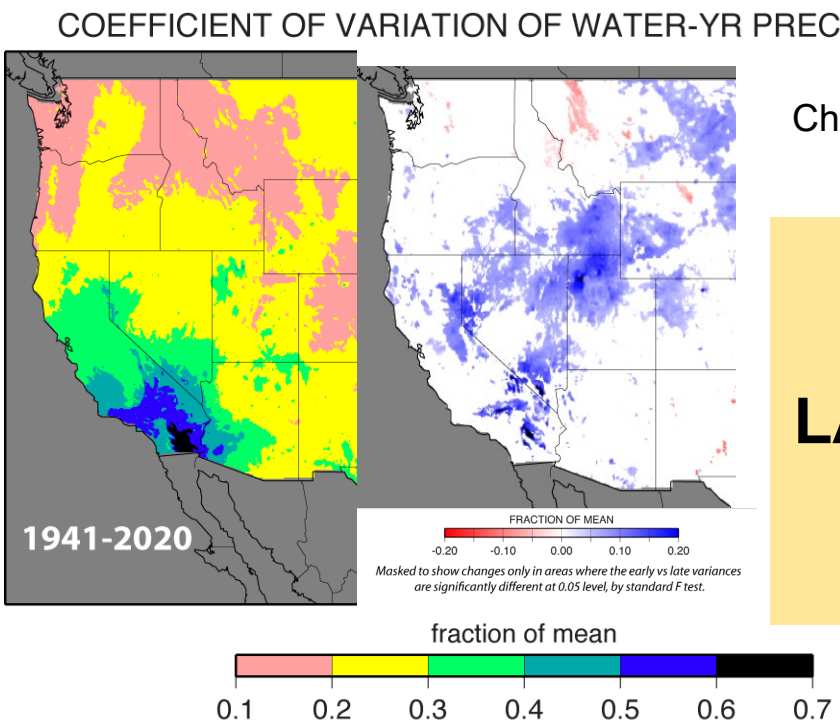

Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO
UC San Diego
SCRIPPS INSTITUTION OF OCEANOGRAPHY
From Drought to Flood
and Science to Solutions
F. Martin Ralph
Director, Center for Western Weather and Water Extremes (CW3E)
at UC San Diego/Scripps Institution of Oceanography
Southern California Water Dialog
25 January 2023
Contact
F. Martin Ralph
mralph@ucsd.edu


Center for Western Weather
and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY
AT UC SAN DIEGO
A LAND OF EXTREMES
(...INCREASINGLY SO)
SCRIPPS INSTITUTION OF
OCEANOGRAPHY

CALIFORNIA HAS A WILDLY VARIABLE PRECIPITATION REGIME



Change from 1941-1980 to 1981-2020 averages

Wettest days are now a LARGER FRACTION of annual precip than in the past

Courtesy Mike Dettinger
Based on prism.oregonstate.edu

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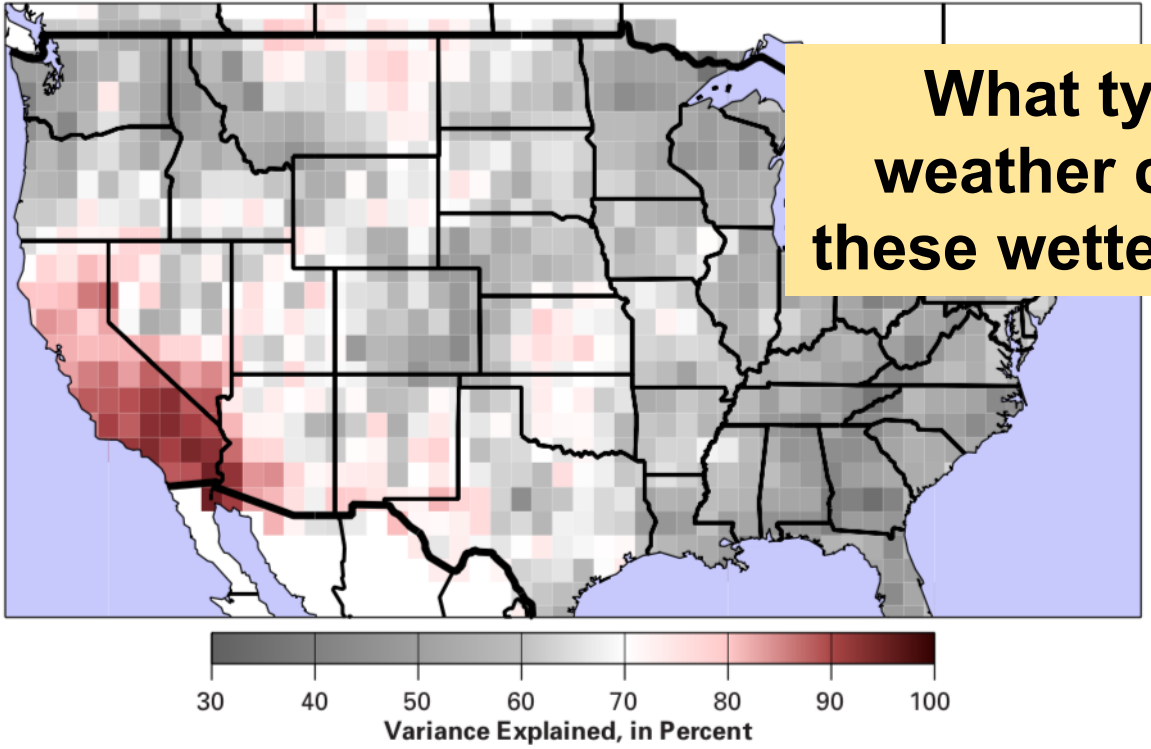
… AND CALIFORNIA'S FLOODS AND DROUGHTS ARE UNIQUELY TIED TO EACH OTHER

Percentage of Water-Year Precip Variance explained by Precip from wettest 7 days/yr



What type of weather creates these wettest days?

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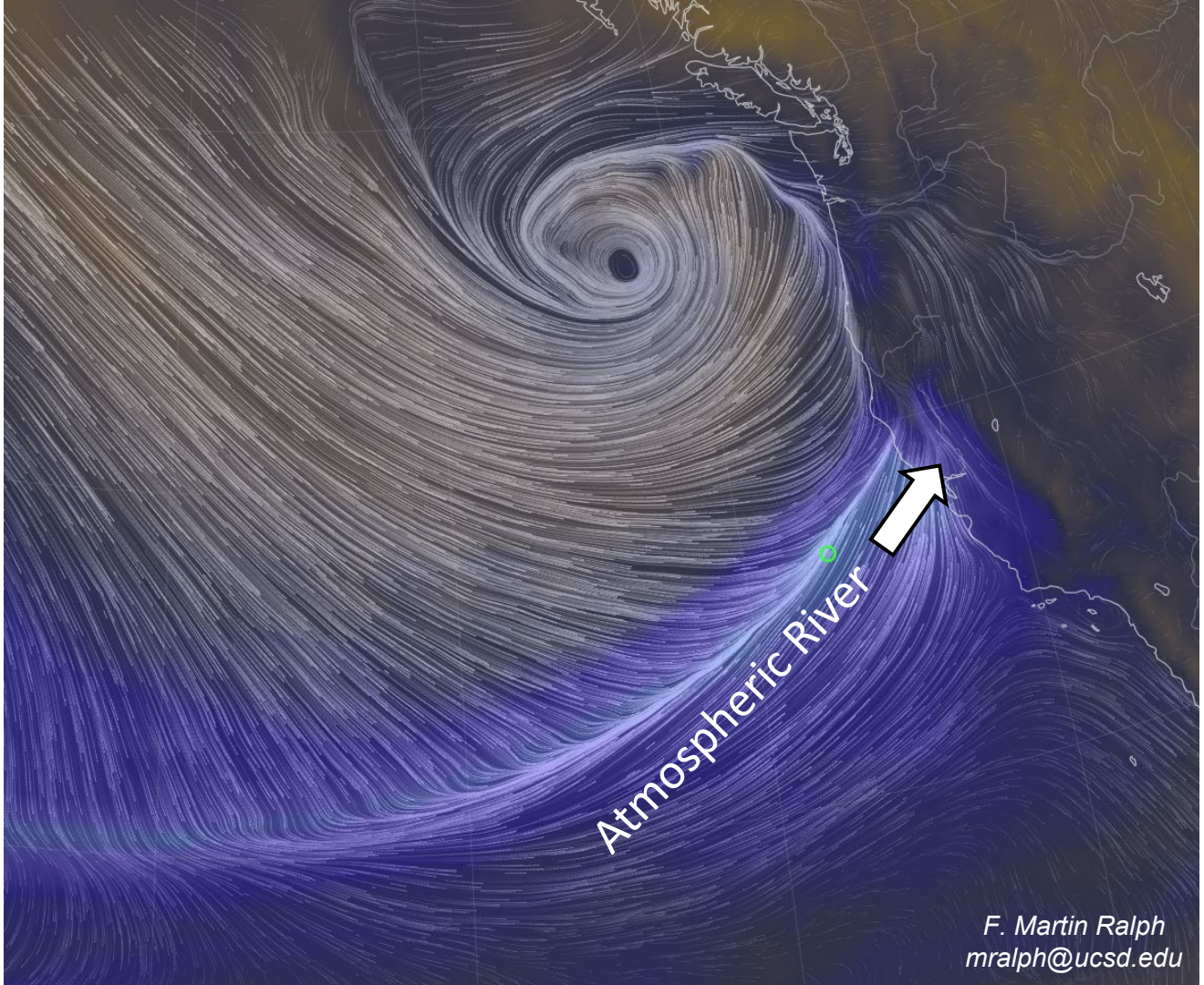

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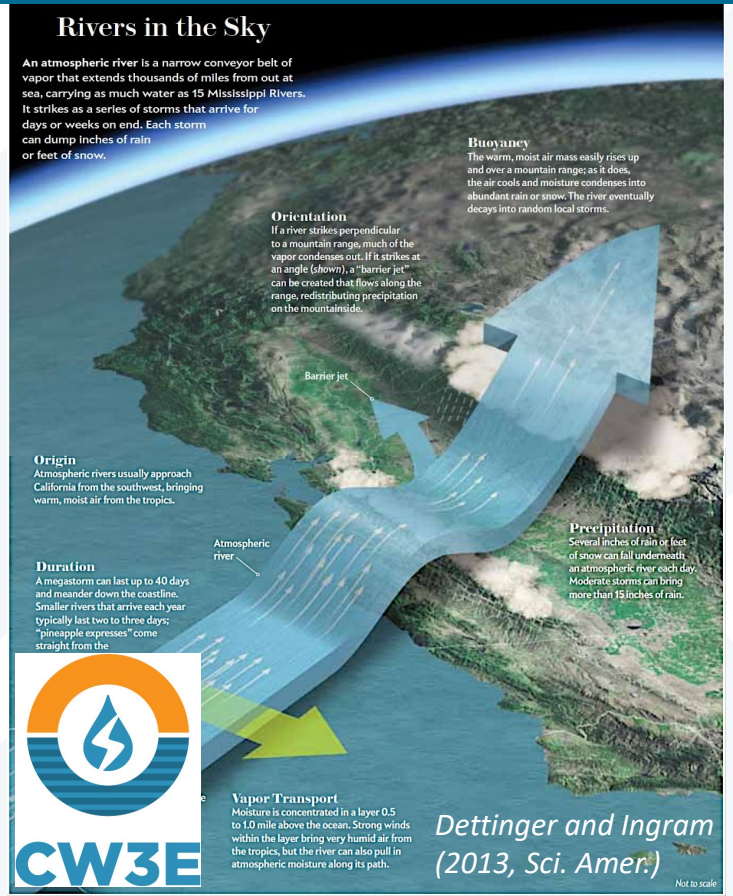
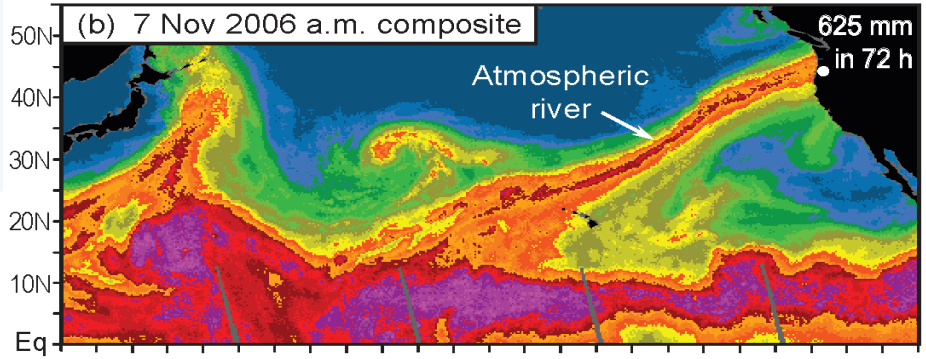
KEY SCIENCE RESULT: ATMOSPHERIC RIVERS: PRIMARY SOURCE OF MOISTURE FOR PRECIPITATION IN THE REGION; USEABLE PREDICTIVE SKILL



Atmospheric Rivers (ARs) are *Rivers in the Sky,* i.e., long narrow bands of airborne water vapor, carrying as much water as 25 Mississippi Rivers*.



An AR that hit Washington & Oregon produced 25 inches of rain in 3 days.

ARs Can produce extreme precipitation and flooding.

However, ARs also provide up to half of annual precipitation and mountain snow that are key to water supply.

*Ralph et al. (2017)

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ONE OF 2021'S $BILLION WEATHER DISASTERS (PER NOAA)

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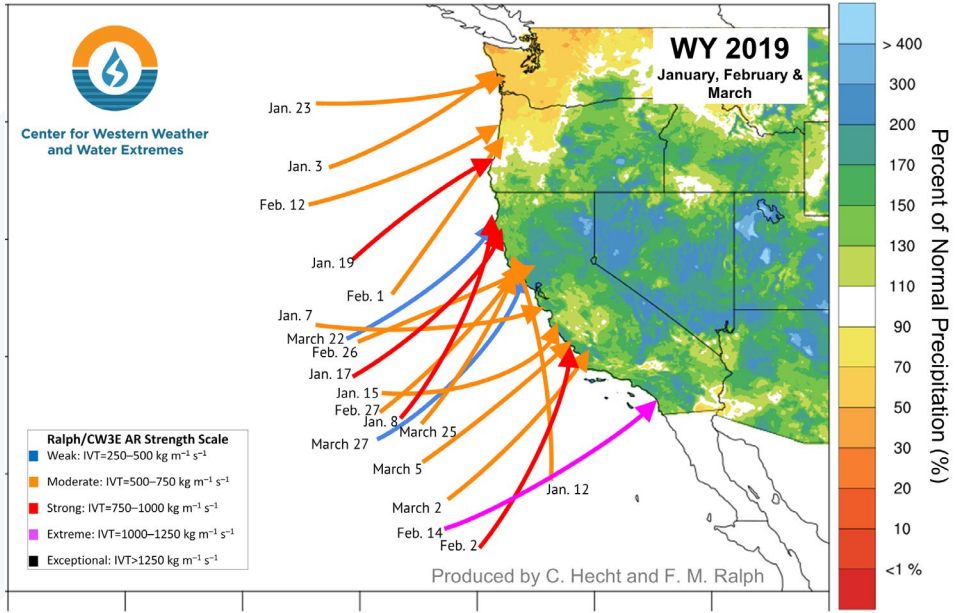
https://www.washingtonpost.com/photography/interactive/2021/california-atmospheric-river-mudslides-snow/

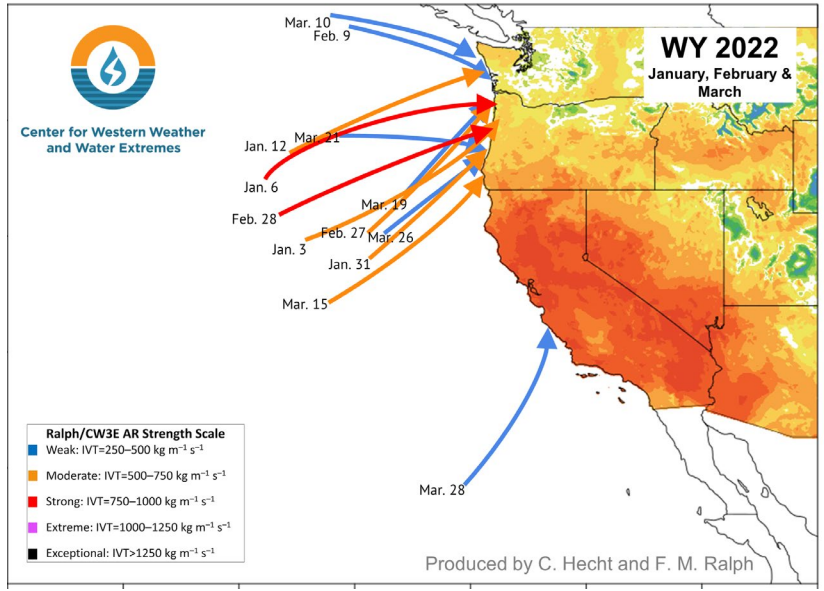
Central Sierra Got almost 50% of its 2021 Snow from this one AR

Snow falls at a rate of two to four inches per hour in Mammoth Lakes on Wednesday.

PETER MORNING

VARIABLITY & AR LANDFALLS





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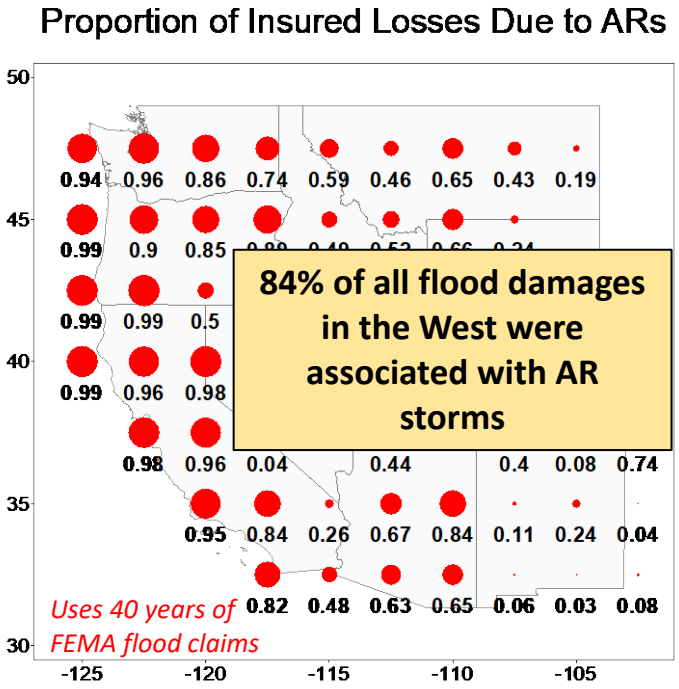
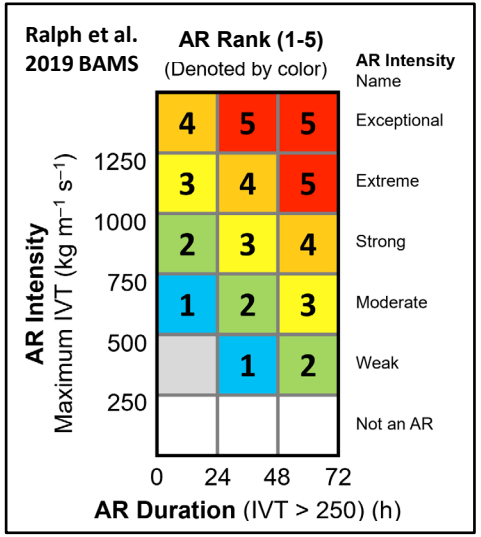
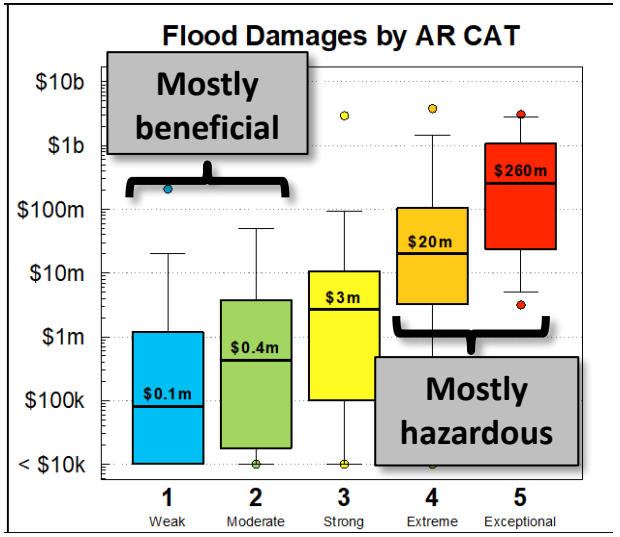
ARs drive flood damages in the western U.S.



Corringham, Ralph, Gershunov, Cayan and Talbot, Sci. Advances (2019)





Corringham et al.2019, Science Advances

Flood damages increase exponentially with AR Ranking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FROM SCIENCE TO SOLUTIONS
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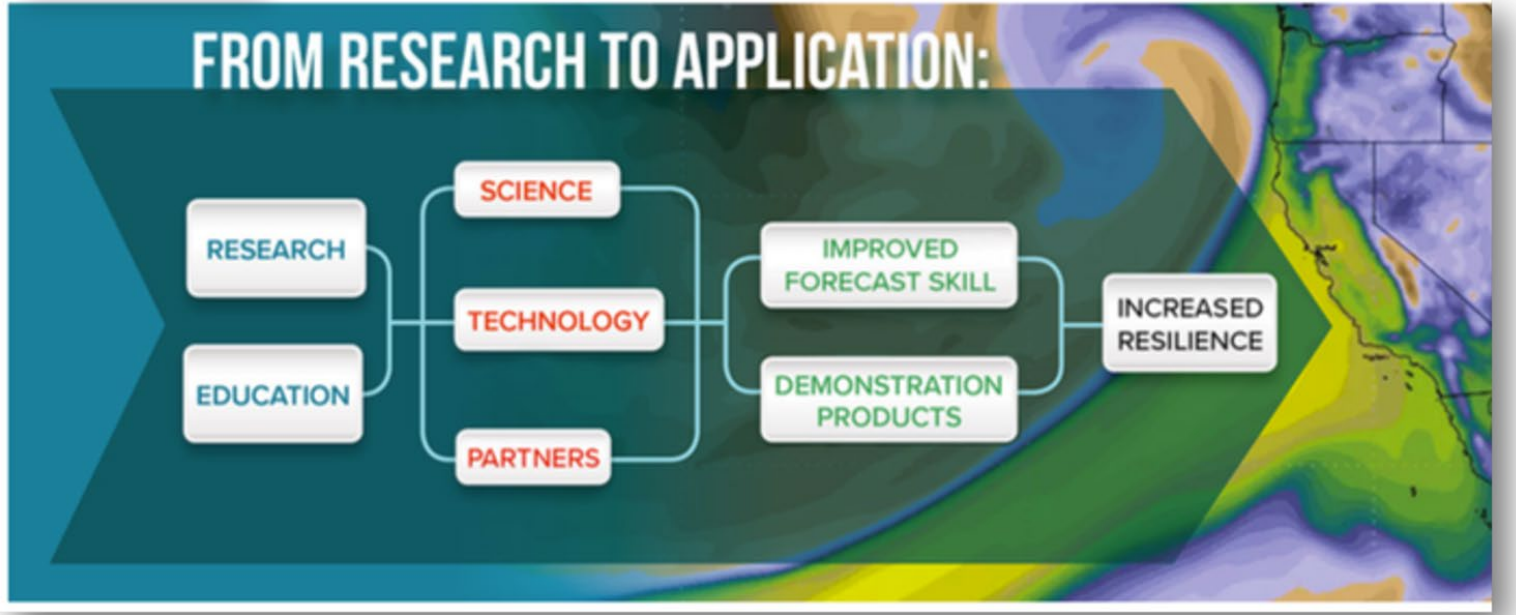
The Center for Western Weather and Water Extremes

- Created in 2013 to develop new **science and tools supporting water management from drought to flood**
- At UC San Diego/Scripps Institution of Oceanograp

Organizational innovations



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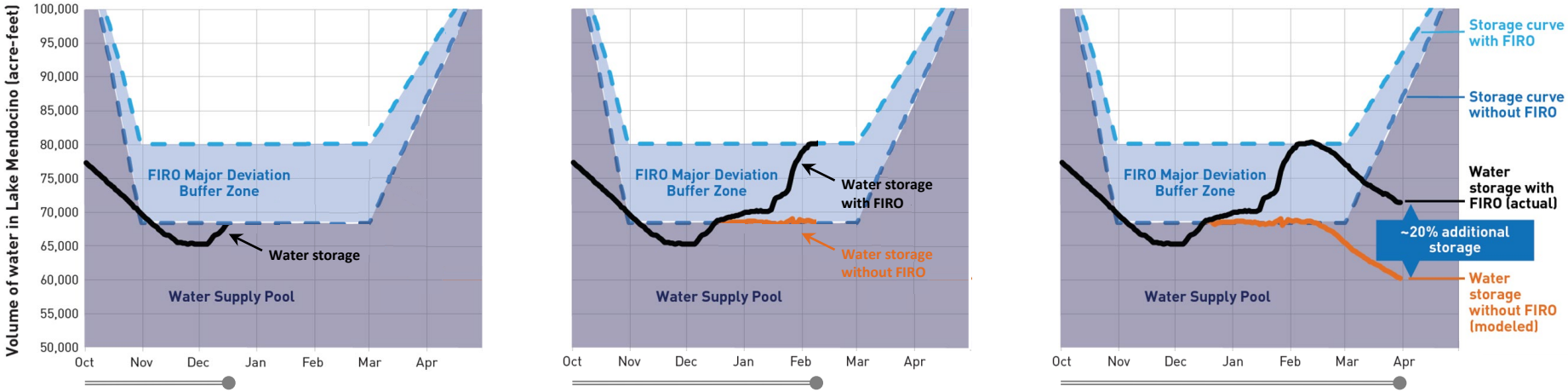
FIRO brings reservoir operators together with engineers and scientists in a "Research And Operations Partnership"

FIRO explores using AR and related forecasts to

- Hold extra water after a storm, pending a forecast of an AR
- Release water ahead of an AR to increase flood risk mitigation capacity



Reservoir operations innovations

https://cw3e.ucsd.edu/firo/

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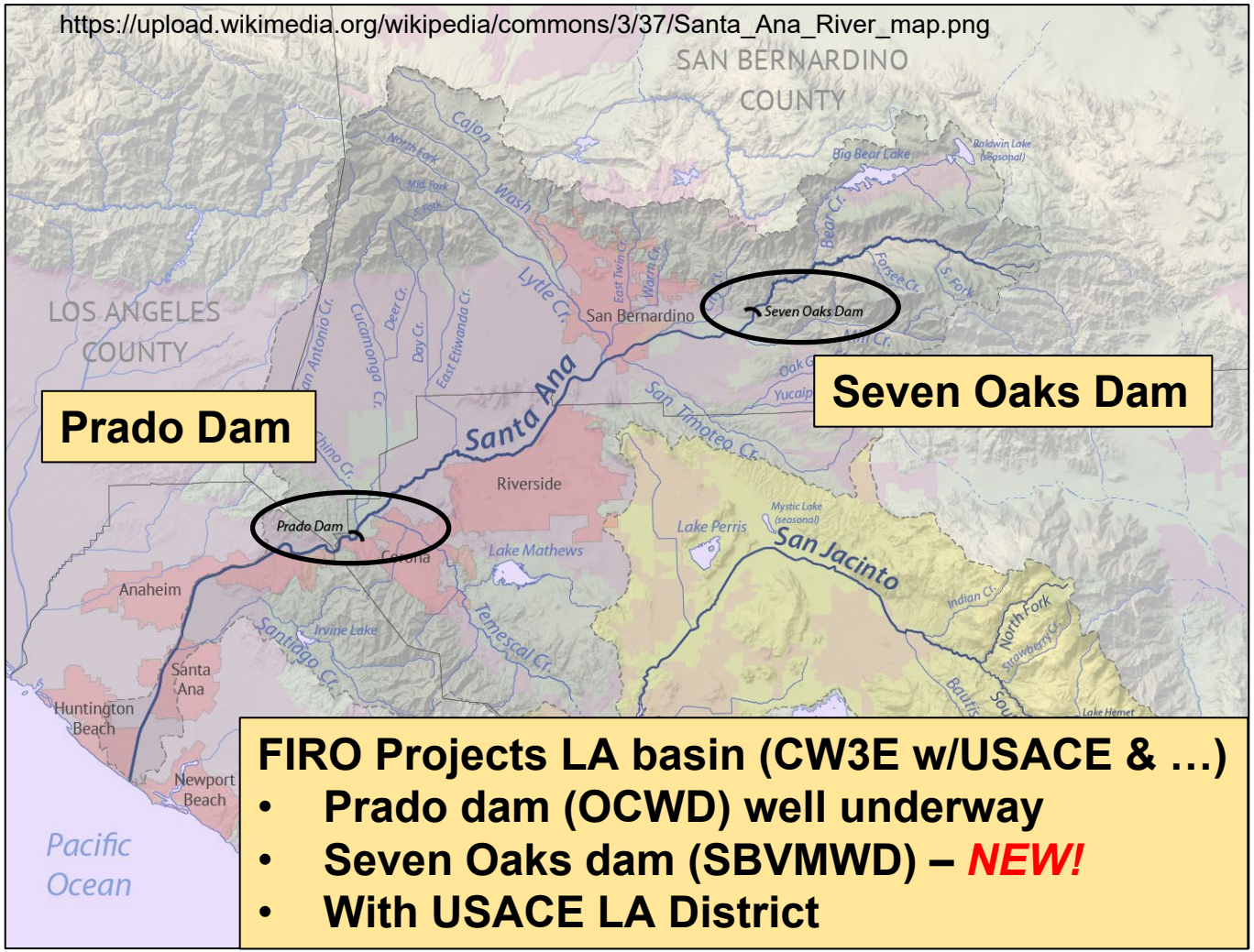
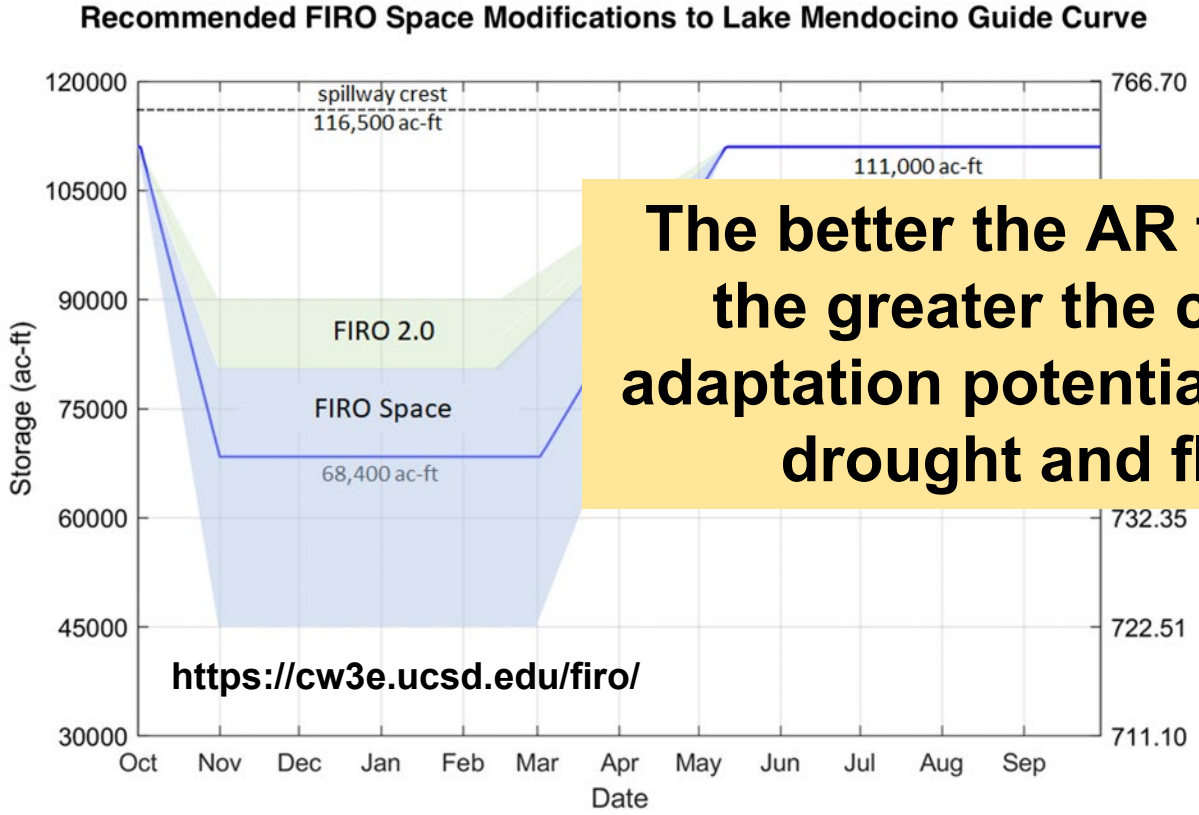

https://upload.wikimedia.org/wikipedia/commons/3/37/Santa_Ana_River_map.png
SAN BERNARDINO COUNTY
LOS ANGELES COUNTY
Prado Dam
Seven Oaks Dam
Santa Ana
San Bernardino
Riverside
Anaheim
Huntington Beach
Newport Beach
Pacific Ocean
Lake Mathews
Lake Perris
Irvine Lake
Big Bear Lake
Baldwin Lake (seasonal)
Mystic Lake (seasonal)
Lake Hemet
Cajon Wash
Lytle Cr.
Cucamonga Cr.
Deer Cr.
Day Cr.
East Etiwanda Cr.
San Timoteo Cr.
Temescal Cr.
Santiago Cr.
Bear Cr.
Forsee Cr.
Indian Cr.
Strawberry Cr.
FIRO Projects LA basin (CW3E w/USACE & …)
• Prado dam (OCWD) well underway
• Seven Oaks dam (SBVMWD) – NEW!
• With USACE LA District

Concept of FIRO Space and "FIRO 2.0"



The better the AR forecast, the greater the climate adaptation potential for both drought and flood

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ATMOSPHERIC RIVER RECONNAISSANCE

Filling Gaps in Pacific Weather Observations

Observational innovations

Started in 2016 as a "Research And Operations Partnership"

- Greatly improved the forecasts of the January 2021 AR and its impacts
- Increased lead time in the forecast from 2 days to 5 days

Ralph et al. 2019 BAMS
Zheng et al. 2021 BAMS
Stone et al. 2020 MWR
Reynolds et al. 2019 MWR
Lavers et al. 2018 GRL
Lavers et al. 2020 Wea Fore
Lavers et al. 2020 Nature Comms
Zhang and Ralph 2021 MWR
Prince et al. 2021 GRL
Haase et al. 2021 JGR

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AR RECON: Research And Operations Partnership

Accurate flood warnings, with substantial lead time, and Forecast-Informed Reservoir Operations require skillful forecasts of ARs. The more skill, the greater the benefits.

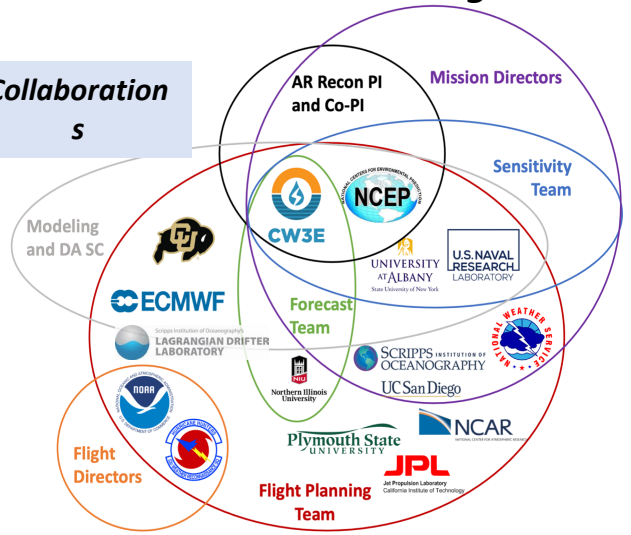
CA Dept. of Water Resources' AR Program and USACE have partnered with UC San Diego/Scripps Institution of Oceanography/CW3E to develop new science-based forecasting methods and tools.

CW3E has partnered with NOAA and US Air Force to create AR Recon as a way to improve forecasts through aircraft observations and specialized weather modeling.

Leading institutions and meteorologists have joined in collaborating on the development and execution of AR Recon.

AR Recon improves forecasts of ARs and associated extreme precipitation and flooding

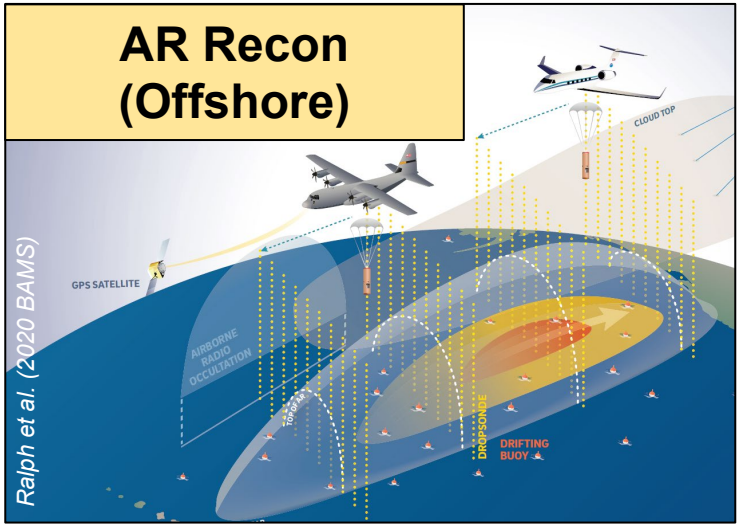
- ***Real-time obs' aid current 1-5 day forecasts***
- ***Scientific advances by AR Recon improve models and methods in the long term***

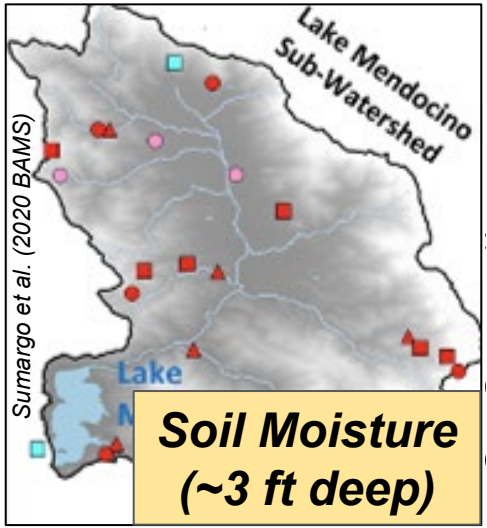


F. Martin Ralph, PI *(UC San Diego/SIO/CW3E)*
Vijay Tallapragada, Co-PI *(NOAA/NWS/NCEP)*

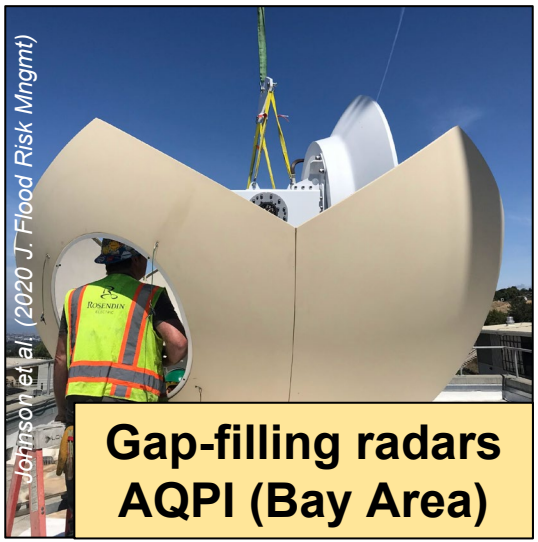
Observational Innovations in California Associated with Water Cycle Extremes

AR Recon (Offshore)



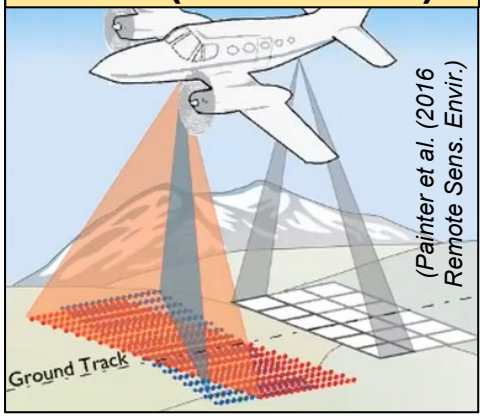


Soil Moisture (~3 ft deep)

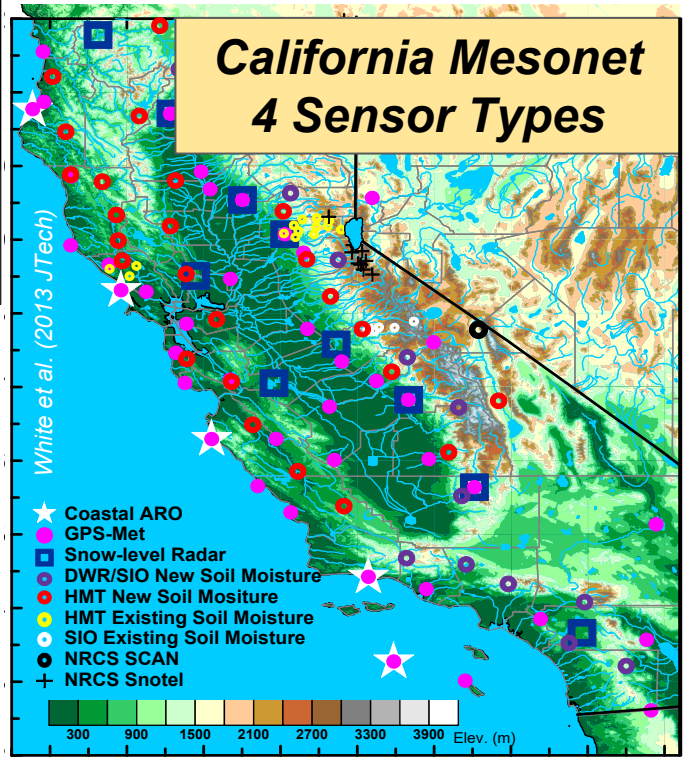


Gap-filling radars AQPI (Bay Area)

Airborne Snow Obs' (Mountains)



California Mesonet 4 Sensor Types

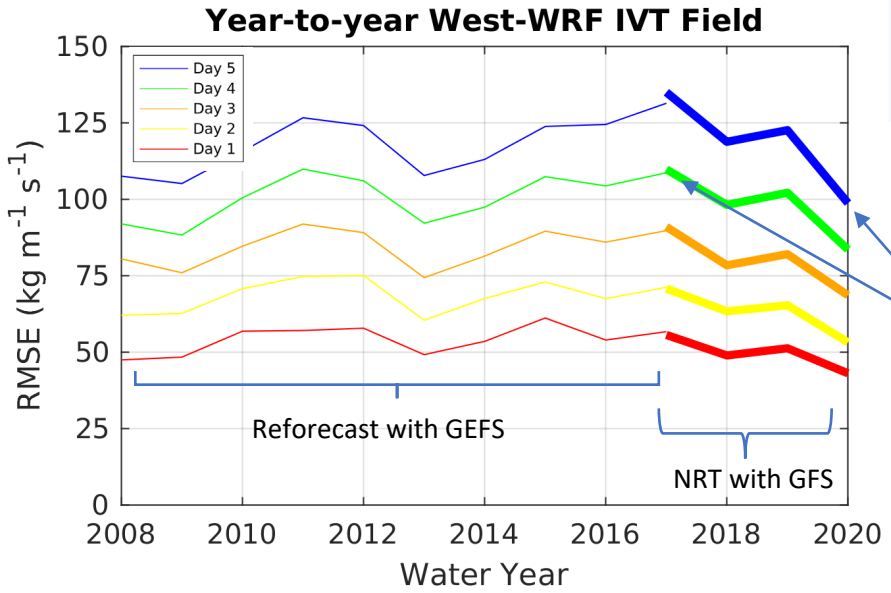


Summary by F. Martin Ralph (Director, CW3E at UCSD/Scripps Oceanography), mralph@ucsd.edu

West-WRF: Developed to Improve Skill in Predicting ARs

IVT Forecast Performance WY-to-WY tracking

Compared domain-wide 9-km West-WRF NRT forecasts (2017-2020), 30+ year reforecast (2008-2017) to MERRA-2 reanalysis



Weather modeling innovations

CW3E's "West-WRF" weather forecast model is tailored to be the best forecast model for atmospheric rivers

Reduced RMSE in 5-day lead time IVT forecasts by roughly 20% in 4 years

Skill in WY 2020 IVT at 5-day lead time is better than 4-day lead time in WY 2017

Research is improving the skill of predicting ARs

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Examples of Media Usage of the AR Scale

Situational awareness innovations

CAPITAL WEATHER GANG

Category 5 atmospheric river blasts Pacific Northwest, with up to 10 inches of rain possible

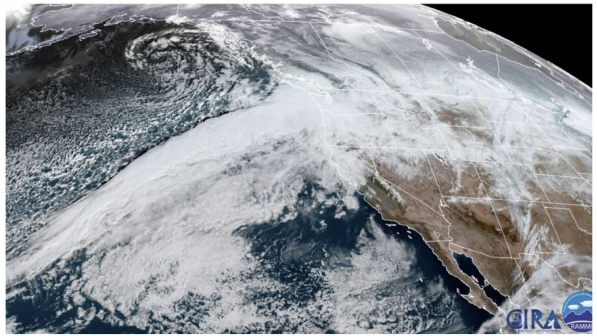
The 'exceptional' event could cause strong winds, flash flooding and landslides

What does a 'Category 5' Atmospheric River mean? Scale aims to rate nature's largest soakers

By Scott Sistek | Published November 19, 2021 | Scott's Weather Blog | FOX 13 Seattle

'Category 4' Atmospheric River heading our way. What's that mean?!?

by Scott Sistek | KOMONews.com Meteorologist | Thursday, December 19th 2019



Satellite image shows an atmospheric river heading toward the Pacific Northwest on Dec. 19, 2019 (Photo: NOAA / RAMMB/CIRA)

New 'Atmospheric River' scale aims to measure damage potential of incoming rain storms

by Scott Sistek | KOMONews.com Meteorologist | Thursday, September 24th 2020

FILE - Flooding on the Snoqualmie River (KOMO Photo)

WEATHER UNDERGROUND | Sensor Network | Maps & Radar | Severe Weather | News & Blogs | Mobile Apps | More

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Cat 1 to Cat 5: A Scale for Atmospheric Rivers

Bob Henson · February 4, 2019, 10:46 PM EST

CNN Weather | Climate | Storm Tracker | Wildfire Tracker | Video | Audio | Live TV

A category 4 atmospheric river is forecast to drench the Pacific Northwest early this week

By Haley Brink, CNN meteorologist

Updated 5:22 AM ET, Mon February 28, 2022

TV Meteorologists Using “AR” for the Public

19 Sept 2020, KOMO, Seattle, WA USA

Scientific American, September 2022
F. Martin Ralph

Science to Solutions

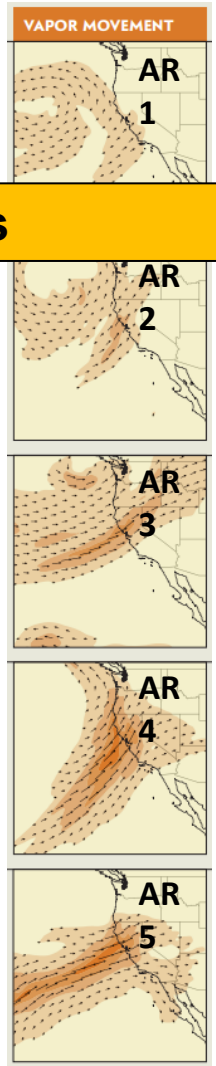
METEOROLOGY

FORECASTING ATMOSPHERIC RIVERS

Knowing when torrents of rain will strike can save property and lives

By F. Martin Ralph

Illustration by Mark Ross



AR Scale(examples)

2022 Annual Forest-Informed Reservoir Operations (FIRO) Workshop

Innovative Collaborations

https://cw3e.ucsd.edu/firo/


CA Gov. Newsom Press Conference on 2
Declared Regional Drought Emergency –
Leadership to Meet Future Challenges

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California has the US' greatest variation in extremes

Extremes in wet, in dry and in hot are increasing
Drought and Flood can follow each other rapidly

Atmospheric river science and predictions, tailored to CA's unique needs support Climate Resiliency through Forecast-Informed Reservoir Operations (FIRO), etc…

CA's leadership in **science, innovation and collaboration** are already providing early solutions, and are positioned to accelerate these to meet the challenges of climate extremes

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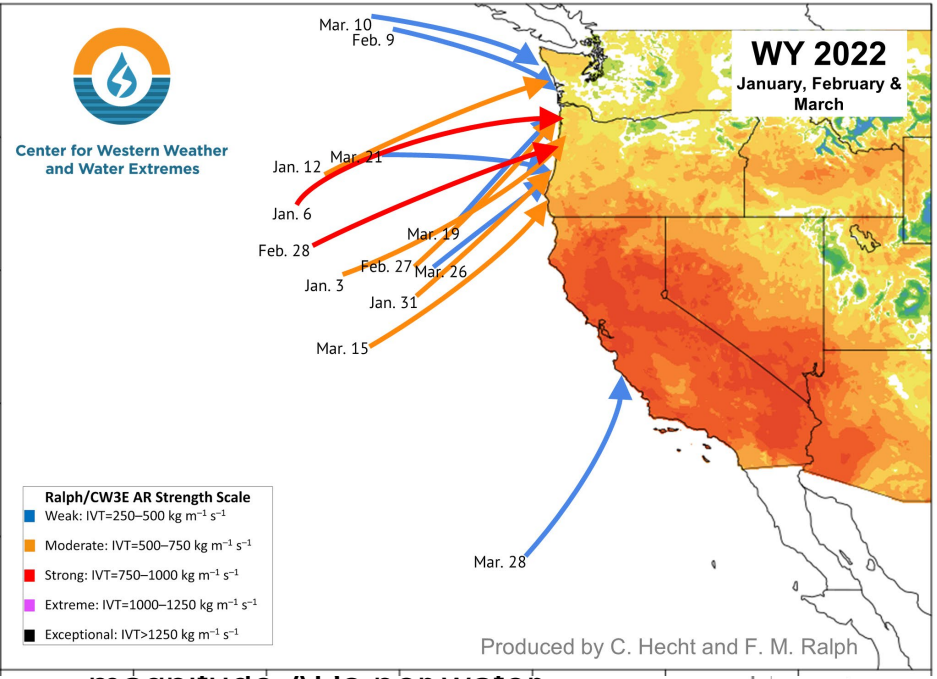
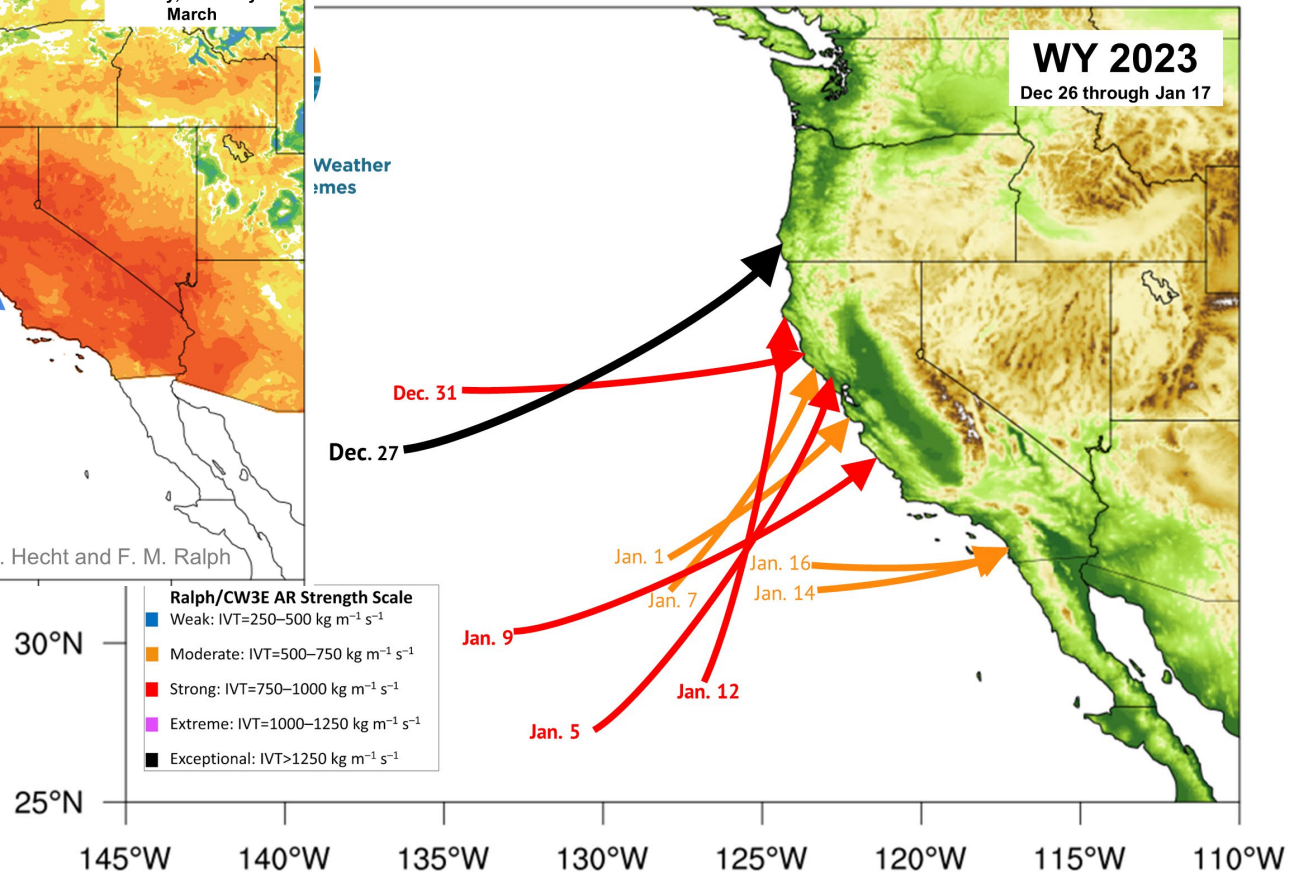
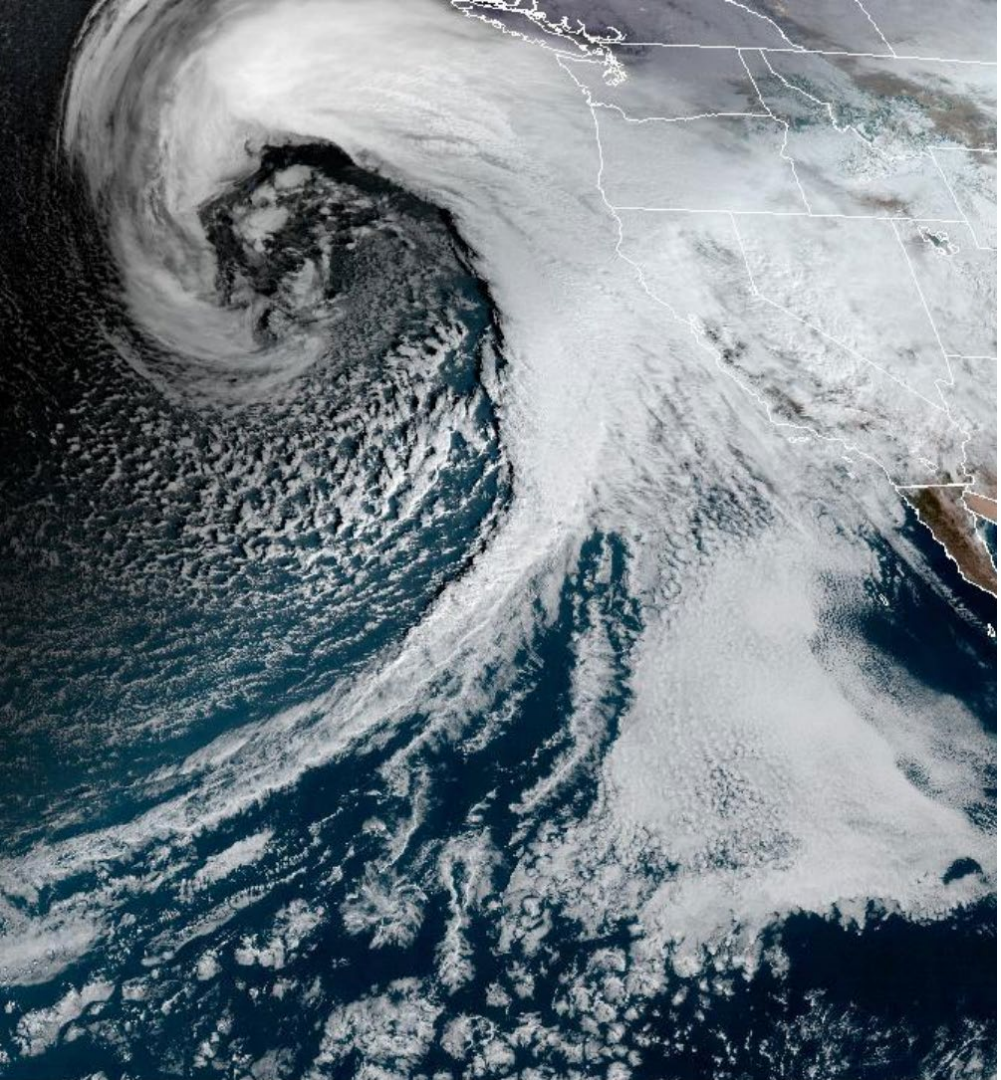
F. Martin Ralph (mralph@ucsd.edu), Director, CW3E
at UCSD/Scripps Institution of Oceanography

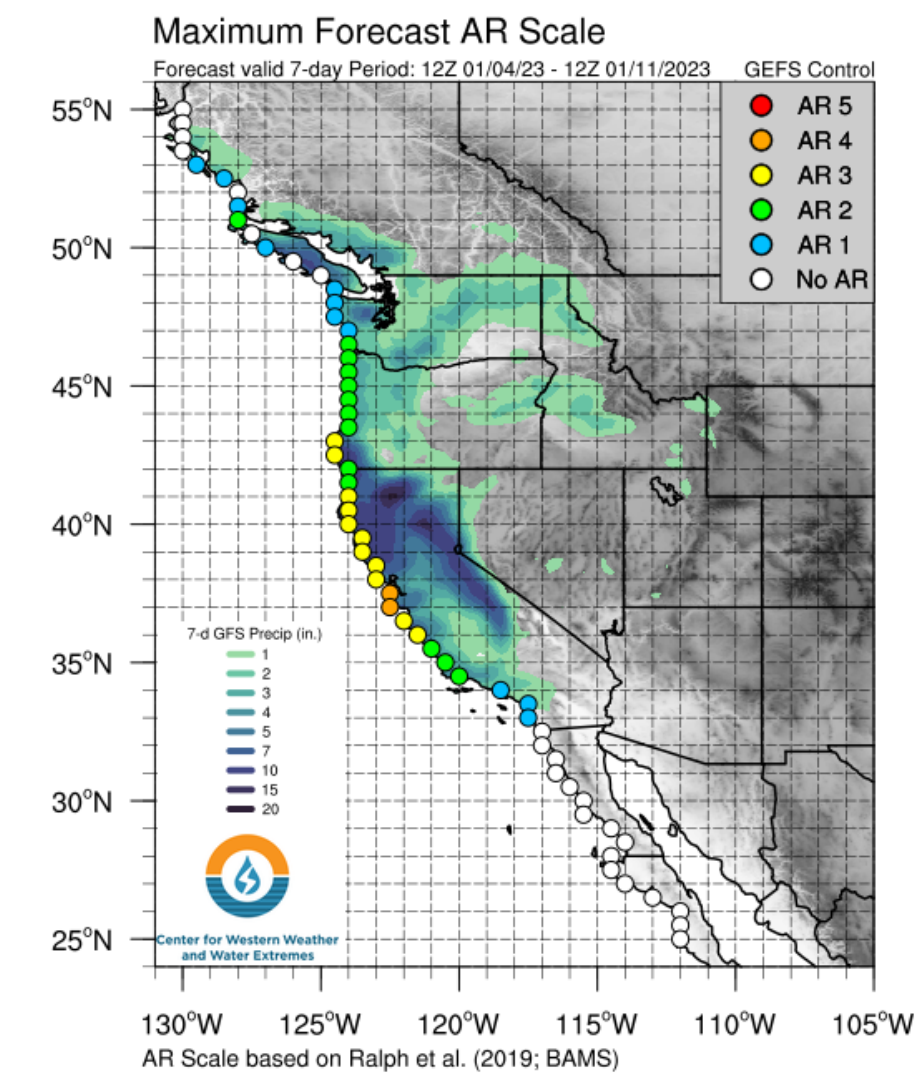


magnitude ARs per water year since 2012

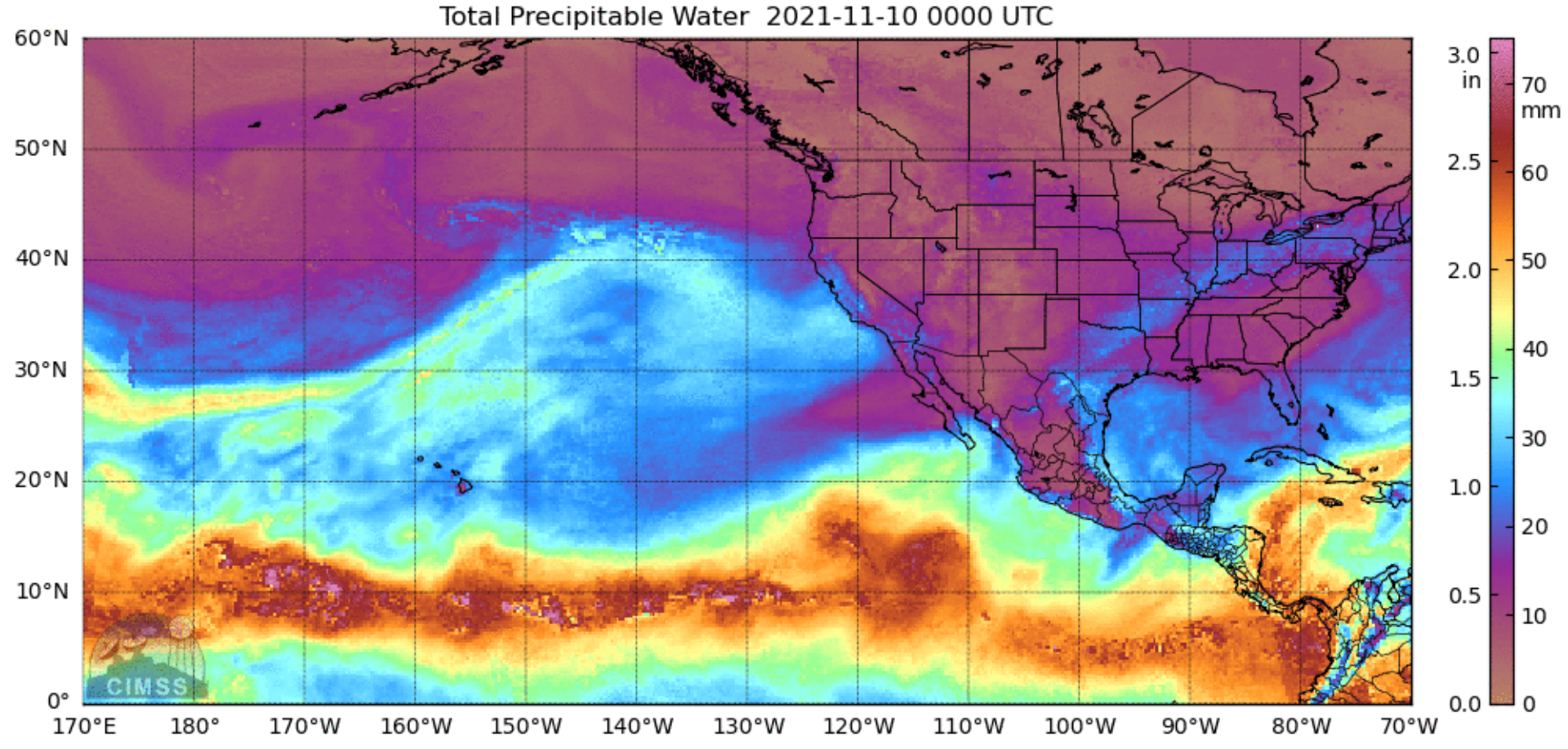
- For reference, California experienced 13 strong+ ARs during Water Year 2017



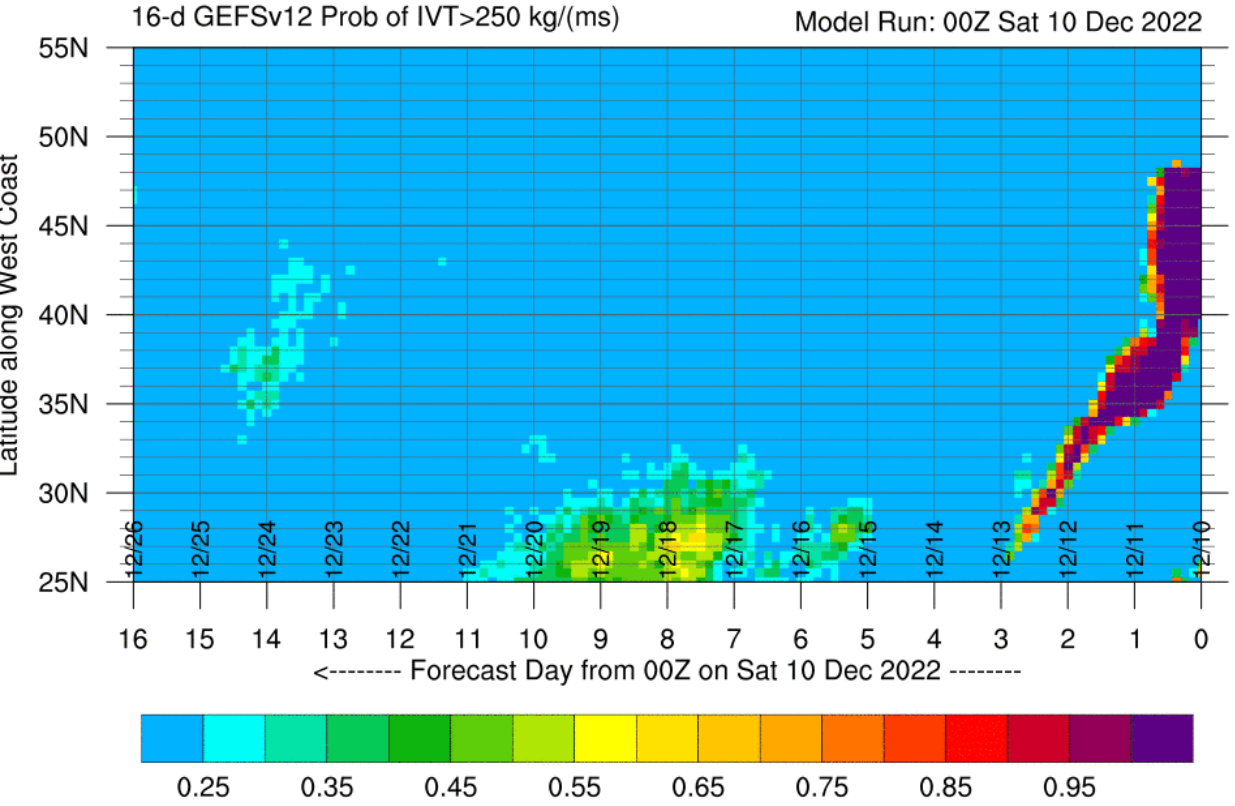


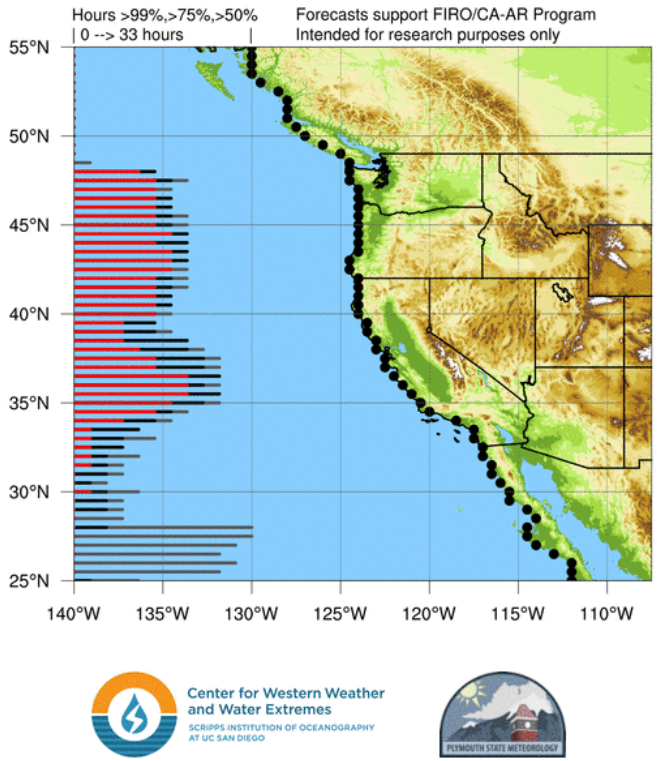

Maximum Forecast AR Scale
Forecast valid 7-day Period: 12Z 01/04/23 - 12Z 01/11/2023
GEFS Control
AR 5
AR 4
AR 3
AR 2
AR 1
No AR
55°N
50°N
45°N
40°N
35°N
30°N
25°N
7-d GFS Precip (in.)
1
2
3
4
5
7
10
15
20
Center for Western Weather and Water Extremes
130°W
125°W
120°W
115°W
110°W
105°W
AR Scale based on Ralph et al. (2019; BAMS)

The AR Onslaught of Dec 24th to January 17th



Evolution over time





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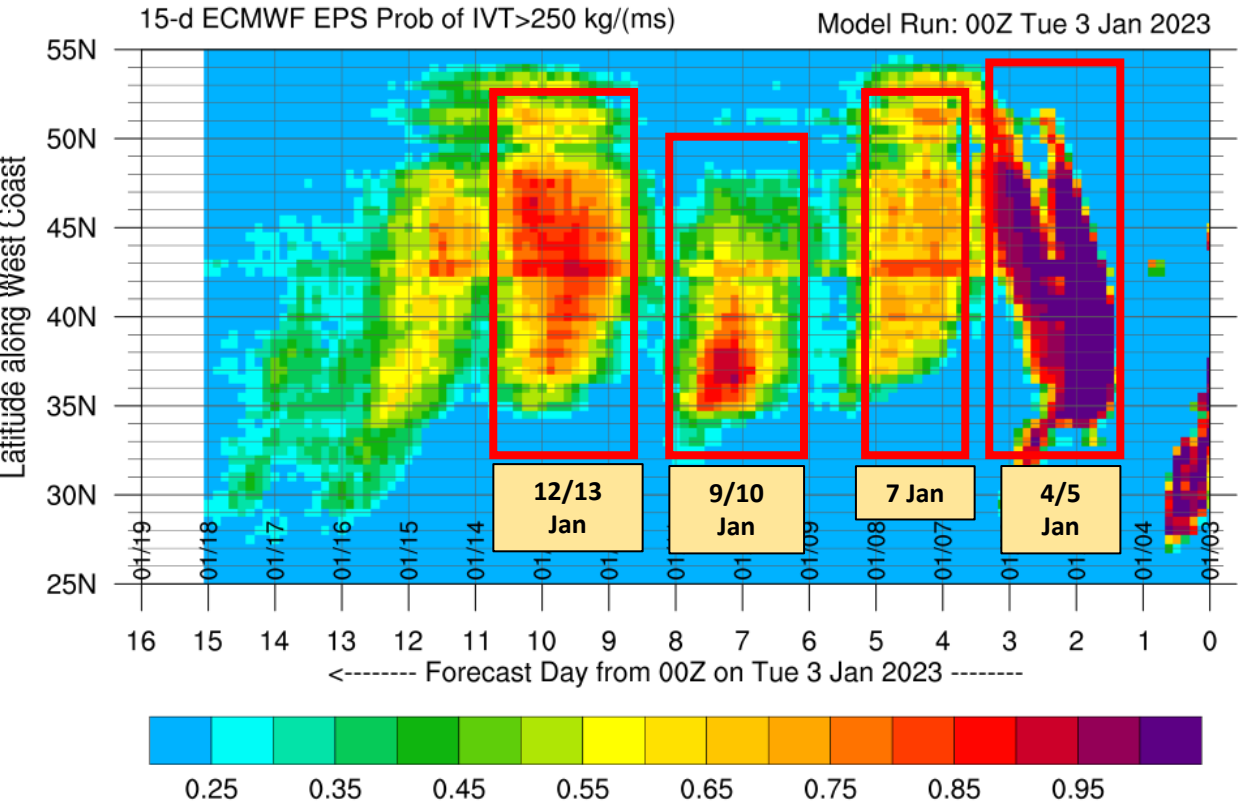
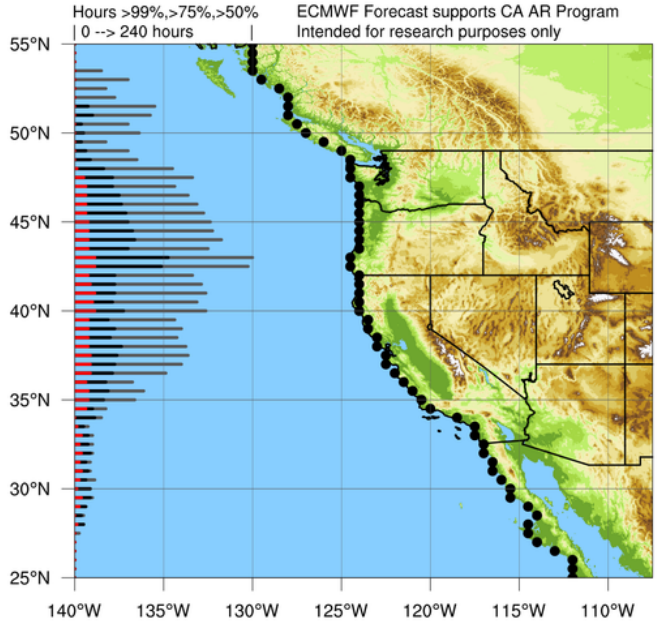
PLYMOUTH STATE METEOROLOGY

Both GFS and ECMWF indicate that this very active AR landfall period is likely to continue for NorCal and Oregon
(Recall that forecasts of AR intensity and likelihood are normally biased low at longer forecast lead times)





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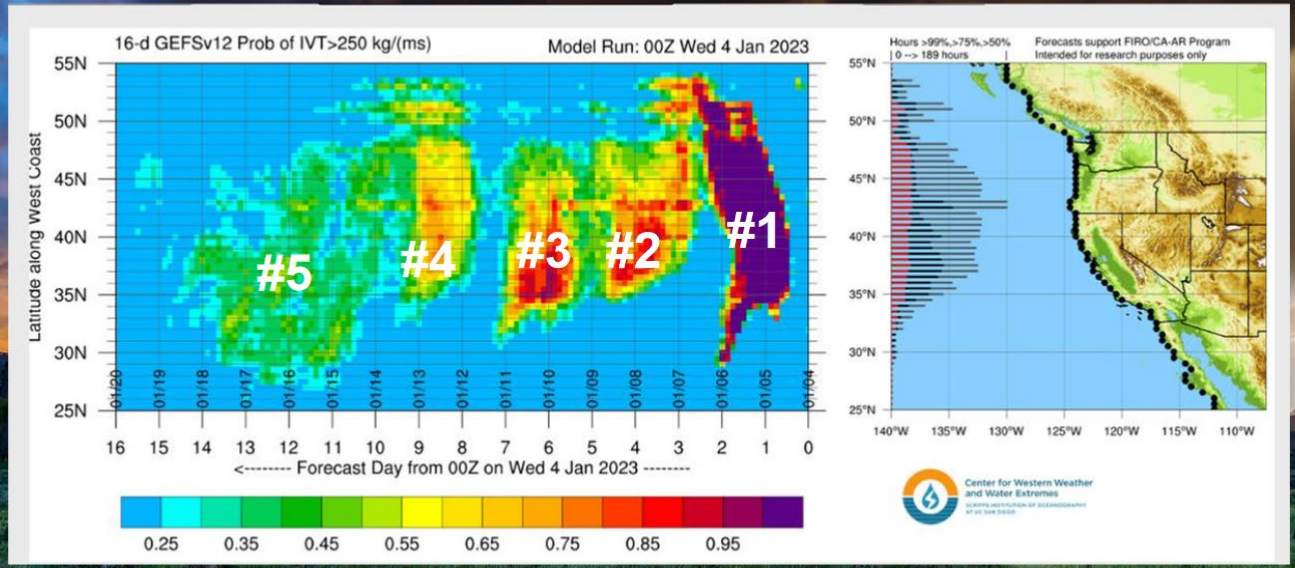
*See National Weather Service for detailed forecasts, including flood warnings and other specific hazard alerts

Series of atmospheric rivers

Next 10 days for January 5 to 16

Weather Forecast Office
San Diego, CA
Wednesday, January 4



Atmospheric River #1

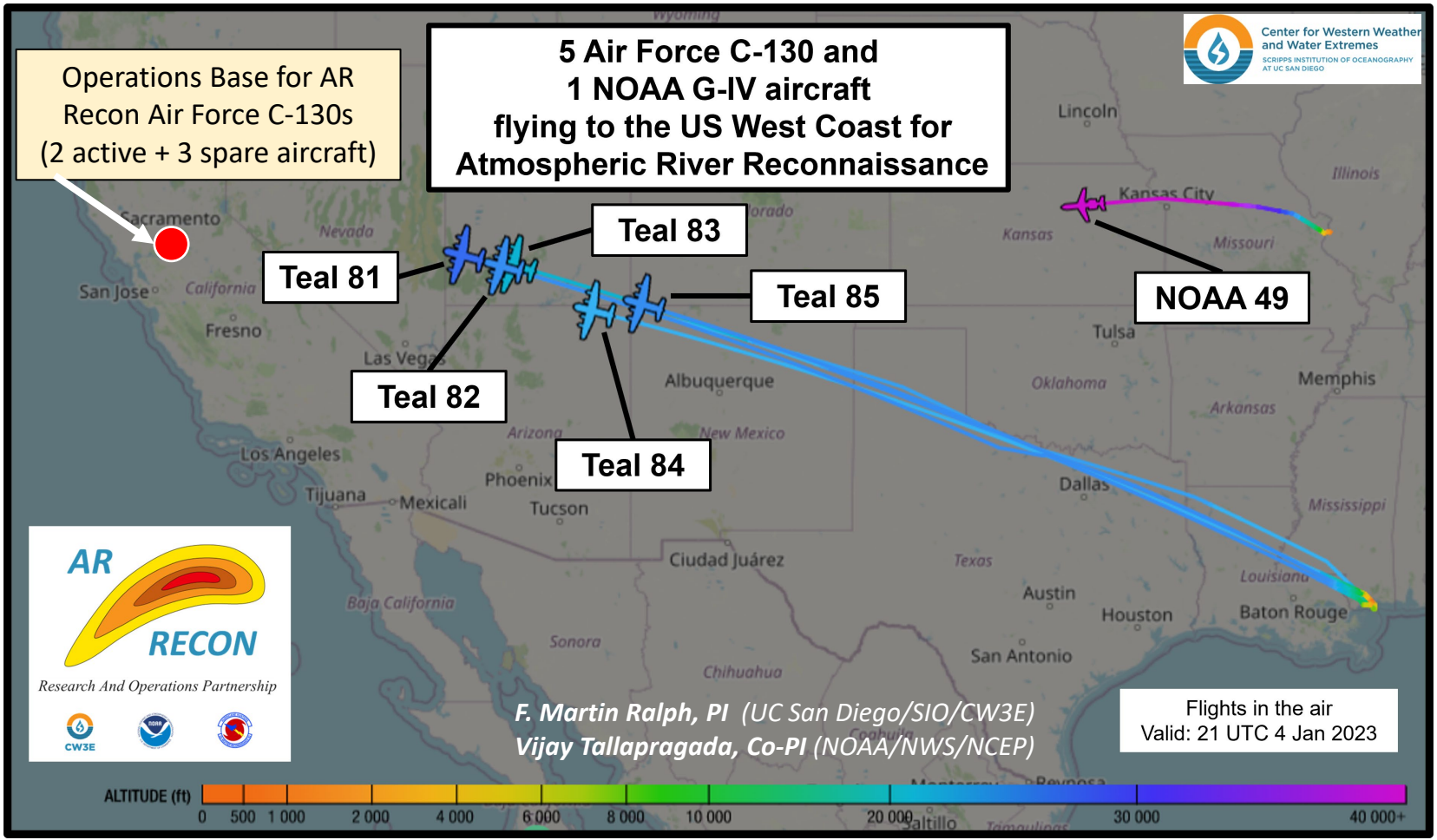
January 4-5, 2022

Weather Forecast Office
San Diego, CA
Wednesday, January 4

Approaching AR tonight


QUIKSILVER

AR Recon: On 4 Jan 2023 Air Force Weather Reconnaissance Squadron is moving 5 of its C-130s to Sacramento to support AR forecast improvements for the West Coast, and NOAA G-IV (NOAA 49) heading to Hawaii



AR RECON

Research And Operations Partnership

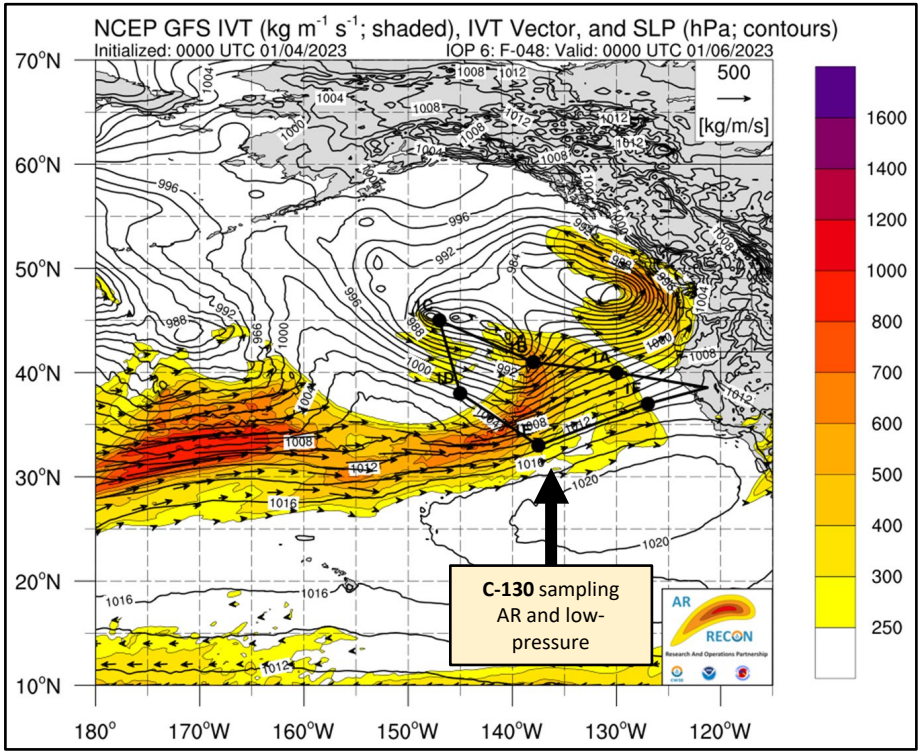
CW3E

F. Martin Ralph, PI *(UC San Diego/SIO/CW3E)*
Vijay Tallapragada, Co-PI *(NOAA/NWS/NCEP)*

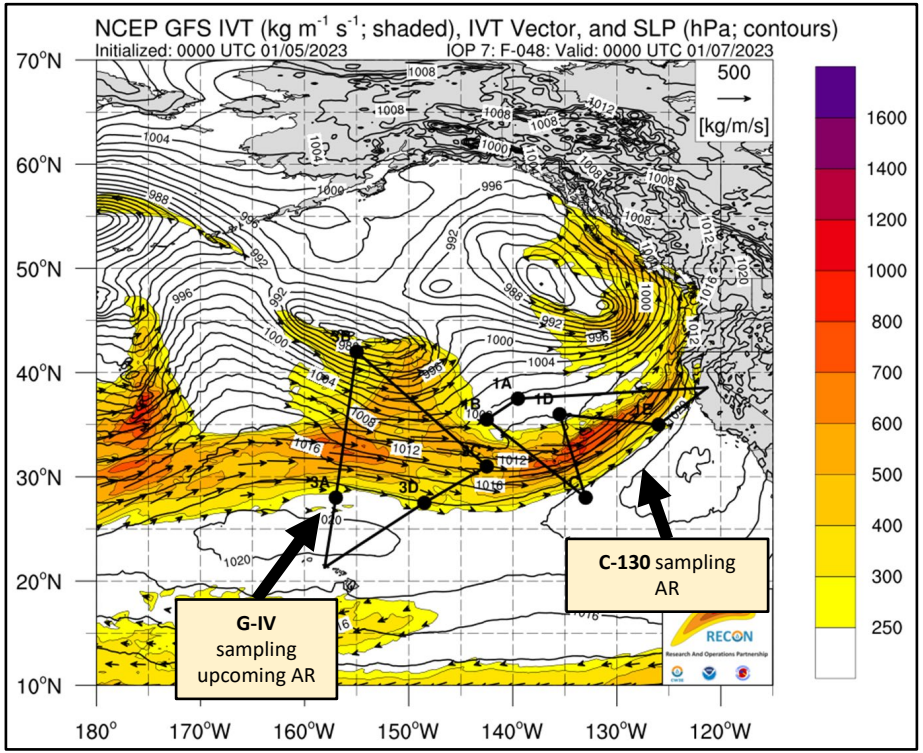
Air Force C-130WJs at Mather airfield in Sacramento, CA for AR Recon 2023
Photo on 5 Jan. 2023 courtesy of USAF 53rd Weather Reconnaissance Squadron

Flight paths for AR Recon flights over the Pacific on January 5th & 6th 2023

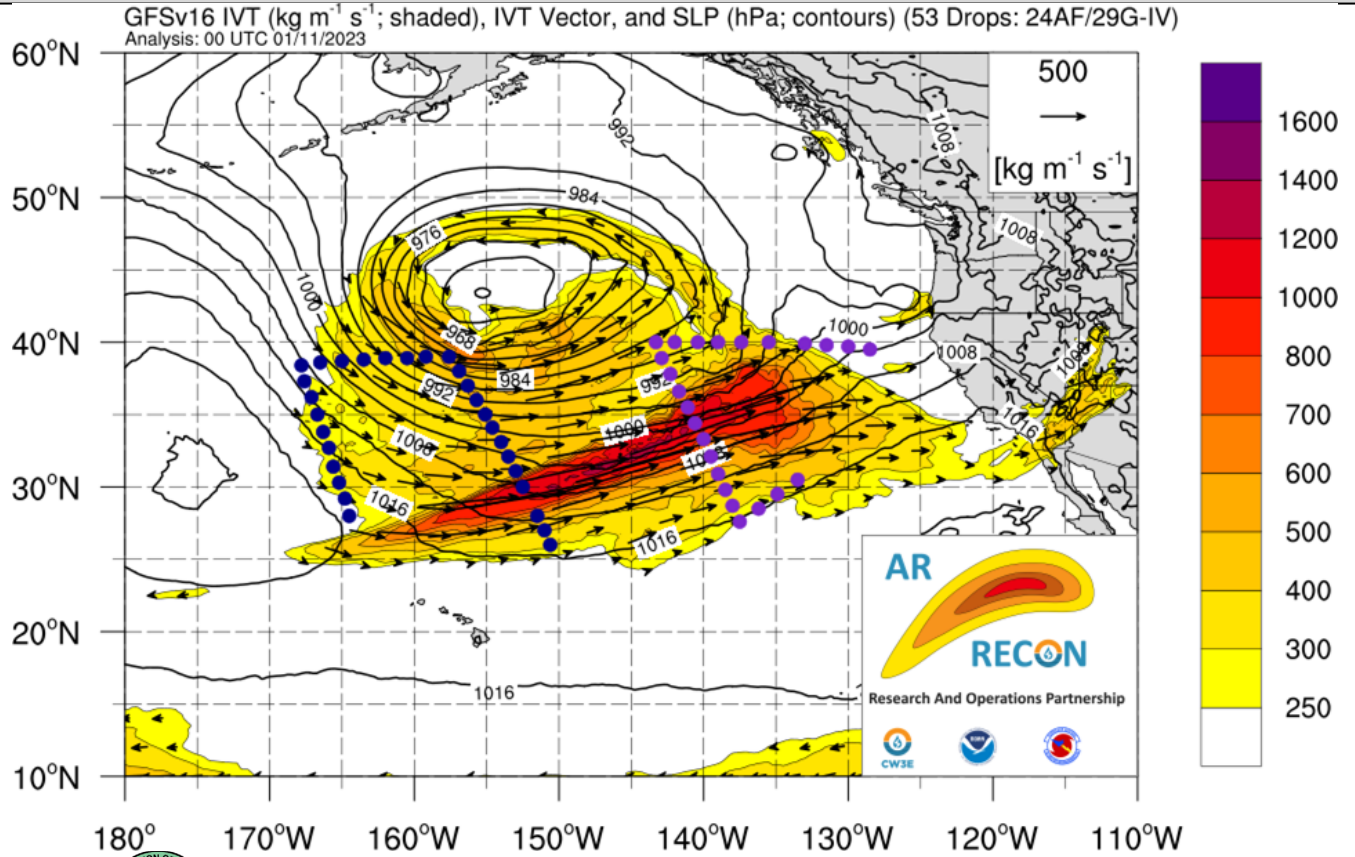
5 Jan 2023: 1 Air Force C-130



6 Jan 2023: 1 Air Force C-130 & 1 NOAA G-IV



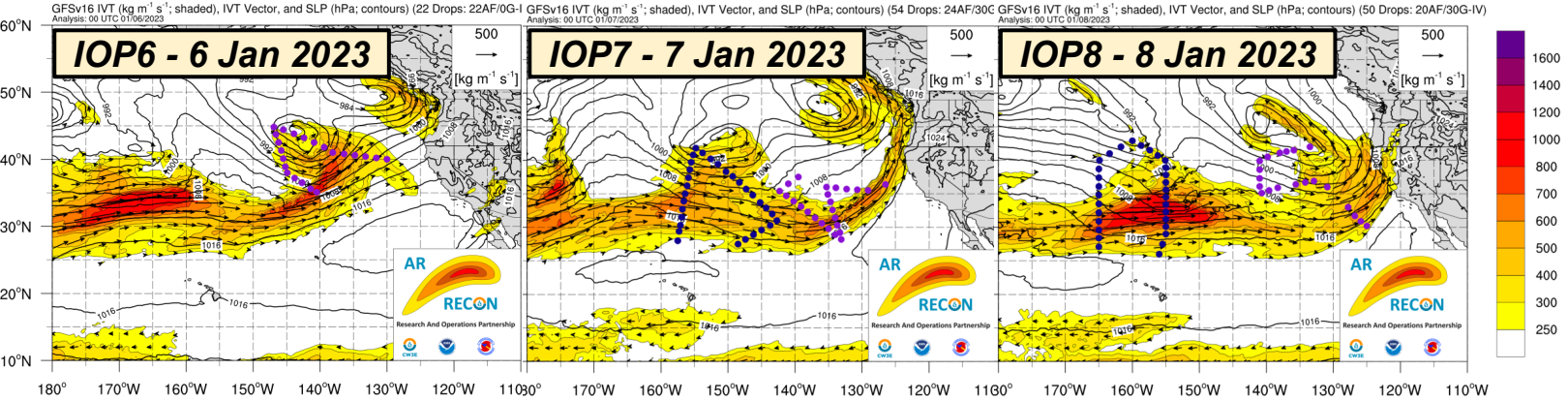
IOP11, 11 Jan 2023

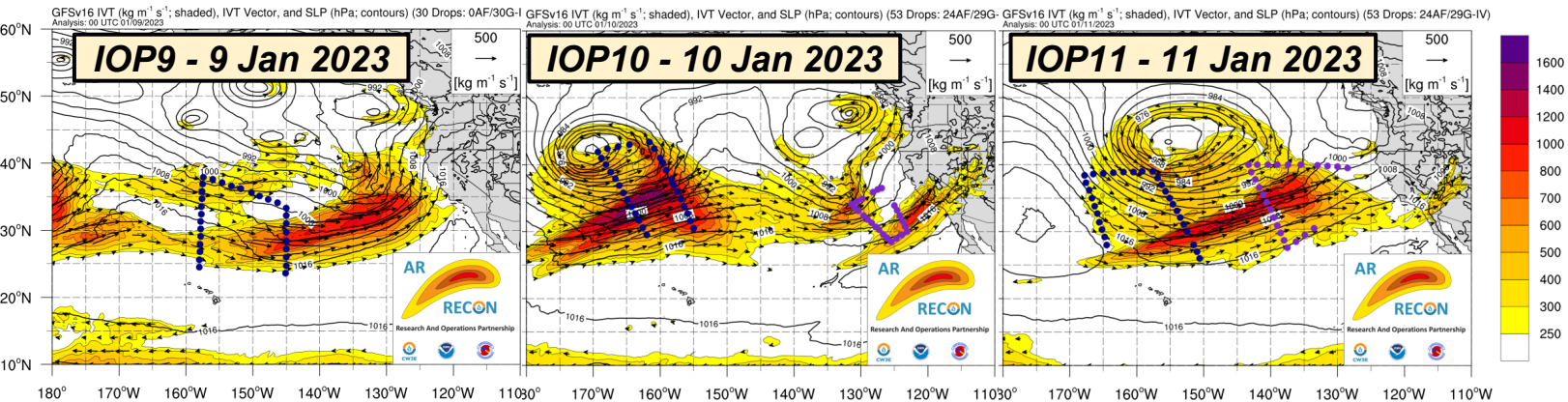


Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

F. Martin Ralph (UCSD/SIO/CW3E) - PI
Vijay Tallapragada (NWS/NCEP) - Co-PI
Anna Wilson (UCSD/SIO/CW3E) - Coordinator

Atmospheric River Reconnaissance 2023 Sequence-1





Aircraft observations of wind, temperature, pressure and moisture are collected as a dropsonde descends, and are radioed to the aircraft. They are then transmitted via satellite to a Global Weather Data Hub for immediate assimilation by global weather models, thus impacting the forecasts of ARs and rainfall as the storms generally move from west to east.

Key support from California Department of Water Resources-AR Program and US Army Corps of Engineers-FIRO NOAA/OMAO & NWS US Air Force 53rd Weather Squadron

Center for Western Weather and Water Extremes
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AR RECON 2023

Status 25 January 2023

First-ever AR Recon Pre-Season Took Place in Nov-Dec 2022 with 5 ARs flown
Core AR Recon season: 5 January through 31 March 2023

4 USAF C-130 aircraft based at Mather Field in Sacramento, California
1 NOAA G-IV Jet based in Honolulu, Hawaii (through January 2023)

**IOP = Intensive Observing Period, indicate days when AR Recon flights are flown*

Jan 2023 Longest Flight Sequence on Record Planned
included IOPs for 13 consecutive days*

- Team conducted 13 days in a row of flight planning and missions
  - 21 individual aircraft flights, with >700 Dropsondes from the aircraft
- 91 drifting buoys with pressure available over the NE Pacific (86 through AR Recon partnership with NOAA's Global Drifter Program)
- Radiosondes launched by CW3E across CA during ARs
- Data are used in US, Navy, European, and other global forecast models

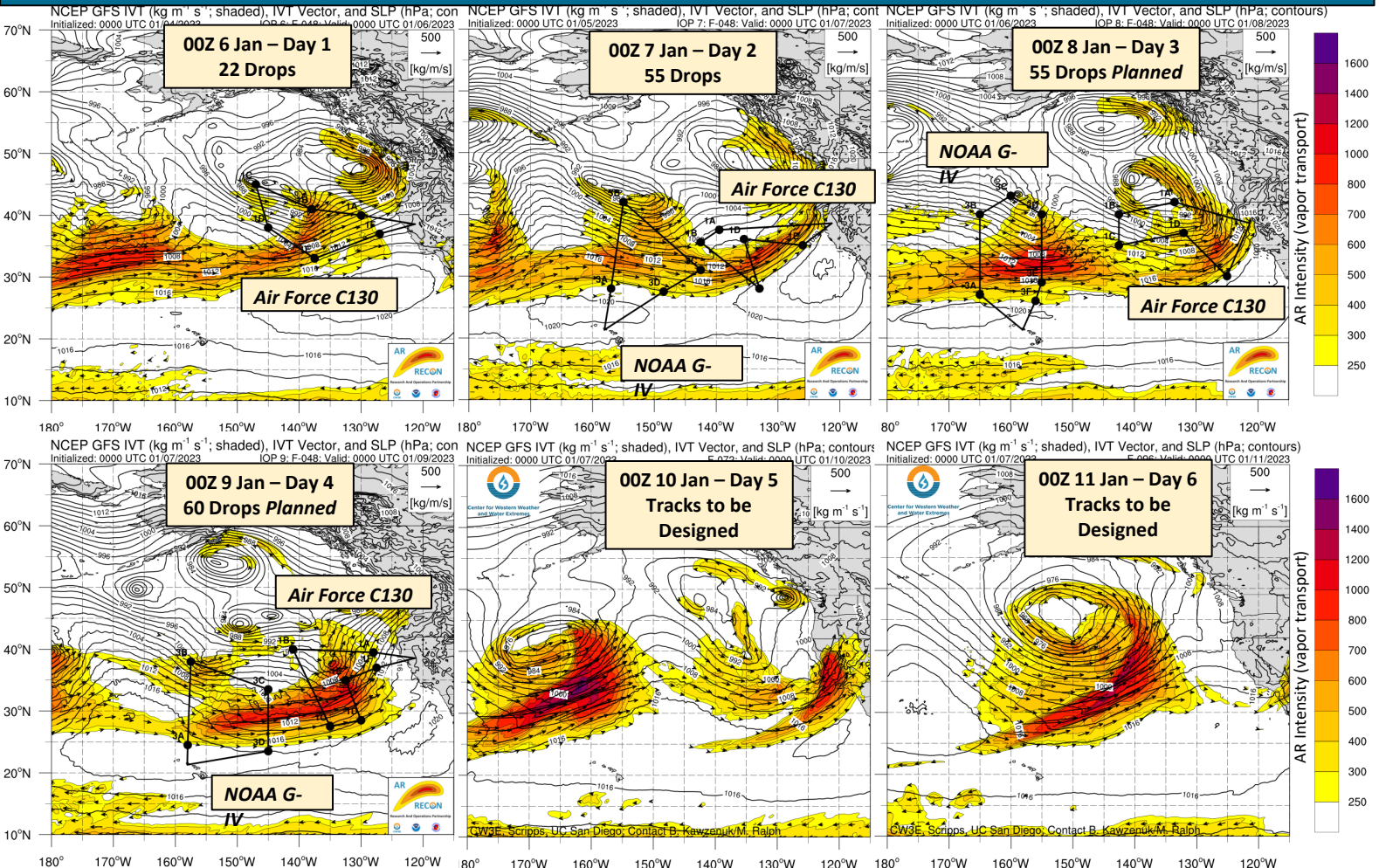
Key support from California Department of Water Resources/AR Program and US Army Corps of Engineers/FIRO Program

CW3E Center for Western Weather and Water Extremes

F. Martin Ralph, PI (UC San Diego/SIO/CW3E)
Vijay Tallapragada, Co-PI (NOAA/NWS/NCEP)

UC San Diego | Scripps Institution of Oceanography

Atmospheric River Reconnaissance 2023 Sequence-1



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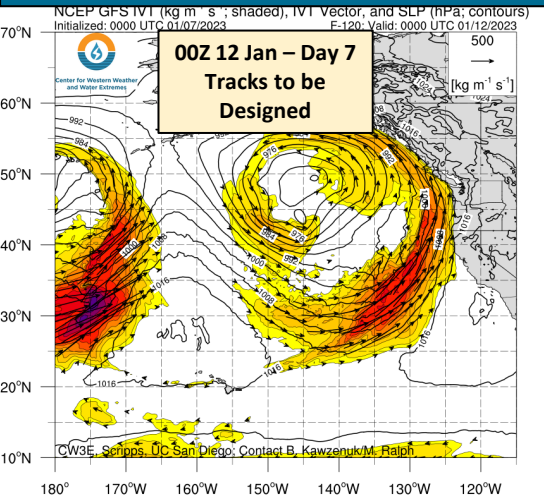
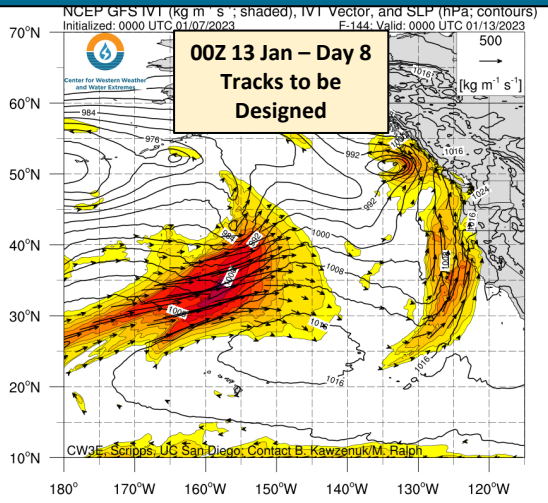
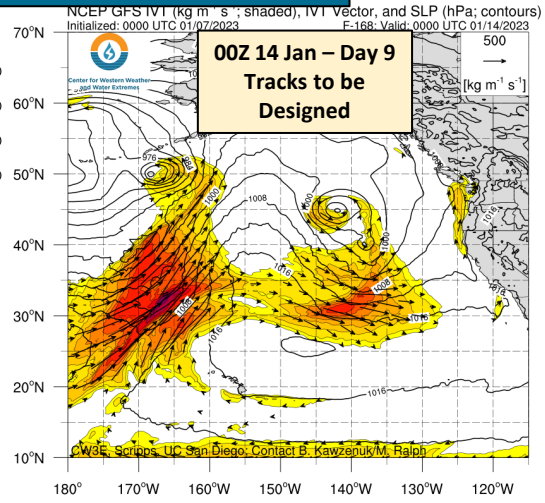
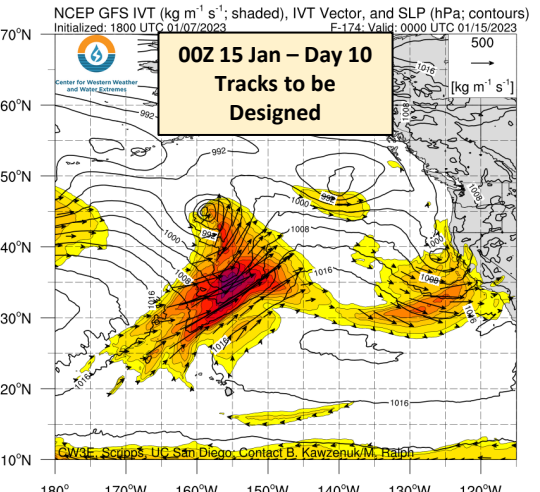
Atmospheric River Reconnaissance 2023 Sequence-1





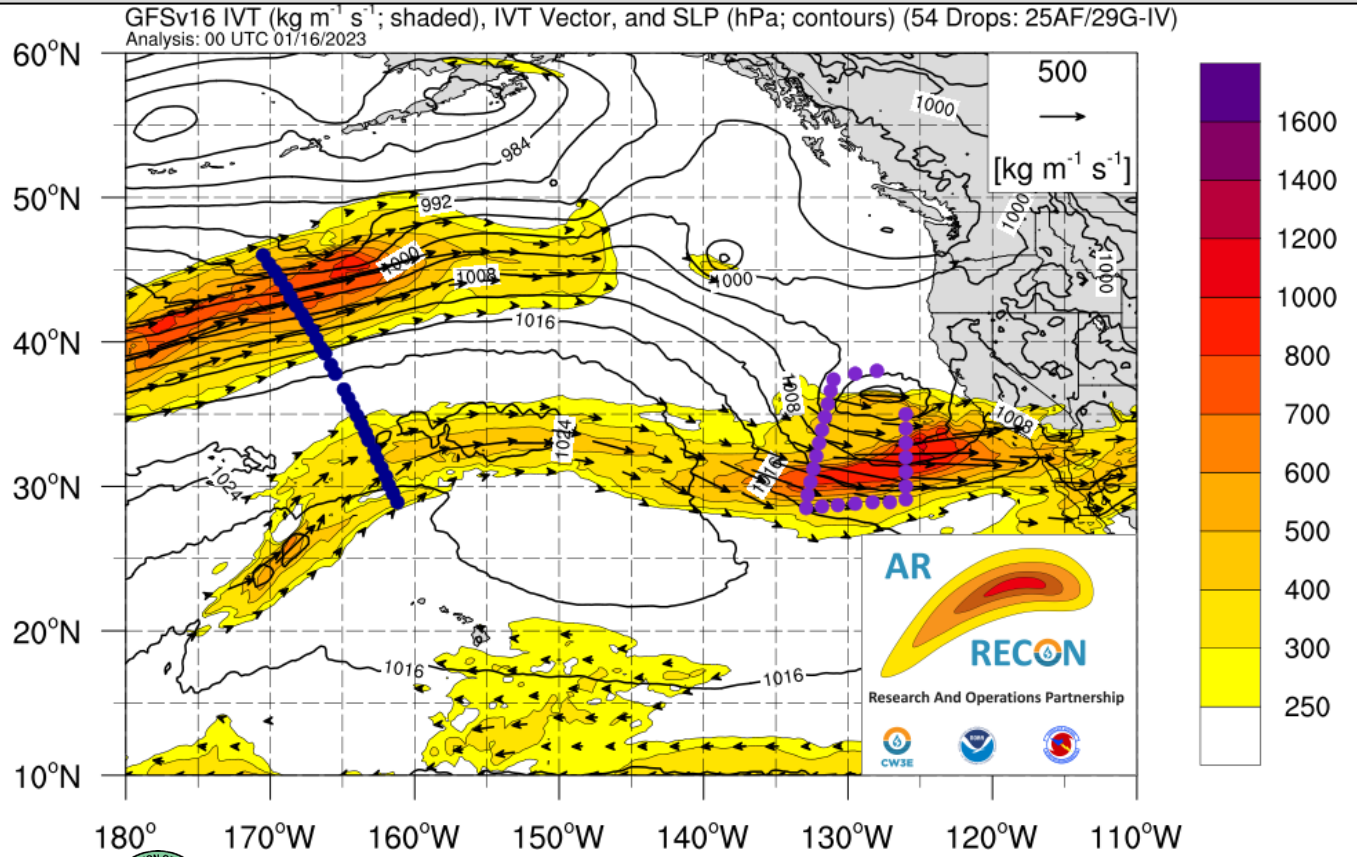




Flight Tracks

- Track patterns are designed and confirmed the day before takeoff with team of experts from a variety of agencies and institutions under CW3E leadership (PI F. Martin Ralph) and NWS leadership (Co-PI V. Tallapragada). Teams use CW3E's unique AR forecast tools.
- Air Force Reserve Command 53rd Weather Reconnaissance Squadron has 2 crews and 4 C130-WJ aircraft at Mather in Sacramento, CA. Up to two aircraft can fly per day. Each crew needs a day of crew rest between flights.
- NOAA Aircraft Operations Center has 1 crew and 1 G-IV aircraft in Honolulu, HI. The crew can fly up to 6 days in a row before needing a crew rest day.

IOP16, 16 Jan 2023

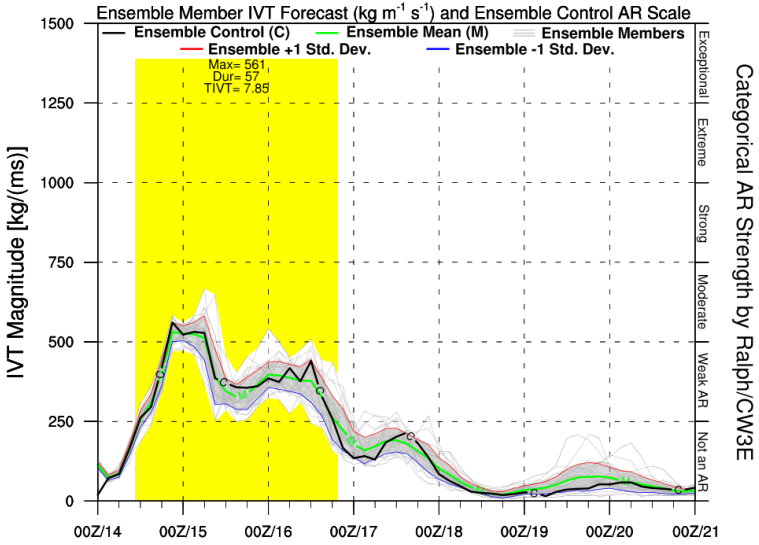


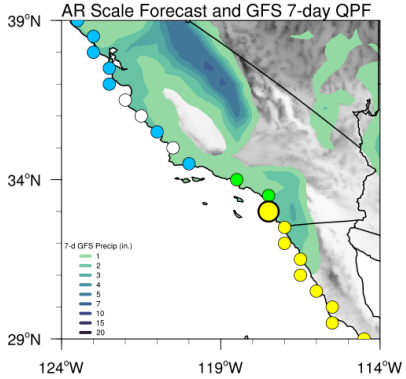
Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

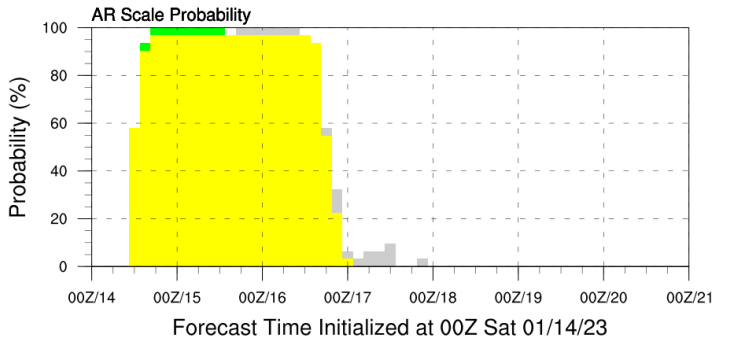
F. Martin Ralph (UCSD/SIO/CW3E) - PI
Vijay Tallapragada (NWS/NCEP) - Co-PI
Anna Wilson (UCSD/SIO/CW3E) - Coordinator

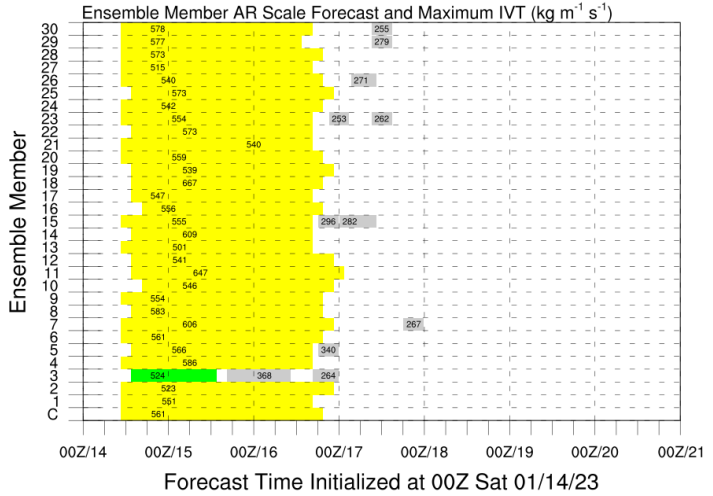
GFS Ensemble Inititialized: 00Z Sat 01/14/23

Location: 33°N 117.5°W









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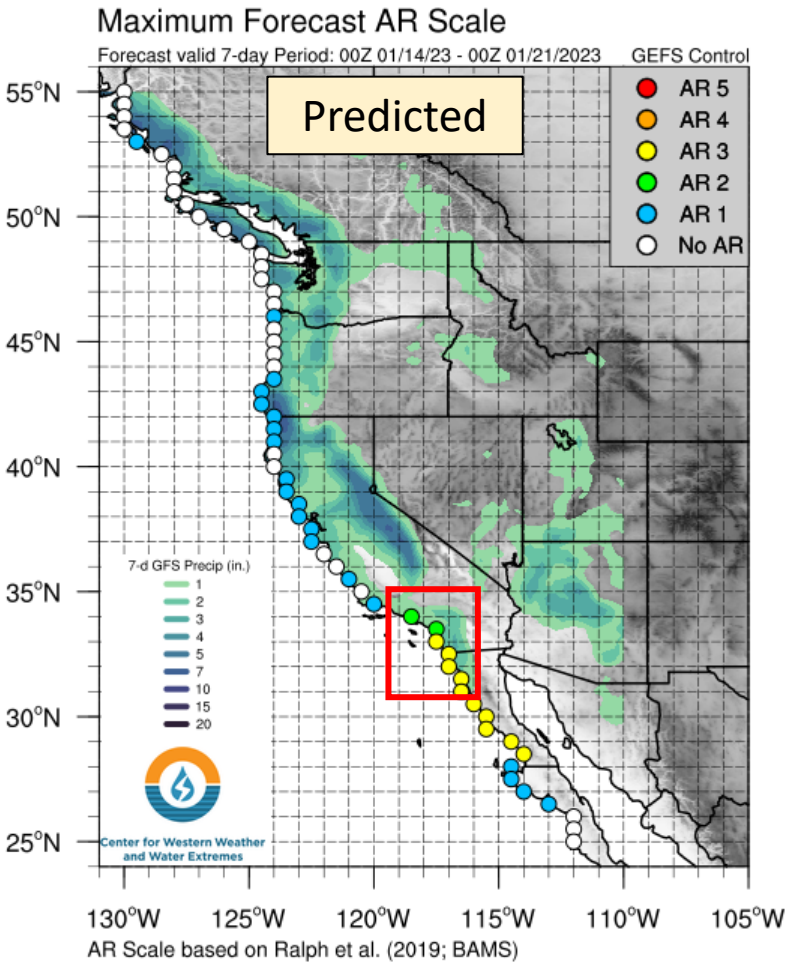
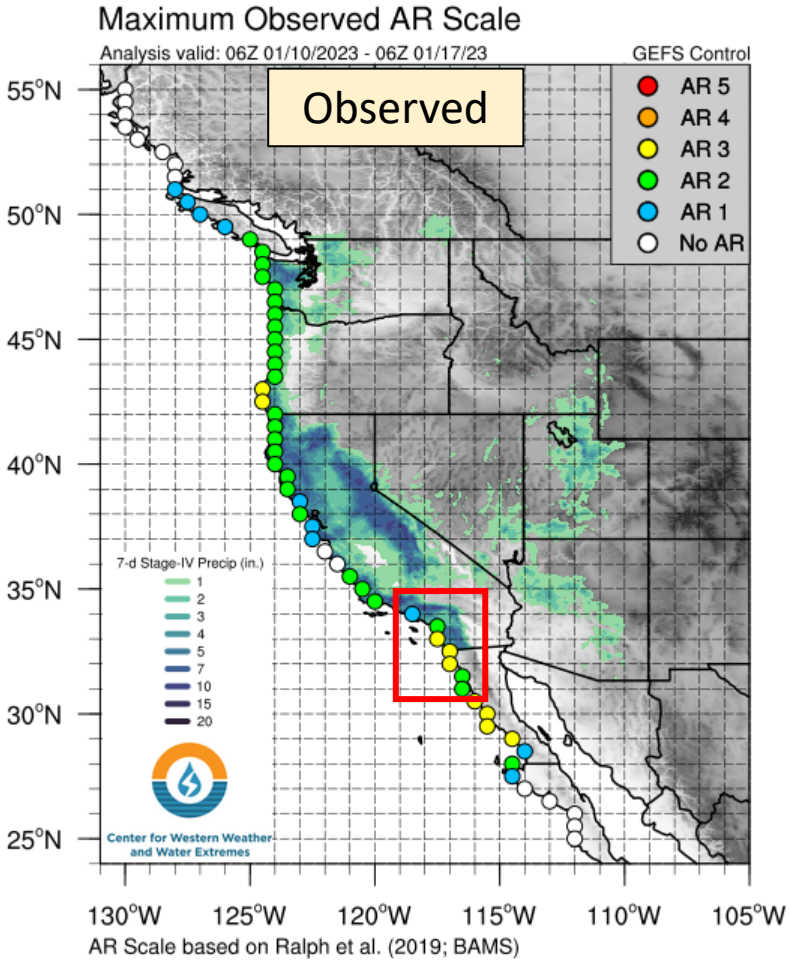
AR 1 AR 2 AR 3 AR 4 AR 5

Image created: 14 UTC 01/14/2023

More information: http://cw3e.ucsd.edu AR Scale based on Ralph et al. (2019; BAMS), contact M. Ralph


Maximum Forecast AR Scale
Forecast valid 7-day Period: 00Z 01/14/23 - 00Z 01/21/2023
GEFS Control
Predicted
AR 5
AR 4
AR 3
AR 2
AR 1
No AR
7-d GFS Precip (in.)
1
2
3
4
5
7
10
15
20
Center for Western Weather and Water Extremes
55°N
50°N
45°N
40°N
35°N
30°N
25°N
130°W
125°W
120°W
115°W
110°W
105°W
AR Scale based on Ralph et al. (2019; BAMS)


Maximum Observed AR Scale
Analysis valid: 06Z 01/10/2023 - 06Z 01/17/23
GEFS Control
Observed
AR 5
AR 4
AR 3
AR 2
AR 1
No AR
7-d Stage-IV Precip (in.)
1
2
3
4
5
7
10
15
20
Center for Western Weather and Water Extremes
55°N
50°N
45°N
40°N
35°N
30°N
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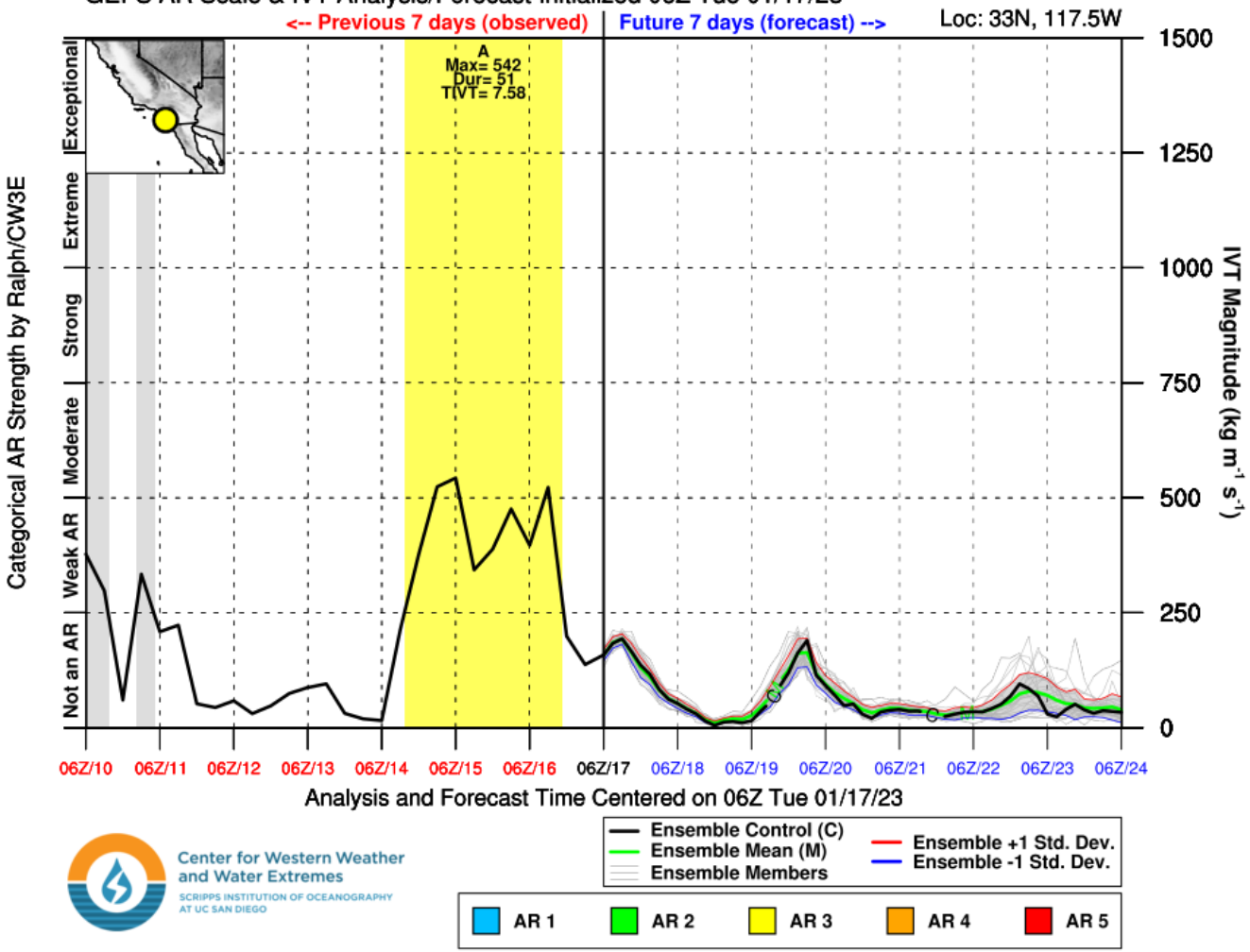


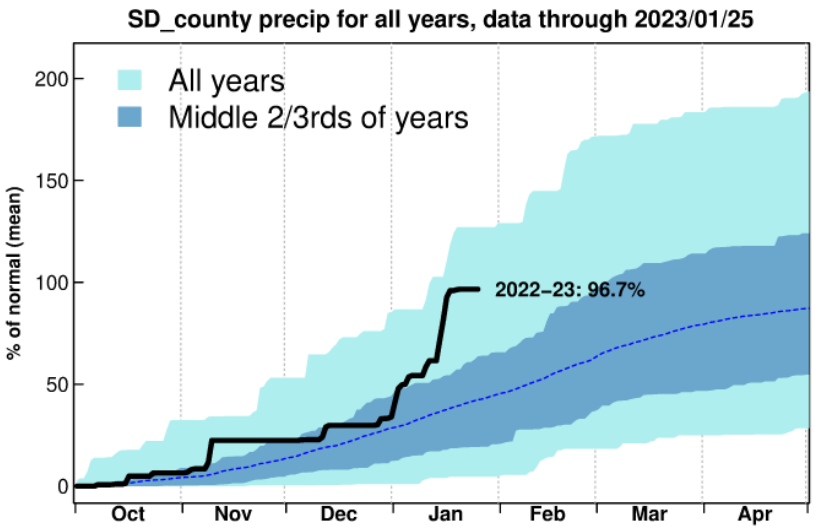
Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

Image created: 11 UTC 01/17/2023

More information: http://cw3e.ucsd.edu AR Scale based on Ralph et al. (2019; BAMS), contact M. Ralph

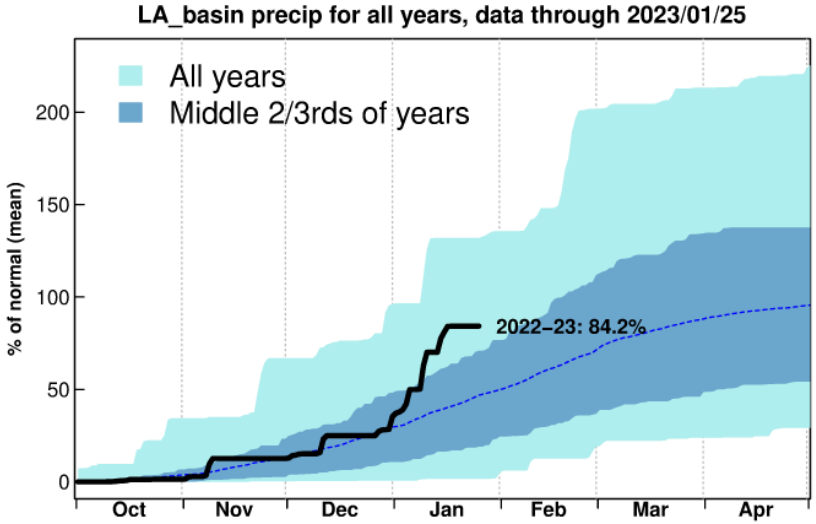
San Diego County: 97% of normal total precip for the water year

- The AR3 of 14-16 Jan produced the equivalent of 24% of annual average precip, in just 3 days



Los Angeles Basin: 84% of normal total precip for the water year

- The AR of 9-11 Jan produced the equivalent of 18% of annual average precip, in just 3 days



Major reservoir levels

Reservoirs get us through the dry months

98%

of average levels

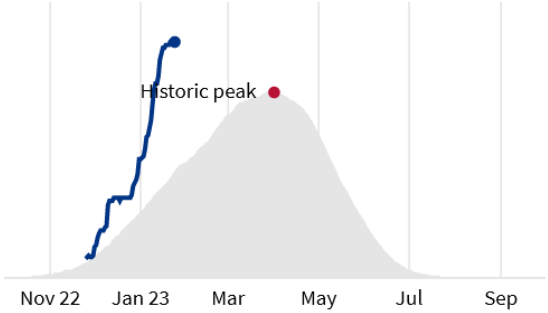
Updated daily

More about reservoirs

Statewide snowpack levels

Snow melt feeds our reservoirs & rivers

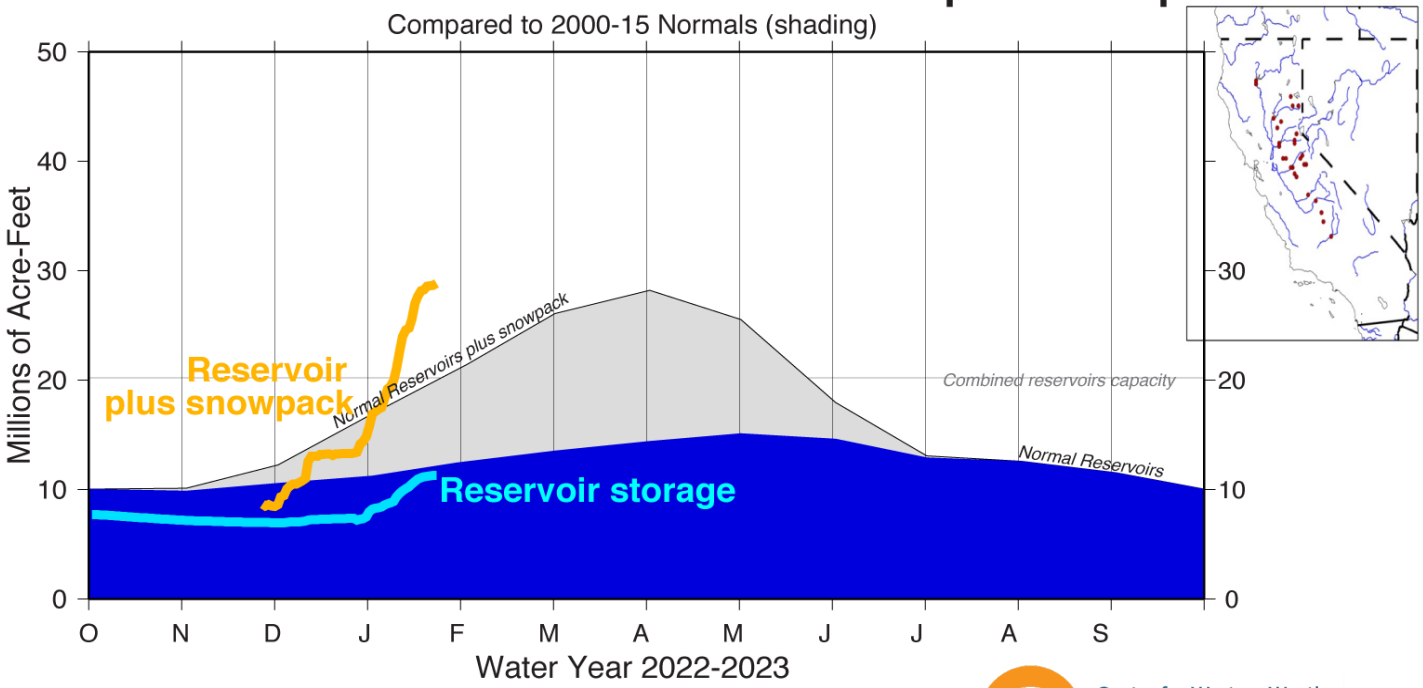
127% of average peak snowpack



Updated daily

More about snowpack levels

Water Stored in 28 Western Sierra Reservoirs plus Snowpack



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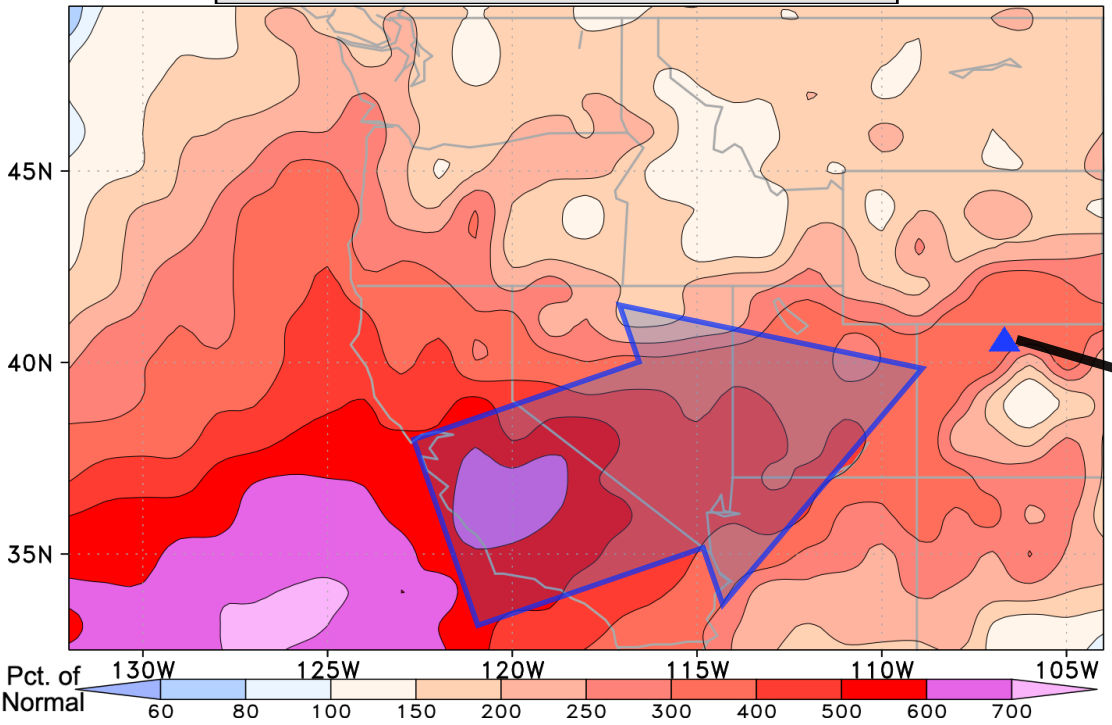
SOURCES: SWE dailies from https://cdec.water.ca.gov/querySWC.html
SWE volume conversion factor based on Margulis et al, JHM 2016, SWE reanalysis
Reservoir storage from https://cdec.water.ca.gov/queryDaily.html
Reservoirs: SHA, KES, ORO, ANT, FRD, DAV, BUL, ENG, FOL, UNV, LON, ICH, NAT, CMN, PAR, DON, BRD, TUL, NML, DNP, HTH, CHV, EXC, MIL, PNF, TRM, SCC, ISB

For info: mddettinger at gmail.com
https://cnap.ucsd.edu/storage_in_sierra_ucrb/

Updated: 23 January 2023

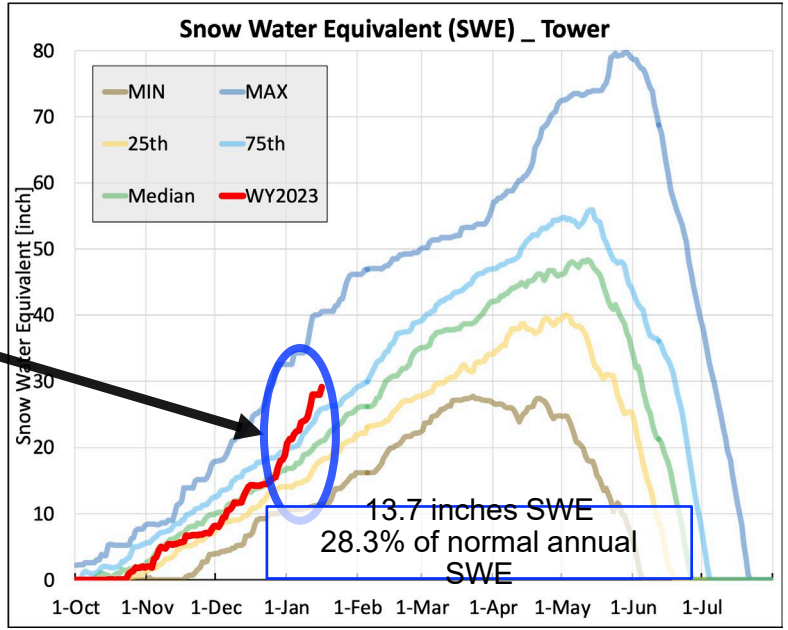
Water Vapor Transport Associated with ARs in 2022/12/26–2023/01/15

AR T-IVT — Percentage of Normal



AR T-IVT as percentage of normal (mean AR T-IVT in 1979-2021 NOV-MAR)

SWE at SNOTEL Site Tower



Snow Water Equivalent (SWE) at SNOTEL site Tower in the Upper Colorado River Basin
Climatology is based on 30 water years (WY1991-2020)

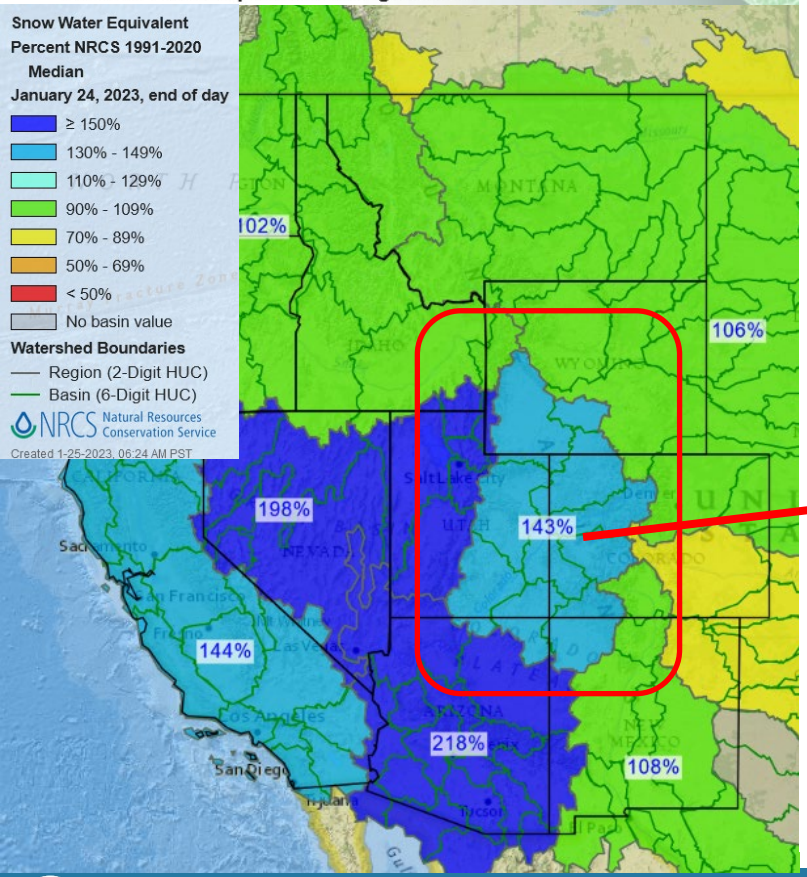
ARs penetrated around or above 300% of normal AR T-IVT in 3 weeks into the southwestern U.S.

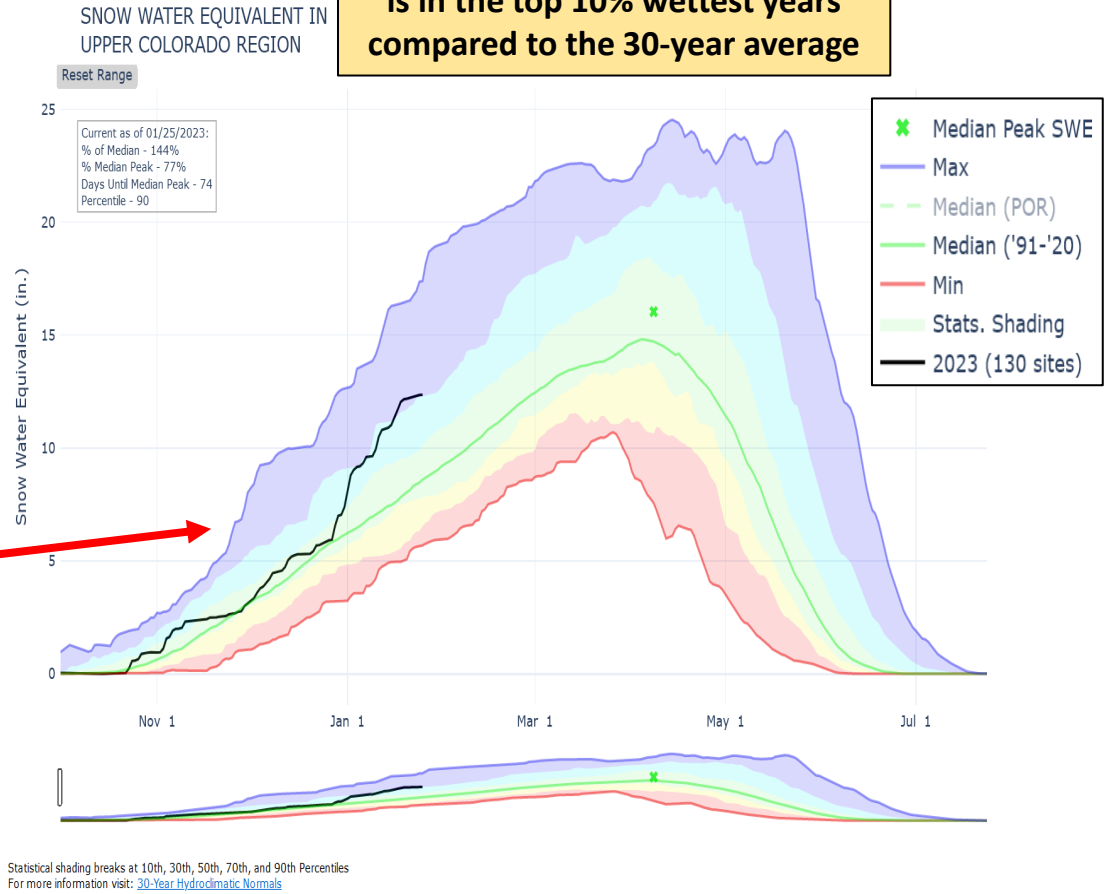
USDA Logo

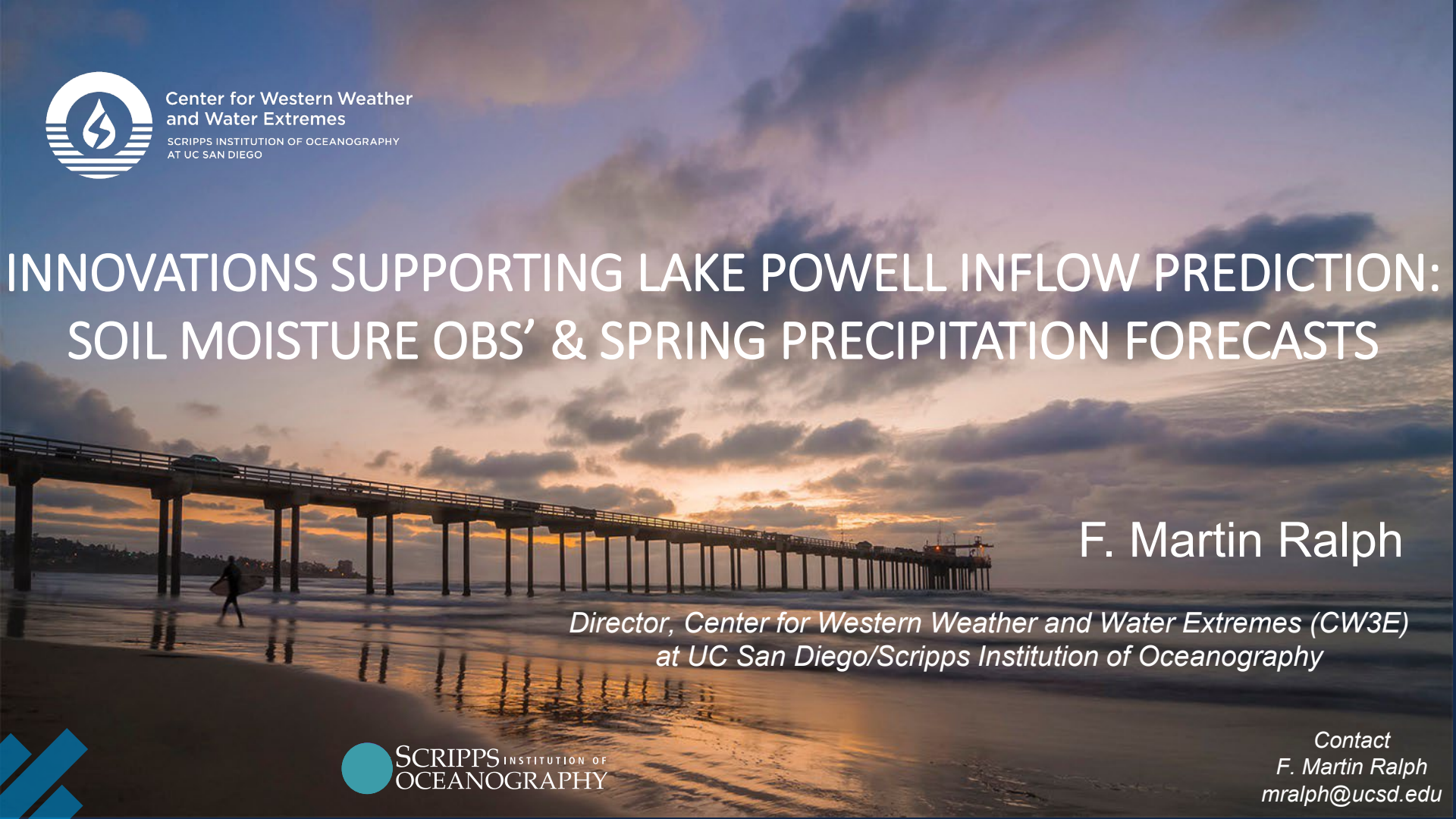
Natural Resources Conservation Service
National Water and Climate Center

United States Department of Agriculture

Upper Colorado Basin Snowpack is in the top 10% wettest years compared to the 30-year average







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INNOVATIONS SUPPORTING LAKE POWELL INFLOW PREDICTION: SOIL MOISTURE OBS' & SPRING PRECIPITATION FORECASTS

F. Martin Ralph

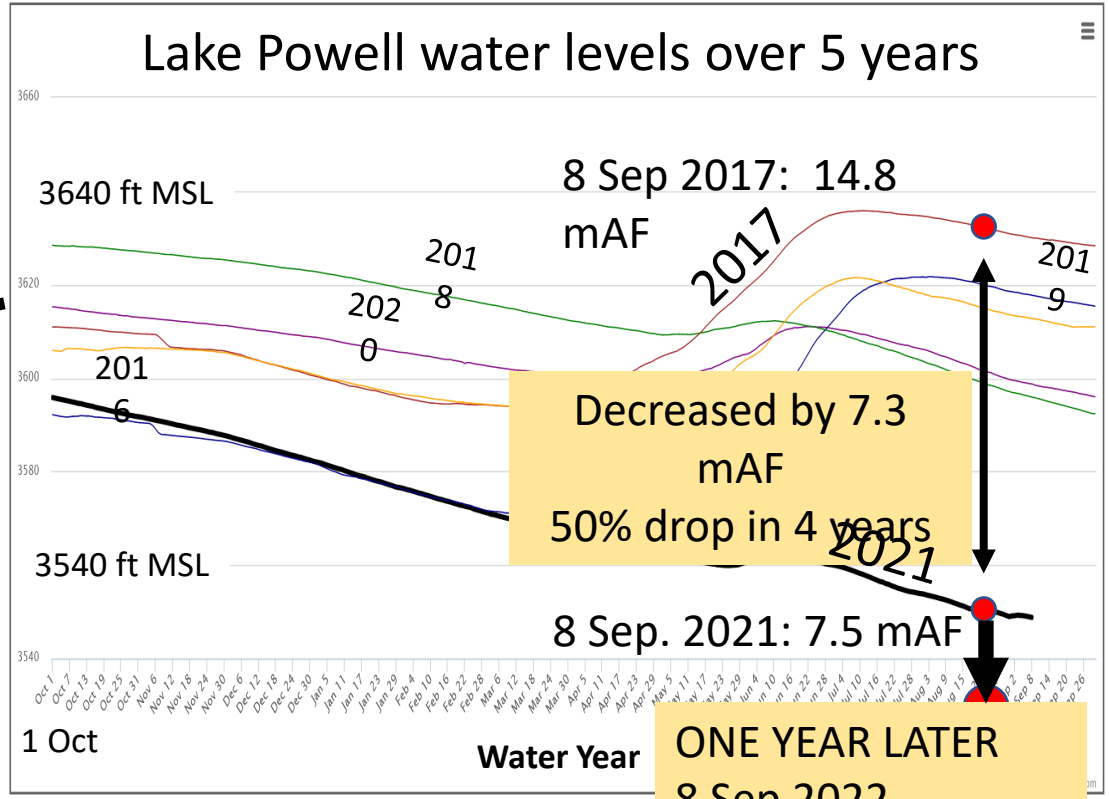
Director, Center for Western Weather and Water Extremes (CW3E)
at UC San Diego/Scripps Institution of Oceanography

SCRIPPS INSTITUTION OF OCEANOGRAPHY

Contact
F. Martin Ralph
mralph@ucsd.edu

Colorado River is the largest river and most important surface water source in the Southwestern US

More than 90% of its streamflow is generated from snowmelt in the Upper Colorado River Basin (UCRB)

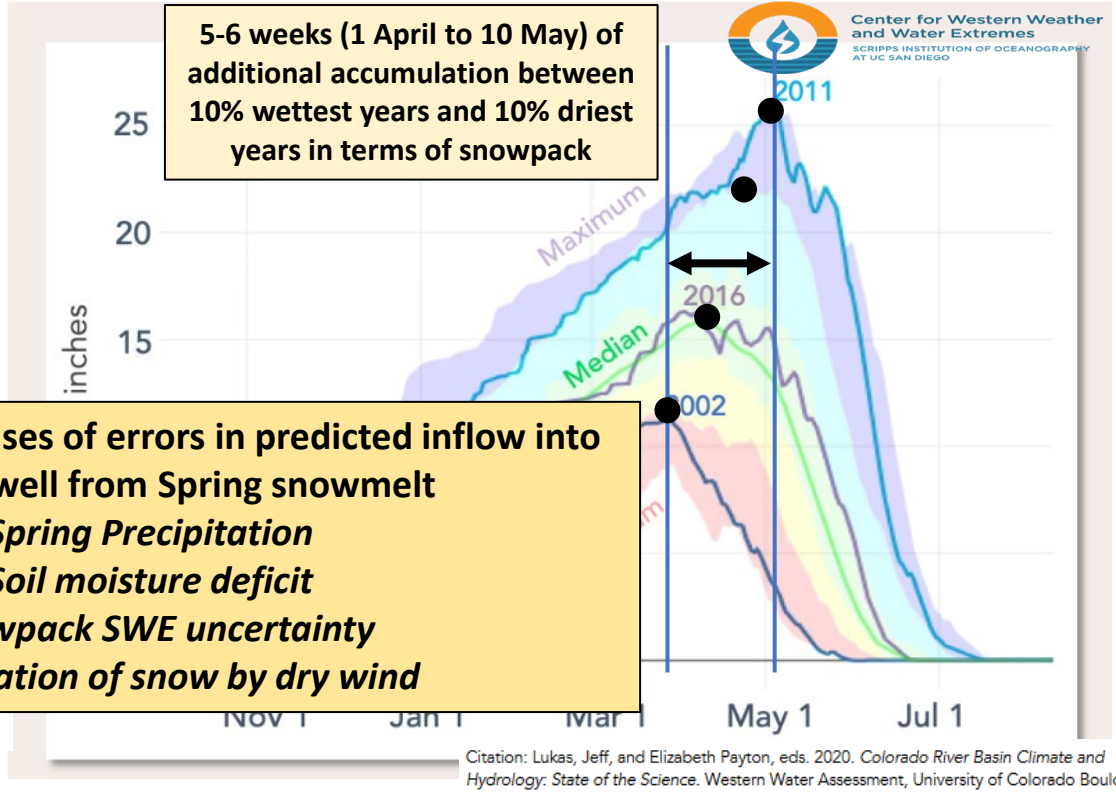


Colorado River – Difficult to predict the vital inflow into Lake Powell from spring snowmelt

Predicted** (in March) vs observed April to July inflow into Lake Powell

Water year	March forecast (m AF*)	Apr-Jul actual (m AF*)	Error (m AF*)	Error % annual avg*
2018	3400	2602	-798	-9 %

5-6 weeks (1 April to 10 May) of additional accumulation between 10% wettest years and 10% driest years in terms of snowpack



Four likely key causes of errors in predicted inflow into Lake Powell from Spring snowmelt

Spring Precipitation

Soil moisture deficit

Snowpack SWE uncertainty

Sublimation of snow by dry wind

Citation: Lukas, Jeff, and Elizabeth Payton, eds. 2020. *Colorado River Basin Climate and Hydrology: State of the Science*. Western Water Assessment, University of Colorado Boulder. DOI: https://doi.org/10.25810/3hcv-w477.

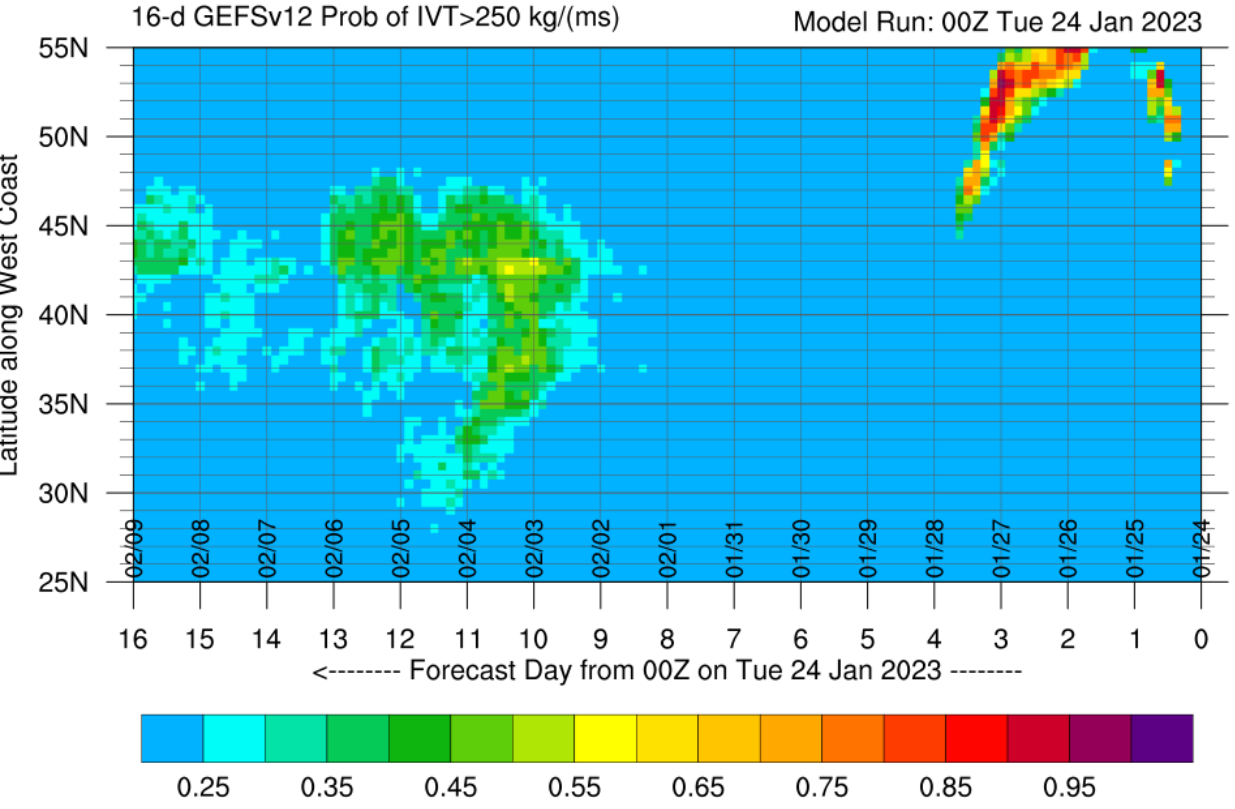
*Assumes average annual total inflow to Lake Powell of 8.5 million acre feet (m AF) from 2002-2021

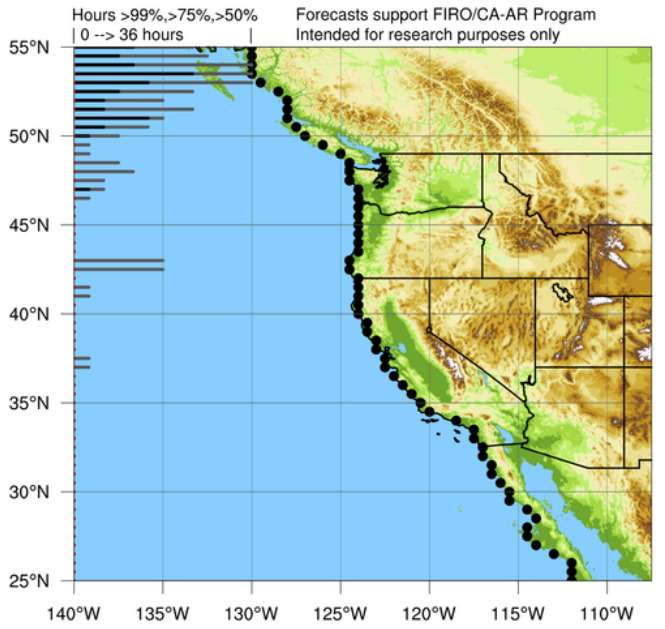
**50% probability; NOAA/NWS/Colorado Basin River Forecast Center

A few extreme snow events, or early heat waves can impact outcome

Soil Moisture In Situ Observing Network Concept for the Upper Colorado Basin

Photos: Marty Ralph July 2022
Upper Colorado Basin





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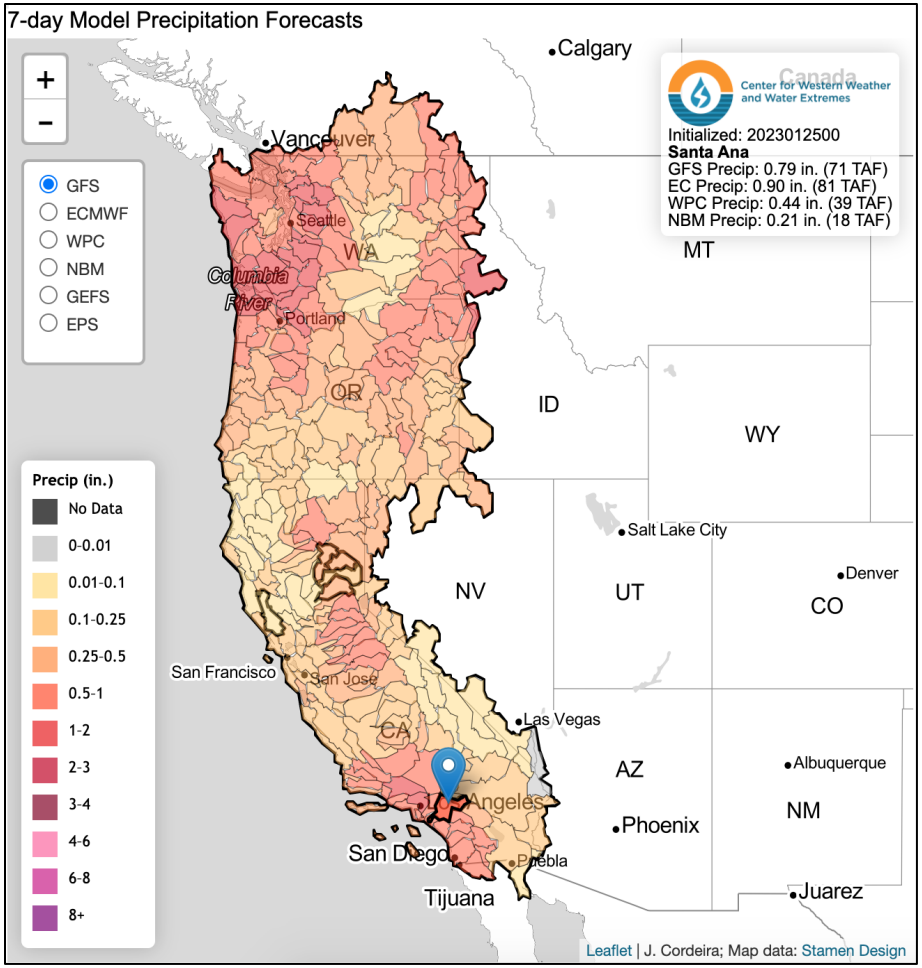
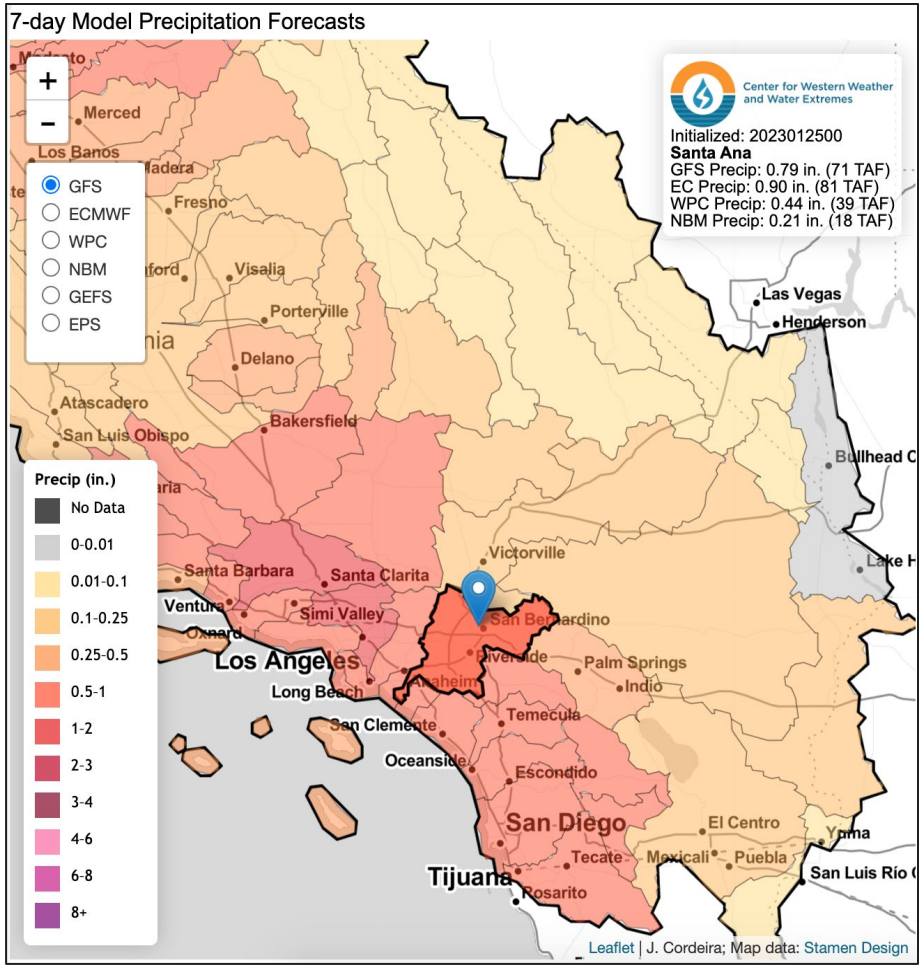
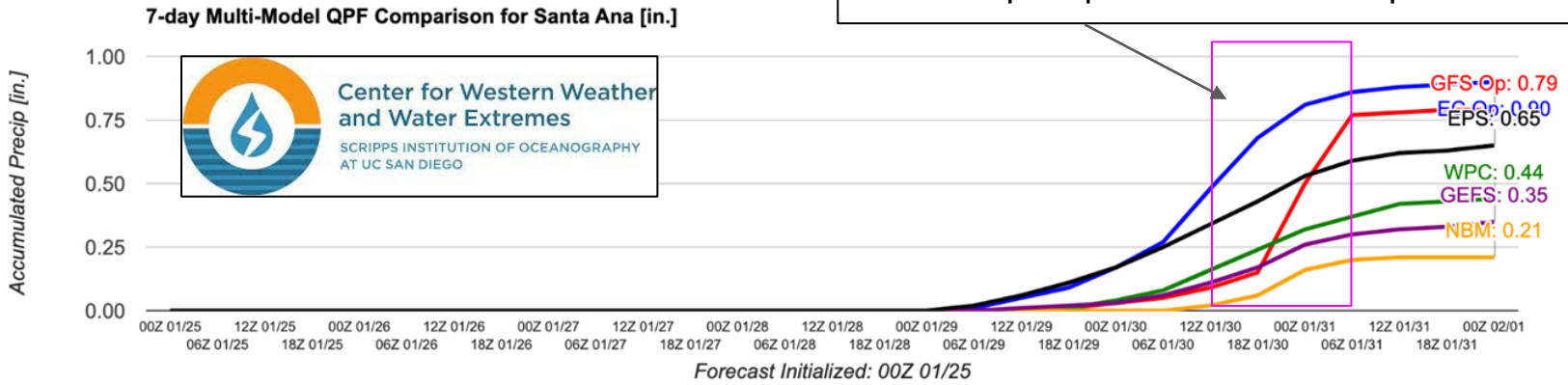
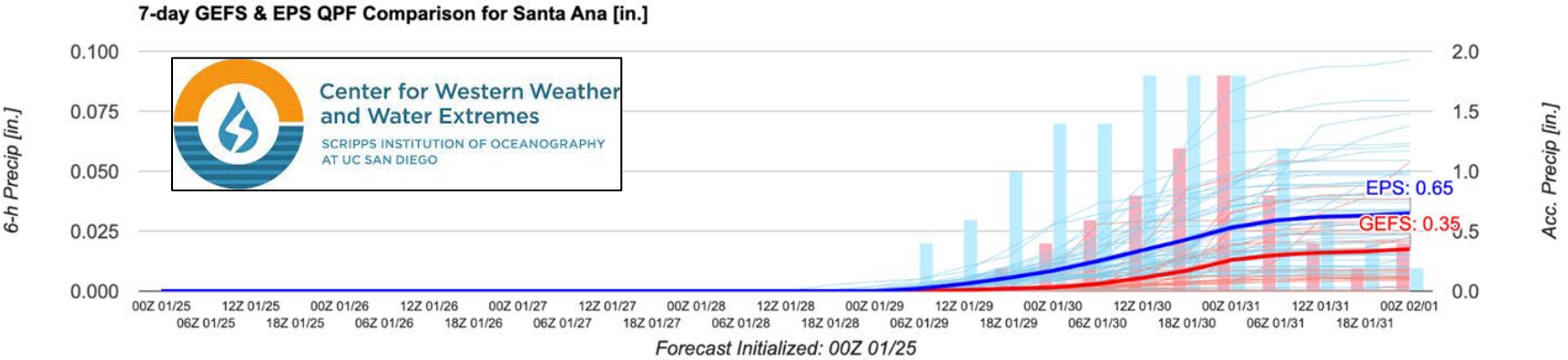




Data Access: https://cw3e.ucsd.edu/Projects/QPF/QPF-HUC8.html

Heaviest precipitation is ~4am-10pm PT Mon 30 Jan

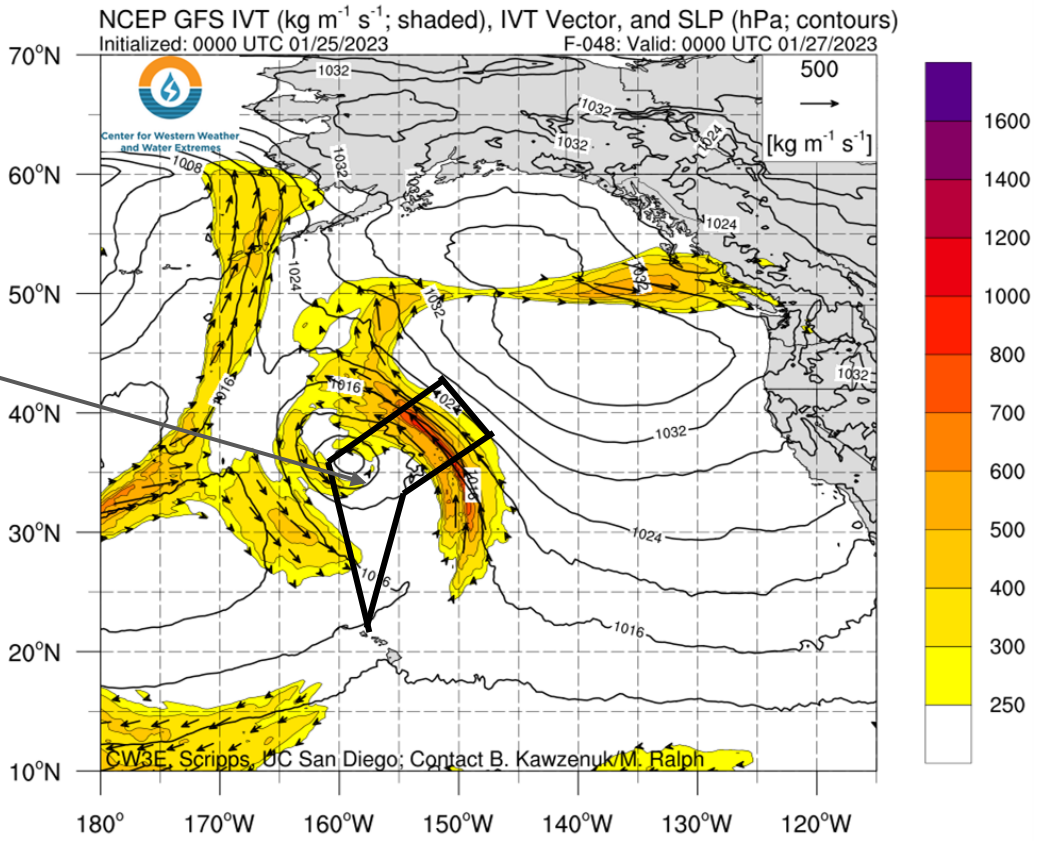




Data Access: https://cw3e.ucsd.edu/Projects/QPF/QPF-HUC8.html

GFS Day IVT Forecast and Planned G-IV Track

0000 UTC 27 Jan



Planned G-IV
AR Recon Flight

Thank You

Contact: mralph@ucsd.edu