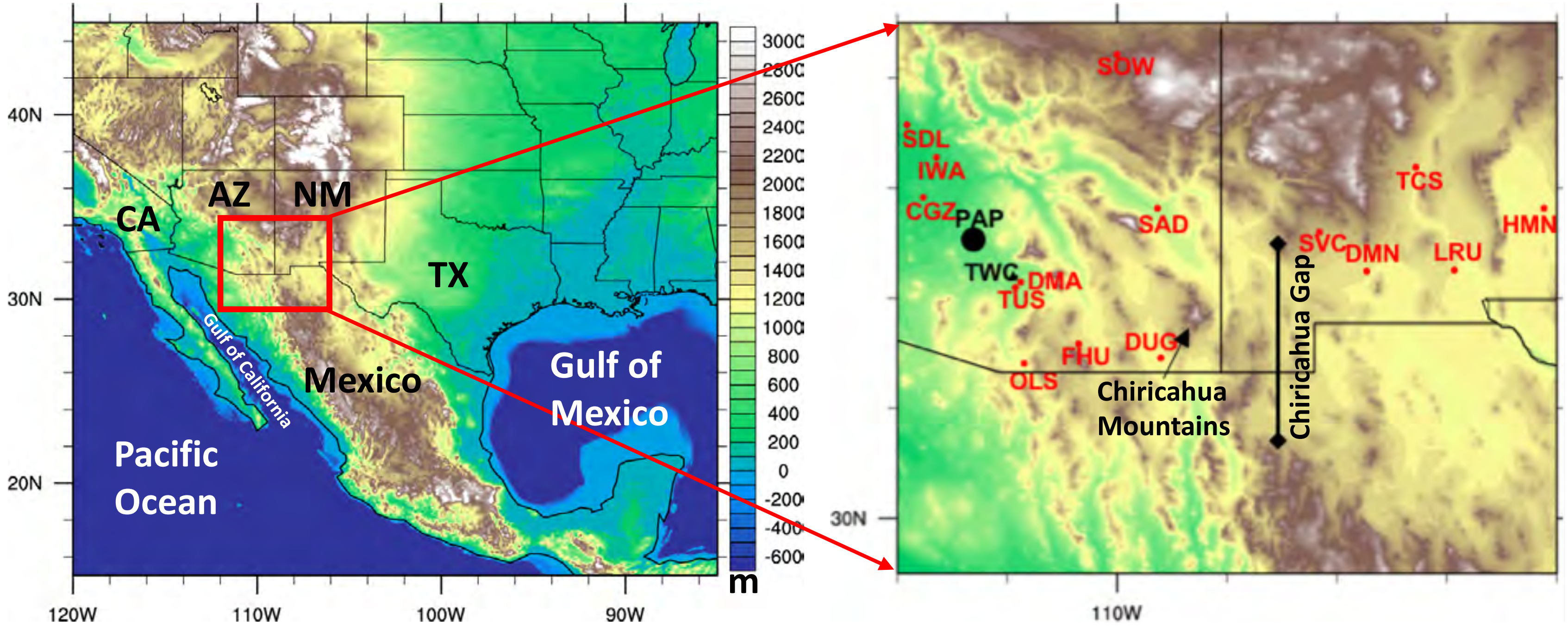

Thank you!



For more information

cw3e.ucsd.edu/FIRO/

A Key Terrain Gap Exists, Apparently Unnamed



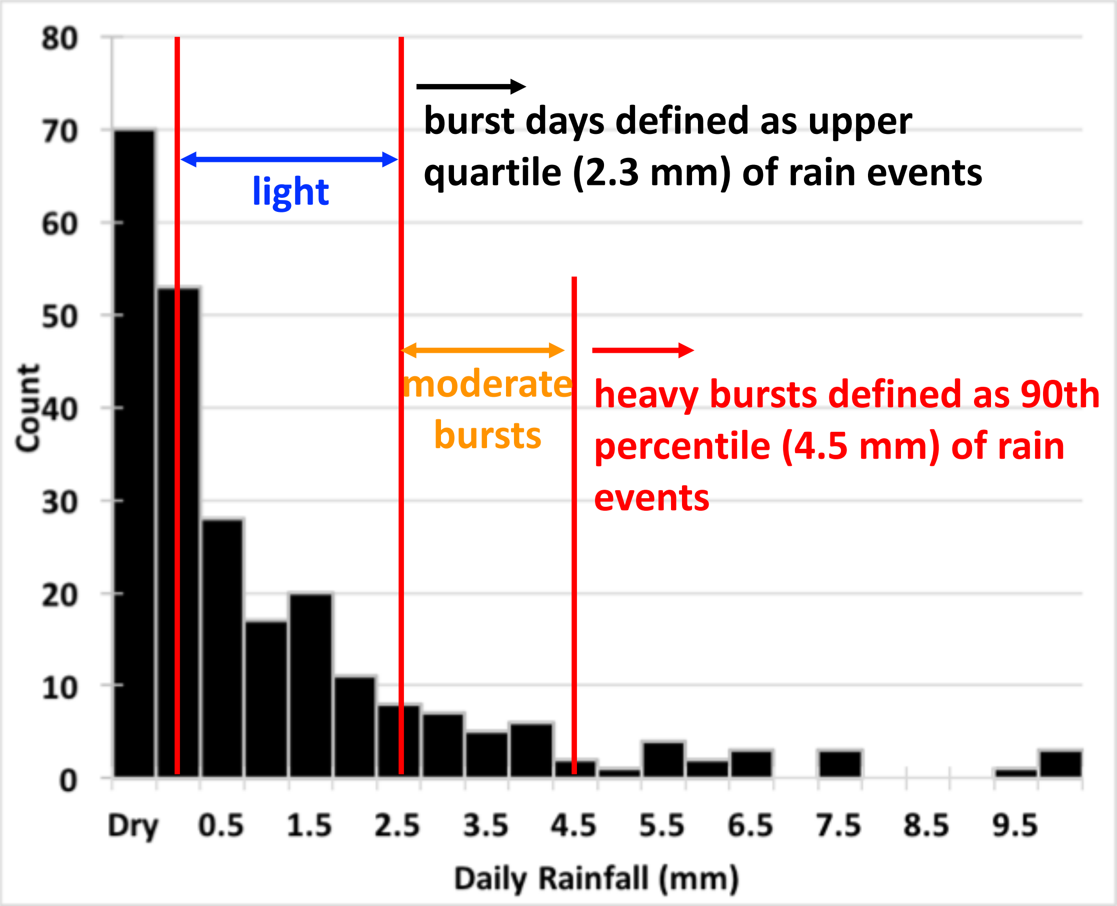
NOAA NCEI ETOPO1 1 Arc-Minute Terrain Height and Bathymetry (m)

The name **"Chiricahua Gap"** is proposed here, reflecting both the name of a key mountain range near the gap, and the region's Native American history

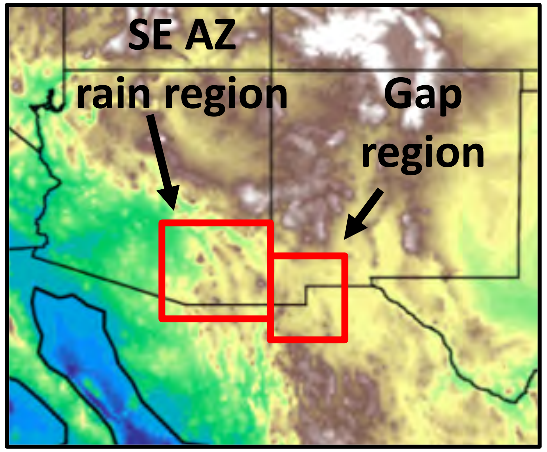
Ralph and Galarneau, *JHM, 2017*

Climatology of IVT in the Chiricahua Gap and SE Arizona Monsoon "Bursts" in 2009-2010

Distribution of Daily Rainfall (mm) in 2009 and 2010



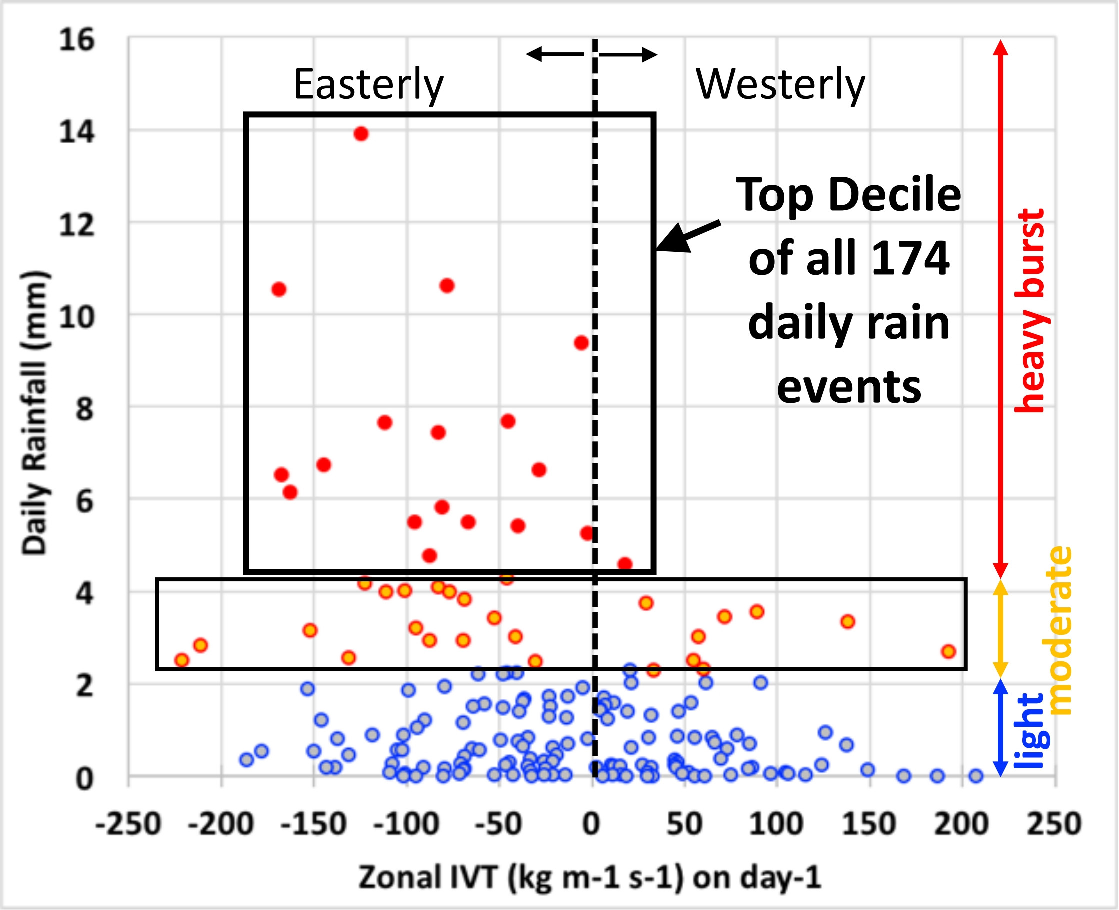
- "Day" defined here as 24-h period ending at 1200 UTC
- Define monsoon season as 16 Jun–15



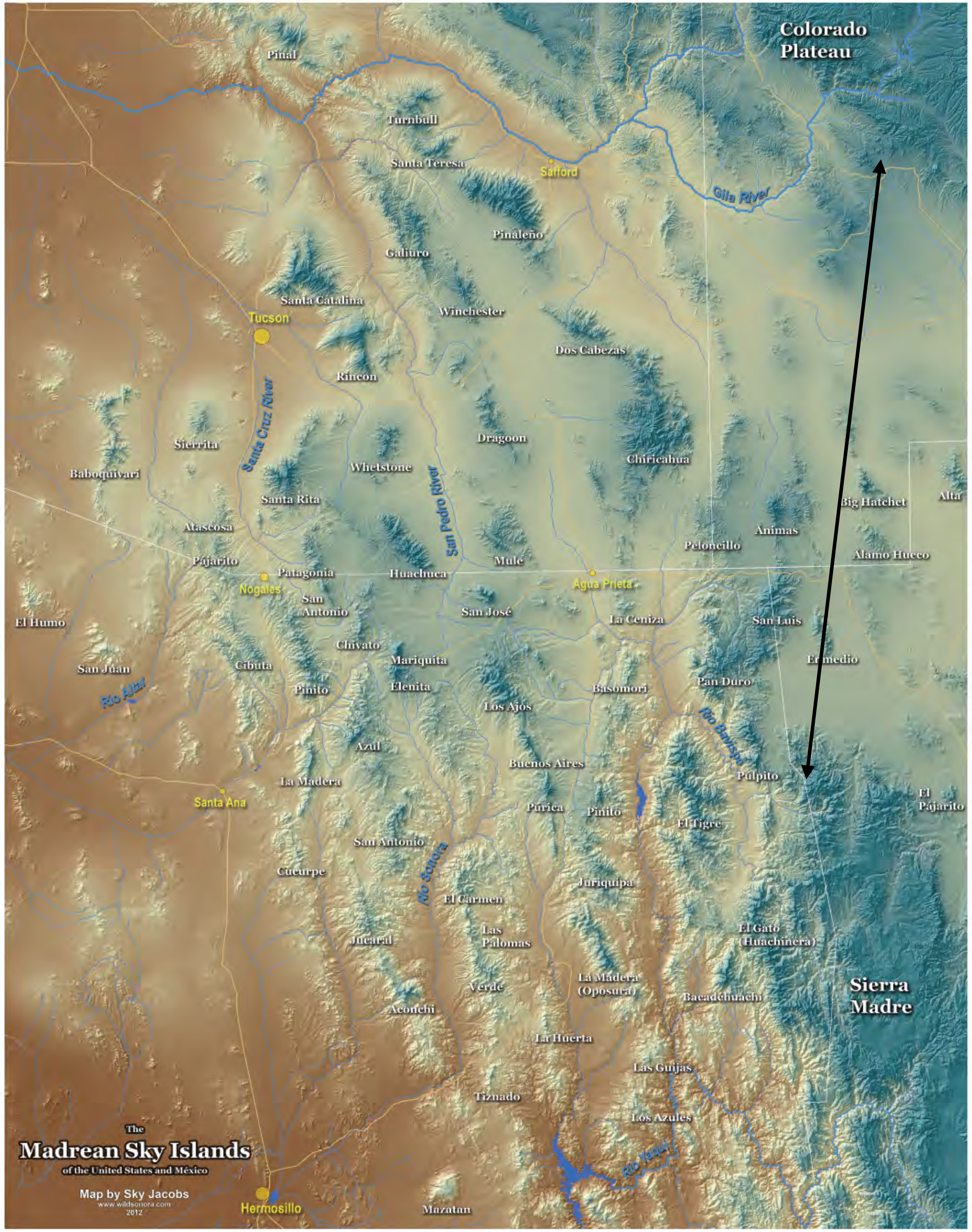
SE Arizona defined as 31.5–33.5N; 111–109W
Gap defined as 30.5–32.5N; 109–107W

Climatology of IVT in the Chiricahua Gap and SE Arizona Monsoon "Bursts" in 2009-2010

Daily Rainfall (mm) versus IVT ($kg\ m^{-1}\ s^{-1}$) on Day–1



- 55% (71/130) of light rain events have easterly IVT
- 65% (17/26) of moderate bursts have easterly IVT
- **94% (17/18) of heavy bursts have easterly IVT**



ID	Mountain Range	Elev. (ft)	Elev. (m)	Notes
1	Aconchi	7198	2194	
2	Álamo Hueco	6159	1877	
3	Alta	7546	2300	The eastern edge of the Sky Island region is unclear
4	Ánimas	8519	2597	
5	Atascosa	6422	1957	Larger complex with Pájarito
6	Azul	8038	2450	
7	Baboquivari	7734	2357	
8	Bacadéhuachi	7874	2400	Somewhat connected to the Sierra Madre
9	Big Hatchet	8356	2547	
10	Basomori	6263	1909	
11	Buenos Aires	7546	2300	A chain of islands is formed by the Los Ajos, Buenos Aires, and Púrica
12	Chiricahua	9759	2974	
13	Chivato	7185	2190	
14	Cíbuta	5774	1760	Part of a larger complex including Guacomea, Las Avispas and Esmeralda
15	Cucurpe	5741	1750	Has oak woodland, but not extensive
16	Dos Cabezas	8354	2546	
17	Dragoon	7519	2292	
18	El Carmen	6398	1950	
19	El Gato (Huachinera)	8629	2630	Connected to the Sierra Madre (Aprrox. same peak height as Los Ajos)
20	El Humo	5413	1650	Surrounded by low elevation Sonoran Desert
21	El Pájarito	6955	2120	East side of the Sierra Madre
22	El Tigre	7743	2360	Pass between Sierra Madre and El Tigre has a few scattered oaks
23	Elenita	8169	2490	Connected with Mariquita
24	Enmedio	7087	2160	
25	Galiuro	7663	2336	
26	Huachuca	9466	2885	
27	Jacural	6234	1900	Peak elevation approximate
28	Juriquipa	7152	2180	
29	La Ceniza	5971	1820	
30	La Huerta	5840	1780	
31	La Madera	6726	2050	AKA Sierra Magdalena
32	La Madera (Opusera)	7743	2360	Sometimes known as the Sierra Oposura
33	Las Guijas	5643	1720	
34	Las Palomas	5840	1780	Chain of sierras including El Carmen, Verde, and Las Palomas
35	Los Ajos	8629	2630	Highest point in Sonora (almost a tie with the Sierra Huachinera)
36	Los Azules	5413	1650	
37	Mariquita	8202	2500	Connected to Elenita
38	Mazatán	5085	1550	Southernmost Sky Island?
39	Mule	6535	1992	
40	Pájarito	5236	1560	Part of greater complex with the Atascosa
41	Pan Duro	7546	2300	San Luis complex, naming complicated, split to 2 major formations here
42	Patagonia	7221	2201	Somewhat connected to Sierra San Antonio
43	Peloncillo	6625	2019	One name for a very long string of hills and mountains
44	Pinal	7848	2392	Certainly a Sky Island, but "Madrean" status questionable
45	Pinaleño	10720	3267	Highest point in the Sky Islands
46	Pinito	7480	2280	Southeast of Nogales
47	Pinito	7431	2265	East of Púrica
48	Púlpito	8136	2480	Part of Sierra Madre? (AKA Huachita Hueca)
49	Púrica	8071	2460	A chain of islands is formed by the Los Ajos, Buenos Aires, and Púrica
50	Rincon	8482	2585	
51	San Antonio	7251	2210	Somewhat connected to Patagonia
52	San Antonio (South)	7316	2230	NW of Sierra El Carmen
53	San José	8333	2540	
54	San Juan	5348	1630	Western Sky Island also in the Sonora Desert proper
55	San Luis	8268	2520	Complex, naming complicated, split to 2 major formations here
56	Santa Catalina	9157	2791	
57	Santa Rita	9453	2881	
58	Santa Teresa	7481	2280	Connected to Turnbull?
59	Sierrita	6206	1892	
60	Tiznado	5774	1760	Also known by other names
61	Turnbull	8282	2524	Connection to Santa Teresas
62	Verde	5840	1780	Difficult to determine best name to use for this range
63	Whetstone	7711	2350	
64	Winchester	7640	2329	

Disclaimers

* Defining what counts as a Sky Island in the southern Sky Islands is difficult without further data / field work.

* Names of Sky Islands are variable - choosing from possible or multiple names is sometimes problematic.

* Dividing a complex of ranges for naming purposes is often subjective.

* Elevation information is sometimes difficult to find and even data layers are not always correct. Elevations are approximate and were acquired and distilled from a variety of sources, so accuracy is not guaranteed.

Other Info

List compiled by Sky Jacobs at Wild Sonora (www.wildsonora.com). For further information or to help improve this map or list contact Sky at skyjacobs@gmail.com. Please help protect and restore the Sky Island region. Research it, learn about it, and share your knowledge.