Recent advances in observations, models, tracking, and prediction of atmospheric rivers

F. Martin Ralph
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International Atmospheric Rivers Conference
25-28 June 2018
La Jolla, CA

California Central valley in flood on 21 January 2017 near Sacramento; Photo courtesy John Neilson-Gammon

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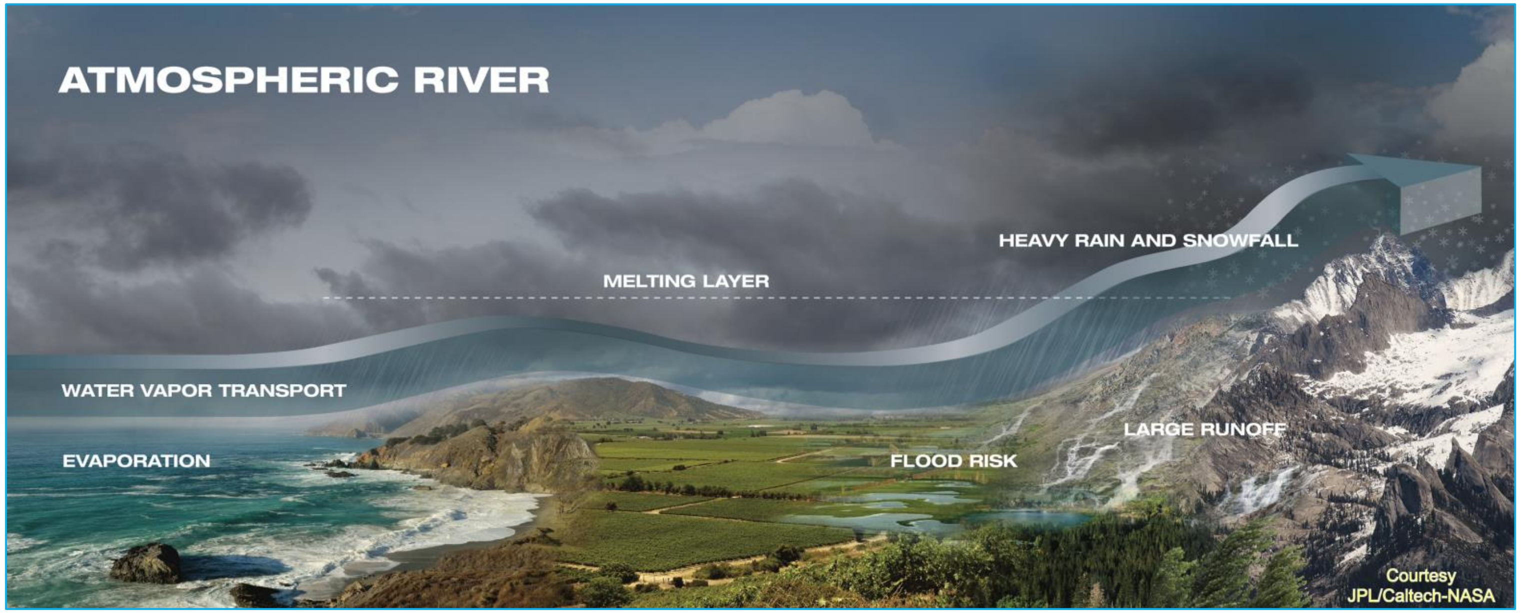
UNIVERSITY OF CALIFORNIA SAN DIEGO LET THERE BE LIGHT

Glossary of Meteorology

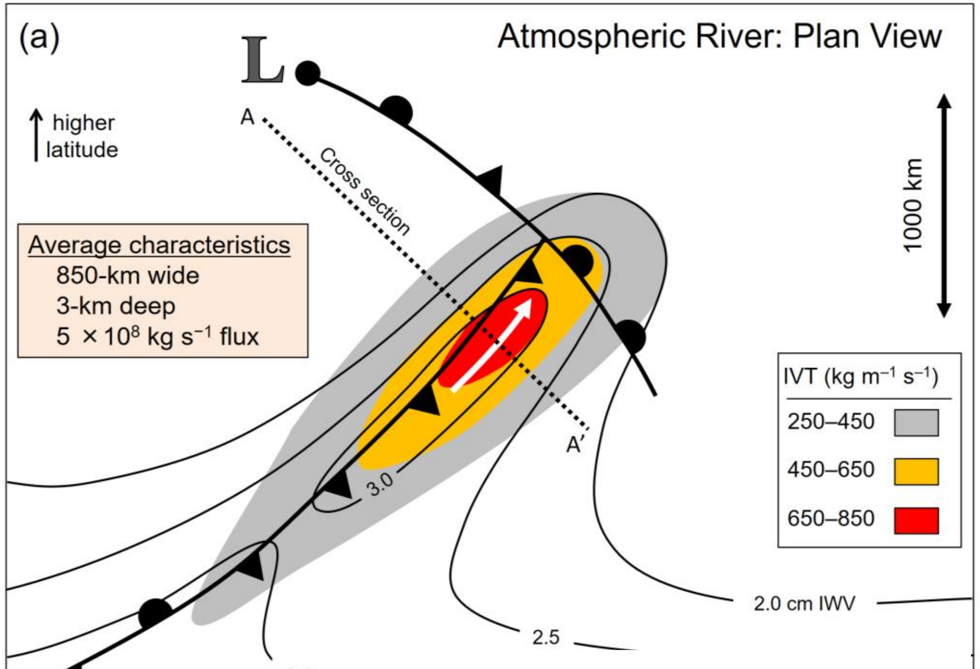
AR definition added May 2017

Definition development described in BAMS (Ralph et al. 2018)

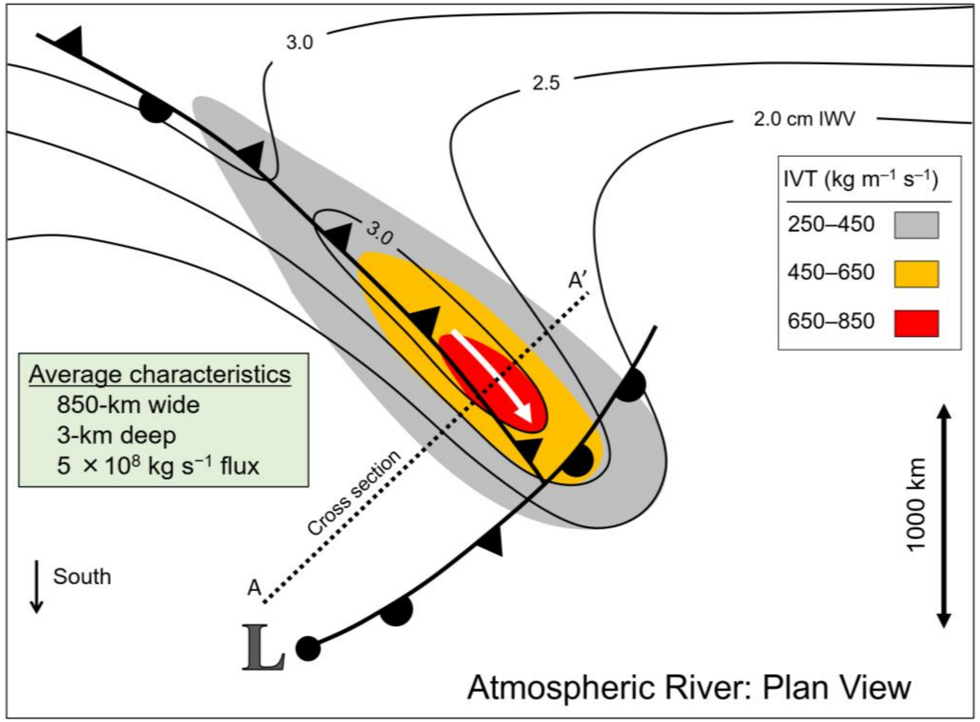


ATMOSPHERIC RIVER

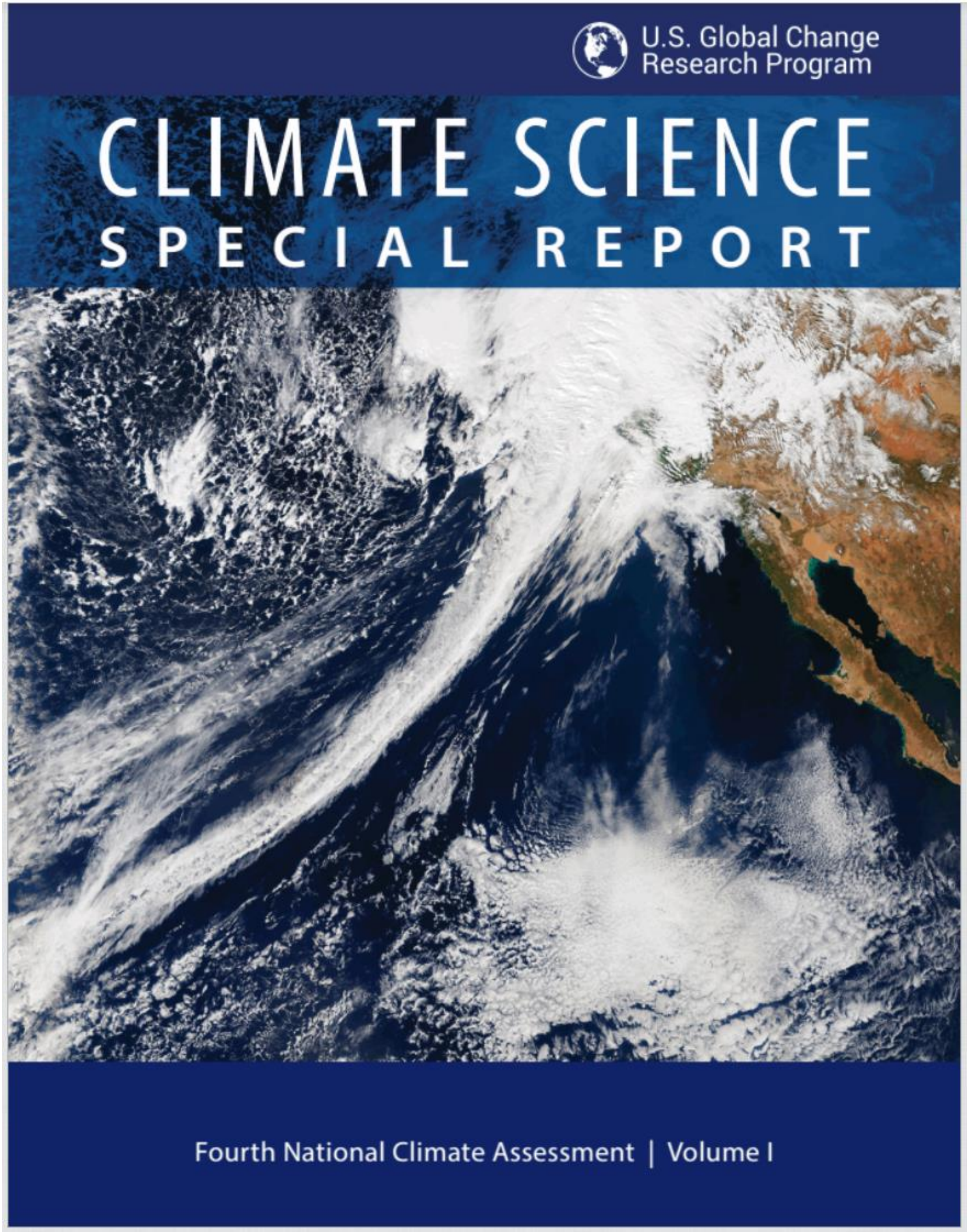
A long, narrow and transient corridor of strong horizontal water vapor transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapor in atmospheric rivers is supplied by tropical and/or extratropical moisture sources. Atmospheric rivers frequently lead to heavy precipitation where they are forced upward, e.g., by mountains or by ascent in the warm-conveyor-belt. Horizontal water vapor transport in the mid-latitudes occurs primarily in atmospheric rivers and is focused in the lower troposphere.



Figures from Ralph et al. 2017 (JHM)



Southern Hemisphere Perspective



Atmospheric Rivers Highlighted in the U.S. Fourth National Climate Assessment, released on 3 November 2017

9 Extreme Storms

KEY FINDINGS

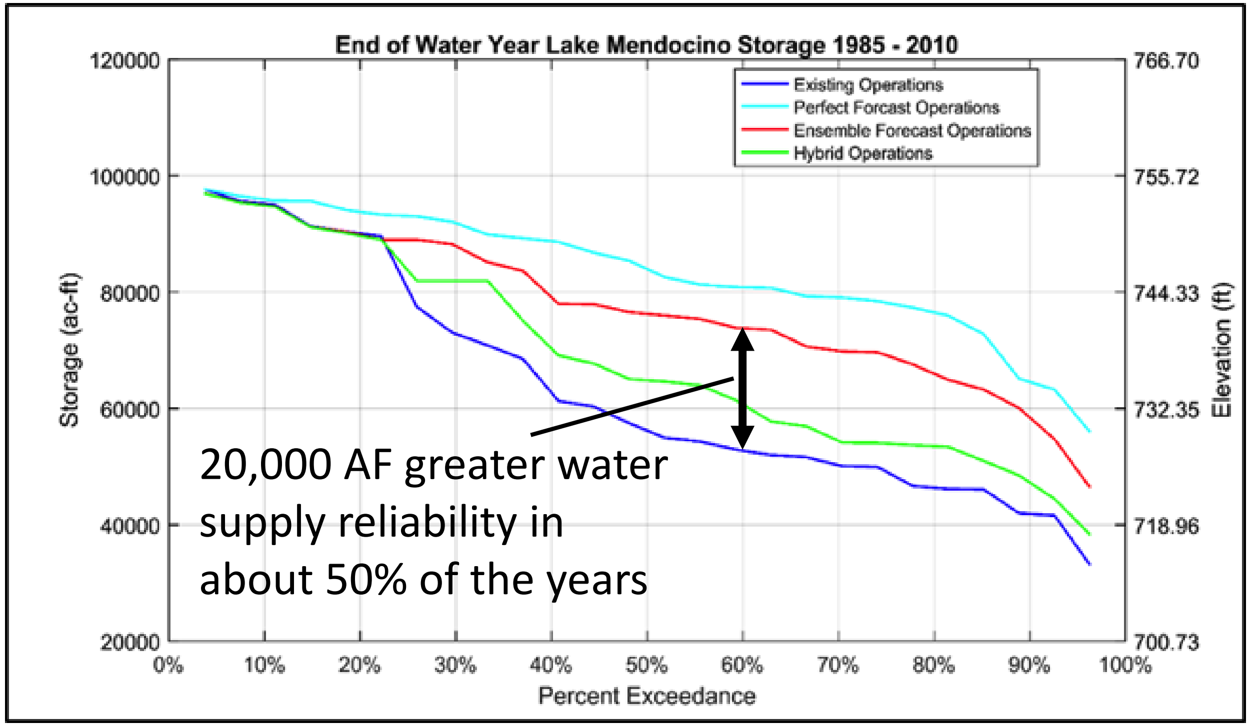
5. The frequency and severity of landfalling "atmospheric rivers" on the U.S. West Coast (narrow streams of moisture that account for 30%–40% of the typical snowpack and annual precipitation in the region and are associated with severe flooding events) will increase as a result of increasing evaporation and resulting higher atmospheric water vapor that occurs with increasing temperature. (*Medium confidence*)

1. Tropical Cyclones (Hurricanes and Typhoons)
2. Severe Convective Storms (Thunderstorms)
3. Winter storms
4. **Atmospheric Rivers (NEW in 4th Assessment)**

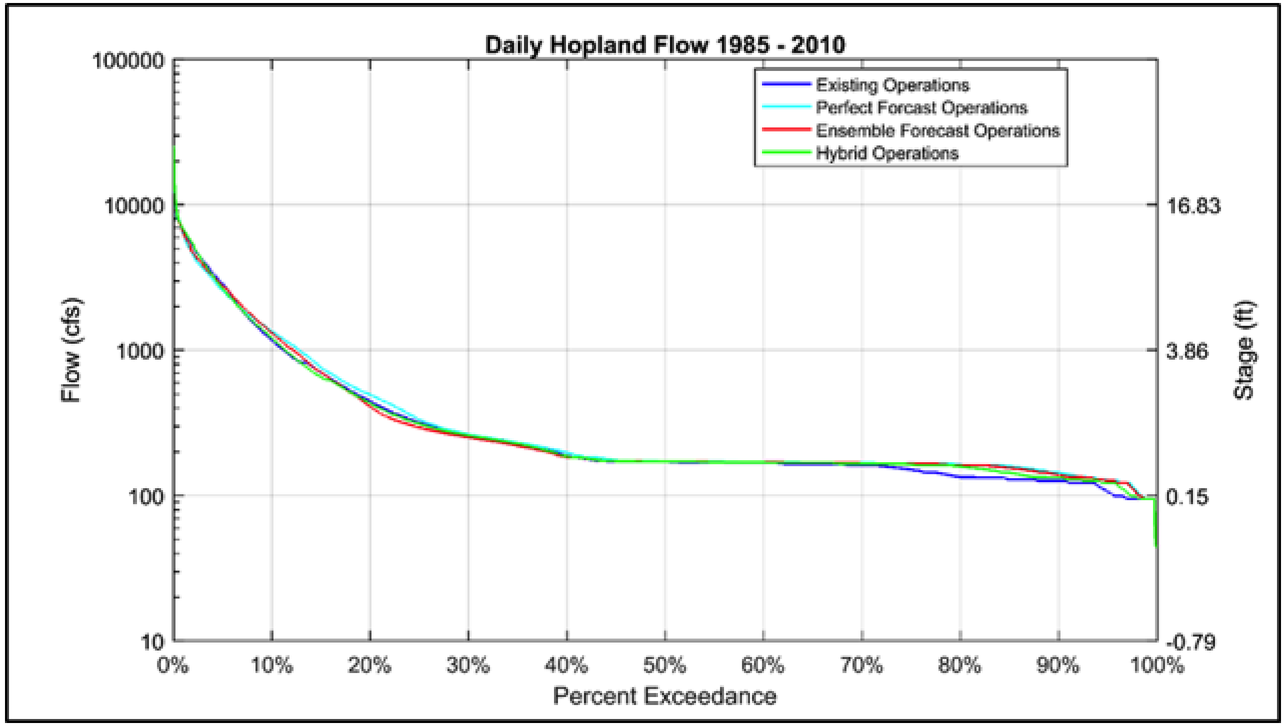
Front Cover: Atmospheric rivers are relatively long, narrow regions in the atmosphere – like rivers in the sky – that transport most of the water vapor outside of the tropics. When an atmospheric river makes landfall, extreme precipitation and flooding can often result. The cover features a natural-color image of conditions over the northeastern Pacific on 20 February 2017, helping California and the American West emerge from a 5-year drought in stunning fashion. Some parts of California received nearly twice as much rain in a single deluge as normally falls in the preceding 5 months (October–February). The visualization was generated by Jesse Allen (NASA Earth Observatory) using data from the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (NPP) satellite.

Hypothetical Impacts of FIRO* on Water Supply and Flood Risk at Lake Mendocino in Northern California (FIRO Steering Committee; Jasperse and Ralph co-chairs)

Water Supply



Flood Risk



✓Substantial gains in water storage over existing operations by leveraging information in streamflow forecasts enabled by skill in AR forecasts

✓Downstream flood control benefits are not impacted

*Forecast-Informed Reservoir Operations
cw3e.ucsd.edu/FIRO/

FIRO at Southern California's Prado Dam

With Orange County Water District and US Army Corps of Engineers

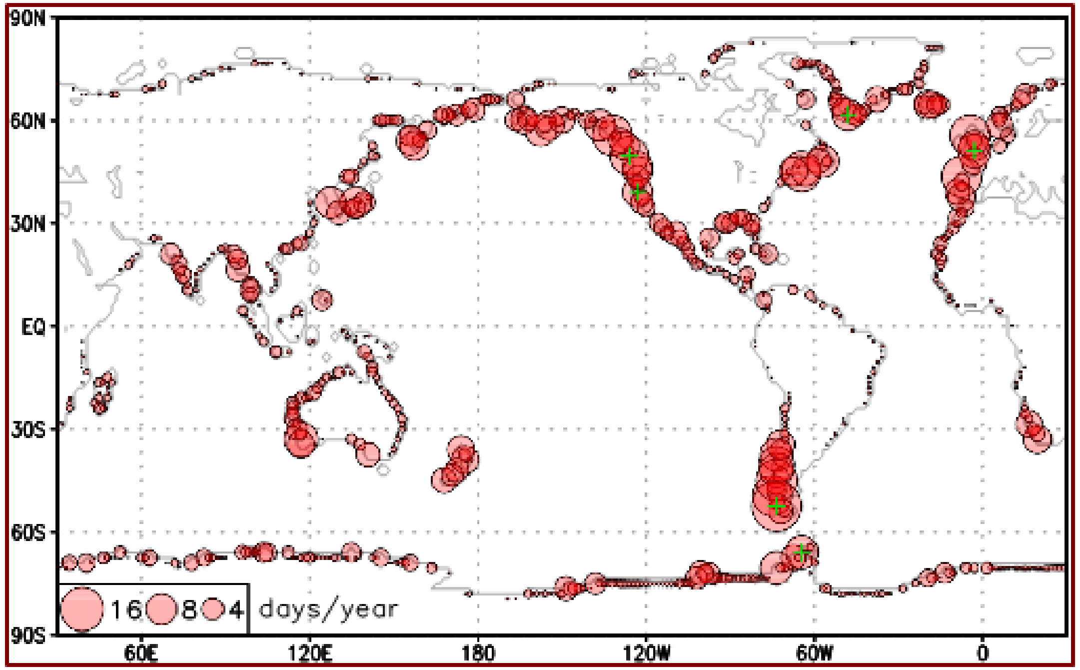
F. Martin Ralph

Center for Western Weather and Water Extremes, UC San Diego/Scripps Institution of Oceanography

Center for Western Weather and Water Extremes

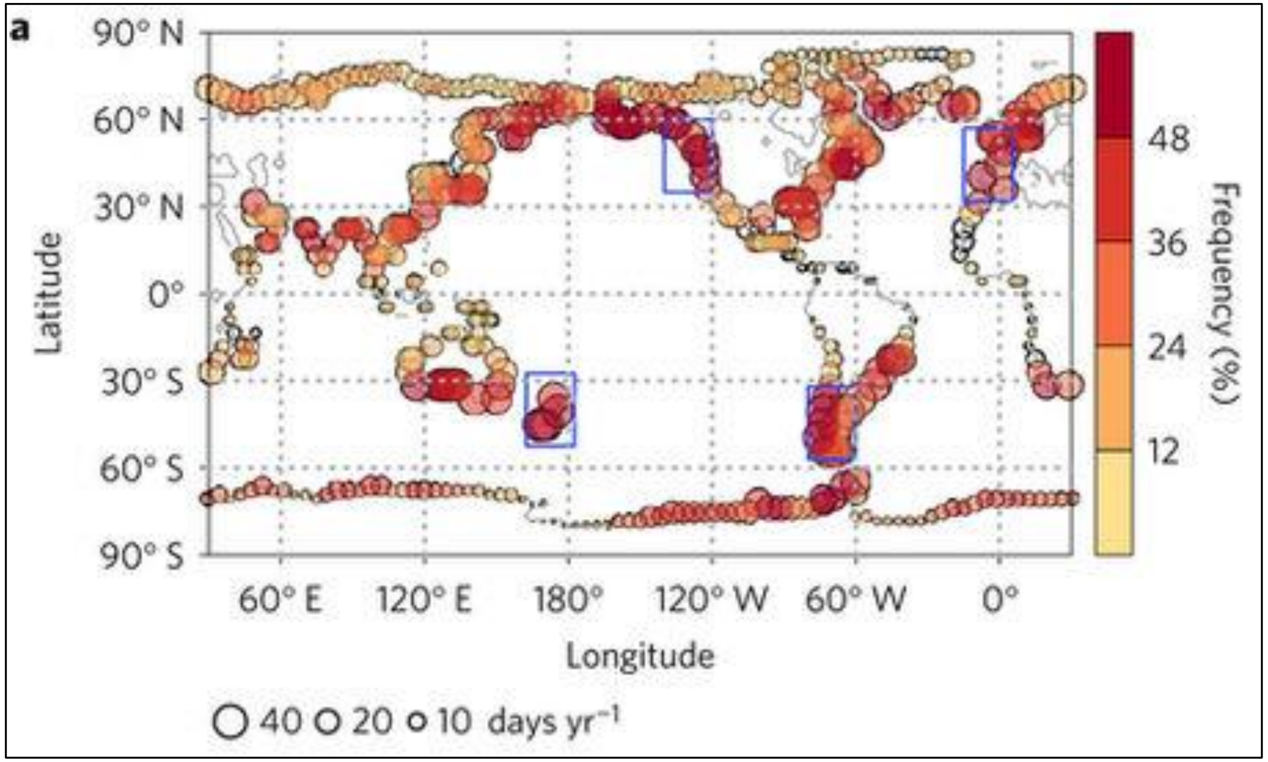
Where do Atmospheric Rivers Make Landfall Globally?

Relationship Between Coastal Extreme Surface Winds and AR Landfall?



Locations (dots), and frequencies (dot sizes) of landfalling atmospheric rivers

Guan and Waliser, 2015 (JGR)



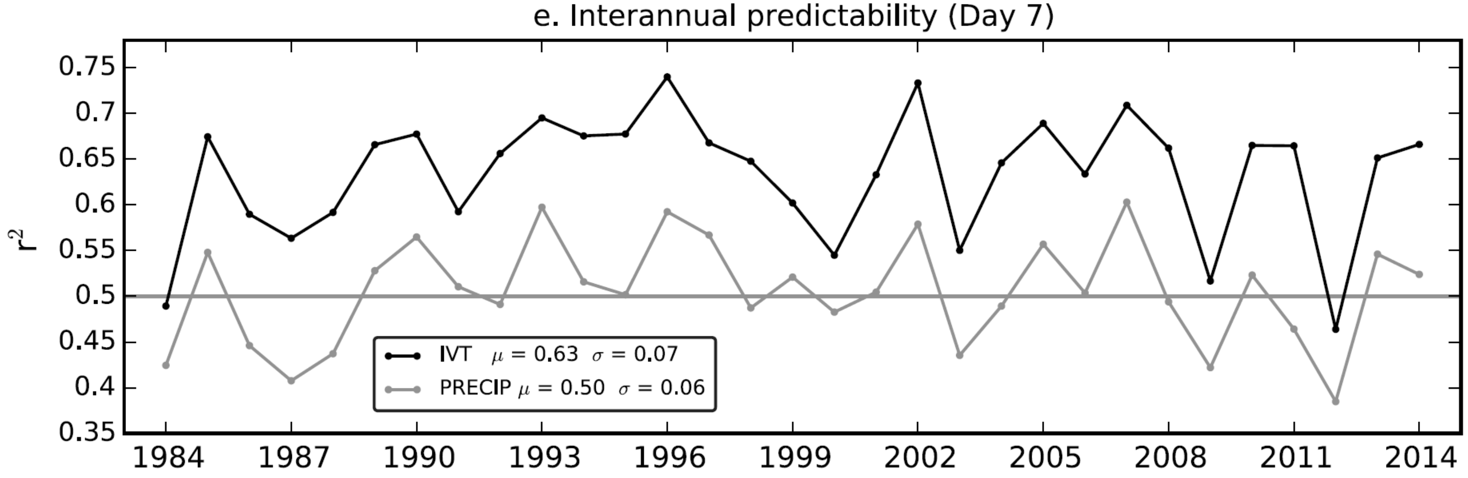
Percentage of coastal extreme surface winds events that are associated with landfalling atmospheric rivers (color fill), and frequency of occurrence (dot size).

Waliser and Guan, 2017 (Nat. Geoscience)

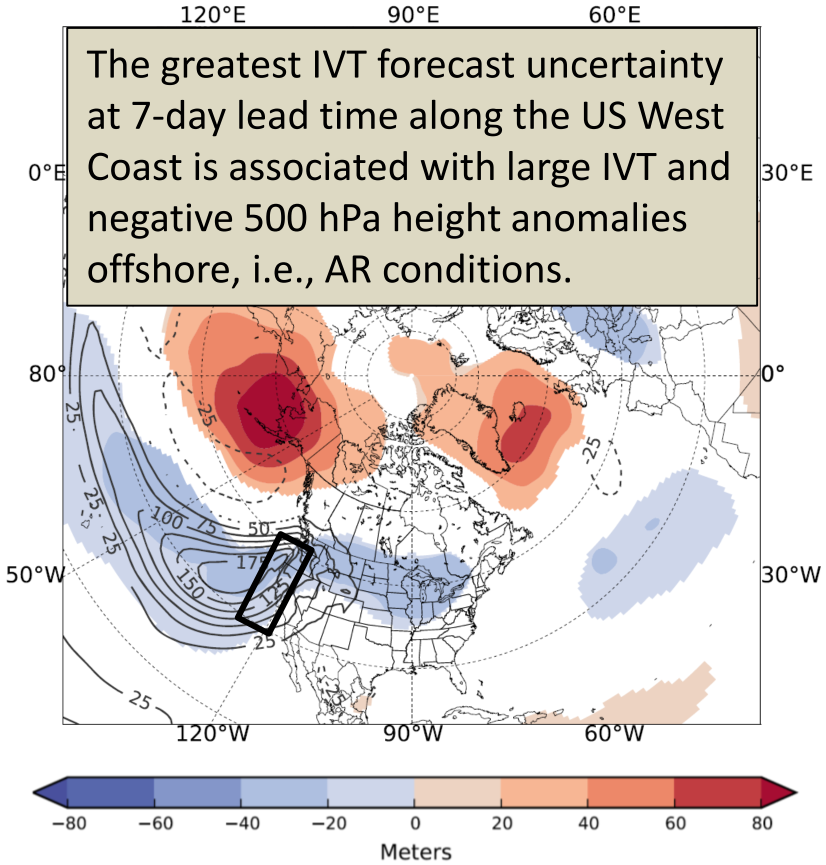
Predictability of horizontal water vapor transport relative to precipitation: Enhancing situational awareness for forecasting western U.S. extreme precipitation and flooding

David A. Lavers, Duane E. Waliser, F. Martin Ralph, Michael D. Dettinger, *Geophys. Res. Lett. 2016*

Applying the potential predictability concept to NCEP global ensemble reforecasts, across 31 winters, IVT is found to be more predictable than precipitation in the region 30-50°N, 120-125° W.



The greatest IVT forecast uncertainty at 7-day lead time along the US West Coast is associated with large IVT and negative 500 hPa height anomalies offshore, i.e., AR conditions.

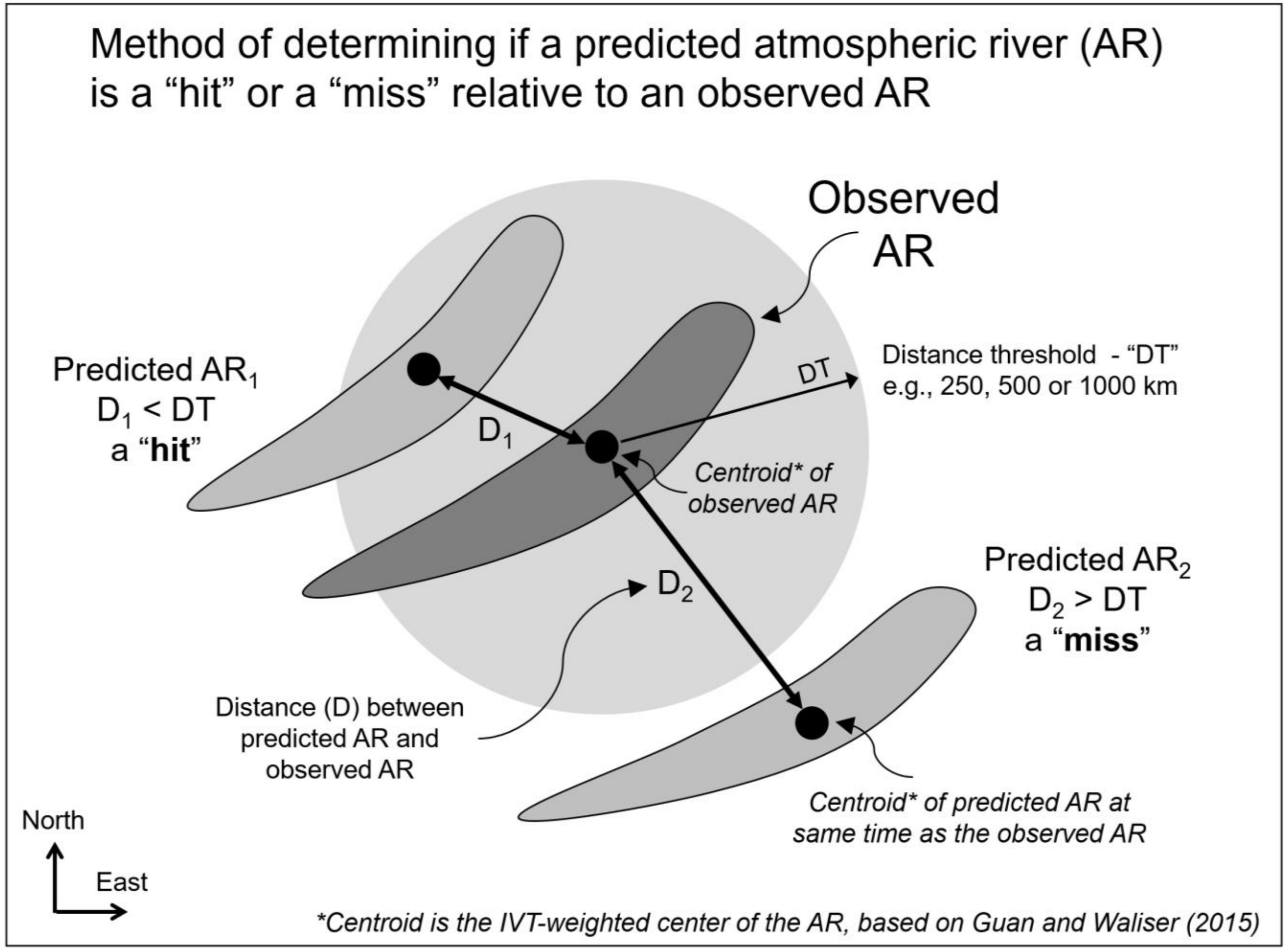


Composite mean of the 500 hPa geopotential height anomalies at the analysis time (shading, in meters) and of the ensemble mean IVT forecast anomalies (contours, dashed where less than climatology) during the 140 largest ensemble spreads on forecast day 7. Colored and contoured regions indicate areas where the composite mean is different from zero at the 90% significance level.

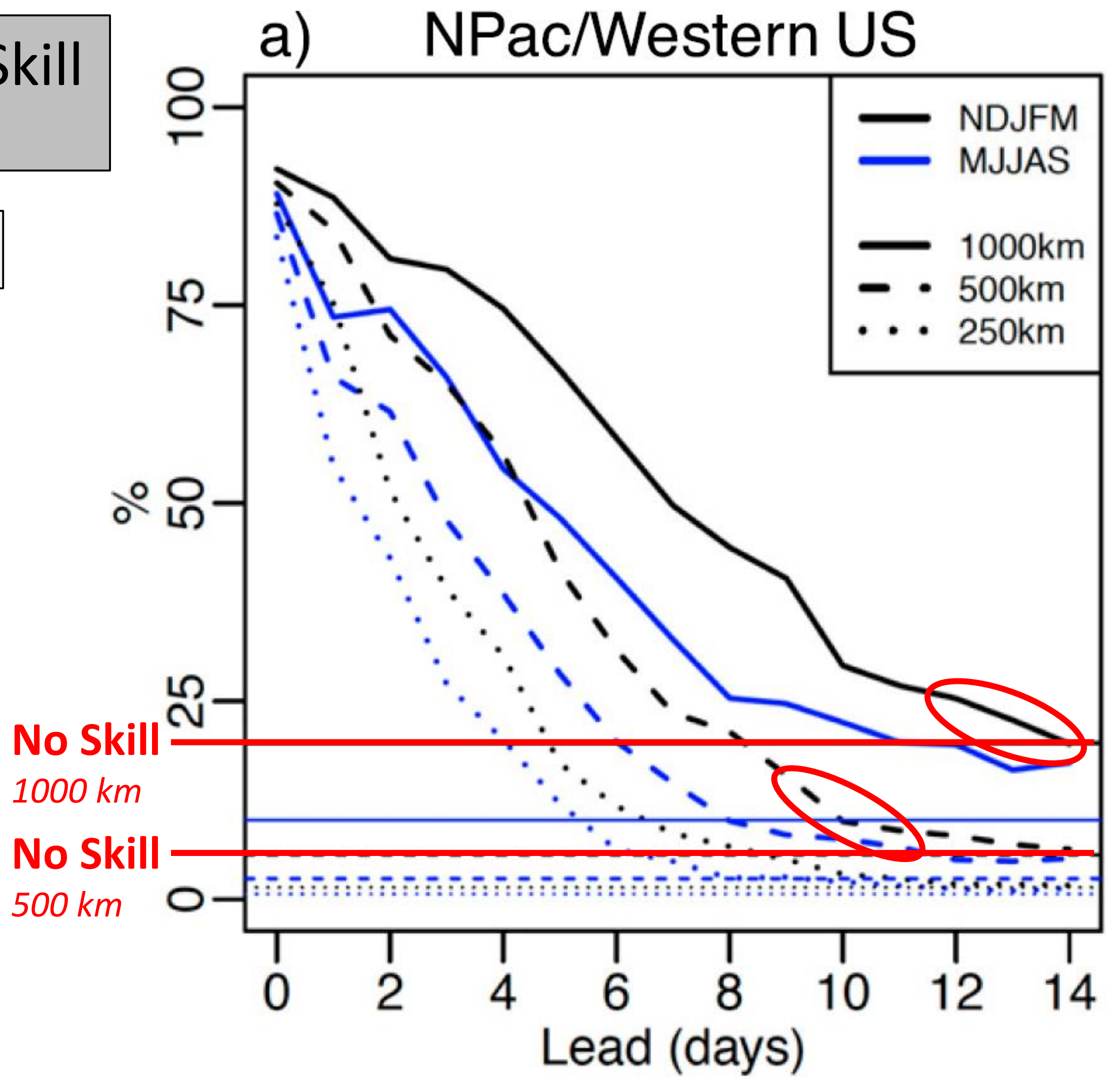
Global Assessment of Atmospheric River Prediction Skill

DeFlorio, Waliser, Guan, Lavers and Ralph (*JHM 2018)*

Uses ECMWF forecasts and Guan and Waliser (2015) AR Catalog



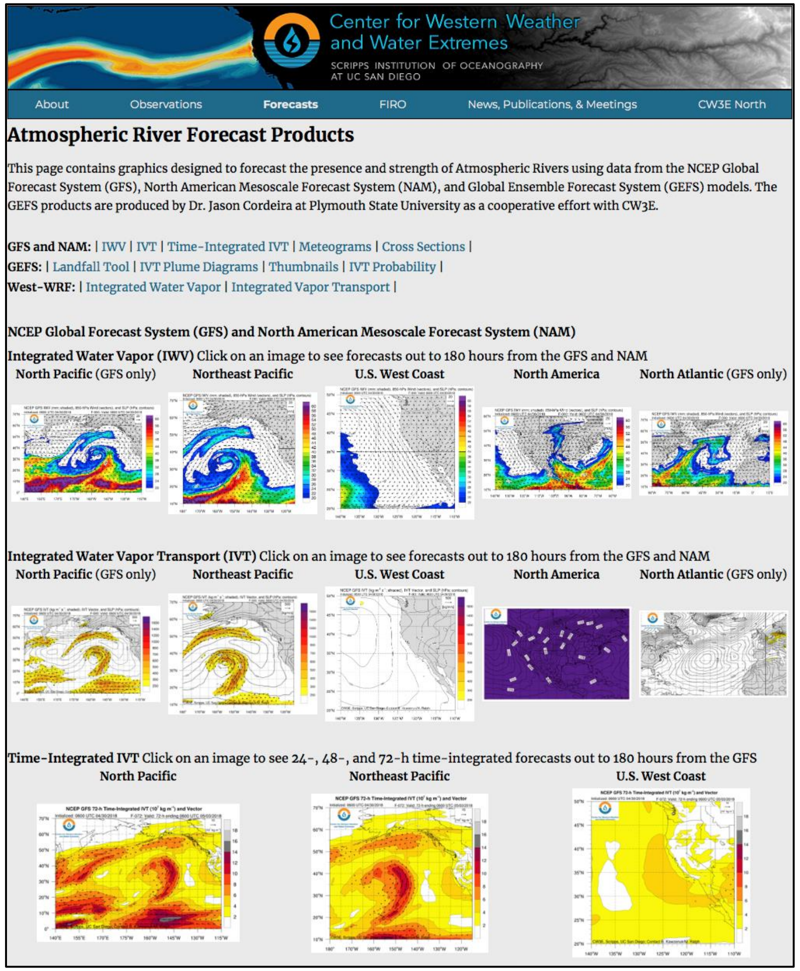
*Centroid is the IVT-weighted center of the AR, based on Guan and Waliser (2015)

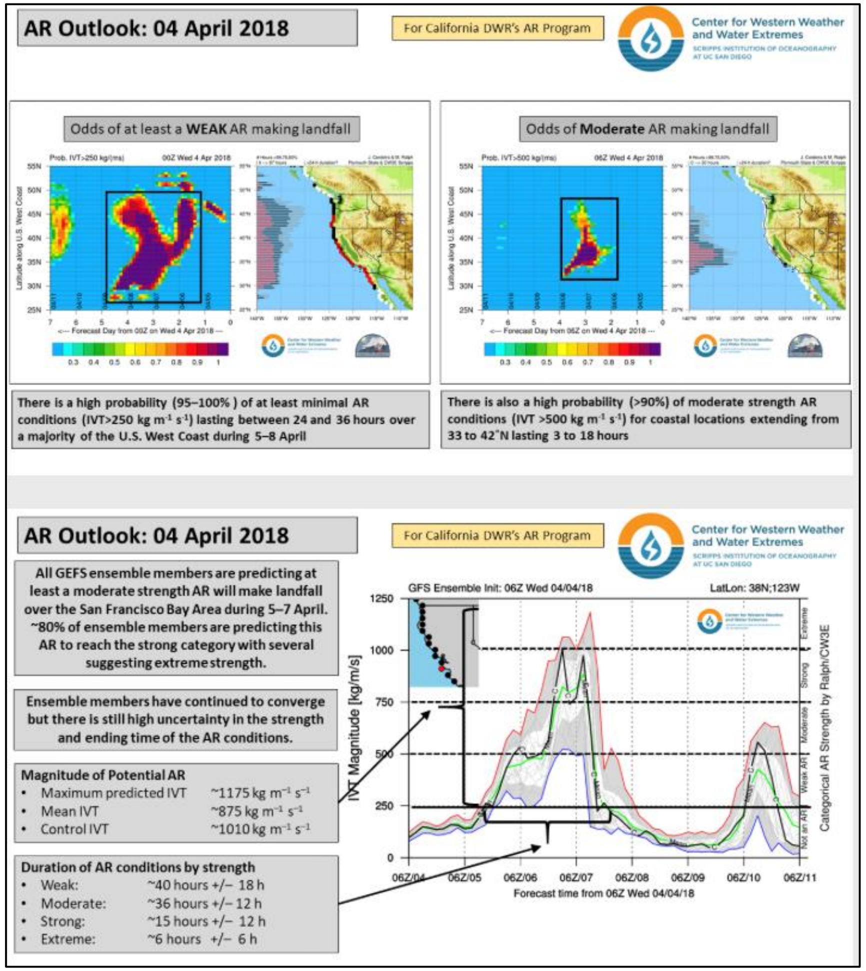


In Cool Season, analysis shows there is some skill for 500 km range out to 10 days and for 1000 km range out to 12 days

AR Monitoring and Prediction Tools (cw3e.ucsd.edu)

- CW3E develops and maintains a growing number of AR monitoring & prediction tools
  - *These are the basis for key parts of the AR forecast information shown on NOAA/PSD's website*
- Expanding to include more decision support tools, interactive analyses and forecast, watershed-scale tools, pre-event outlooks, and post-event analyses
- See Cordeira et al. BAMS (2017)





Provided by J. Cordeira, F.M. Ralph and CW3E staff

AR Update: 4 April 2017

For California DWR's AR Program

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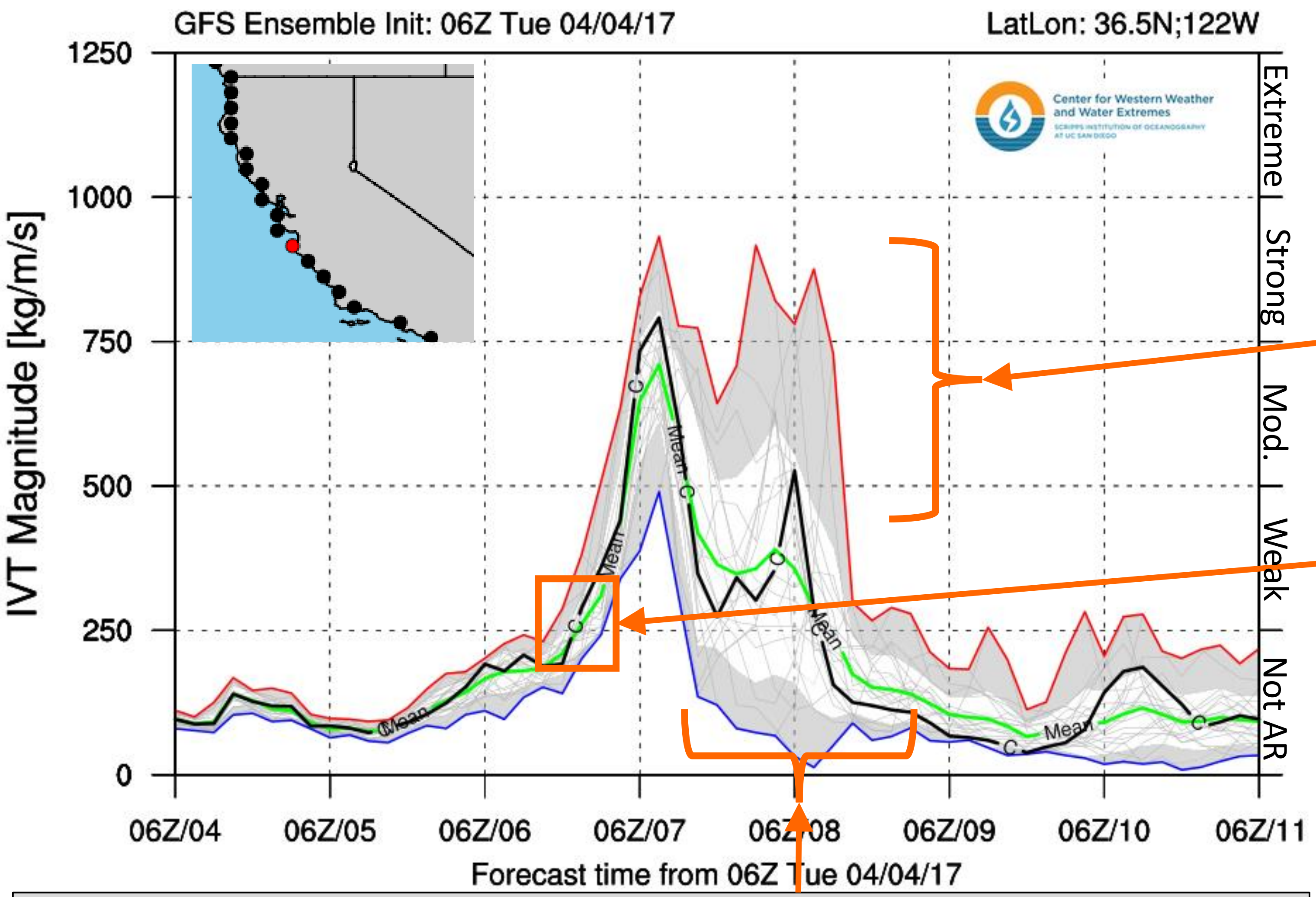


Monterey, CA could experience strong AR conditions IVT> 750 kg m^{-1} s^{-1}

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

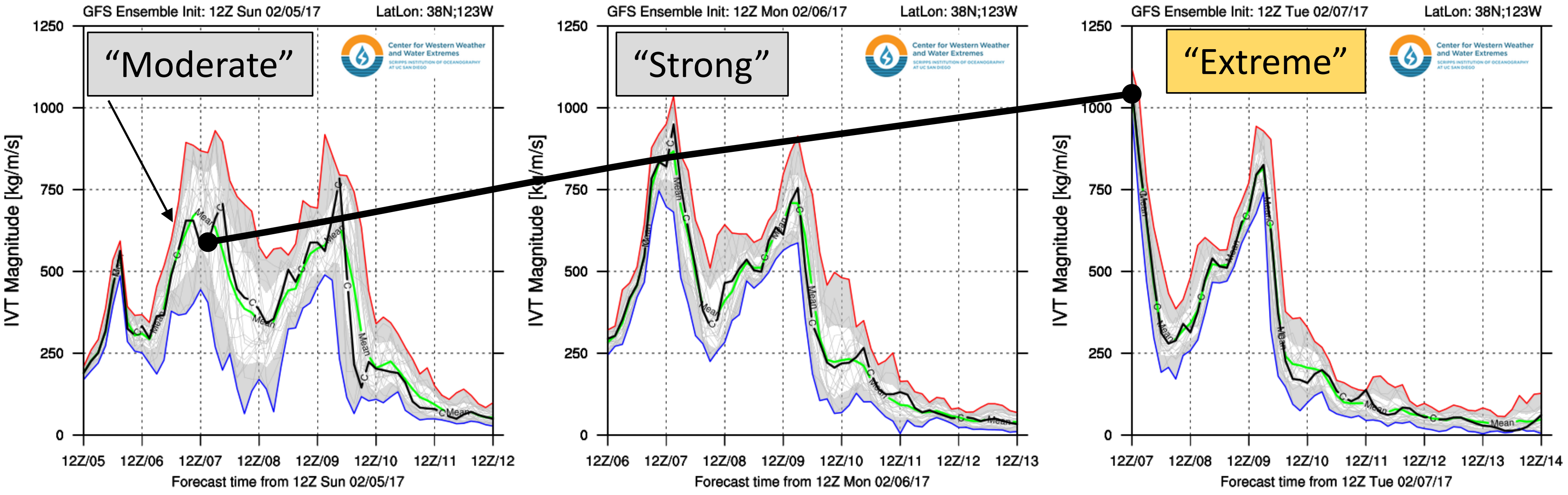
- Weak: ~36 hours +/– 20 h
- Moderate: ~10 hours +/– 20 h
- Strong ~3 hours +/– 3 h

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

NCEP GEFS dProg/dt Example from February 2017 – "Oroville Case" (dam spillway issue)

Oroville Dam Spillway



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**.

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F. M. Ralph (mralph@ucsd.edu) and J. Cordeira

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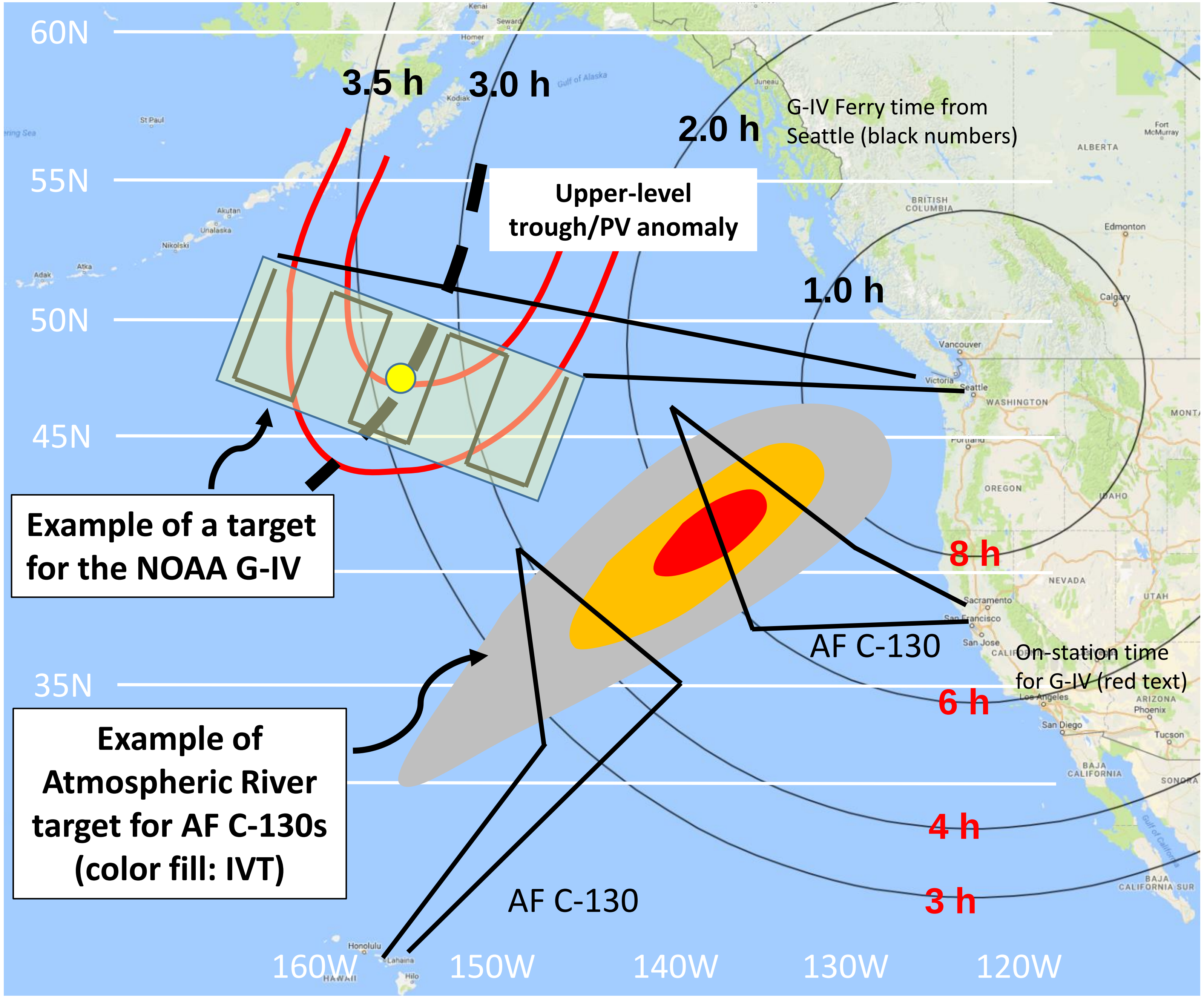
2018 Atmospheric River Reconnaissance Flight Strategies

Center time: 0000 UTC
Dropsonde deployment window:
2100 – 0300 UTC



Each aircraft has a range of about 3500 nm

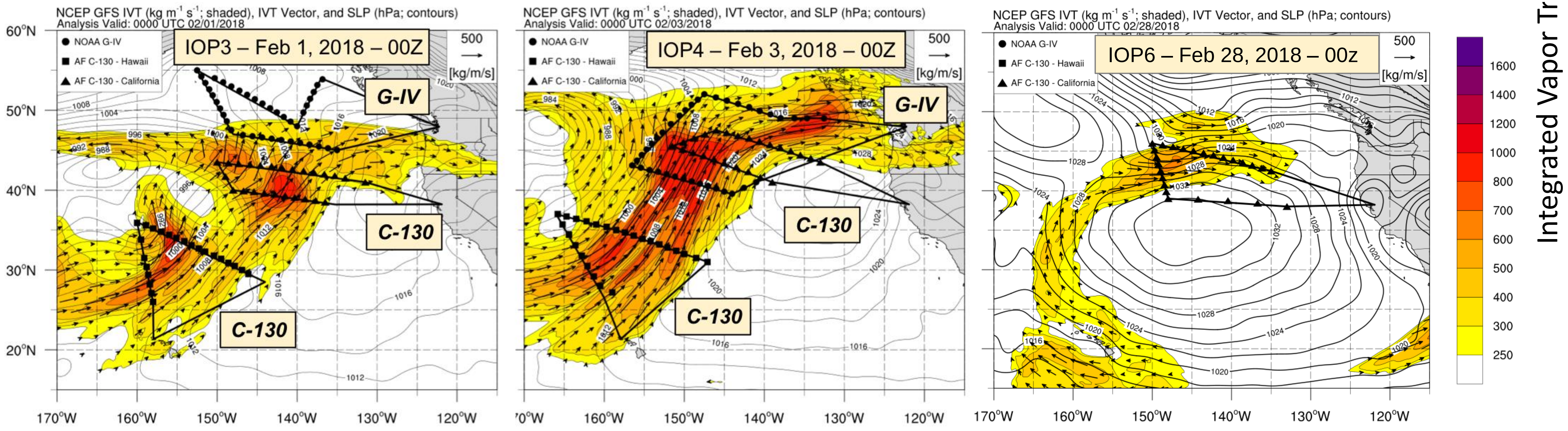
F.M. Ralph (AR Recon PI) and AR Recon Team

AR Recon Modeling and Data Assimilation Steering Committee

Formation of an “AR DA Steering Committee” and “AR DA Technical Work Plan”

Steering Committee

- F. Martin Ralph – (UCSD/Scripps/CW3E) - AR Recon PI and AR DA SC Co-Chair
- Vijay Tallapragada (NOAA/NWS/NCEP) – AR Recon Co-PI and AR DA SC Co-Chair
- Jim Doyle (NRL)
- Aneesh Subramanian (UCSD/Scripps/CW3E)
- Chris Davis (NCAR/MMM)
- Florian Pappenberger (ECMWF)



AR Recon – 2019: Requesting 3 Aircraft to Sample 9 Storms

Two Air Force C-130s and NOAA's G-IV

- ✓ Feb 2016: 3 Storms (2 aircraft per storm)
- ✓ Jan-Feb 2018: 6 Storms (3 aircraft per storm in 3 storms; 2 aircraft in 1 storm; 1 aircraft in 2 storms)
- o Jan-Mar 2019 (Requested): 9 storms (3 aircraft per storm)
- o **Target total number of cases: 18 storms, with 1, 2 or 3 aircraft sampling each storm**
- ✓ Interagency, International Steering Committee in place
  - Carry out assessments
  - Refine data assimilation methods
  - Create appropriate evaluation metrics
  - Provide impact results in peer-reviewed publications

Contacts
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V. Tallapragada (vijay.tallapragada@noaa.gov)

How Many ARs Hit California Each Year?
A Comparison of Atmospheric River Detection Tools

Submitted to Climate Dynamics April 2018; Accepted pending revision

F. Martin Ralph,[1] Anna Wilson[1], Tamara Shulgina[1], Brian Kawzenuk[1], Scott Sellars[1,6], Jon Rutz[2], Maryam Asgari-Lamjiri[1], Elizabeth Barnes[3], Alexander Gershunov[1], Bin Guan[4], Kyle Nardi[3], Tashiana Osborne[1], Gary Wick[5]

1-Center for Western Weather and Water Extremes, Scripps Institution of Oceanography, University of California San Diego; 2-NOAA/NWS/Western Region Headquarters; 3-Department of Atmospheric Science, Colorado State University; 4-Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles; 5-NOAA/Earth System Research Laboratory/Physical Sciences Division; 6-National Science Foundation

Center for Western Weather and Water Extremes
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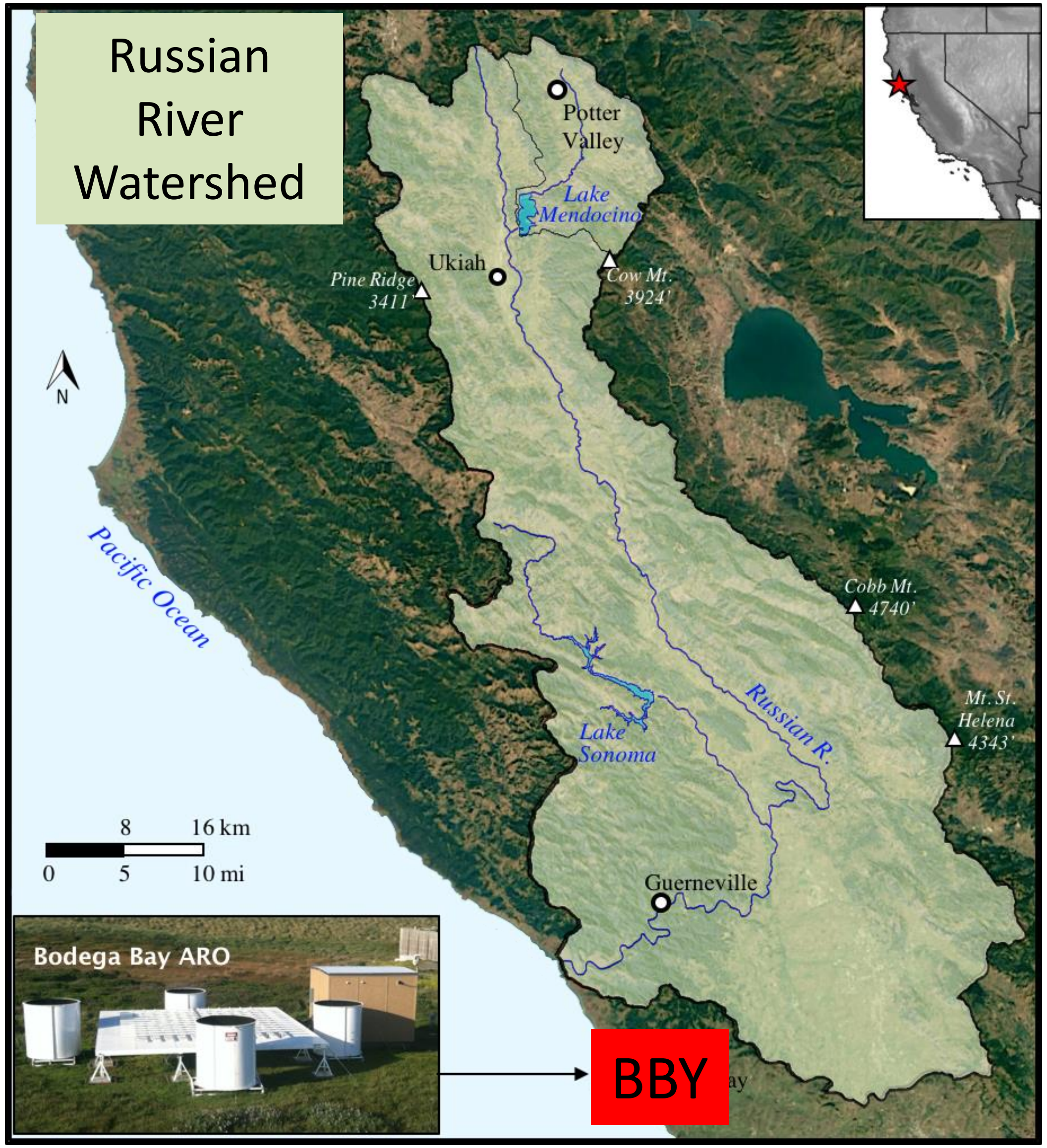
ARTMIP Workshop – 23 April 2018

Motivation

- The question "**How many ARs hit California?**" comes up often from the public and in science
- How much does it depend on the ARDT?
- How much does it depend on the reanalysis used?
- How do counts from ARO observations compare?

Approach

- Use one location where a unique 12-year long observational dataset from an Atmospheric River Observatory (ARO) is available (Bodega Bay, CA)
- Evaluate several ARDTs applied to their native data
- Evaluate several ARDTs on the same reanalysis
- Evaluate one ARDT on several reanalyses



Map provided by Forest Cannon

DIFFERENT METHODS – DIFFERENT REANALYSIS

Gershunov et al., 2017 – NCEP
Guan and Waliser, 2015 – ERA-Interim
Mundhenk et al., 2016 – MERRA-1
Ralph et al., 2013 – ARO Observations
Rutz et al., 2014 – NCEP
Ralph et al., 2013 – ARO Observations – moderate strength
Sellars et al., 2013 – MERRA-2 – moderate strength

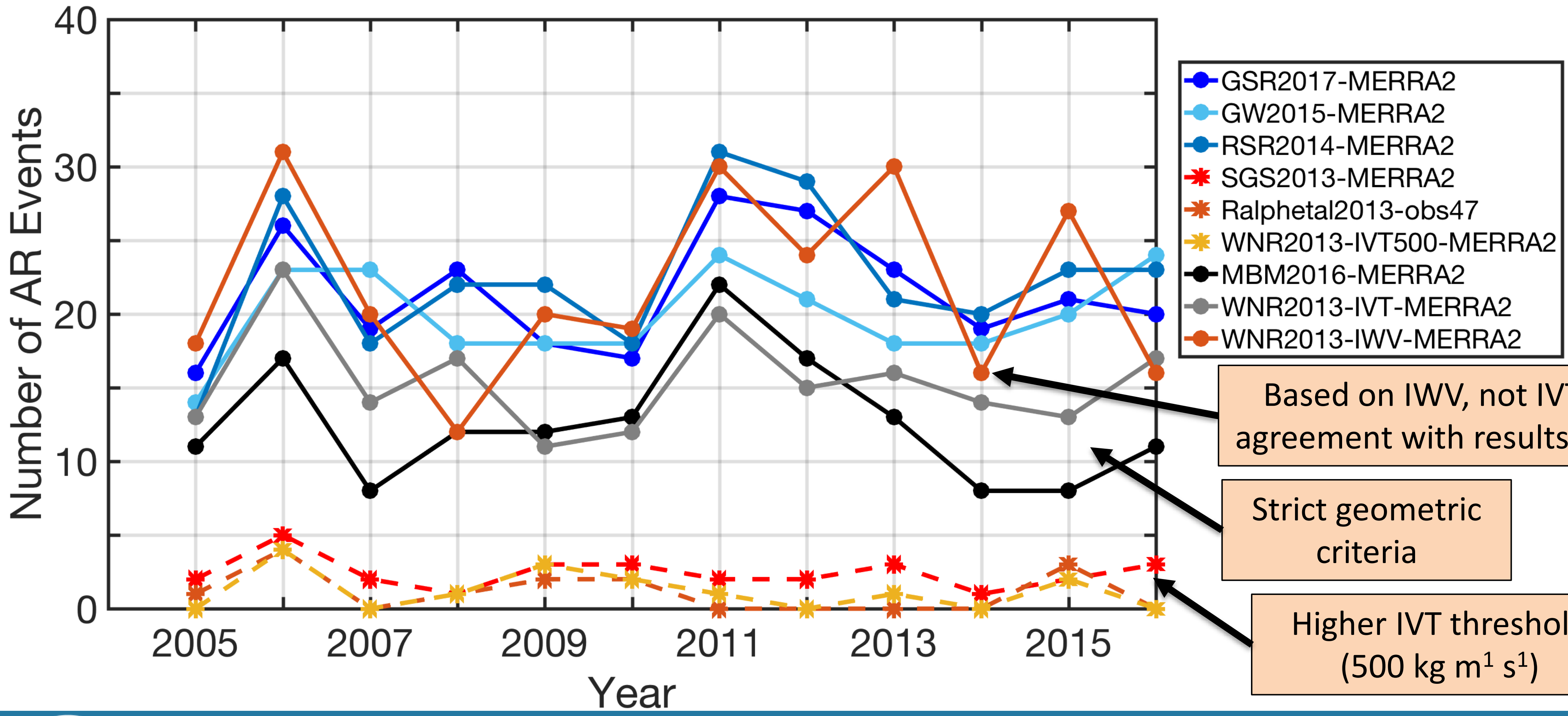
DIFFERENT METHODS – SAME REANALYSIS

Gershunov et al., 2017 – MERRA-2
Guan and Waliser, 2015 – MERRA-2
Mundhenk et al., 2016 – MERRA-2
Ralph et al., 2013 – ARO Observations
Rutz et al., 2014 – MERRA-2
Wick et al., 2013 – MERRA-2 – IWV
Wick et al., 2013 – MERRA-2
Ralph et al., 2013 – ARO Observations – moderate strength
Sellars et al., 2013 – MERRA-2 – moderate strength
Wick et al., 2013 – MERRA-2 – moderate strength

SAME METHOD – DIFFERENT REANALYSIS

Rutz et al., 2014 – NCEP
Rutz et al., 2014 – ERA-Interim (Nov-Apr)
Rutz et al., 2014 – MERRA-2

One Reanalysis (MERRA-2) - Different ARDTs

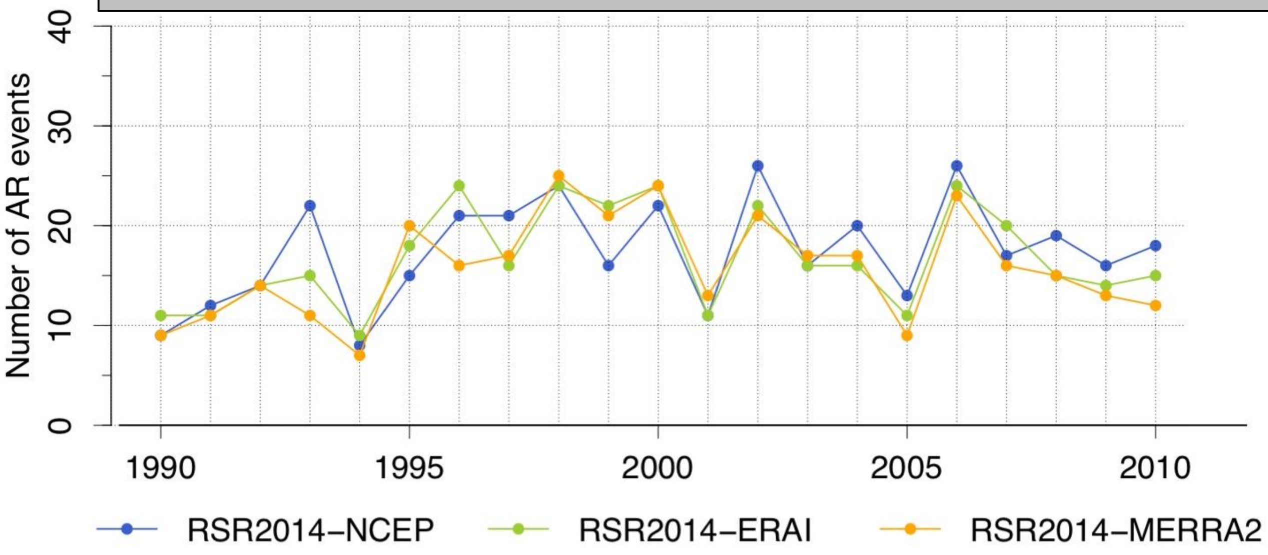


Based on IWV, not IVT, but in fair agreement with results based on IVT

Strict geometric criteria

Higher IVT threshold (500 kg m^1 s^1)

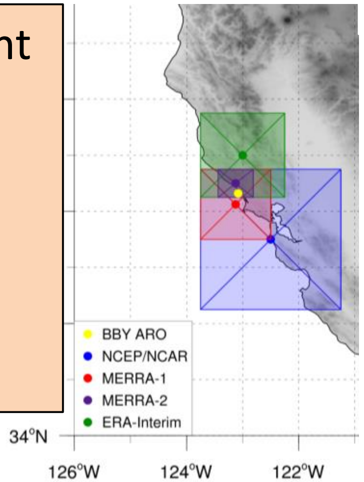
One ARDT (Rutz et al. 2014) – Different Reanalyses

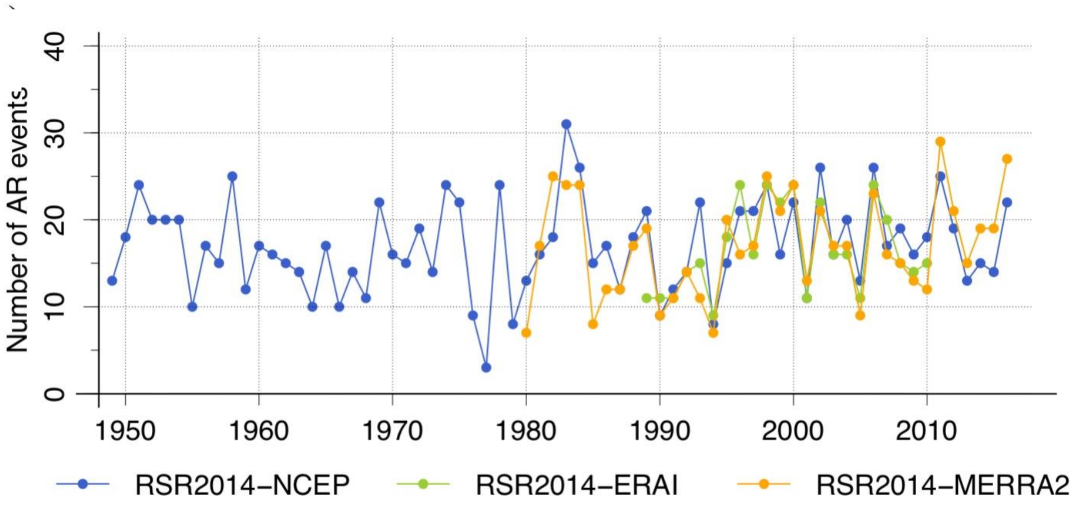


	NCEP (2.5°)	ERA-Interim (1.5°)	MERRA-2 (0.5°)
Max IVT	1088	1436	1436
AR Events/ Nov-Apr *	17.9	17.2	14.8
AR Duration (hr)	25.9	25.4	24.8

There is more agreement using RSR2014 on different reanalyses than there is using different ARDTs on MERRA-2.

This gives confidence that the longer, but low-resolution NCEP-NCAR reanalysis can be used to study ARs over the longer (~80 yrs) period



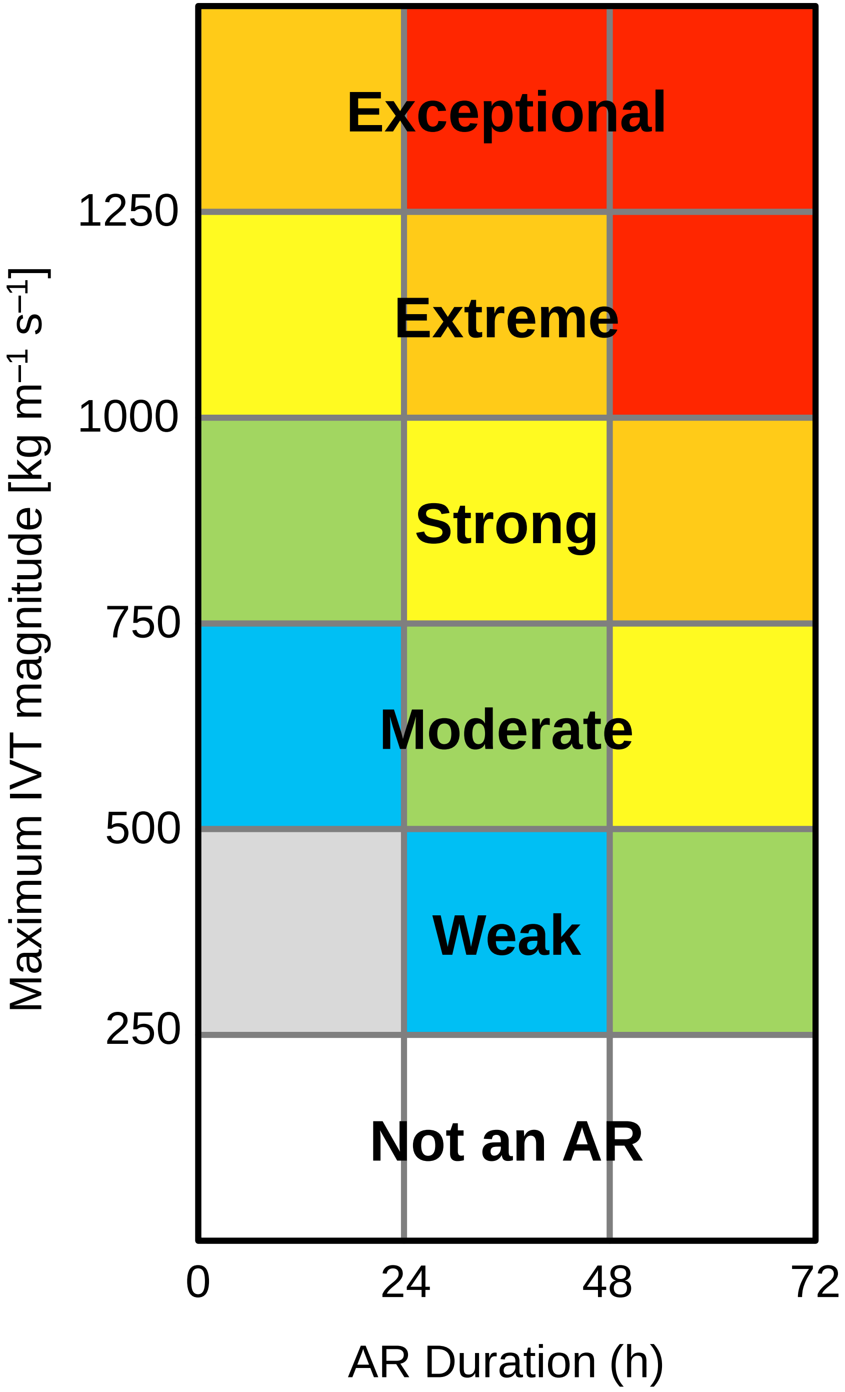


Conclusions

- 19 ± 7 ARs hit BBY per year on average, depending on the choice of ARDT (except for high-threshold ARDTs that yield 1-2 ARs/yr avg)
- ARDT's with tougher geometric criteria yield fewer ARs
- Use of different reanalyses, even with very different resolutions, introduces some of the variance in AR counts, but less so than use of different ARDTs
- AR counts from AROs suffer from data gaps
- Average AR duration and IVT vary across ARDTs by only about ±10% (vs ± 37% uncertainty in AR count)
- ARDTs of similar nature (RSR2014, GW2015, GSR2017) yield very similar AR counts of 22-25 ARs per year and AR durations of 24-25 h, and average IVT of 300-370 kg m^{-1} s^{-1}

ARDT	Avg Annual AR Count	Avg Duration (hrs)	Avg IVT (kg m^{-1} s^{-1})
Using "Native" reanalysis			
GSR2017-NCEP	22	25	342
GW2015-ERAI	24	25	299
RSR2014-NCEP	25	25	336
Range of AVG	**3**	**0**	**43**
Using Merra-2 reanalysis			
GSR2017	21	24	372
GW2015	20	24	344
RSR2014	22	25	369
Range of AVG	**2**	**1**	**28**

- **Other ARDTs can be compared using these data and this method to put them in context**



A Scale to Characterize the Strength and Impacts of Atmospheric Rivers

F.M. Ralph (UCSD/Scripps Institution of Oceanography/CW3E), J. J. Rutz (NWS), J. M. Cordeira (Ply.State), M. Dettinger (USGS), M. Anderson (CA DWR), L. Schick (USACE), C. Smallcomb (NWS)

Bull. Amer. Meteor. Soc. (accepted pending revision; revision submitted)

AR Scale Category	Max. IVT* (kg m^{-1} s^{-1})	Duration of AR Conditions (h)	Benefits vs. Hazards of Impacts
	< 250	N/A	Beneficial
AR Cat 1	250–500	< 24	Primarily beneficial
AR Cat 2	500–750	24–48	Mostly beneficial, but also hazardous
AR Cat 3	750–1000	24–48	Balance of beneficial and hazardous
AR Cat 4	1000–1250	24–48	Mostly hazardous, but also beneficial
AR Cat 5	> 1250	> 48	Primarily hazardous

Cat 5 – Primarily hazardous

Cat 4 – Mostly hazardous, also beneficial

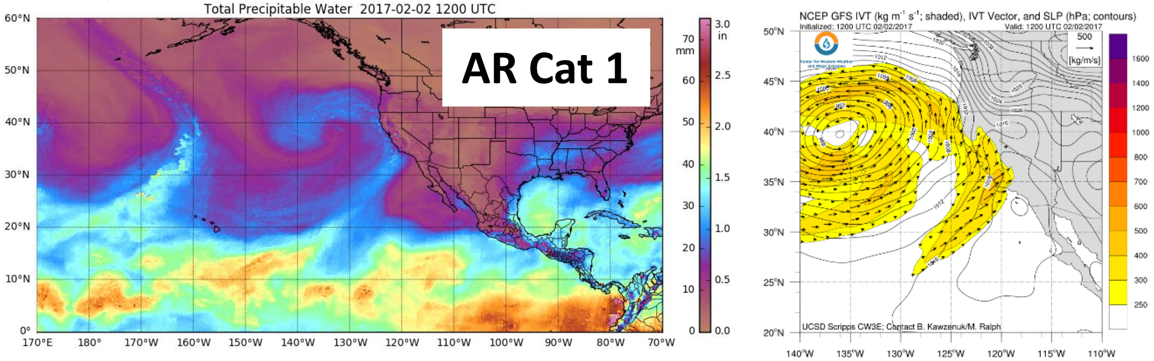
Cat 3 – Balance of beneficial and hazardous

Cat 2 – Mostly beneficial, also hazardous

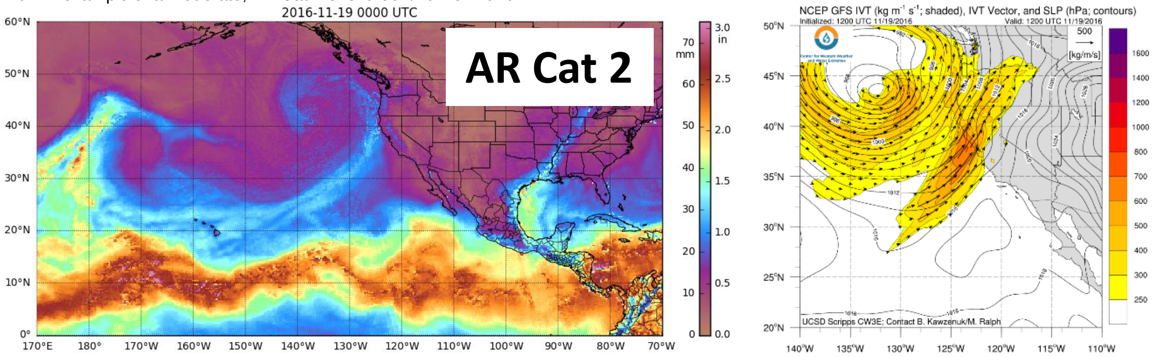
Cat 1 – Primarily beneficial

AR Categories: Examples from Bodega Bay CA

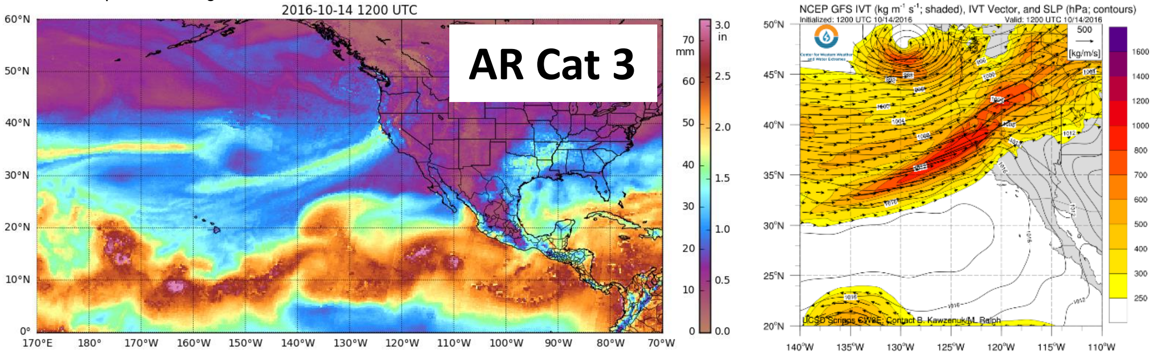
a. An example of a weak, AR Cat 1 event: 12Z/2 Feb 2017



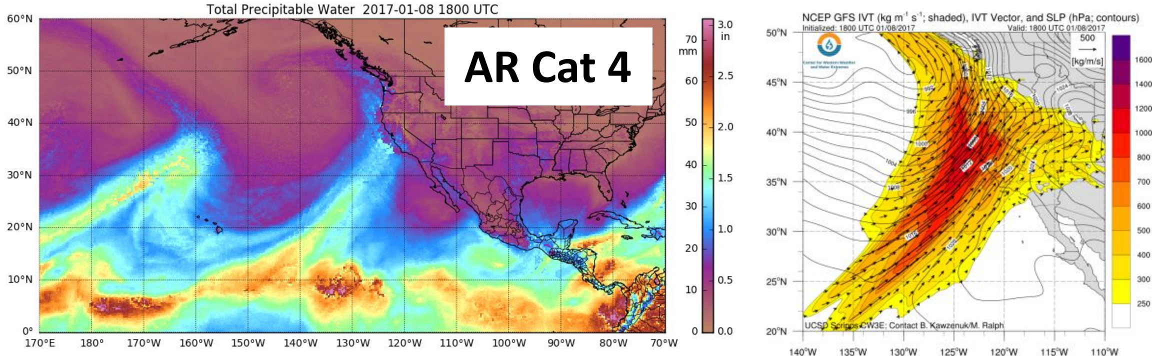
b. An example of a moderate, AR Cat 2 event: 00Z/19 Nov 2016



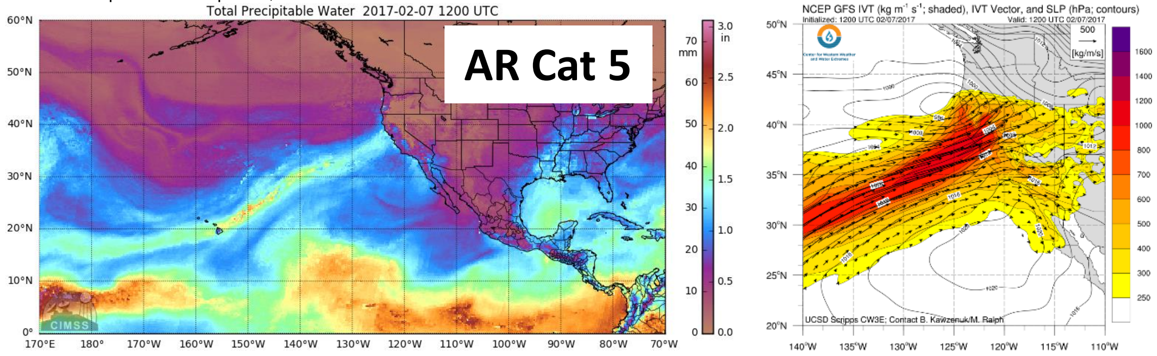
c. An example of a strong, AR Cat 3 event: 12Z/14 Oct 2016



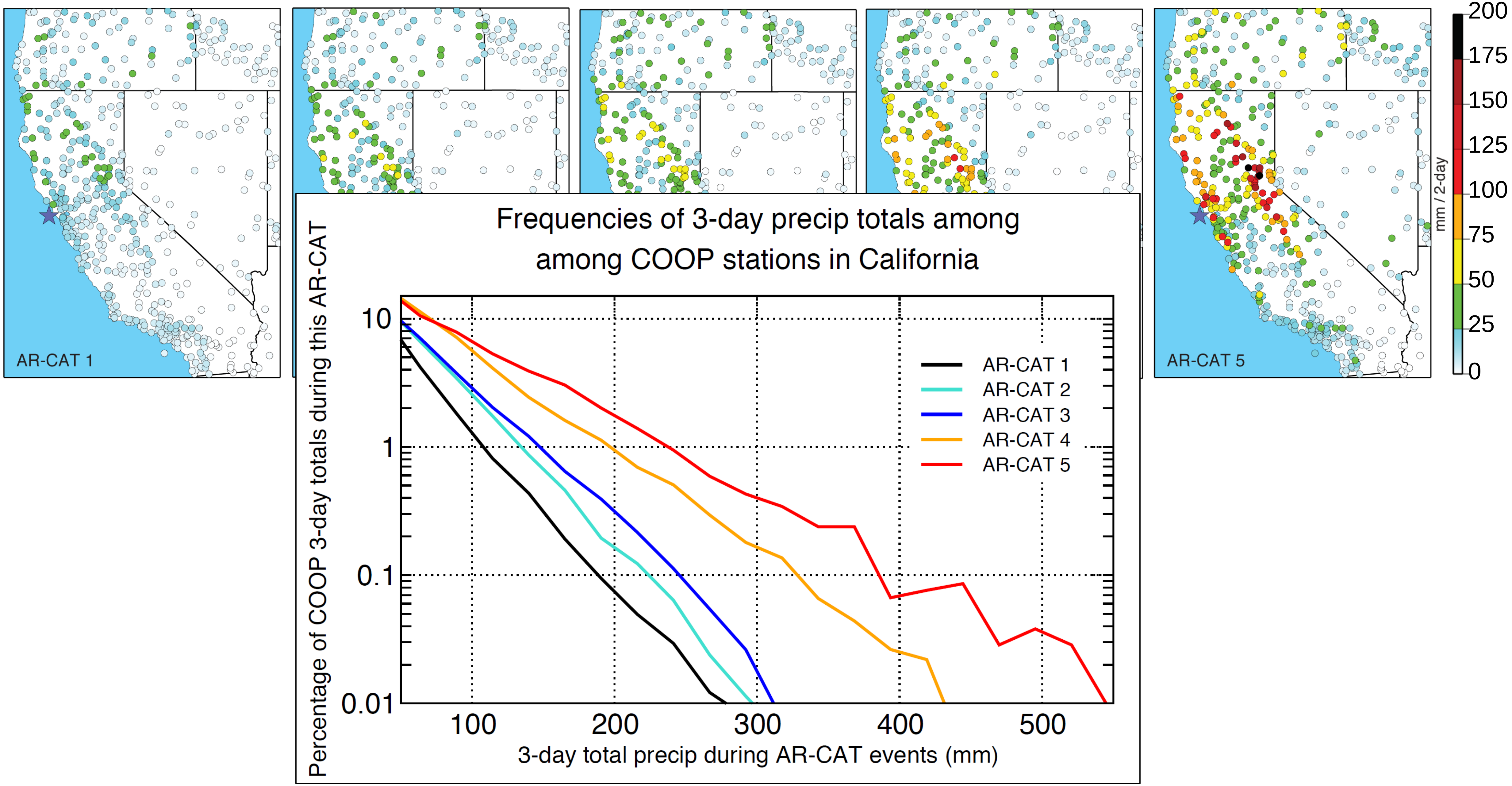
d. An example of an extreme, AR Cat 4 event: 18Z/8 Jan 2017



e. An example of an exceptional, AR Cat 5 event: 12Z/7 Feb 2017



48-h average precipitation starting on AR landfall day at 38ºN,123.125ºW (1980–2010)



S2S Outlooks Supporting Water

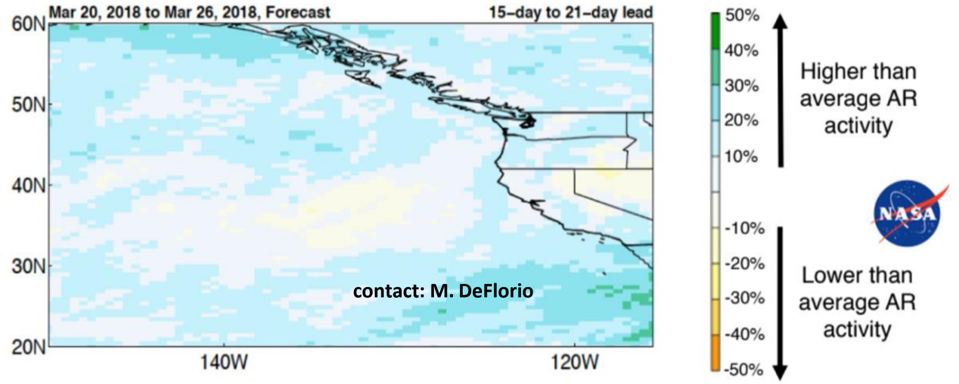
Goal: Develop week-2 and week-3 outlooks for AR activity on the US West Coast. Evaluate and improve understanding of outlooks on these timescales.

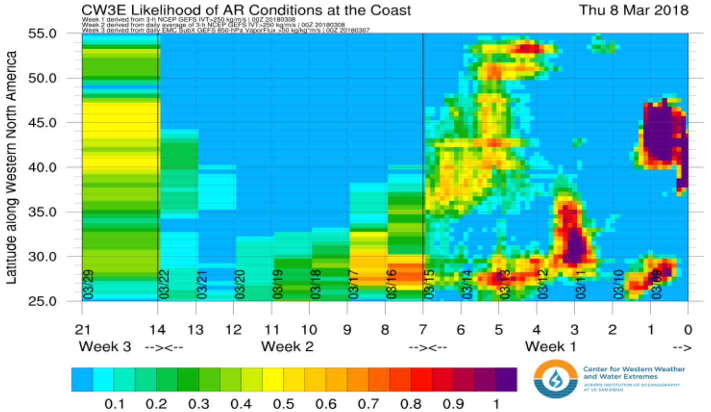
Scripps Institution of Oceanography: F.M. Ralph (PI), A. Subramanian
JPL : Duane Waliser, Mike DeFlorio, Bin Guan, Alex Goodman
PSU : Jay Cordeira
CSU : Elizabeth Barnes

Data : WCRP / WWRP S2S Project

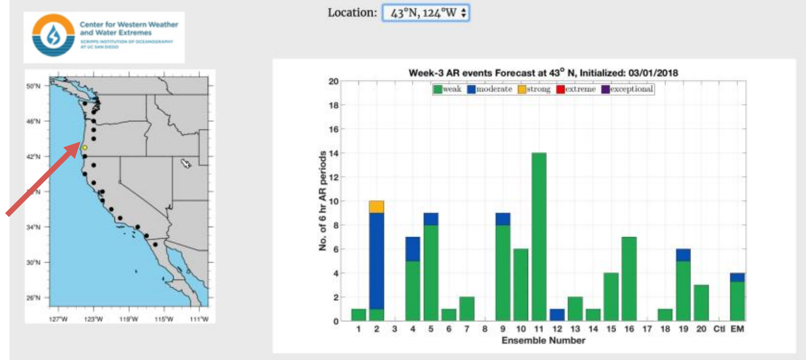
Supported by CA Dept. of Water Resources
Proposed working with NWS/NCEP/CPC

AR probability maps (DeFlorio & Waliser)





Landfall tool extended to week-2 and week-3 (Cordeira & Ralph)



AR scale probabilities for coastal locations (Subramanian & Ralph)

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Jet Propulsion Laboratory
California Institute of Technology

Plymouth State University

Colorado State University

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Emerging Topic: Impacts of ARs on Polar Regions

The role of atmospheric rivers in anomalous snow accumulation in East Antarctica

Irina V. Gorodetskaya[1], Maria Tsukernik[2], Kim Claes[1], Martin F. Ralph[3], William D. Neff[4,5], and Nicole P. M. Van Lipzig[1]

GRL 2014

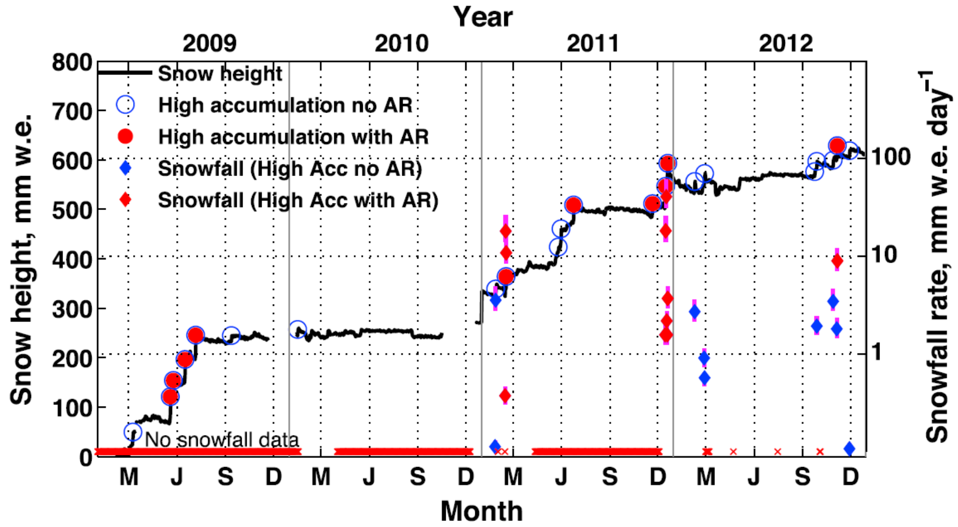
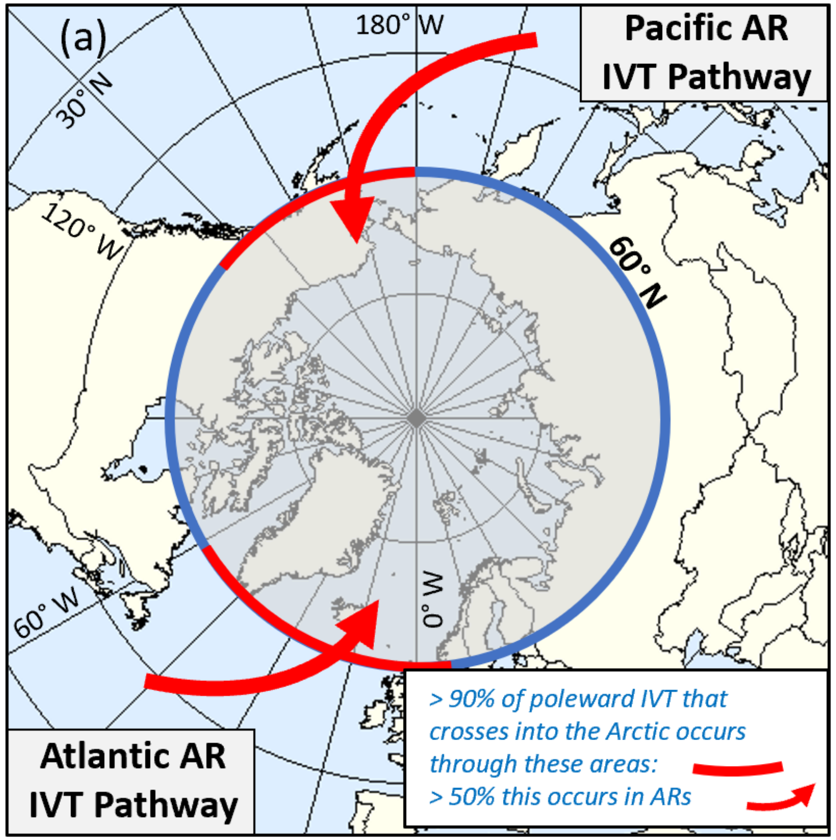


Figure 3. Daily cumulative snow height change and radar-based snowfall rate (S) at PE during 2009–2012. High-accumulation events (>10 mm w.e. d^{-1}) are marked with circles: filled red circles for the events associated with ARs (corresponding S are shown as red diamonds), and open blue circles for the rest (corresponding S are shown as blue diamonds). Vertical magenta line shows uncertainty in S depending on different Z_e-S relationships [*Matrosov*, 2007]. Note the logarithmic scale for snowfall. Horizontal red bar and crosses at bottom show periods of missing S data.

The Role of Atmospheric Rivers in Extratropical and Polar Hydroclimate

Deanna Nash, D Waliser, B. Guan, H. Ye and F.M. Ralph

JGR-Atmos 2018 (in press)



AR Book – "Atmospheric Rivers: Two Decades of Research"

Co-Editors: F. Martin Ralph (Chief), Michael D. Dettinger, Jonathan J. Rutz, Duane Waliser

Contributing Authors: Lance Bosart, Allen B. White, Gary A. Wick, Michael L. Anderson, Harald Sodemann, Heini Wernli, Peter Knippertz, Jason Cordeira, Francina Dominguez, Irina Gorodetskaya, Bin Guan, Huancui Hu, Andreas Stohl, Michael Alexander, Deniz Bozkurt, Irina Gorodetskaya, Alexander Gershunov, David Lavers, Kelly M. Mahoney, Benjamin J. Moore, William Neff, Paul Neiman, Alexandre M. Ramos, Maria Tsukernik, Hans Christian Steen-Larsen, R. Valenzuela, Maximilliano Viale, Christine Albano, Gilbert Compo, Irina Gorodetskaya, Ben Hatchett, David Lavers, William Neff, Paul Neiman, Nina Oakley, Alexandre Ramos, Maximilliano Viale, Andrew Wade, Michael L. Anderson, Lawrence J. Schick, Dale Cox, Jay Jasperse, David Lavers, David Richardson, Florian Pappenberger, and Ervin Zsoter

Production Team: Lauren D. Muscatine, Sheila Chandrasekhar, Mary Beth Sanders

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Sponsor: U.S Army Corps of Engineers

Final Editorial Steps: Submit Remaining Chapter Material, Begin Internal Review, End Internal Review, Begin Chapter Revisions, End Chapter Revisions, Final Production, Deliver to Press

Estimated Publication Date: November 2018

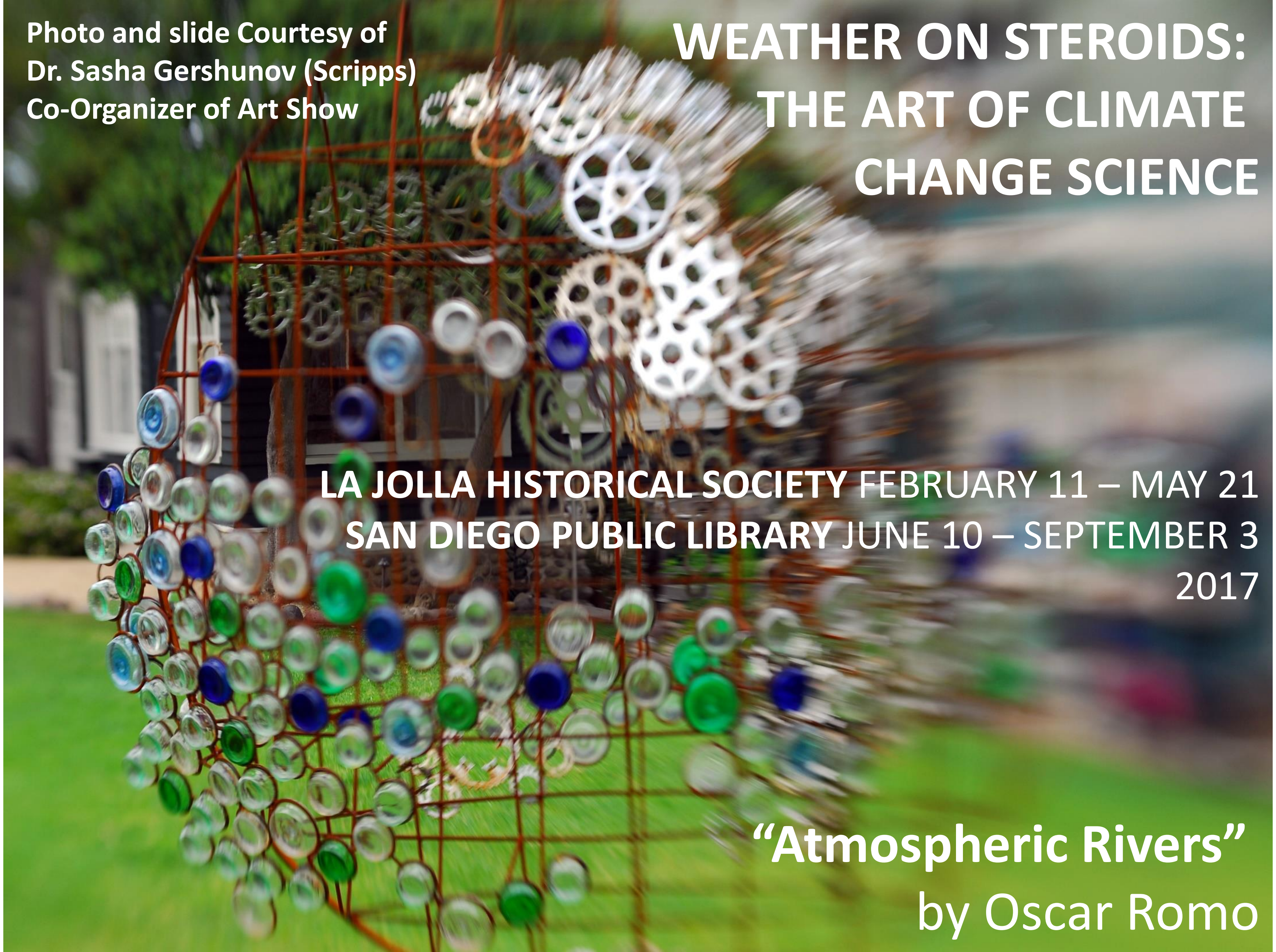


Photo and slide Courtesy of
Dr. Sasha Gershunov (Scripps)
Co-Organizer of Art Show
WEATHER ON STEROIDS:
THE ART OF CLIMATE
CHANGE SCIENCE
LA JOLLA HISTORICAL SOCIETY FEBRUARY 11 – MAY 21
SAN DIEGO PUBLIC LIBRARY JUNE 10 – SEPTEMBER 3
2017
“Atmospheric Rivers”
by Oscar Romo

"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."

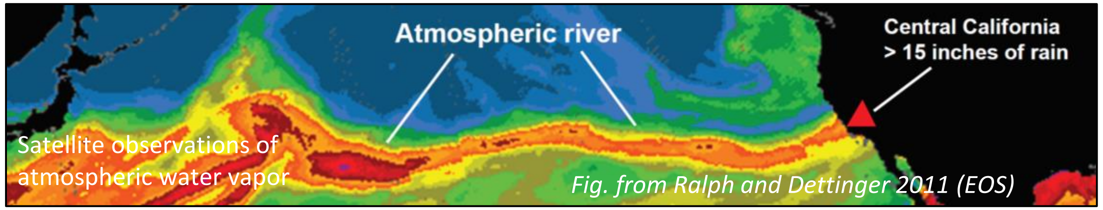
Tweets Tweets & replies Media

South Tahoe NOW.com

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.

"Atmospheric Rivers Research, Mitigation and Climate Forecasting Program"
– California State Senate Bill SB-758



California LEGISLATIVE INFORMATION

- Introduced by State Senator Marty Block (building on CW3E's Vision) – Feb. 2015
- Passed both State Houses with strong bipartisan support - August 2015
- Signed by Governor J. Brown – 9 Oct 2015
- Appropriation – June 2016
- Implementation led by F.M. Ralph (PI; UCSD/Scripps Inst. of Ocean./Center for Western Weather and Water Extremes); supports research at 4 UC Campuses, and several other locations

An act to add Article 8 (commencing with Section 347) to Chapter 2.5 of Division 1 of the Water Code, relating to climate change.

[Approved by Governor October 09, 2015. Filed with Secretary of State October 09, 2015.]

Senate Bill No. 758

CHAPTER 682

"THE PEOPLE OF THE STATE OF CALIFORNIA DO ENACT AS FOLLOWS:

SECTION 1. Article 8 (commencing with Section 347) is added to Chapter 2.5 of Division 1 of the Water Code, to read:

Article 8. Atmospheric Rivers: Research, Mitigation, and Climate Forecasting 347.
(a) The Atmospheric Rivers: Research, Mitigation, and Climate Forecasting Program is hereby established in the Department of Water Resources.

(b) Upon appropriation of special fund moneys, including, but not limited to, private funds, for these purposes, the department shall conduct research relating to climate forecasting and the causes and impacts that climate change has on atmospheric rivers, and shall take all actions within its existing authority to operate reservoirs in a manner that improves flood protection in the state and to reoperate flood control and water storage facilities to capture water generated by atmospheric rivers, thereby increasing water supply, hydropower availability, and the reliability of water resources in the state."

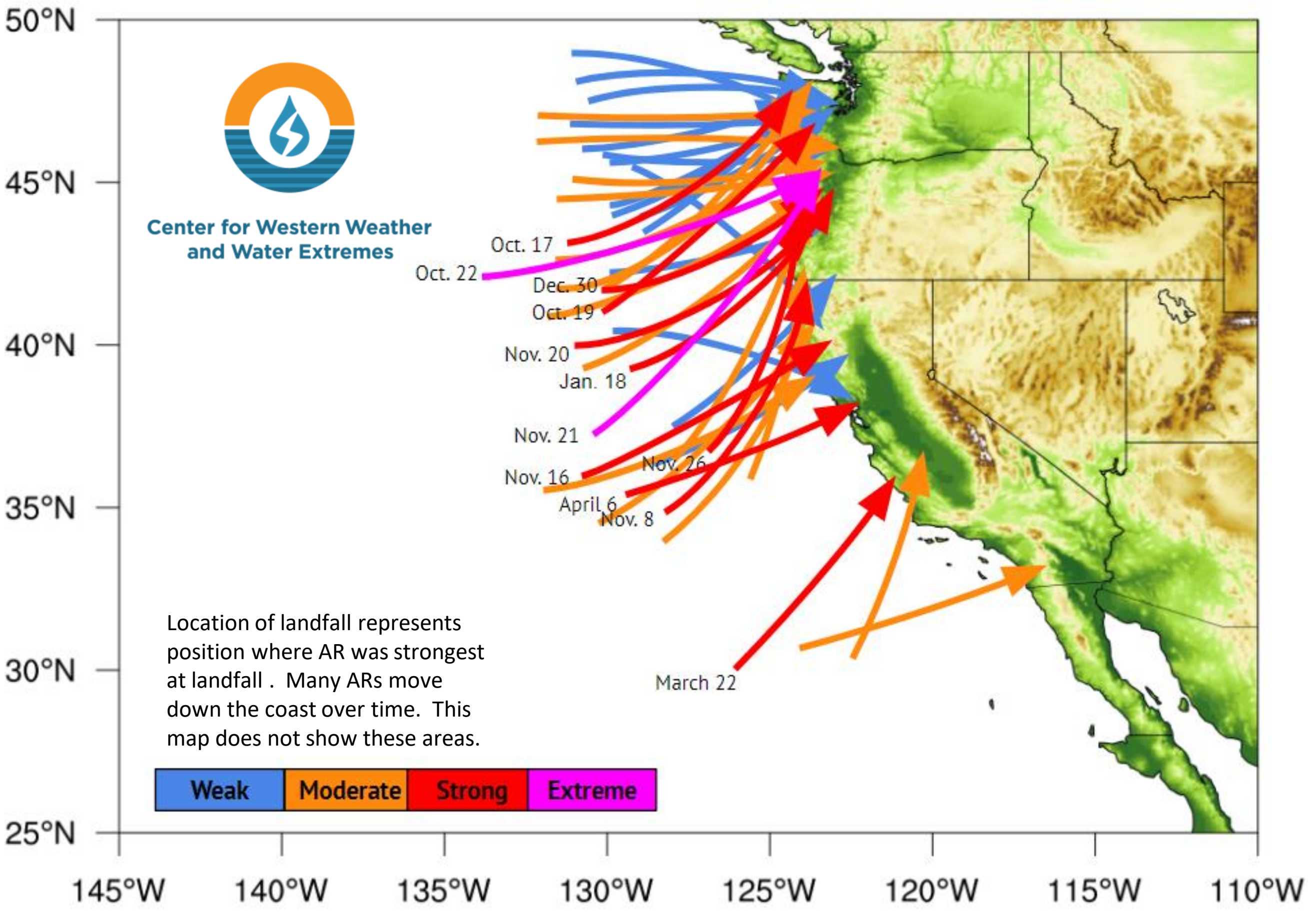
Distribution of Landfalling Atmospheric Rivers on the U.S. West Coast During Water Year 2018 Through April

AR Strength	AR Count
Weak	16
Moderate	16
Strong	10
Extreme	2
Exceptional	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=1000–1250 kg m^{-1} s^{-1}
- Exceptional: IVT>1250 kg m^{-1} s^{-1}

- **44** Atmospheric Rivers made landfall on the West Coast during the 2018 water year through April



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raft (= 9 st in 20

Total
282
762
447
1167

* IARC
* 4th Clim Assmt
* AR Program
* AR Book
* AR Scale
** AR Recon
** ECMWF AR Workshop & other AGU/AMS sessions
** ARTMIP & ARDT paper
* AR Definition
** FIRO
** Polar-ACE
** Global
** S2S
** AR Forecast Skill
Oroville
** AR Colloquium

** Determining error sources in AR water budgets in reanalyses & models & fixing them!
= AREX

Paleo ARs

GAPS ⇒

AREX
AR Recon
West-WRF
ARTMIP
AR Colloquium
S2S

- Major atmospheric river milestones since IARC-2016
  - Definition published in Glossary of Meteorology after inclusive process
  - Strength of ARs quantified using aircraft data and reanalyse
  - Included as a new (4th) style of "extreme storm" in US 4th Climate Assessment Science Summary
  - Atmospheric River Research, Mitigation and Climate Forecasting Program created
  - AR forecast skill determined adequate to enable FIRO at Lake Mendocino
  - Forecast methods mature as do evaluations of forecast skill
  - Scale/categories developed; in revision for BAMS
  - Book nearing completion; to be published by Springer, available at AGU
  - Key global studies completed
- Major activities well underway
  - S2S tools focused on ARs being developed
  - AR Recon airborne monitoring under development
  - AR Tracking Intercomparison (ARTMIP) project has formed and is providing initial results
- Remaining gaps and emerging directions

Russian River Reservoirs are Dual Purpose

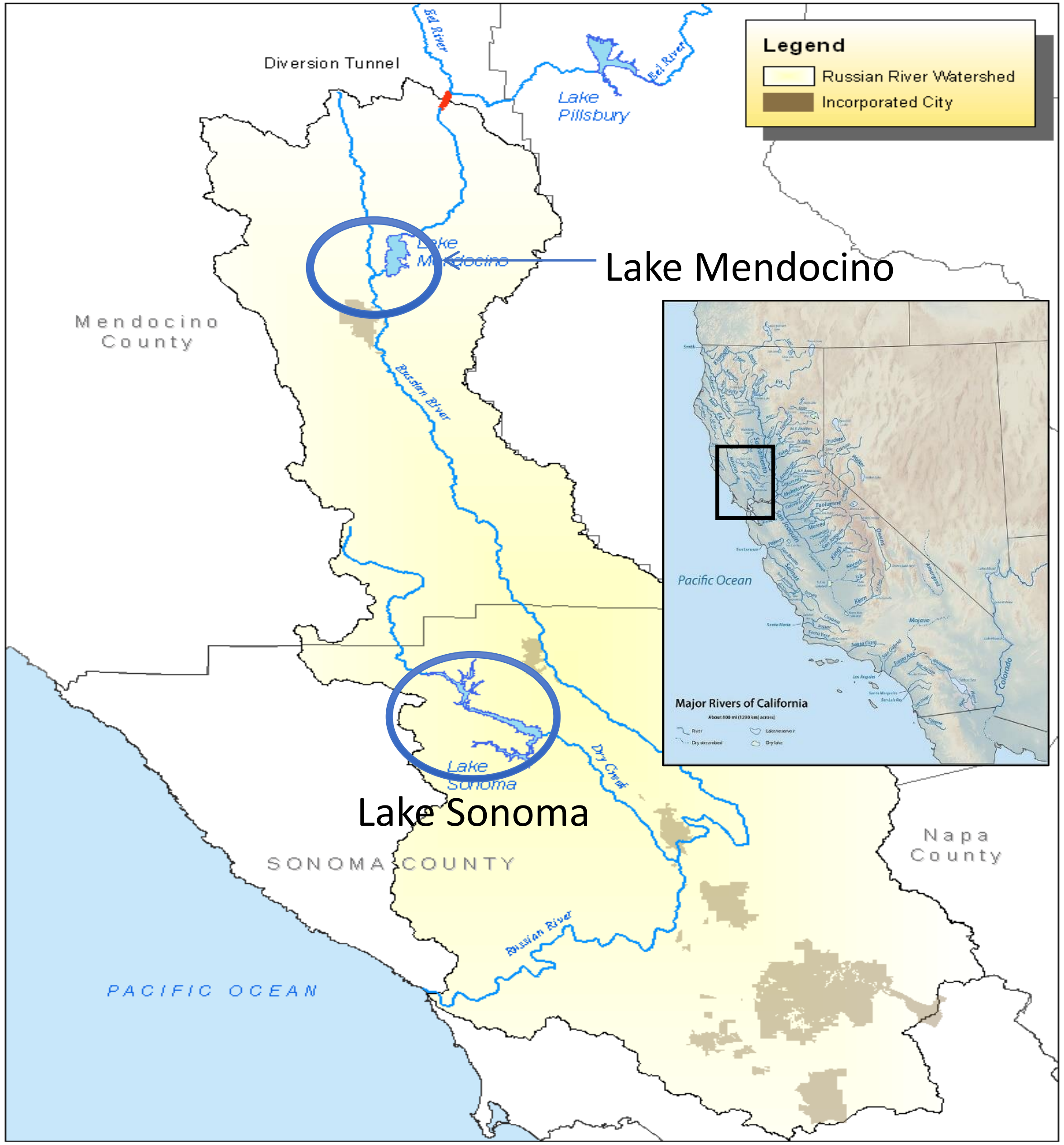
Flood protection in a flood-prone watershed
(US Army Corp of Engineers)

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)

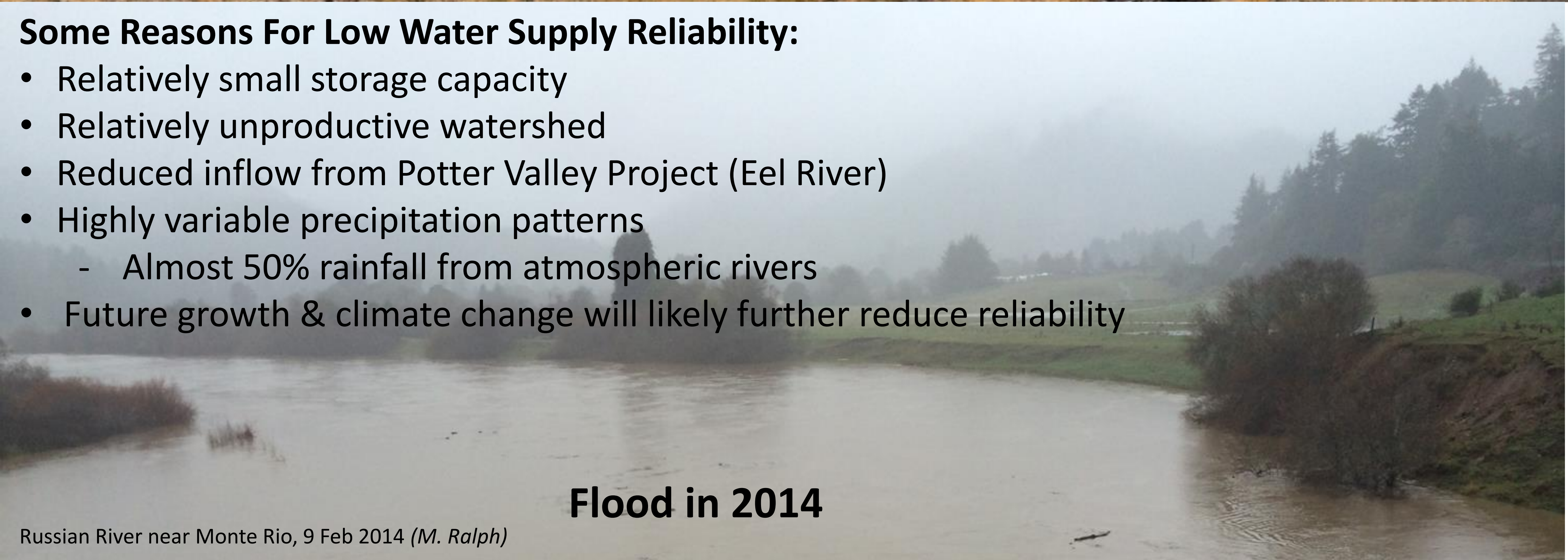


The Issue: Lake Mendocino's Water Supply Is Not Reliable

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



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

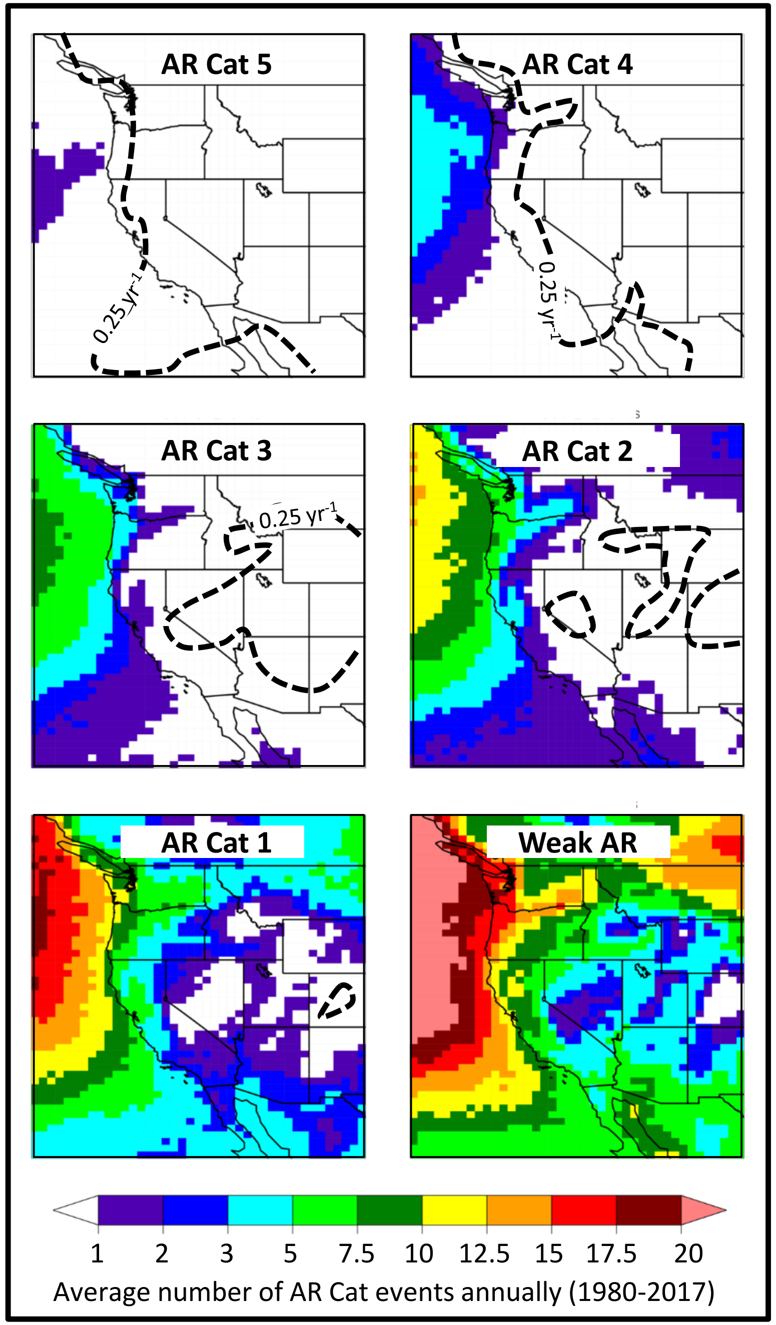
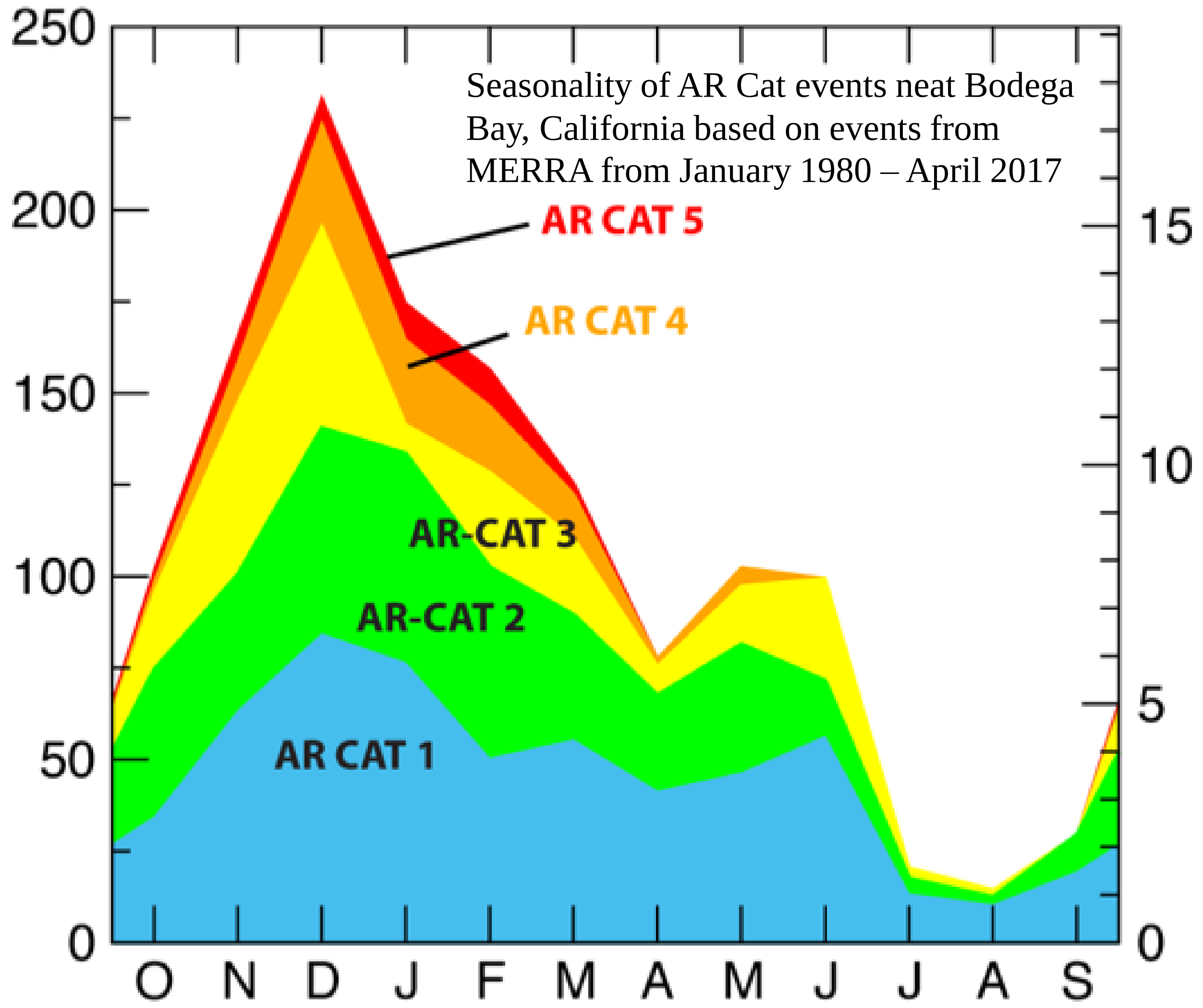


Figure 6: Average annual number of weak ARs and AR Cat 1–5 events from January 1980 – April 2017. Analysis is based on MERRA. Values of at least one per year or greater are shown in color fill, and the frequency of one per four years on average is shown (dashed line).



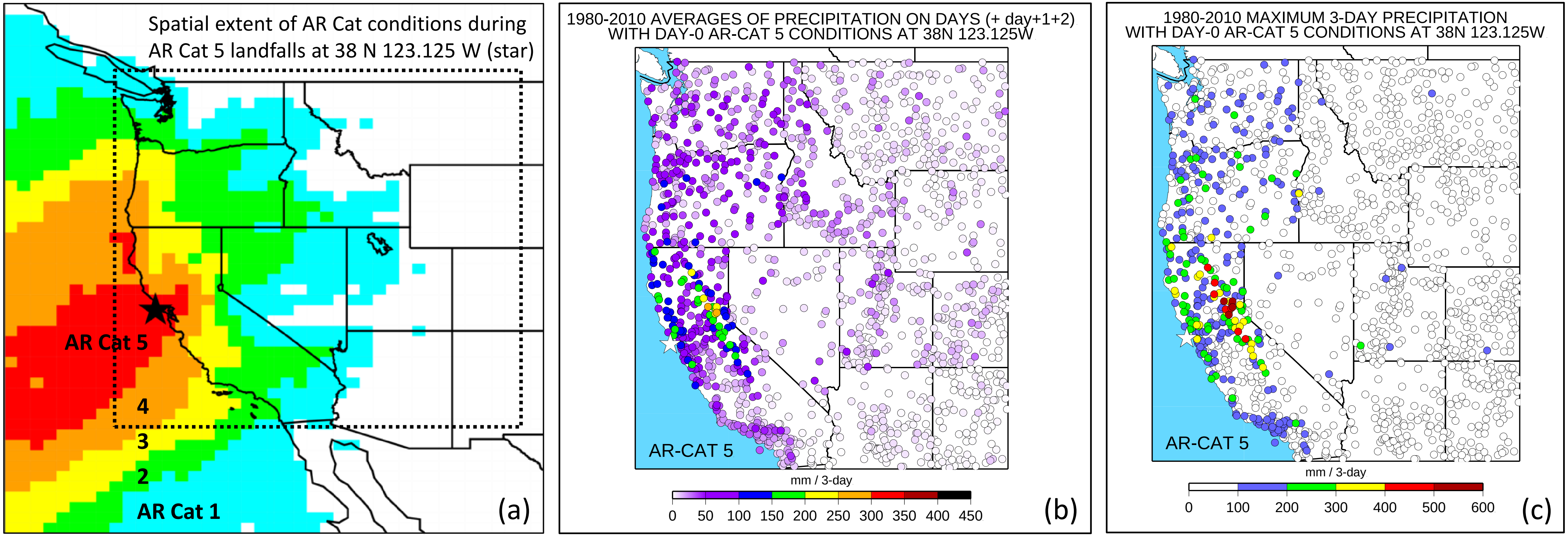
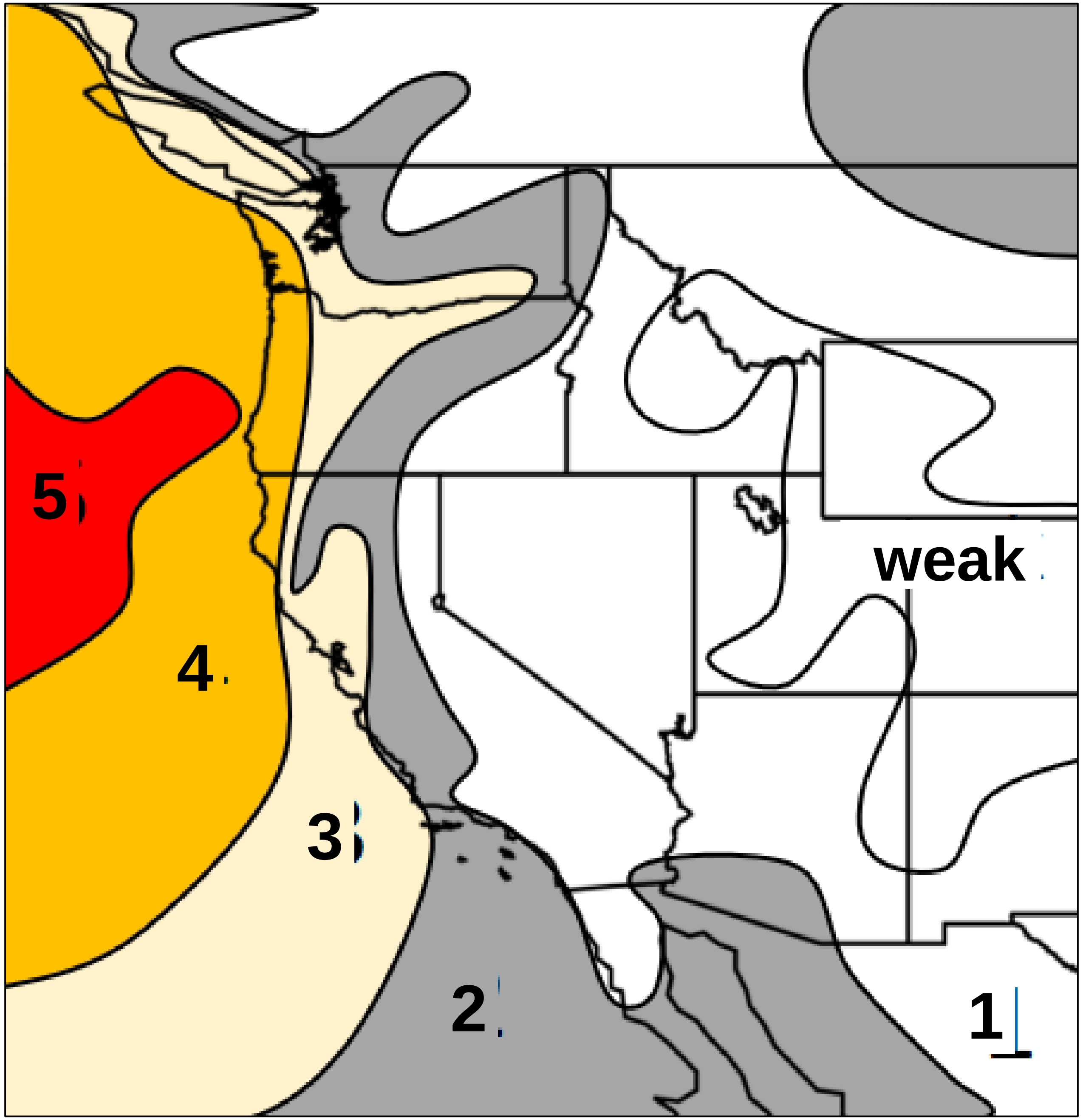


Figure 7. (a) Average of maximum AR Cat conditions during all AR Cat 5 events that occurred at a grid cell near Bodega Bay, California [10 events at 38° N 123.125° W (star)] from MERRA January 1980 – April 2017. (b) Average of 3-day precipitation accumulation on 10 AR Cat 5 events that hit Bodega Bay; 3-day intervals start with the day the event started at Bodega Bay. (c) Same as (b) except that the maximum 3-day totals across all 10 AR Cat 5 events are shown. (b) and (c) use daily COOP precipitation observations (i.e., each dot shown).

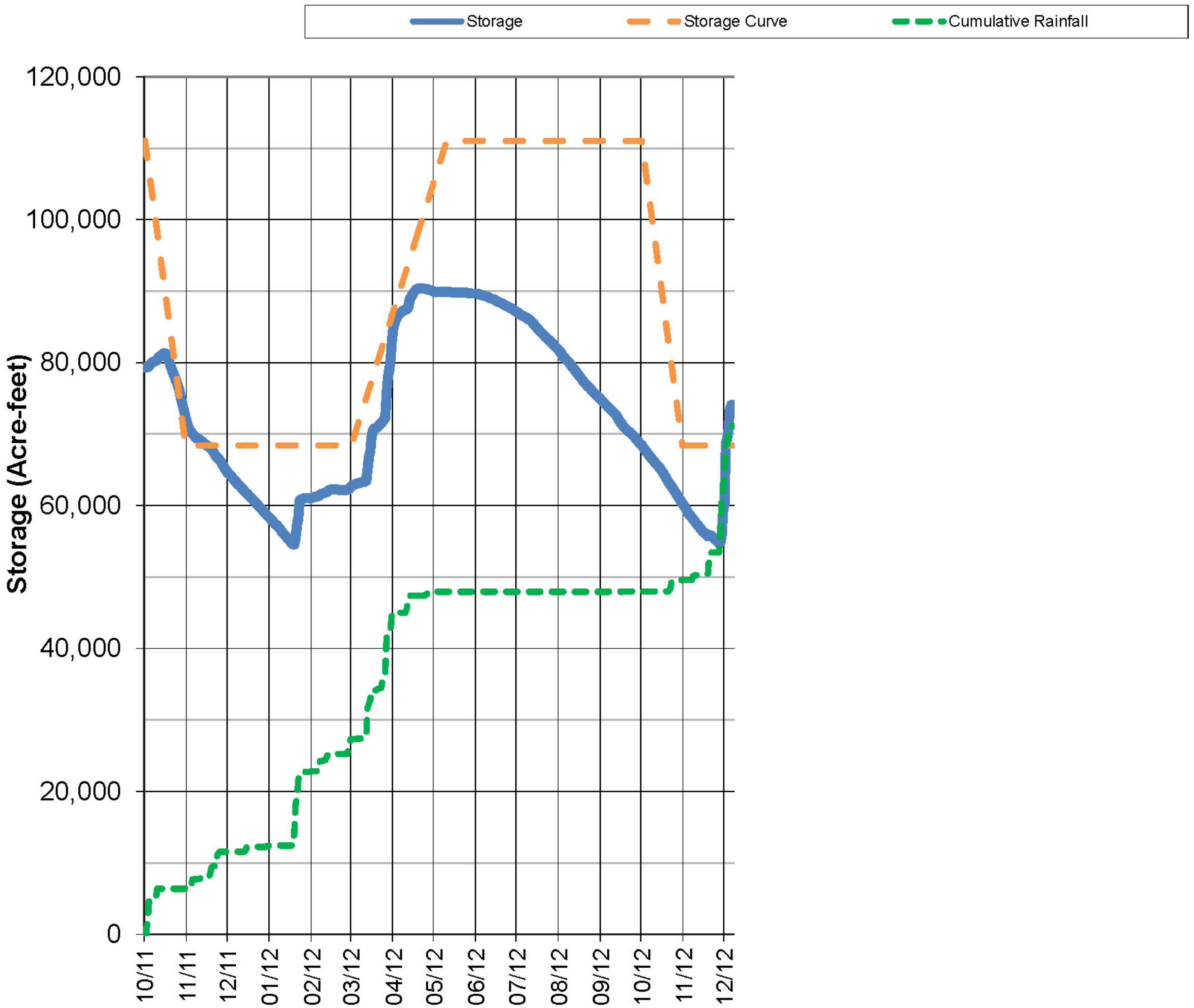
Table 4. Summary of average AR Cat characteristics for ARs that struck Bodega Bay from January 1980 – April 2017.

Characteristic	Weak	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5
# of Events	392	268	138	78	22	9
# of AR Cat Days	599	484	316	225	74	36
Avg duration (h)	13.3	21.0	32.1	47.6	58.2	71.7
StDev duration (h)	4.7	9.5	10.7	18.4	20.6	29.4
Avg Maximum IVT (kg m^{-1} s^{-1})	373.7	480.0	599.4	701.1	896.6	1118.0
StDev Maximum IVT (kg m^{-1} s^{-1})	62.4	108.6	104.4	147.0	111.1	127.6
Avg Storm-total IVT (10^7 kg m^{-1})	1.6	2.8	4.8	7.7	10.7	15.4
StDev Storm-total IVT (10^7 kg m^{-1})	1.2	1.1	1.4	2.8	3.8	5.7
Avg 3-d IVT (10^7 kg m^{-1})*	4.9	5.7	6.7	7.9	9.5	11.2
StDev 3-d IVT (10^7 kg m^{-1})*	0.4	1.5	1.8	2.4	3.0	3.7



Average Annual Maximum AR Cat

Lake Mendocino Water Years 2012 - 2014



Lake Mendocino FIRO Steering Committee

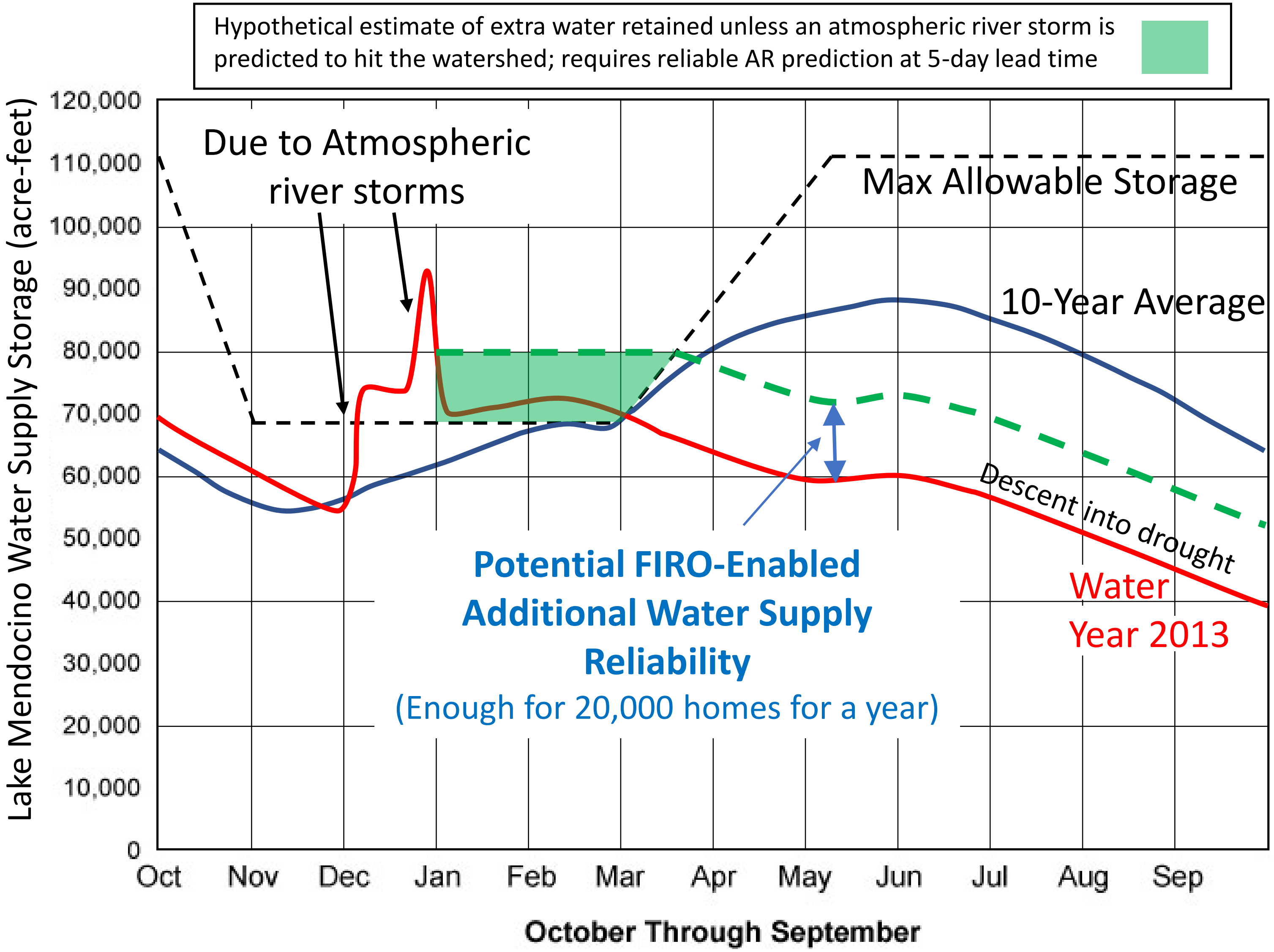
- **Co-Chairs**
  - Jay Jasperse – Sonoma County Water Agency
  - F. Martin Ralph – UCSD / SIO / CW3E
- **Members**
  - Michael Anderson – California DWR
  - Levi Brekke – USBR
  - Mike Dillabough – USACE / SPN
  - Michael Dettinger – USGS
  - Joe Forbis – USACE / SPK
  - Alan Haynes – NOAA / NWS
  -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

Lake Mendocino Forecast-Informed Reservoir Operations Concept

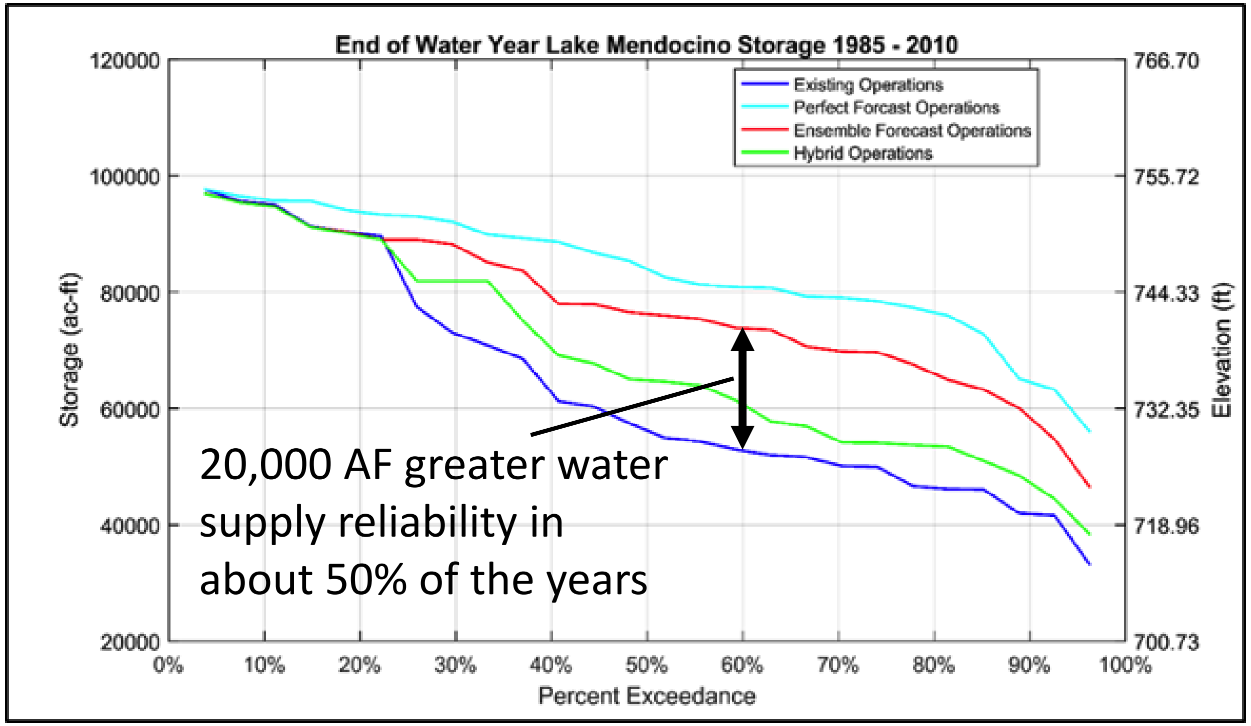


Selected results of FIRO-motivated science

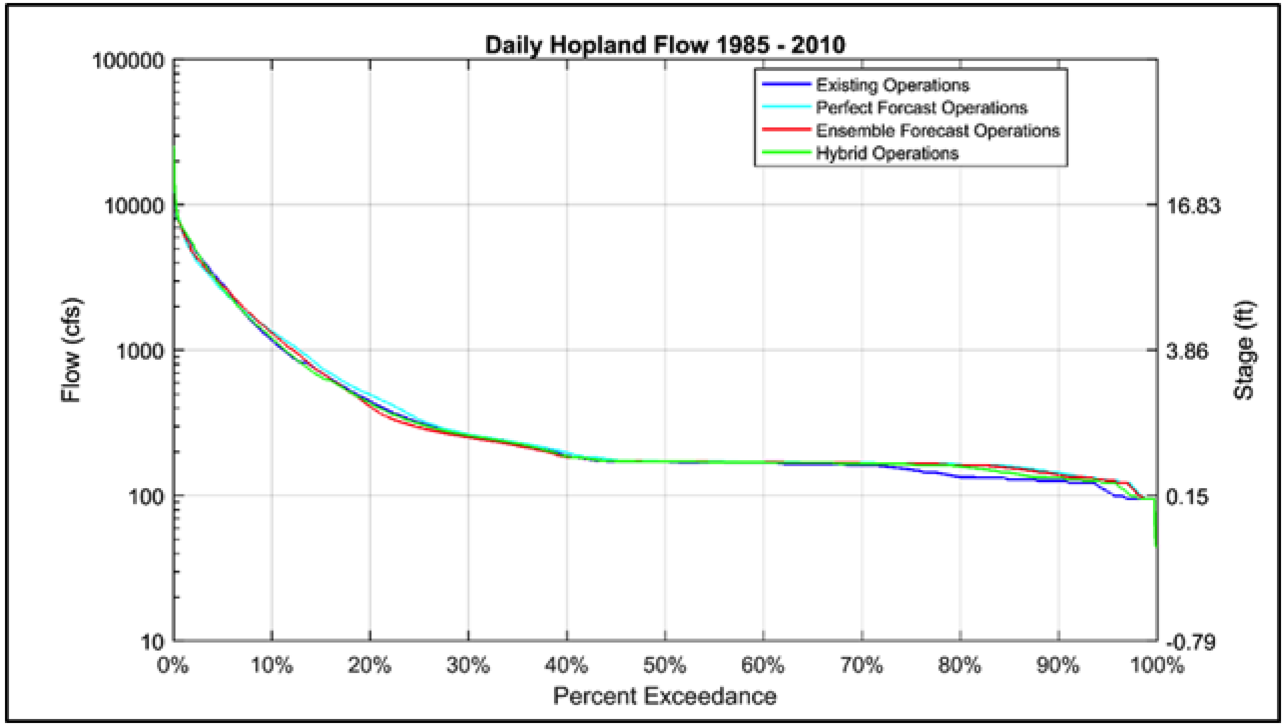
- Established forecast skill requirements, e.g., 3-5 day lead time on heavy precipitation and runoff forecasts
- ARs are the main weather phenomenon that causes extremes
- AR landfall forecasts have useful skill out to a few days
- Mesoscale frontal waves are key source of forecast busts
- AR Recon offers 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 at Lake Mendocino in Northern California (FIRO Steering Committee; Jasperse and Ralph co-chairs)

Water Supply



Flood Risk

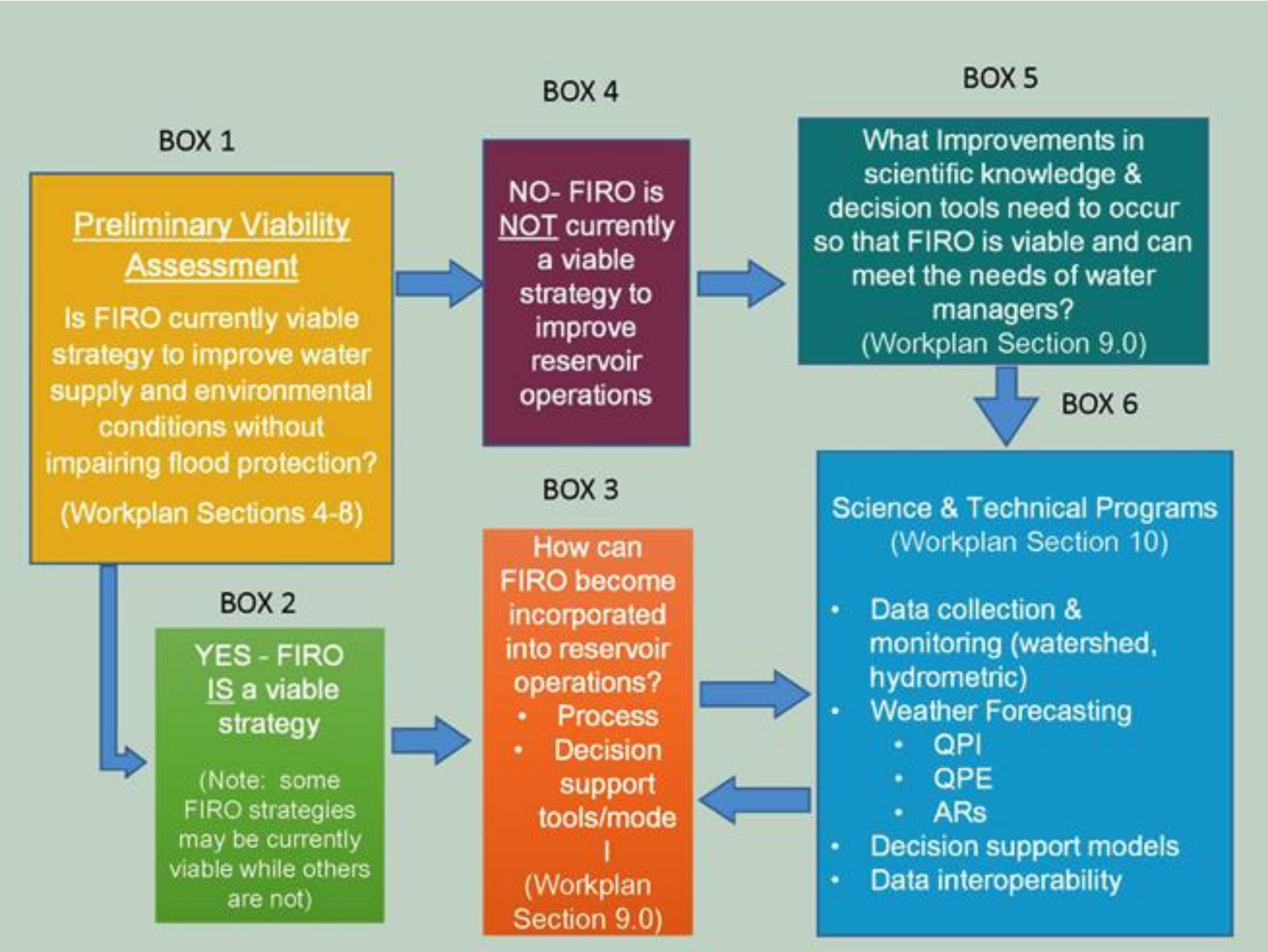


✓Substantial gains in water storage over existing operations by leveraging information in streamflow forecasts enabled by skill in AR forecasts

✓Downstream flood control benefits are not impacted

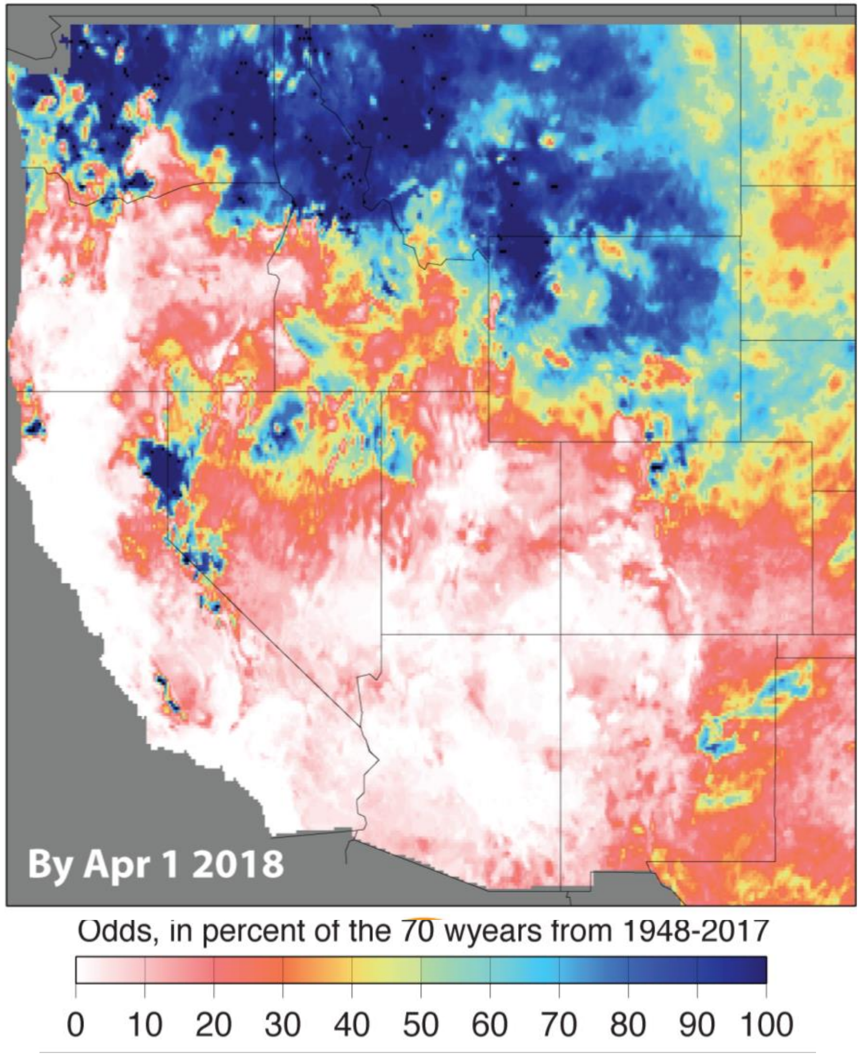
*Forecast-Informed Reservoir Operations
cw3e.ucsd.edu/FIRO/

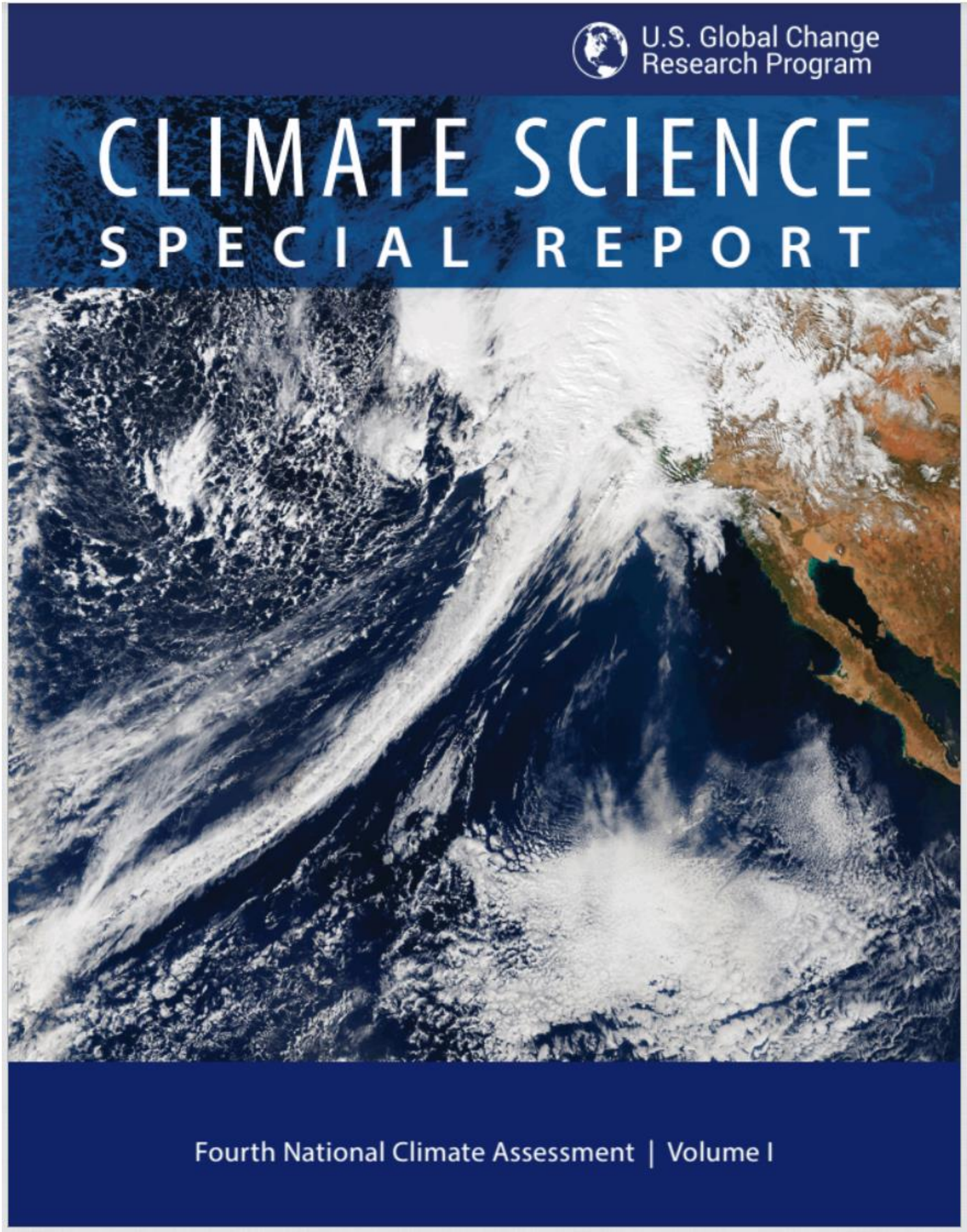
FIRO Viability Assessment Process



ODDS OF WY2018 REACHING 100% OF WATER-YEAR NORMAL PRECIPITATION TOTALS

[based on PRISM monthlies; normal = average of WY1981-2010]



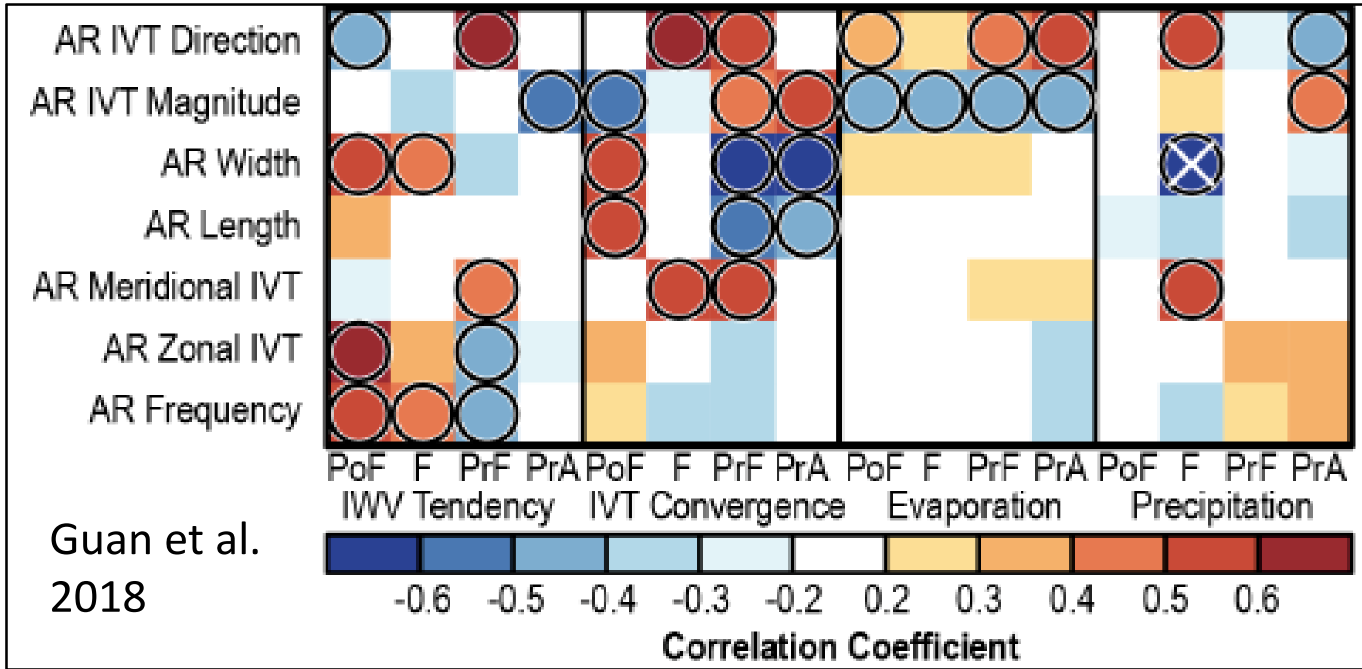


Atmospheric Rivers Highlighted in the U.S. Fourth National Climate Assessment, released on 3 November 2017

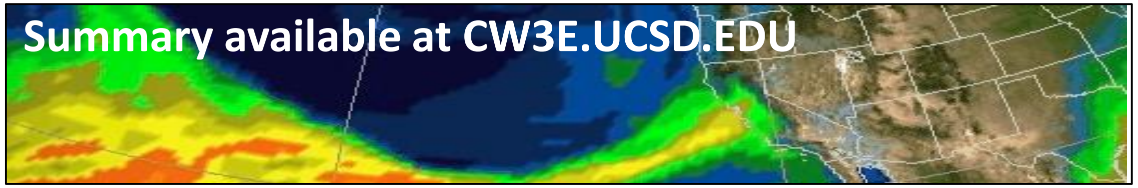
9 Extreme Storms

KEY FINDINGS

5. The frequency and severity of landfalling "atmospheric rivers" on the U.S. West Coast (narrow streams of moisture that account for 30%–40% of the typical snowpack and annual precipitation in the region and are associated with severe flooding events) will increase as a result of increasing evaporation and resulting higher atmospheric water vapor that occurs with increasing temperature. (*Medium confidence*)



Guan et al. 2018

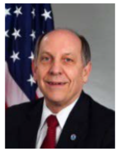


Congressional Staff Briefing on July 13, 2016

"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



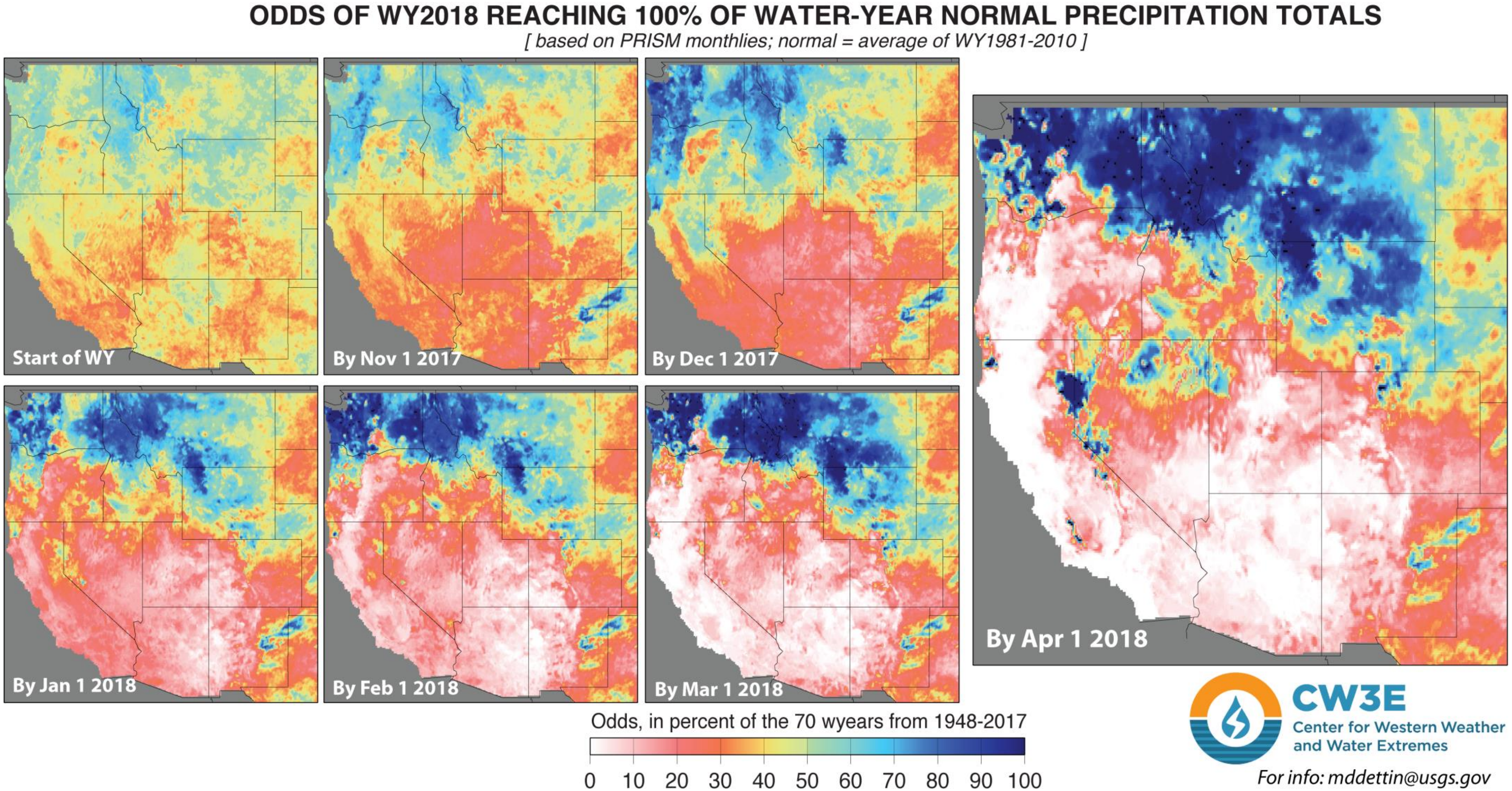
Dr. Louis W. Uccellini is Assistant Administrator for Weather Services, National Oceanic and Atmospheric Administration (NOAA), and Director, National Weather Service. His presentation may be found [HERE].

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.



- How the developing drought has evolved in terms of the odds of reaching 100% of normal precipitation by end of WY2018.

- Notice how drought conditions have developed across the Southwest, as odds of reaching normal have progressively dwindled month by month. Also notice that, although March was pretty wet in California/Nevada, it was—arguably—too little too late to set us up for reaching 100% of normal this year, in all but a few locales.

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
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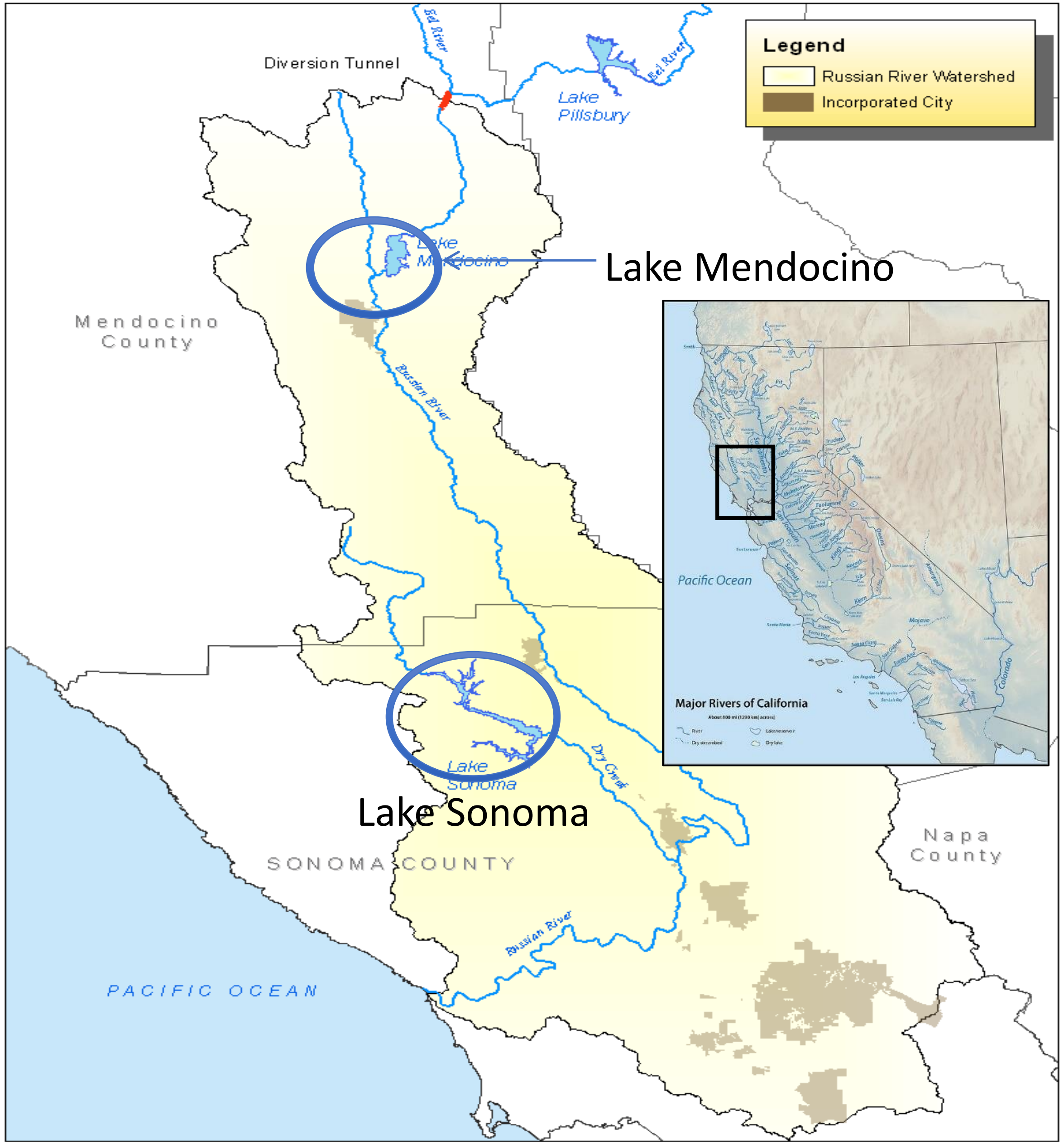
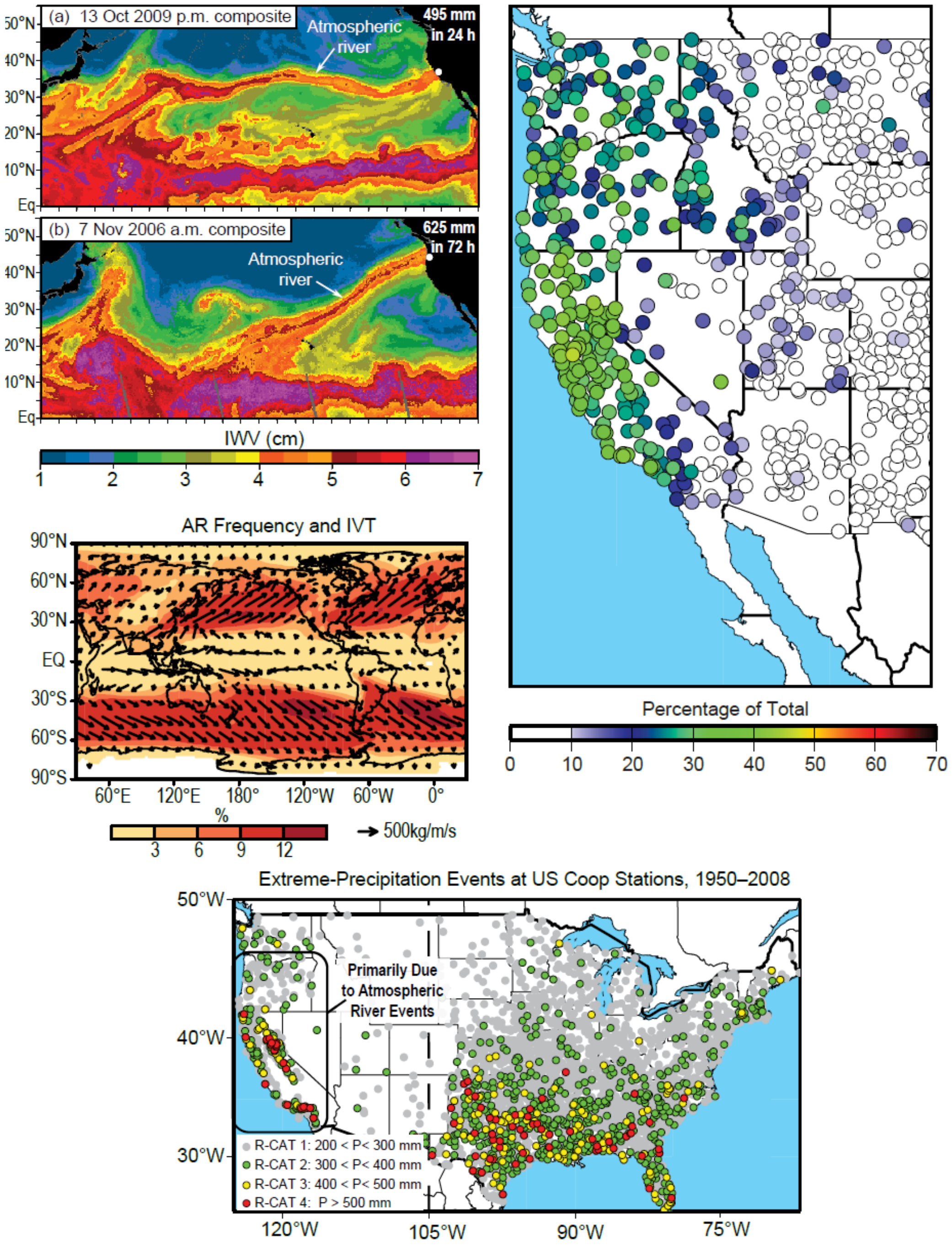




9 Extreme Storms

KEY FINDINGS

1. Human activities have contributed substantially to observed ocean–atmosphere variability in the Atlantic Ocean (*medium confidence*), and these changes have contributed to the observed upward trend in North Atlantic hurricane activity since the 1970s (*medium confidence*).

2. Both theory and numerical modeling simulations generally indicate an increase in tropical cyclone (TC) intensity in a warmer world, and the models generally show an increase in the number of very intense TCs. For Atlantic and eastern North Pacific hurricanes and western North Pacific typhoons, increases are projected in precipitation rates (*high confidence*) and intensity (*medium confidence*). The frequency of the most intense of these storms is projected to increase in the Atlantic and western North Pacific (*low confidence*) and in the eastern North Pacific (*medium confidence*).

3. Tornado activity in the United States has become more variable, particularly over the 2000s, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). Confidence in past trends for hail and severe thunderstorm winds, however, is *low*. Climate models consistently project environmental changes that would putatively support an increase in the frequency and intensity of severe thunderstorms (a category that combines tornadoes, hail, and winds), especially over regions that are currently prone to these hazards, but confidence in the details of this projected increase is *low*.

4. There has been a trend toward earlier snowmelt and a decrease in snowstorm frequency on the southern margins of climatologically snowy areas (*medium confidence*). Winter storm tracks have shifted northward since 1950 over the Northern Hemisphere (*medium confidence*). Projections of winter storm frequency and intensity over the United States vary from increasing to decreasing depending on region, but model agreement is poor and confidence is *low*. Potential linkages between the frequency and intensity of severe winter storms in the United States and accelerated warming in the Arctic have been postulated, but they are complex, and, to some extent, contested, and confidence in the connection is currently *low*.

5. The frequency and severity of landfalling "atmospheric rivers" on the U.S. West Coast (narrow streams of moisture that account for 30%–40% of the typical snowpack and annual precipitation in the region and are associated with severe flooding events) will increase as a result of increasing evaporation and resulting higher atmospheric water vapor that occurs with increasing temperature. (*Medium confidence*)

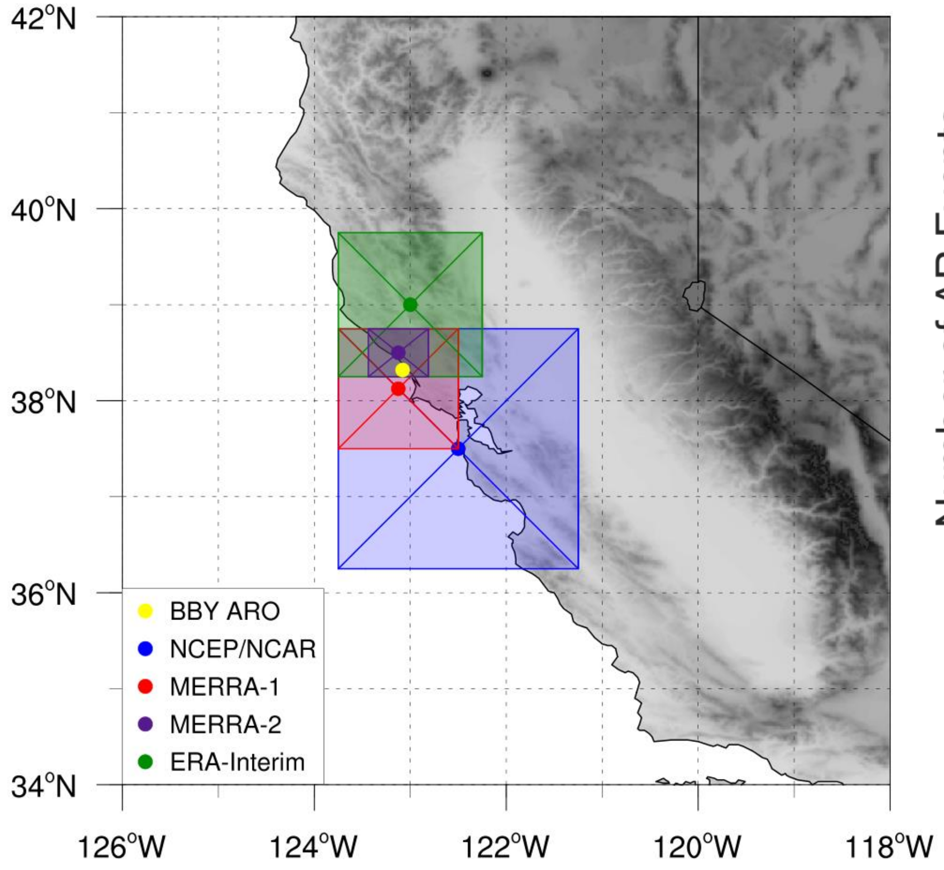
9.5 Atmospheric Rivers

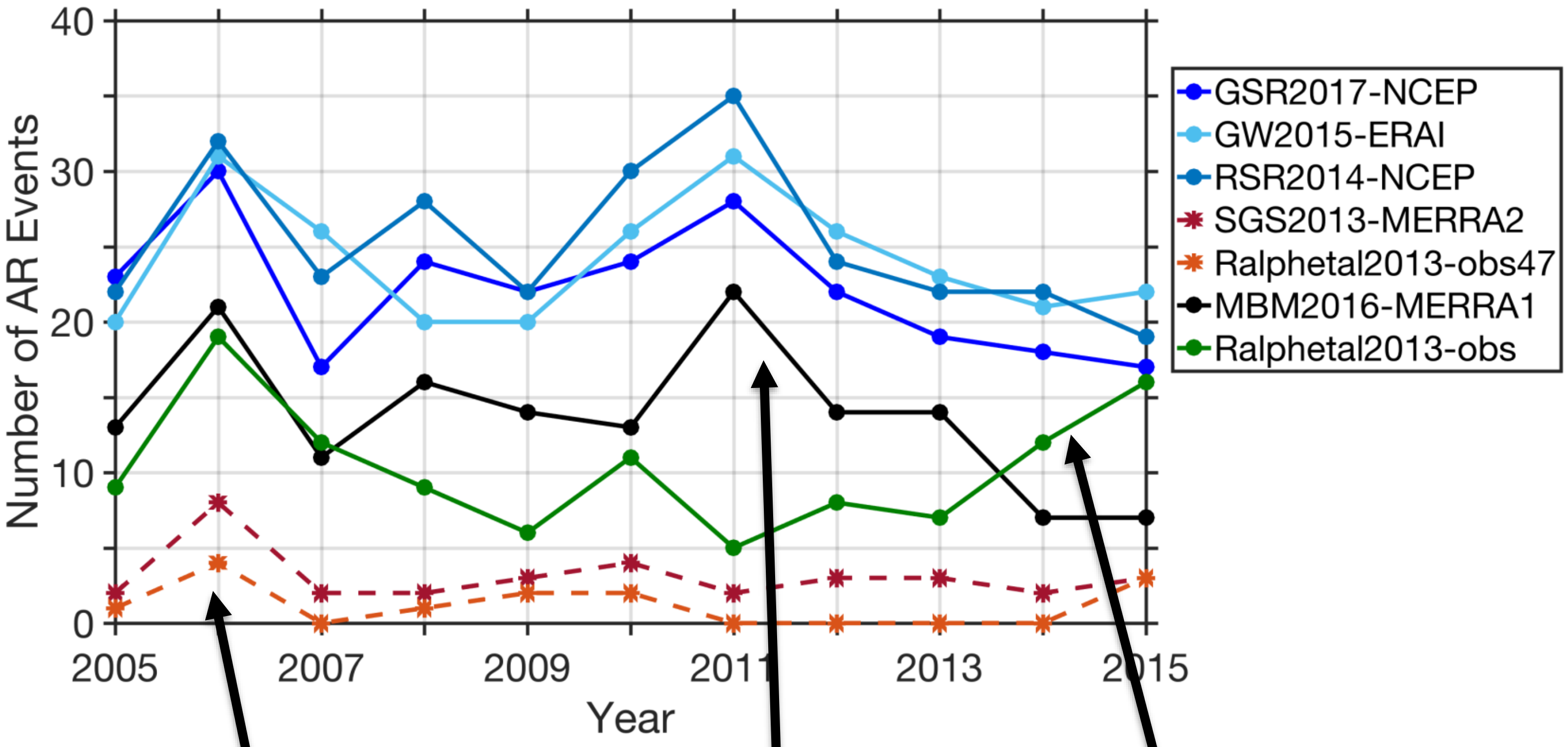
The term "atmospheric rivers" (ARs) refers to the relatively narrow streams of moisture transport that often occur within and across midlatitudes[70] (Figure 9.4), in part because they often transport as much water as in the Amazon River.[71] While ARs occupy less than 10% of the circumference of Earth at any given time, they account for 90% of the poleward moisture transport across midlatitudes (a more complete discussion of precipitation variability is found in Ch. 7: Precipitation Change). In many regions of the world, they account for a substantial fraction of the precipitation,[72] and thus water supply, often delivered in the form of an extreme weather and precipitation event (Figure 9.4). For example, ARs account for 30%–40% of the typical snowpack in the Sierra Nevada mountains and annual precipitation in the U.S. West Coast states[73, 74]—an essential summertime source of water for agriculture, consumption, and ecosystem health. However, this vital source of water is also associated with severe flooding—with observational evidence showing a close connection between historically high streamflow events and floods with landfalling AR events—in the west and other sectors of the United States.[75, 76, 77] More recently, research has also demonstrated that ARs are often found to be critical in ending droughts in the western United States.[78]

Kossin, J.P., T. Hall, T. Knutson, K.E. Kunkel, R.J. Trapp, D.E. Waliser, and M.F. Wehner, 2017: Extreme storms. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 257-276, doi: 10.7930/J07S7KXX

Figure 9.4: (upper left) Atmospheric rivers depicted in Special Sensor Microwave Imager (SSM/I) measurements of SSM/I total column water vapor leading to extreme precipitation events at landfall locations. (middle left) Annual mean frequency of atmospheric river occurrence (for example, 12% means about 1 every 8 days) and their integrated vapor transport (IVT).[72] (bottom) ARs are the dominant synoptic storms for the U.S. West Coast in terms of extreme precipitation[93] and (right) supply a large fraction of the annual precipitation in the U.S. West Coast states.[73] [Figure source: (upper and middle left) Ralph et al. 2011,[94] (upper right) Guan and Waliser 2015,[72] (lower left) Ralph and Dettinger 2012,[93] (lower right) Dettinger et al. 2011;[73] left panels, © American Meteorological Society. Used with permission.]

Different Methods and Different Reanalyses





Higher IVT threshold ($500\ kg\ m^{-1}\ s^{-1}$)

Strict geometric criteria

Observational dataset with missing periods

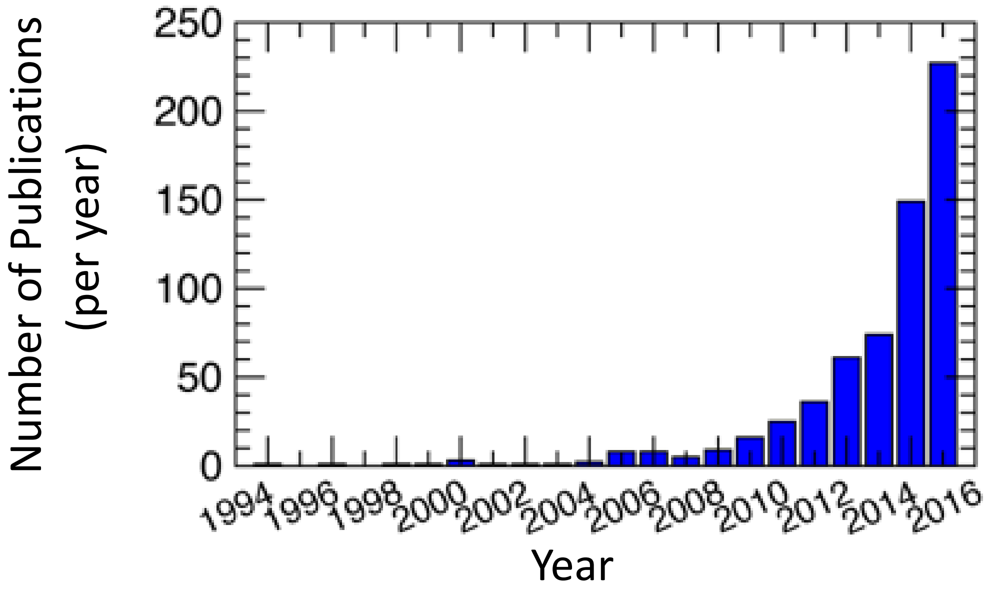
Overall Results – How Many ARs Hit the Russian River?

ARDT	Avg Annual AR Events	IVT Threshold (kg m^{-1} s^{-1})	IWV Threshold (mm)	Geometric (Length, km)	Geometric (Width km, or ratio)	Geometric/ Duration (Other)
RSR2014-NCEP	22±5	250	No	>2000	No	No
GSR2017	21±4	250	15	>1500	No	No
GW2015-ERAI	20±3	166-254	No	>2000	L/W > 2	Yes
WNR2013-IVT*	15±3	250	No	>2000	<1000; L/W > 1.4	Yes
MBM2016	13±3	209-283	No	>1400	L/W > 1.6	Yes
Based on much higher IVT threshold						
SGS2013*	2±1	500	No	No	No	Yes
WNR2013-IVT500*	1±1	500	No	>1500	<1000	Yes
Not based on IVT						
WNR2013-IWV***	22±6	No	20	>1500	<1000	Yes
Ralphetal2013-Obs**	11±5	250 (20 cm m/s)	20	No	No	Yes
Ralphetal-Obs47*,**	1±1	500 (47 cm m/s)	20	No	No	Yes

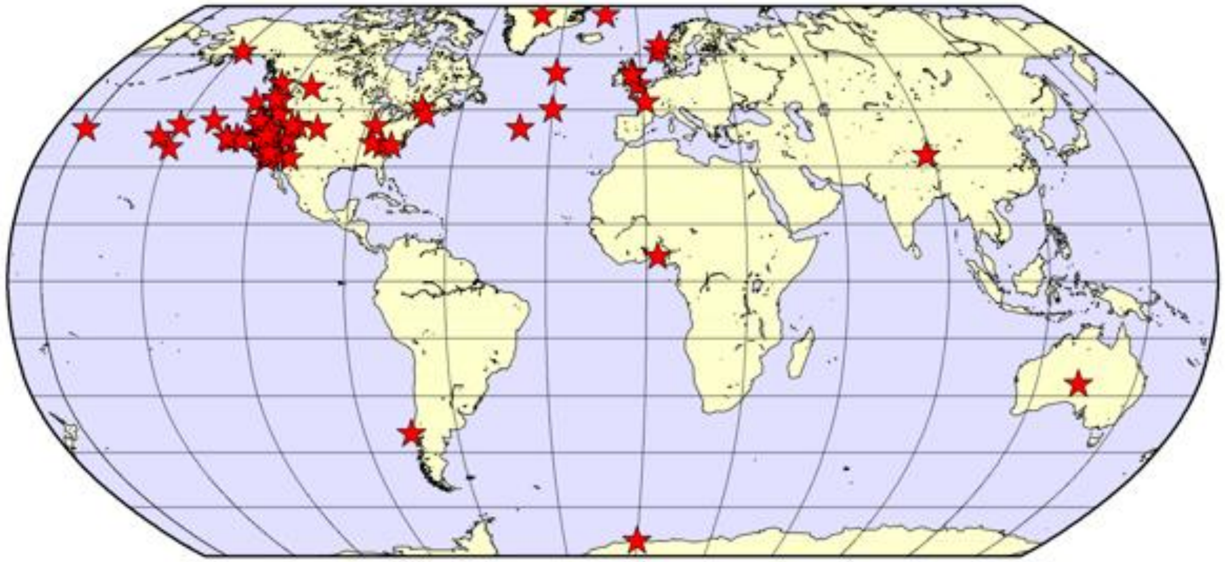
Atmospheric Rivers Emerge as a Global Science and Applications Focus: A summary of the First International Atmospheric Rivers Conference (IARC-2016)

Ralph, F. M., 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

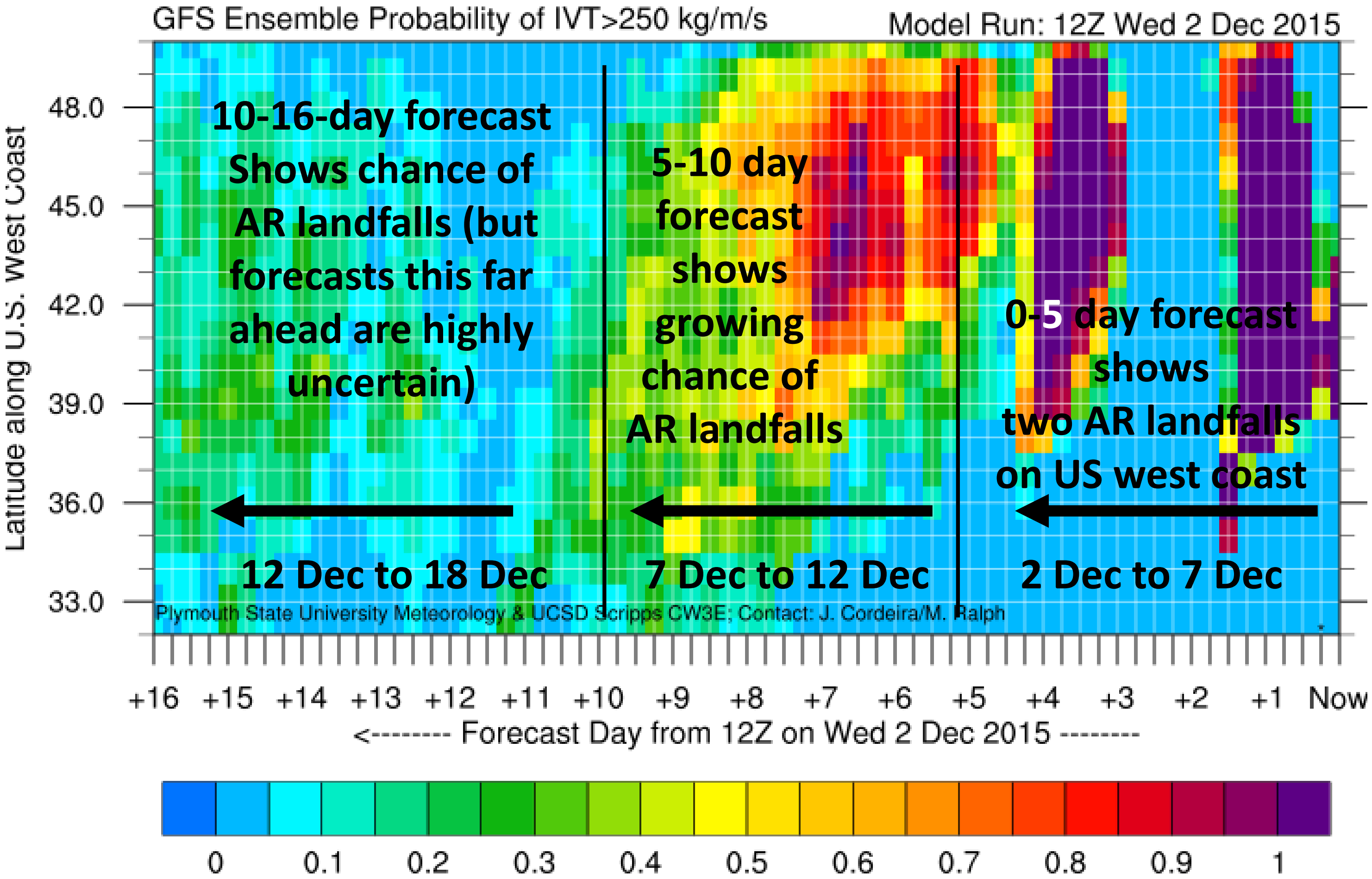
a) Scientific literature discussing ARs

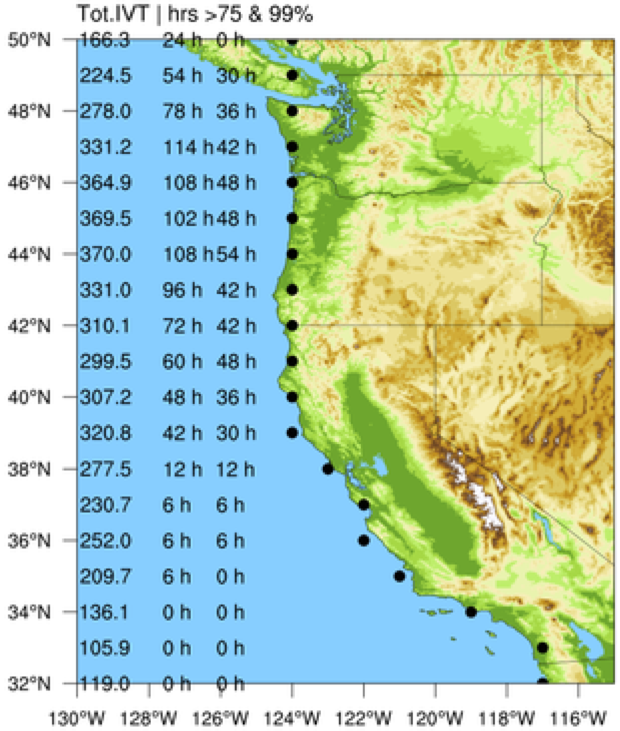


b) Locations of studies and scientists at IARC



Forecast chances of landfall of at least WEAK Atmospheric River conditions on the U.S. West Coast from 2 to 18 Dec 2015 - updates at cw3e.ucsd.edu ***(Cordeira et al. BAMS 2017 describes AR forecasting for CalWater)***





What does this diagram show? The main diagram (left display) is read from *right* to *left* at a given latitude in order to indicate how many days from today AR conditions are likely at the coast. By plotting the display from *right* to *left*, the display shows you "what is in the pipeline" as storm systems generally move from west to east. This diagram shows the chances (i.e., probability) of having at least weak "atmospheric river" conditions (i.e., strong horizontal water vapor transport, called "IVT" exceeding 250 kg/m/s) at different latitudes along the U.S. West Coast from "today" through the next 16 days at 6-hour increments. It uses a threshold of IVT>250 kg/m/s as the threshold for AR conditions based on years of study. The landfall locations are the black dots in the right-most panel. The probability is based on 21 different forecasts run simultaneously with slightly different starting conditions (which simulates the "butterfly effect"). The forecasts are from the NOAA/NWS' "GFS" global weather forecast model. The probability is shaded on a scale from 0% (blue) to 100% (purple). The landfall locations are the black dots in the right-most panel. The right map-panel shows the total 16-day time-integrated IVT (Tot.IVT) for that location in millions of kg/m (left column of numbers). The diagram also shows the number of hours a location along the coast may expect to see AR conditions along with uncertainty. These hours are drawn in the region next to the U.S. West Coast in the right-most panel. These numbers represent the number of hours (over the next 16 days) a location has a 75% chance of AR conditions (middle column of numbers) or a 99% chance of AR conditions (right column of numbers). The higher this number, the longer AR conditions are likely and the more precipitation may be expected!

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. Hydrometeorology (2017)

Method/Data: Uses 21 AR cases observed in 2005 - 2016 with full dropsonde transects.

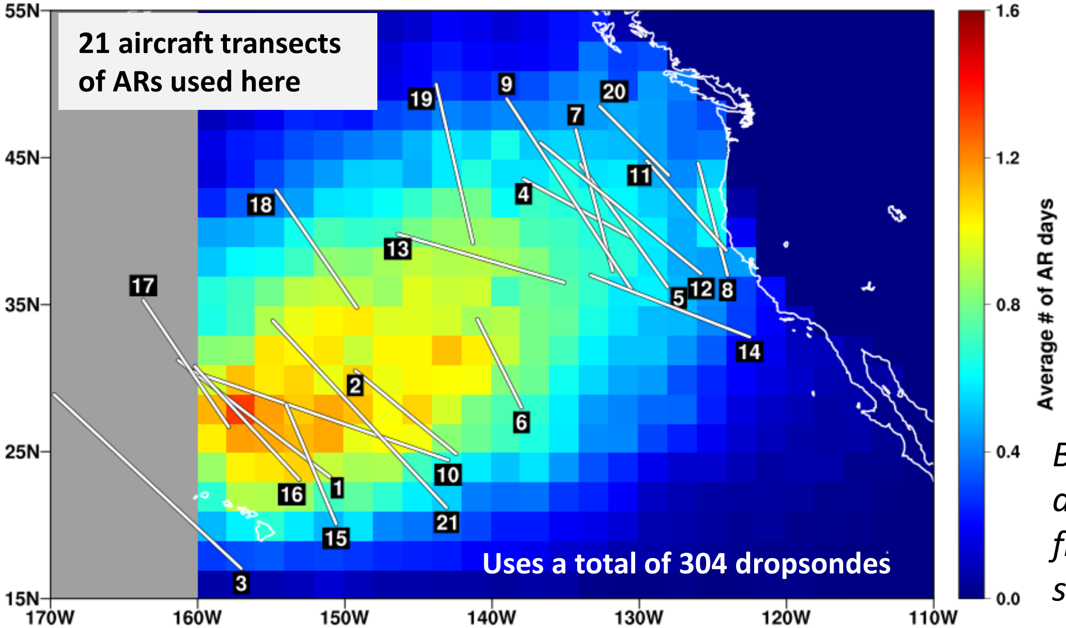
- AR edges best defined by using IVT = 250 kg m^{-1} s^{-1}

Conclusions*:

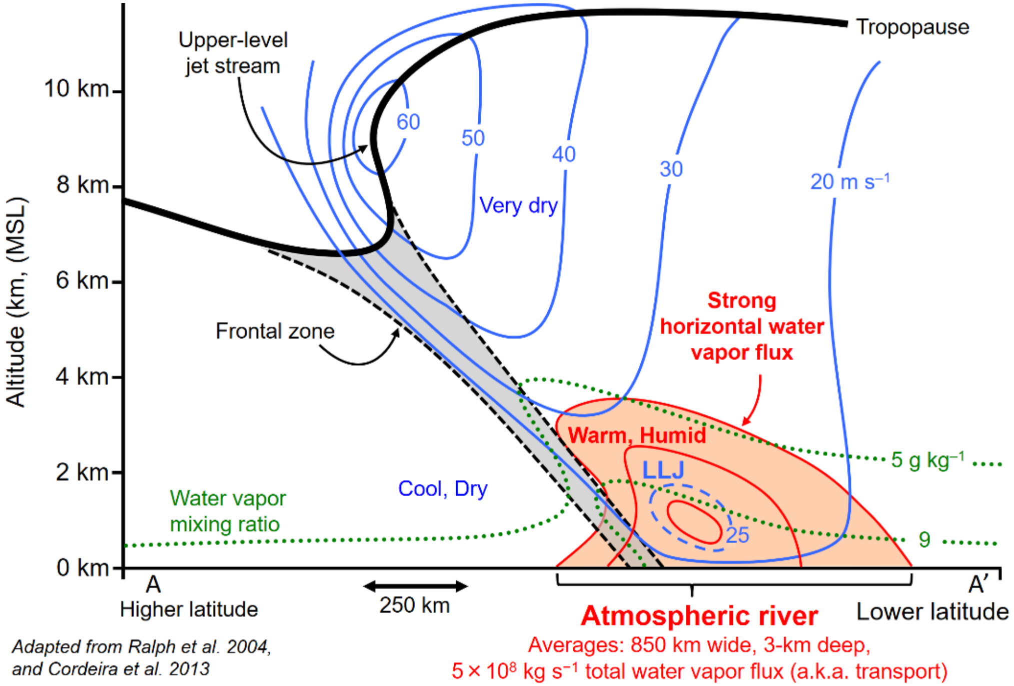
- Average width: 850 km
- 75% of water vapor transport occurs below 3 km MSL; < 1% occurs above 8 km MSL
- Average max IVT: ~800 kg m^{-1} s^{-1}

KEY FINDING

An average AR* transports 4.7 ± 2.0 x 10^8 kg s^{-1} of water vapor, which is equivalent to 2.6 times the average discharge of liquid water by the Amazon River



Synthesis from 21 observed ARs; Used in the Glossary of Meteorology's Definition of "Atmospheric River."

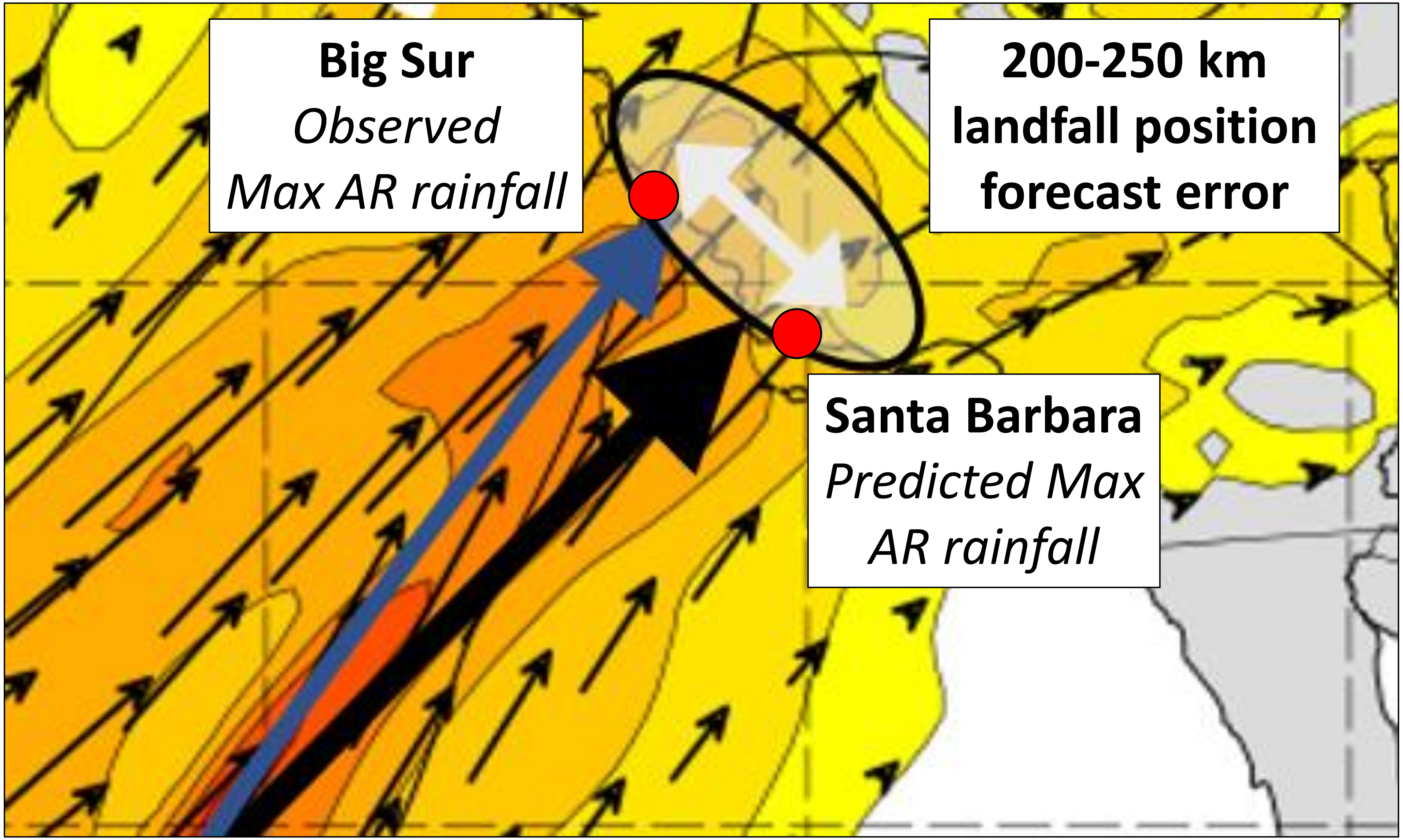


**These values represent averages for the Northeast Pacific Ocean in the January-March season*

Background image denotes weekly AR frequency during cool seasons (Nov -Feb).

AR Forecast Evaluation: 22 March 2018

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



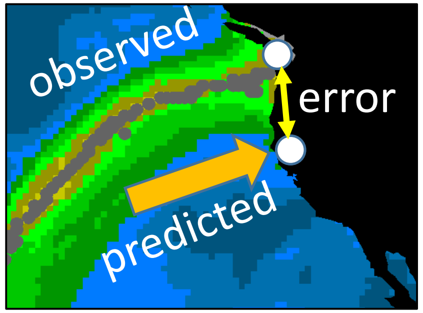
Precipitation forecast error pattern was a dipole, representing mostly a position error in the location of the heavy precipitation

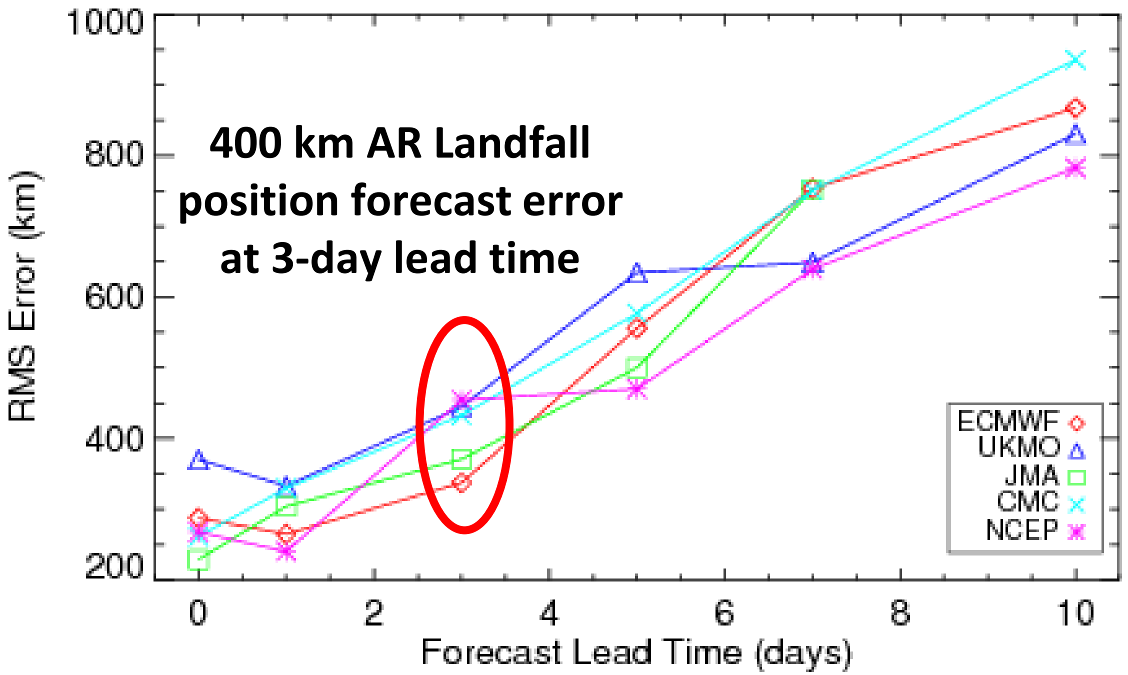
Atmospheric River Reconnaissance

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.

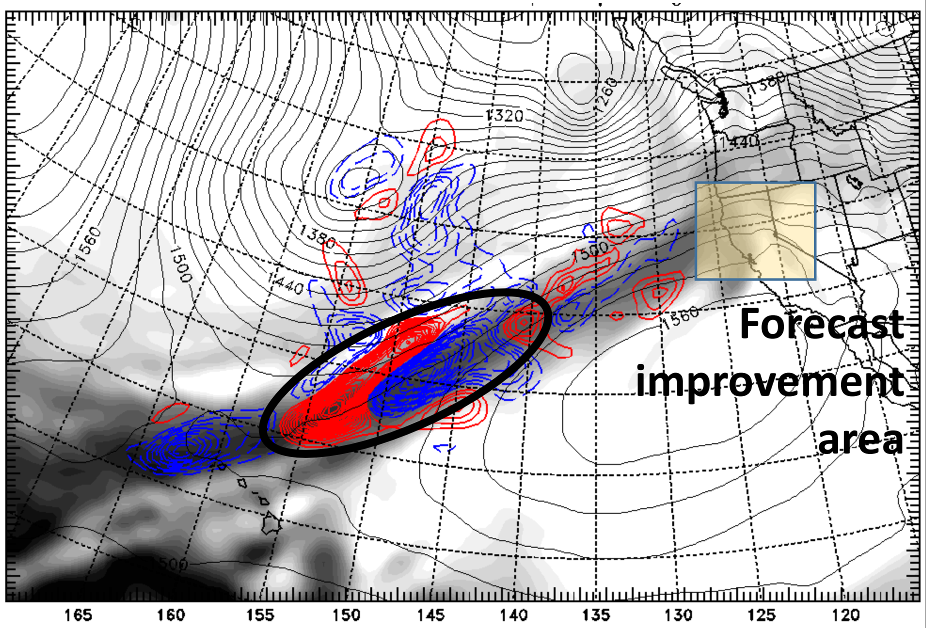
New Adjoint includes moisture – and finds AR is prime target

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.**