

## **Strong Atmospheric Rivers Bring Heavy Precipitation and Flooding in California**

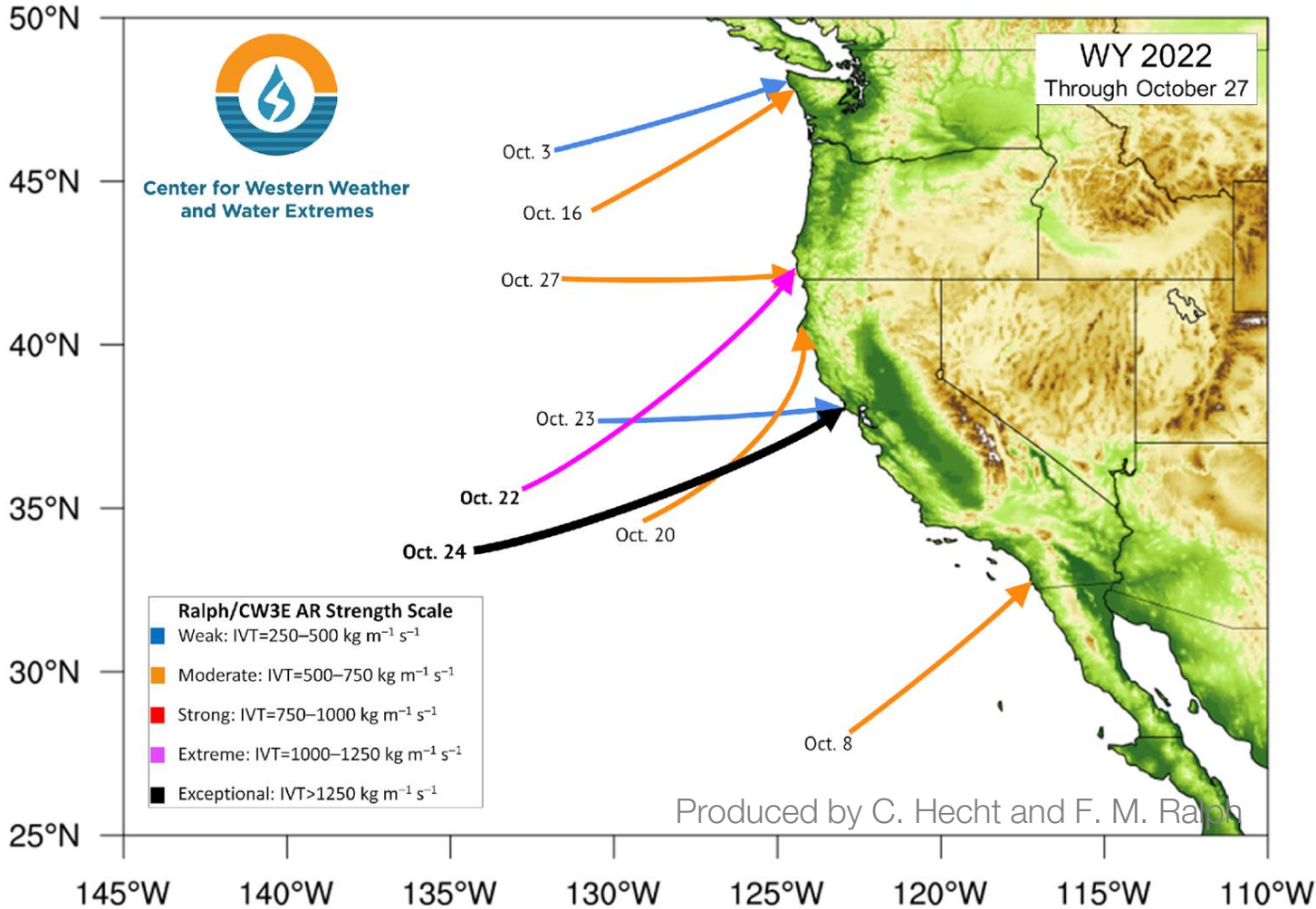
- Multiple atmospheric rivers (ARs) made landfall along and impacted the US West Coast between 19 Oct and 26 Oct
- The first two ARs produced AR 4 conditions in southwestern Oregon and AR 2/AR 3 conditions were observed elsewhere along the coast from the San Francisco Bay Area to the Olympic Peninsula
- The third AR reached AR 5 conditions over California near Point Reyes due to the combination of maximum IVT values ( $> 1000 \text{ kg m}^{-1} \text{ s}^{-1}$ ) and AR duration ( $> 48$  hours) (based on the Ralph et al. 2019 AR Scale).
- The third AR was the strongest October AR to make landfall in the Bay Area in the last 40 years.
- Portions of Northern California received more than 15 inches of total precipitation from the three storms
- Intense rainfall on 24 Oct caused flooding in the Bay Area and triggered multiple slides in Northern California
- The combination of heavy rain and high winds downed trees and caused power outages throughout the Bay Area
- Although there was heavy rain, reservoirs throughout the western Sierra Mountains and else where only saw small gains in storage.
- The third and strongest AR was well forecasted out to 3-days lead time, with the presence of the AR well forecasted out to 6 days.
- Subseasonal forecasts showed higher AR activity 3 weeks out.

# Water Year 2022 Landfalling Atmospheric Rivers through October 27<sup>th</sup>

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

- There were 7 landfalling ARs during the entire month of October 2021
- Of those 7 ARs last October, California only experienced AR conditions from two of the ARs (only in Northern CA; 1 moderate and 1 weak)
- This October (so far), California has experienced AR conditions from 7 ARs and experienced the first **exceptional** AR since February 2015

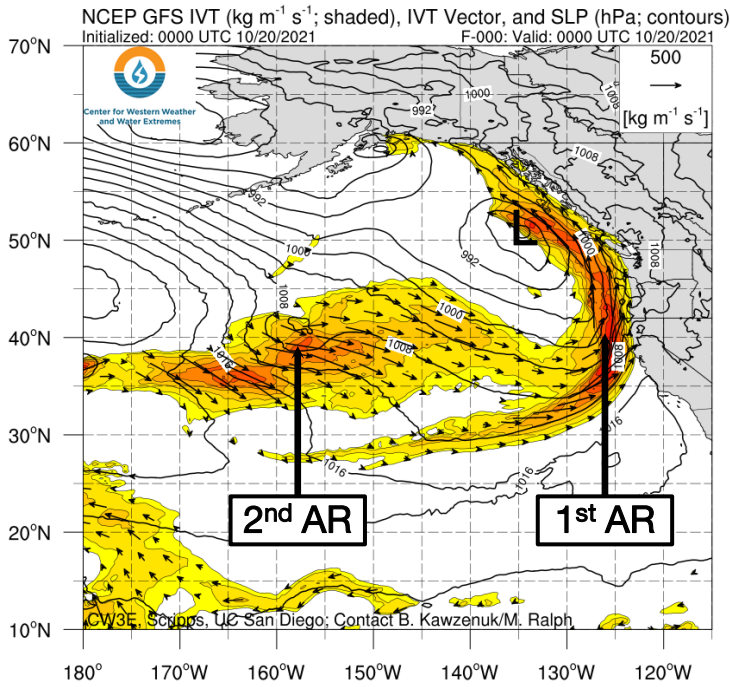
8 atmospheric rivers have made landfall over the U.S. West Coast so far this water year (Oct. 1 through 27)



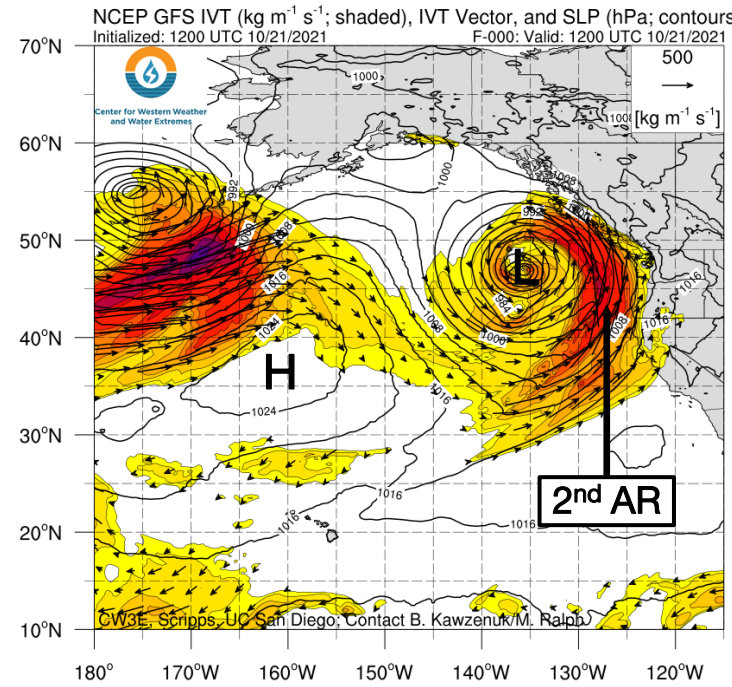
Arrows are placed on the map where each AR was strongest over the coast

## GFS IVT & IWW Analyses of the three ARs

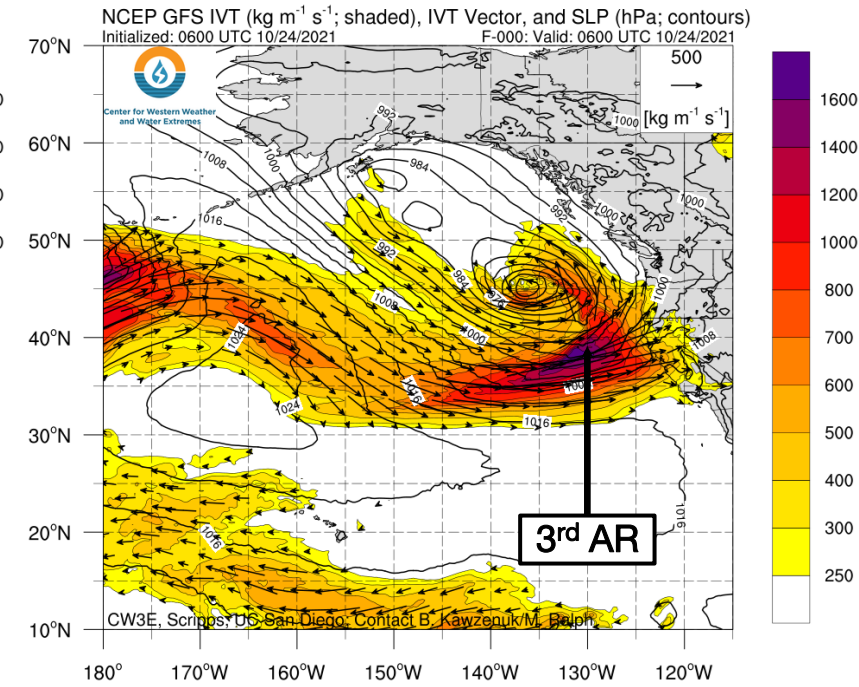
A) Valid: 5 PM PT 19 Oct



B) Valid: 5 AM PT 21 Oct



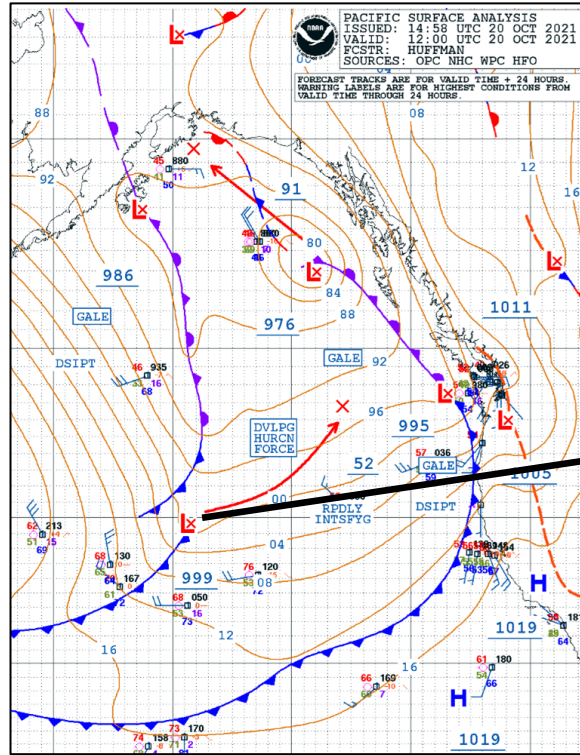
C) Valid: 11 PM PT 23 Oct



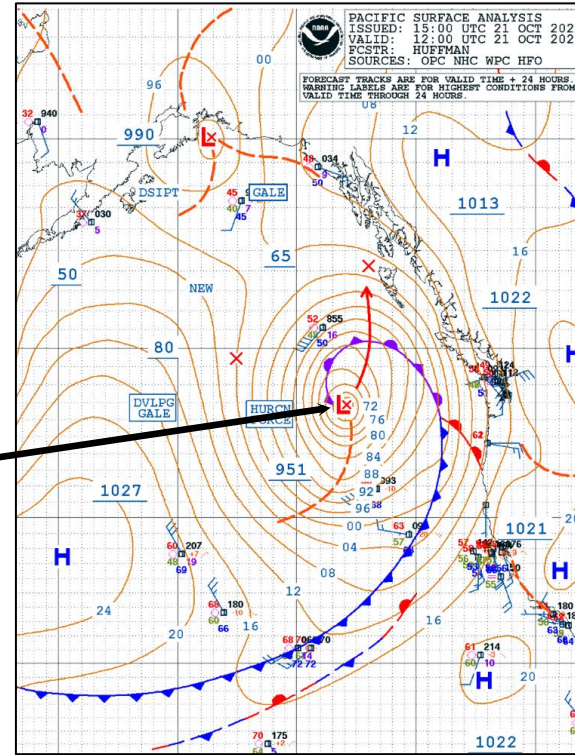
- Between 19 Oct and 24 Oct, a series of low-pressure systems and ARs developed over the Northeast Pacific Ocean and impacted the US West Coast in rapid succession
- The first AR made landfall along the US West Coast during the afternoon of 19 Oct (Figure A)
- The second AR made landfall early on 21 Oct in association with a rapidly intensifying surface cyclone (Figure B)
- The third and strongest AR made landfall in California during the evening of 23 Oct in association with yet another “bomb” cyclone (Figure C)

# CW3E Event Summary: 19–26 Oct 2021

OPC Surface Analysis:  
Valid 12Z 20 Oct 2021

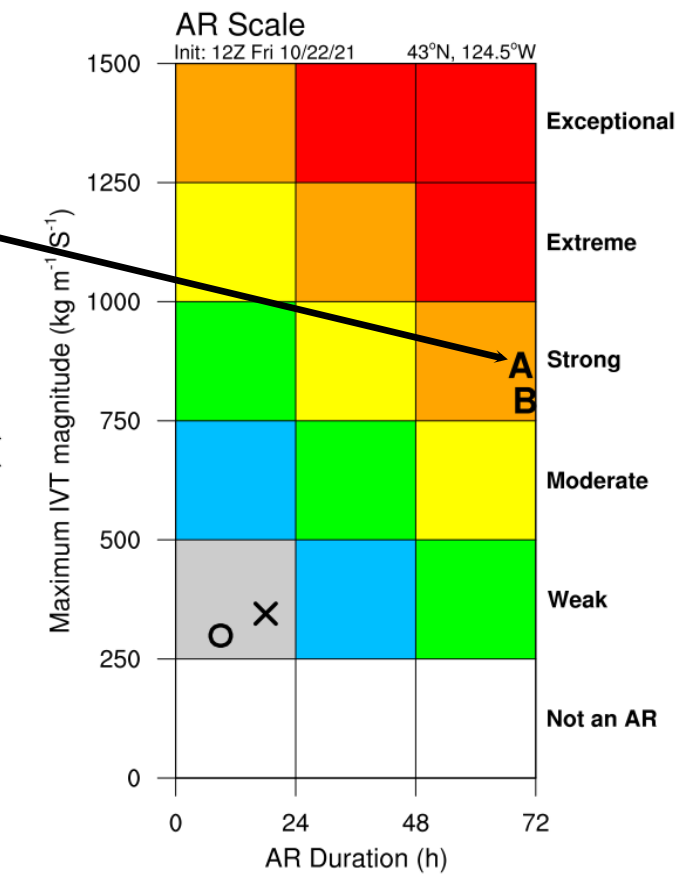
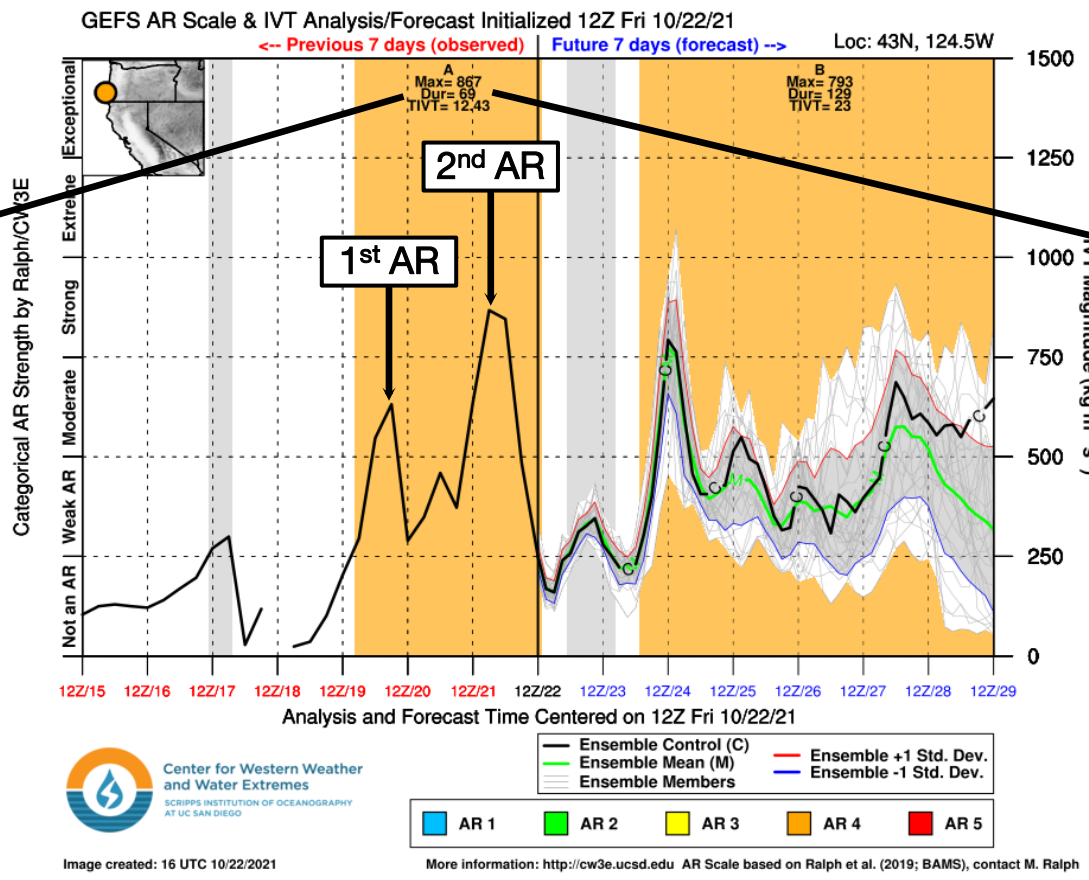
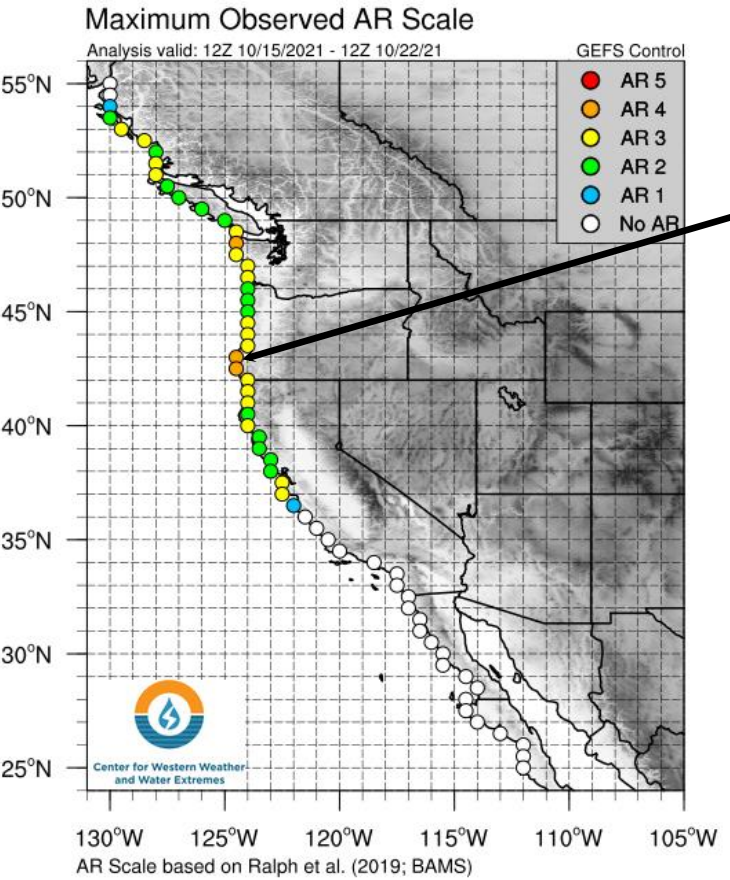


OPC Surface Analysis:  
Valid 12Z 21 Oct 2021



- The second AR was associated with an extratropical cyclone that underwent “explosive cyclogenesis” (i.e., a central pressure drop  $\geq$  24 hPa in a 24-hour period)
- The cyclone deepened more than 40 hPa in a 24-hour period, reaching minimum a pressure of 951-hPa.
- Recent CW3E research has found that 60% of explosive cyclogenesis events in the North Pacific occur in the presence of a pre-existing AR (Zhang and Ralph, 2021)

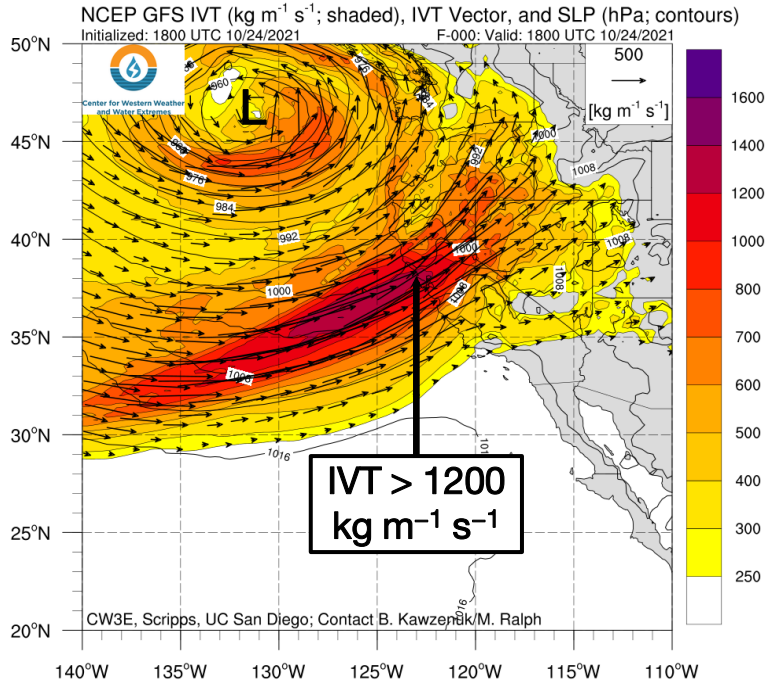
## GEFS AR Scale & IVT Analyses of first and second AR



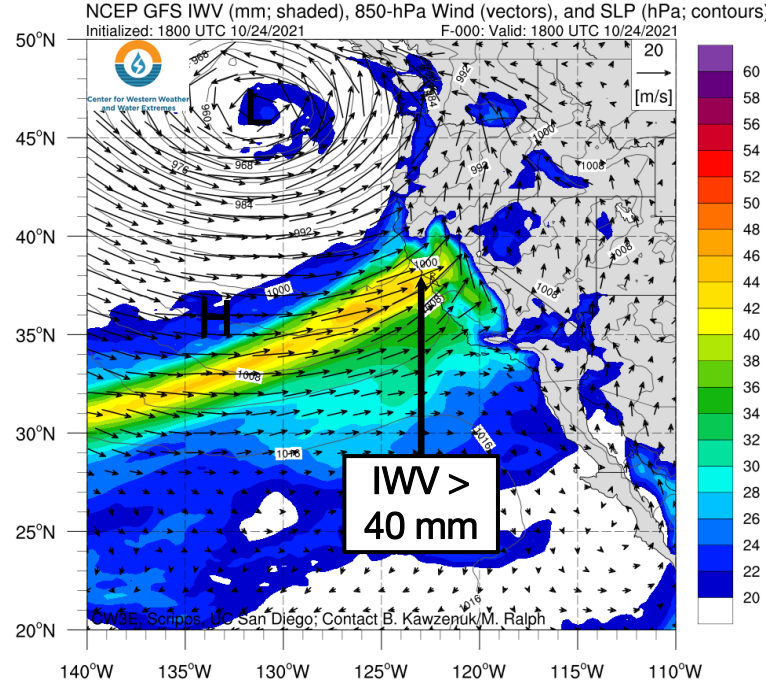
- The first two ARs produced AR 4 conditions (based on the Ralph et al. 2019 AR Scale) in southwestern Oregon and AR 2/AR 3 conditions elsewhere along the coast from the San Francisco Bay Area to the Olympic Peninsula
- A maximum IVT value of  $867 \text{ kg m}^{-1} \text{ s}^{-1}$  and an AR duration of 69 h were observed at  $43^\circ\text{N}$ ,  $124.5^\circ\text{W}$
- Some locations did not experience a break in AR conditions between the first and second ARs

## GFS IVT & IWV Analyses of third AR

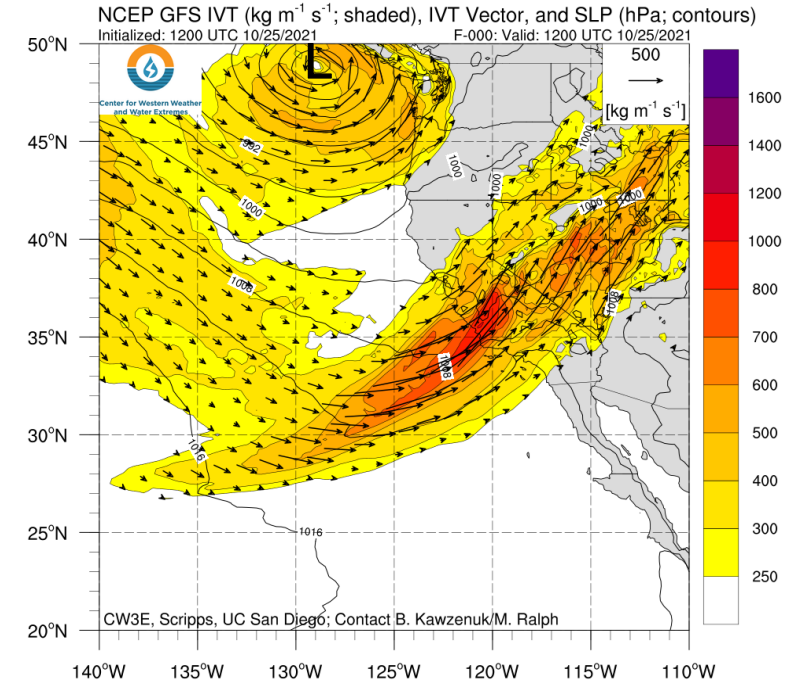
A) Valid: 11 AM PT 24 Oct



B) Valid: 11 AM PT 24 Oct



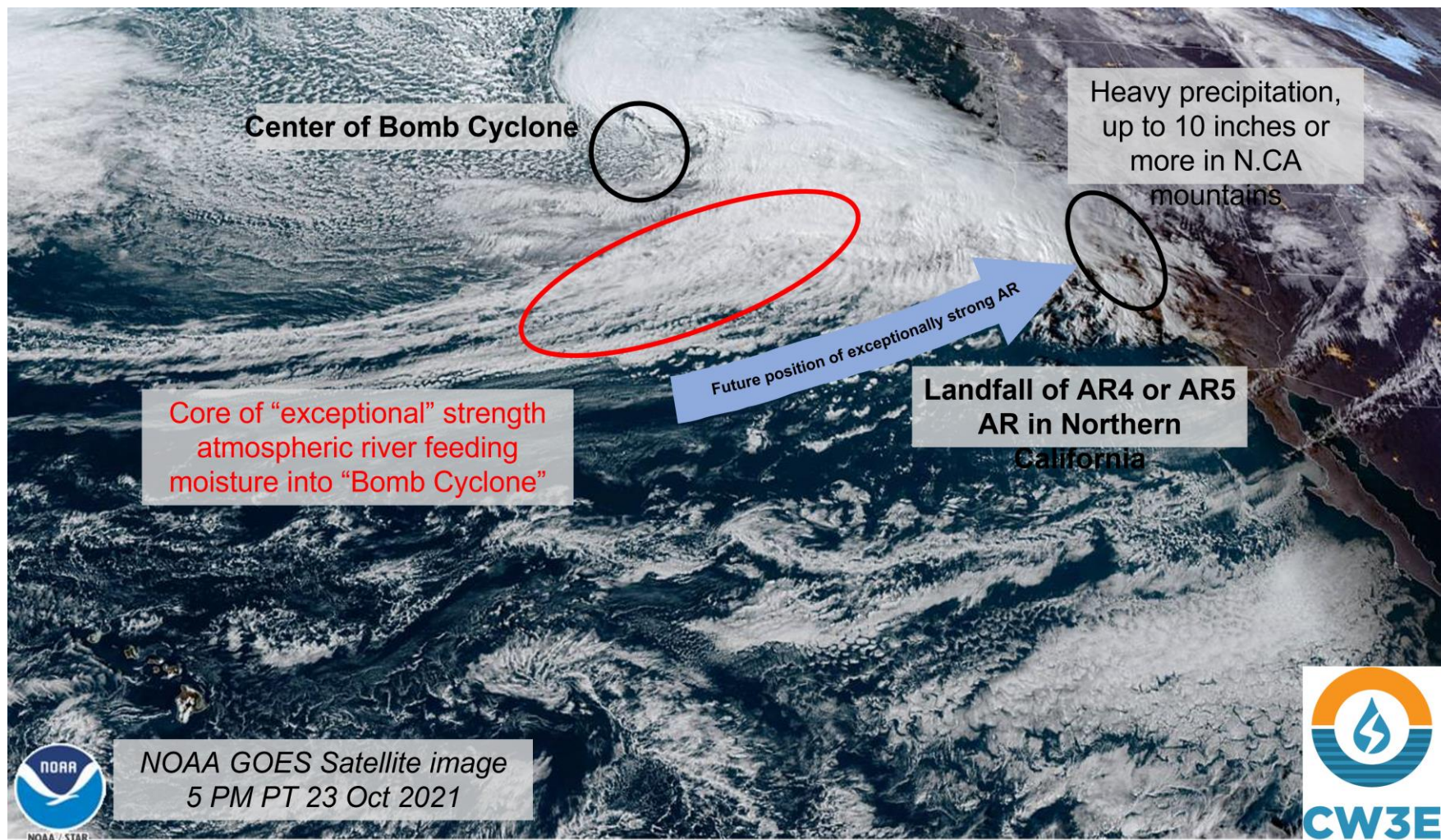
C) Valid: 5 AM PT 25 Oct



- The strongest moisture transport occurred around midday on 24 Oct, with IVT values  $> 1200 \text{ kg m}^{-1} \text{ s}^{-1}$  in Marin and Sonoma Counties (Figure A)
- These exceptional IVT values were the product of extremely moist air ( $\text{IWV} > 40 \text{ mm}$ ) and strong low-to-midlevel winds (Figure B)
- The orientation of the 850-hPa wind suggests that vigorous upslope moisture flux led to orographic enhancement of precipitation in the Coast Ranges and the Northern Sierra Nevada
- As time progressed, the core of the AR moved southward into Central California and high IVT values ( $> 500 \text{ kg m}^{-1} \text{ s}^{-1}$ ) overspread much of the interior western US (Figure C)

## Analyses of third AR

- The core of the exceptional strength Atmospheric River provided significant moisture impacting the rapid intensification of the surface cyclone
- The cyclone deepened more than 40 hPa in a 24-hour period, reaching a minimum pressure of 943-mb.
- After the rapid intensification of the cyclone the AR continued to propagate eastward and made landfall over Northern California as an AR5
- Recent CW3E research has found that 60% of explosive cyclogenesis events in the North Pacific occur in the presence of a pre-existing AR (Zhang and Ralph, 2021)

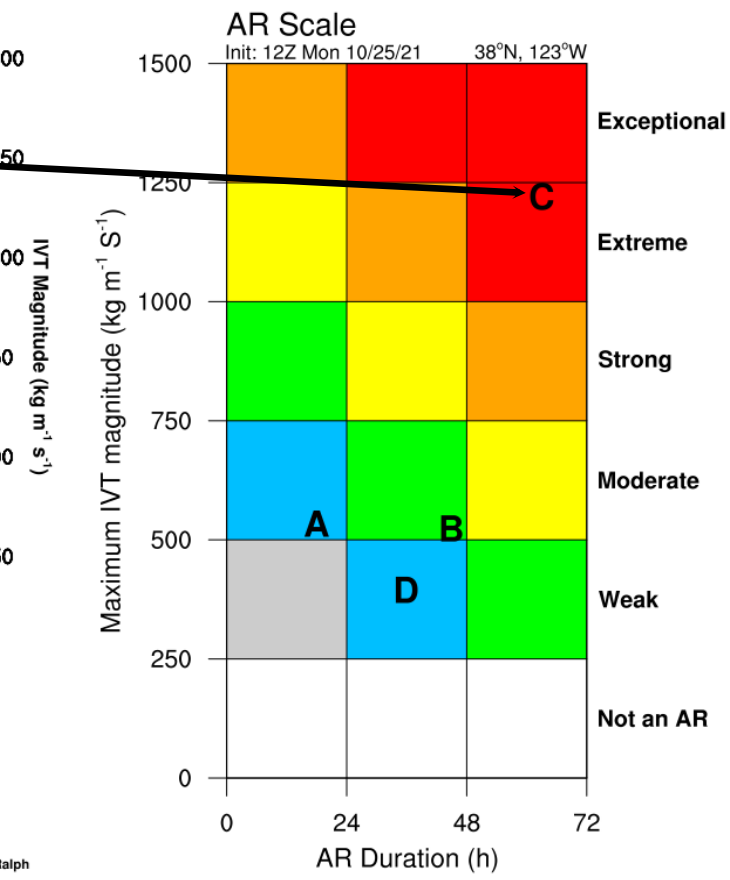
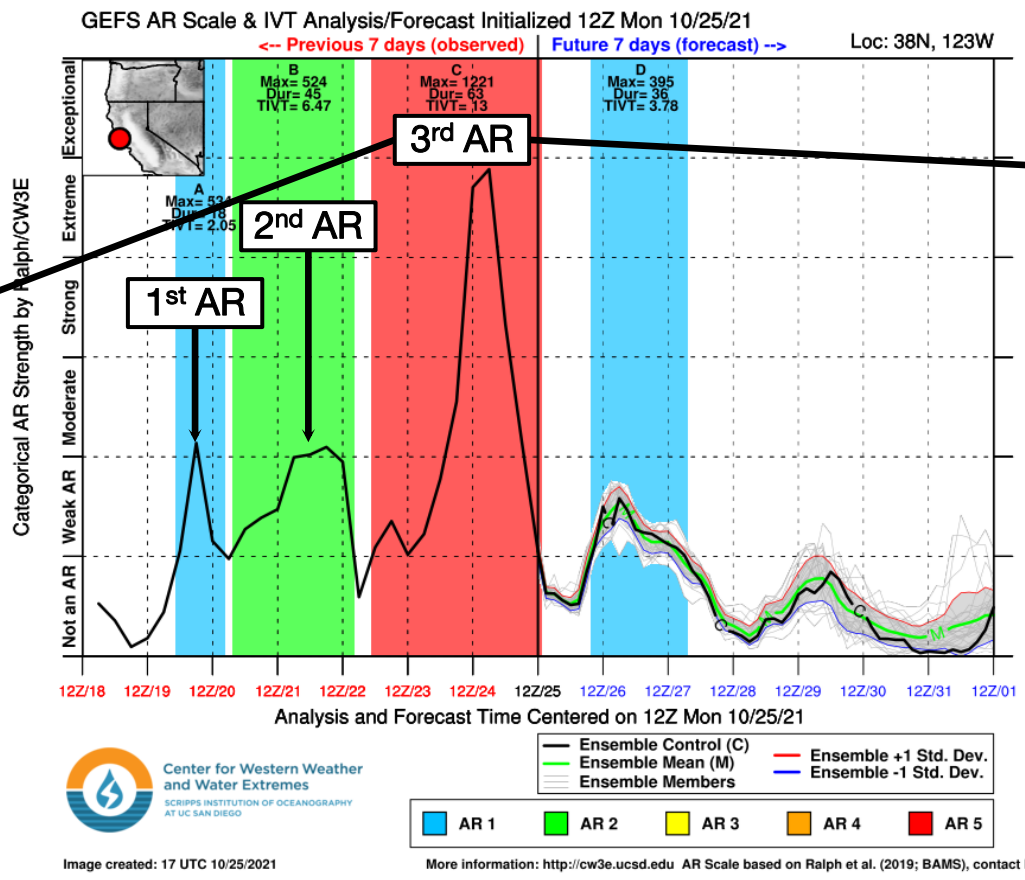
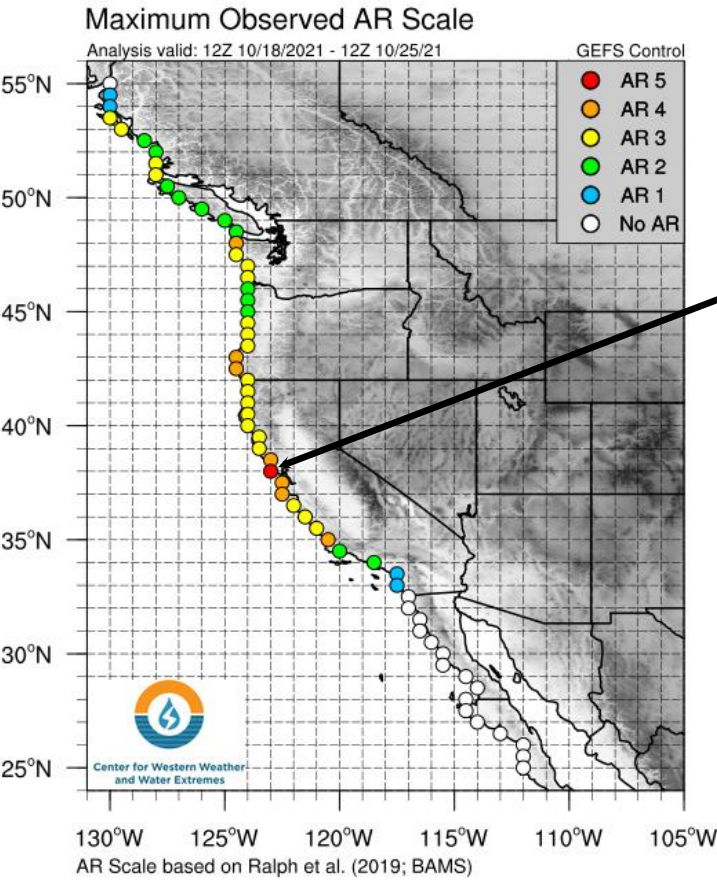


NOAA GOES Satellite image  
5 PM PT 23 Oct 2021

24 Oct 2021 00:01Z NOAA/NESDIS/STAR GOES-West GEOCOLOR



## GEFS AR Scale & IVT Analyses of third AR

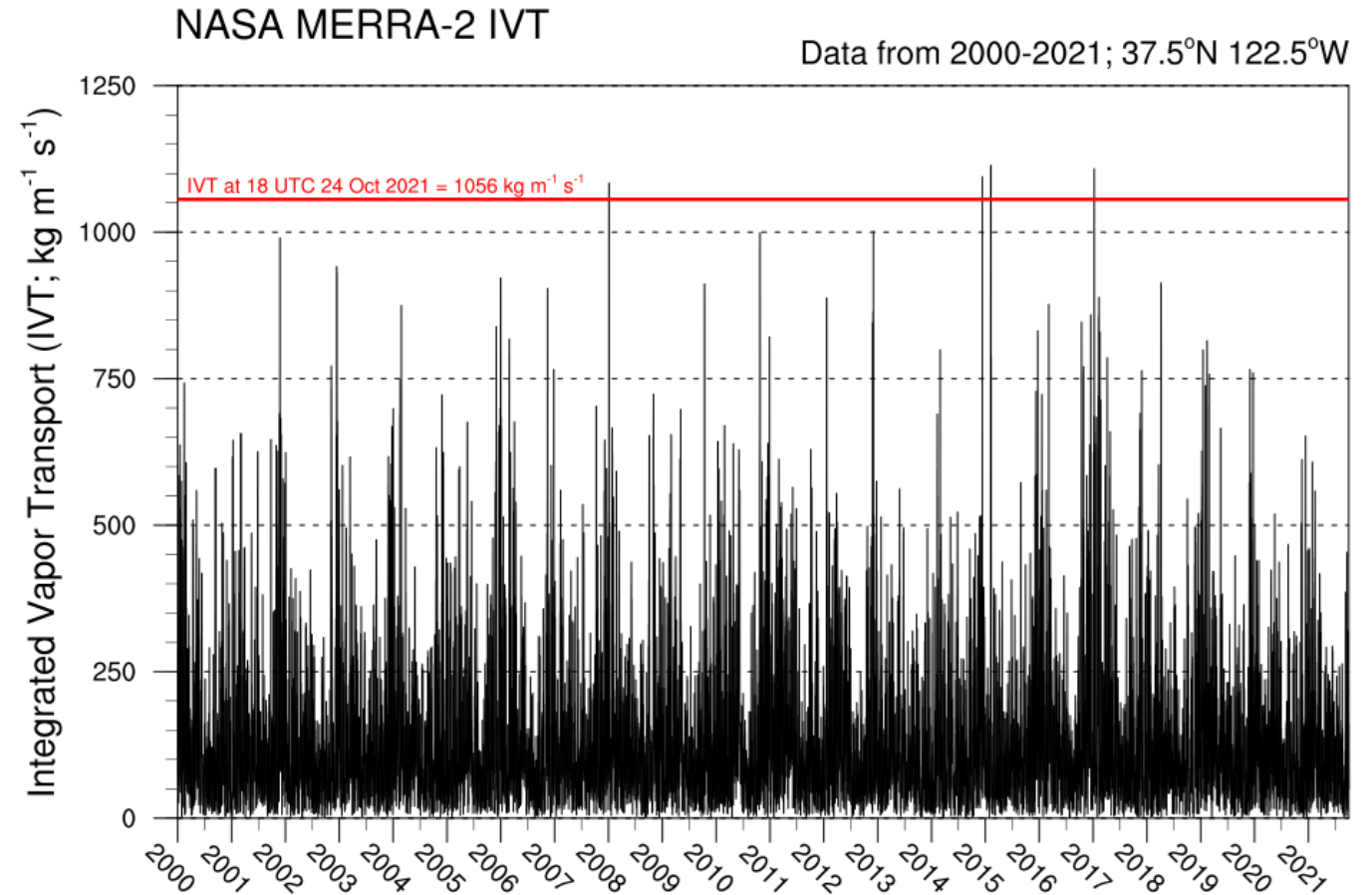


- The third AR produced AR 3-5 conditions throughout coastal Central and Northern California
- A maximum IVT value of  $1221 \text{ kg m}^{-1} \text{ s}^{-1}$  was observed at  $38^\circ\text{N}$ ,  $123^\circ\text{W}$  (near Point Reyes)
- AR conditions ( $\text{IVT} > 250 \text{ kg m}^{-1} \text{ s}^{-1}$ ) persisted for 63 consecutive hours at this location, resulting in an AR 5



## Climatological IVT Analyses of third AR

- Based on GFS analysis the maximum IVT observed over San Francisco was  $1056 \text{ kg m}^{-1} \text{ s}^{-1}$
- A maximum IVT of  $1056 \text{ kg m}^{-1} \text{ s}^{-1}$  makes this the strongest AR to make landfall over San Francisco since Jan 2017, and the 5<sup>th</sup> strongest since 2000 based on NASA MERRA-2 reanalysis
- This is the strongest AR to make landfall over San Francisco during the month of October during the MERRA-2 period of record (1980-2020)

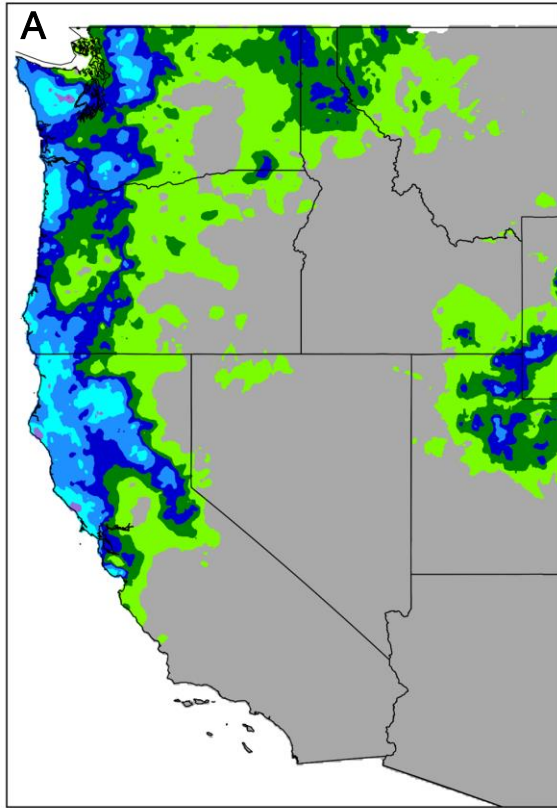


NASA MERRA-2 reanalysis IVT at  $37.5^\circ\text{N}$   $122.5^\circ\text{W}$  from Jan 2000 – September 2021. Red horizontal line represents the observed IVT from GFS analysis at 18 UTC 24 Oct 2021 at  $37.5^\circ\text{N}$   $122.5^\circ\text{W}$

# CW3E Event Summary: 19–26 Oct 2021

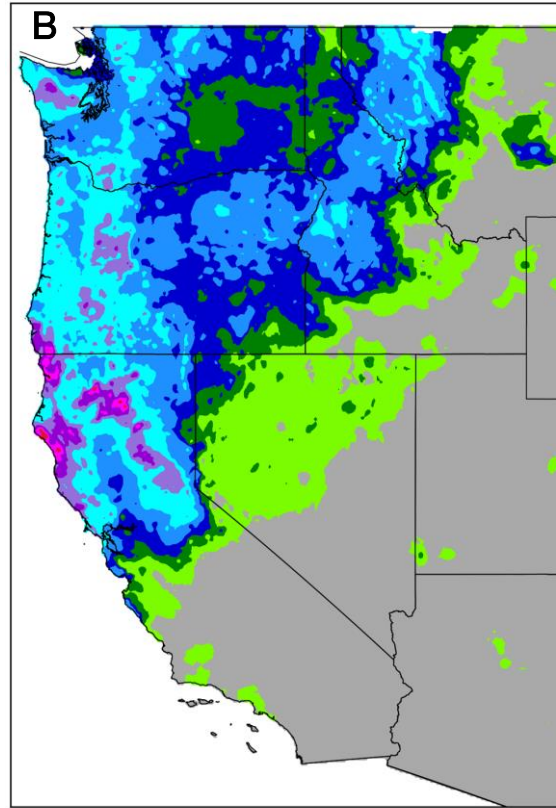
NCEP Stage IV 48-h QPE

Valid: 5 AM PT 19–21 Oct



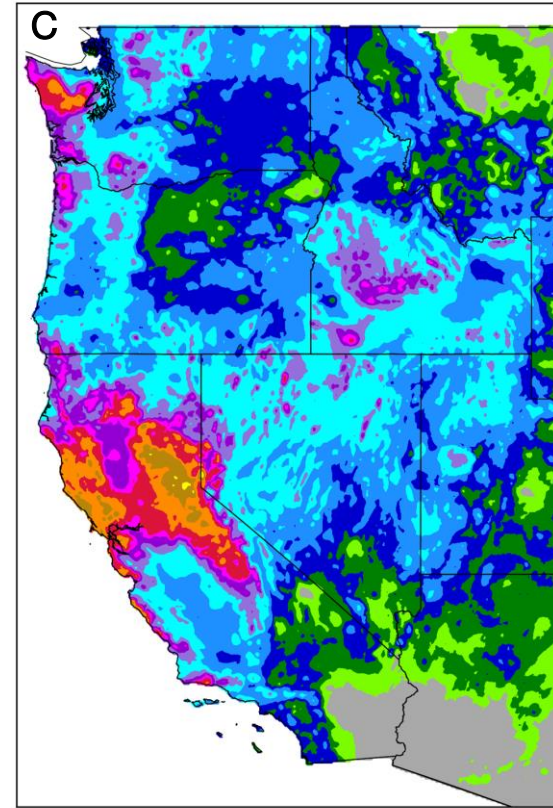
NCEP Stage IV 48-h QPE

Valid: 5 AM PT 21–23 Oct



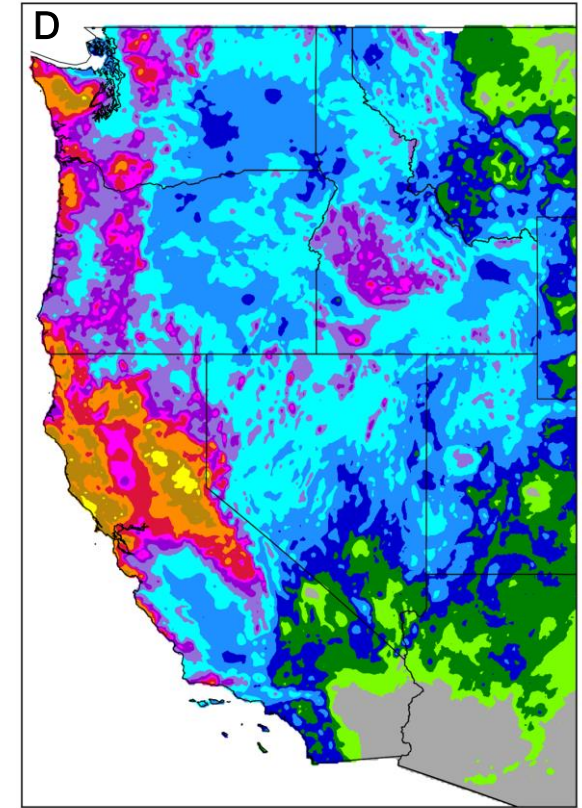
NCEP Stage IV 72-h QPE

Valid: 5 AM PT 23–26 Oct



NCEP Stage IV 7-day QPE

Valid: 5 AM PT 19–26 Oct



- The first AR produced light precipitation (generally < 2 inches) in the Pacific Coast Ranges, Cascades, and Northern Sierra Nevada (panel A)
- The second AR produced about 2–5 inches of precipitation in the Northern California Coast Ranges, Klamath Mountains, and Northern Sierra Nevada (panel B)
- The heaviest and most widespread precipitation occurred with the third AR, which produced more than 10 inches of precipitation in parts of the Northern California Coast Ranges and Northern Sierra Nevada, and more than 3 inches across portions of the higher terrain in Nevada and Idaho (panel C)
- Some locations in Northern California received more than 15 inches of total precipitation from these three storms (panel D)

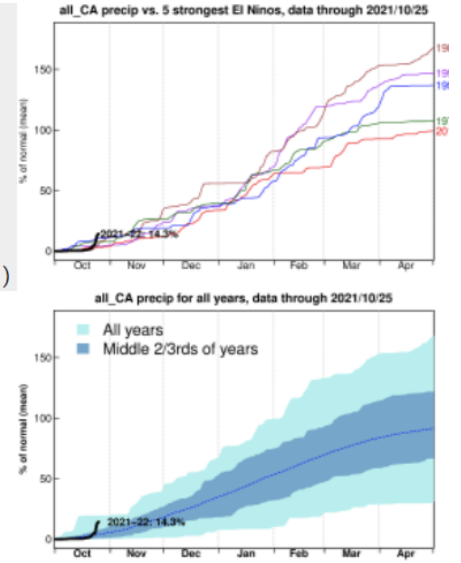
# CW3E Event Summary: 23–26 Oct 2021

## Third AR produced record setting 1-day precipitation totals

- All of California received 7.32% of water year average precipitation.
- The 8-station index received 12.66% of water year average precipitation.

All California ([station list](#)) ([archive of past tables](#))

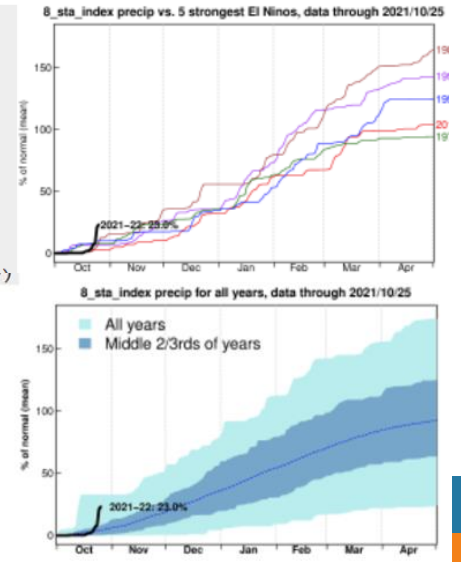
Current:	14.3%	1-day Δ:	1.77%	2-day Δ:	9.09%	3-day Δ:	9.79%
-----							
	(2003/10/25)						
Rec_low:	0.1%	50-ptile:	0.07%	50-ptile:	0.13%	50-ptile:	0.21%
Typ_low:	0.8%	90-ptile:	1.22%	90-ptile:	2.12%	90-ptile:	2.94%
Mean:	4.0%	95-ptile:	1.93%	95-ptile:	3.29%	95-ptile:	4.50%
Typ_high:	7.5%	99-ptile:	3.52%	99-ptile:	5.94%	99-ptile:	7.71%
Rec_high:	19.5%	<b>Record:</b>	<b>7.32%</b>	<b>Record:</b>	<b>11.31%</b>	<b>Record:</b>	<b>13.38%</b>
	(1962/10/25)		(2021/10/24)		(1966/12/06)		(2012/12/02)



Source: Twitter, NWS Sacramento

Northern Sierra Nevada 8-Station Index ([station list](#); a traditional indicator of CA water supply) ([archive of past tables](#))

Current:	23.0%	1-day Δ:	2.24%	2-day Δ:	14.89%	3-day Δ:	15.93%
-----							
	(1978/10/25)						
Rec_low:	0.6%	50-ptile:	0.17%	50-ptile:	0.29%	50-ptile:	0.42%
Typ_low:	0.4%	90-ptile:	1.95%	90-ptile:	3.16%	90-ptile:	4.17%
Mean:	4.4%	95-ptile:	2.86%	95-ptile:	4.62%	95-ptile:	5.98%
Typ_high:	7.7%	99-ptile:	4.87%	99-ptile:	7.52%	99-ptile:	9.77%
Rec_high:	32.8%	<b>Record:</b>	<b>12.66%</b>	<b>Record:</b>	<b>20.38%</b>	<b>Record:</b>	<b>25.34%</b>
	(1962/10/25)		(2021/10/24)		(1962/10/13)		(1962/10/14)



# Atmospheric River Summary: 23-26 October 2021

## Storm Impacts

### Flooded streets in Fairfield, CA



Source: Carlos Barria / REUTERS

### Flooded streets in San Rafael, CA



Source: San Rafael OES Twitter Feed

- Heavy rainfall that began on 23 Oct resulted in areas of localized flooding throughout Northern California making travel difficult and dangerous

# CW3E Event Summary: 23–26 Oct 2021

## Storm Impacts

Rockslide on State Route 70



Minor landslide on Cavedale Rd., Sonoma County



Rockslide on Highway 50 near Echo Summit

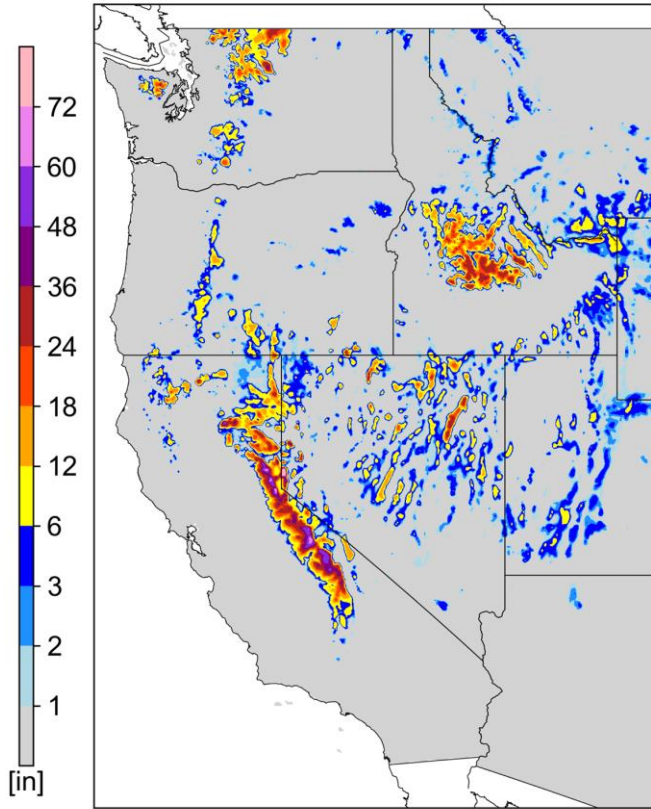


- Large storm total rainfall resulted in landslides and rockslides at various locations in northern California.
- Recent burn scars saw enhanced runoff containing ash and sediment; however, it is unclear whether post-wildfire debris flows occurred at the time of writing. Post-storm evaluations will provide insight to this.
- While persistent moderate rain rates were observed, the short-duration, high-intensity rain rates needed to produce post-fire debris flows may not have been reached.

# CW3E Event Summary: 23–26 Oct 2021

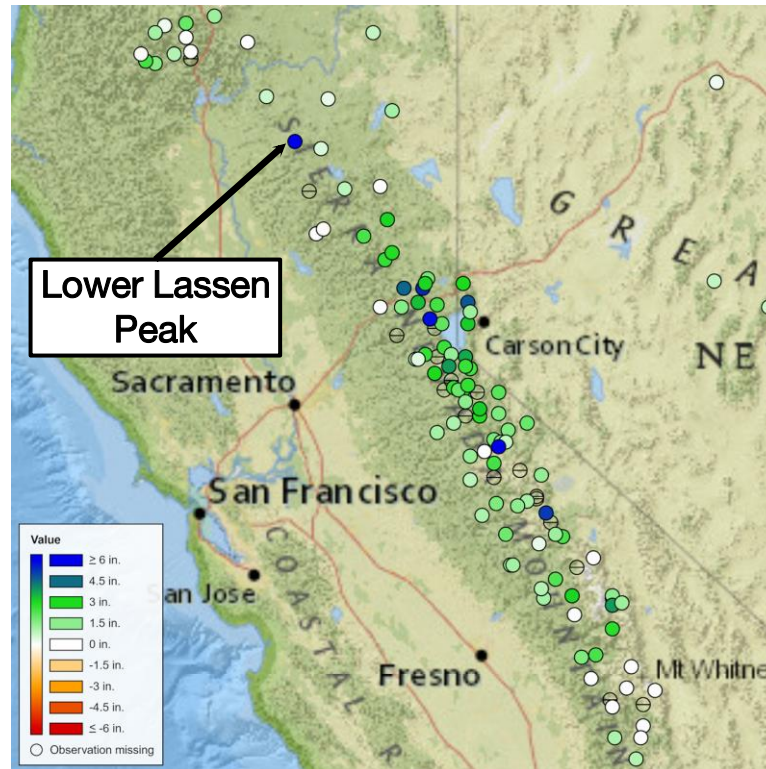
## 72-h Interpolated Snowfall

Valid: 5 AM PT 23–26 Oct

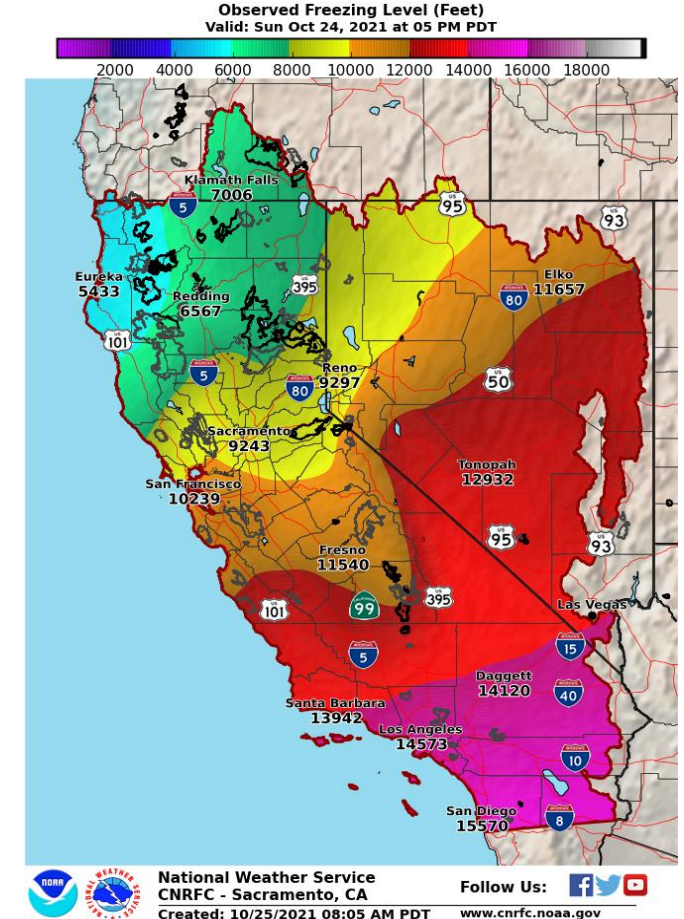


## 3-day SWE Change

Valid: 23–26 Oct (First of Day)



Source: NRCS Water and Climate Center



National Weather Service  
 CNRFC - Sacramento, CA  
 Created: 10/25/2021 08:05 AM PDT  
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[www.cnrfc.noaa.gov](http://www.cnrfc.noaa.gov)

- The third AR also produced significant snowfall accumulations (> 12 inches) in the Sierra Nevada, the Washington Cascades, the Sawtooth Range in Idaho, and the Ruby Mountains in Nevada
- More than 3 feet of snow fell in some locations along the Sierra Crest
- The Lower Lassen Peak snow sensor (8,250 ft) recorded a 3-day SWE increase of 9.6 inches between 23 Oct and 26 Oct
- Given the warm nature of this storm, snow levels were initially quite high, and accumulations were limited below 7,000 feet

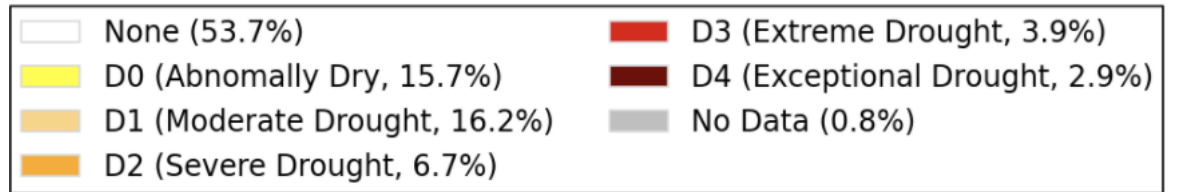
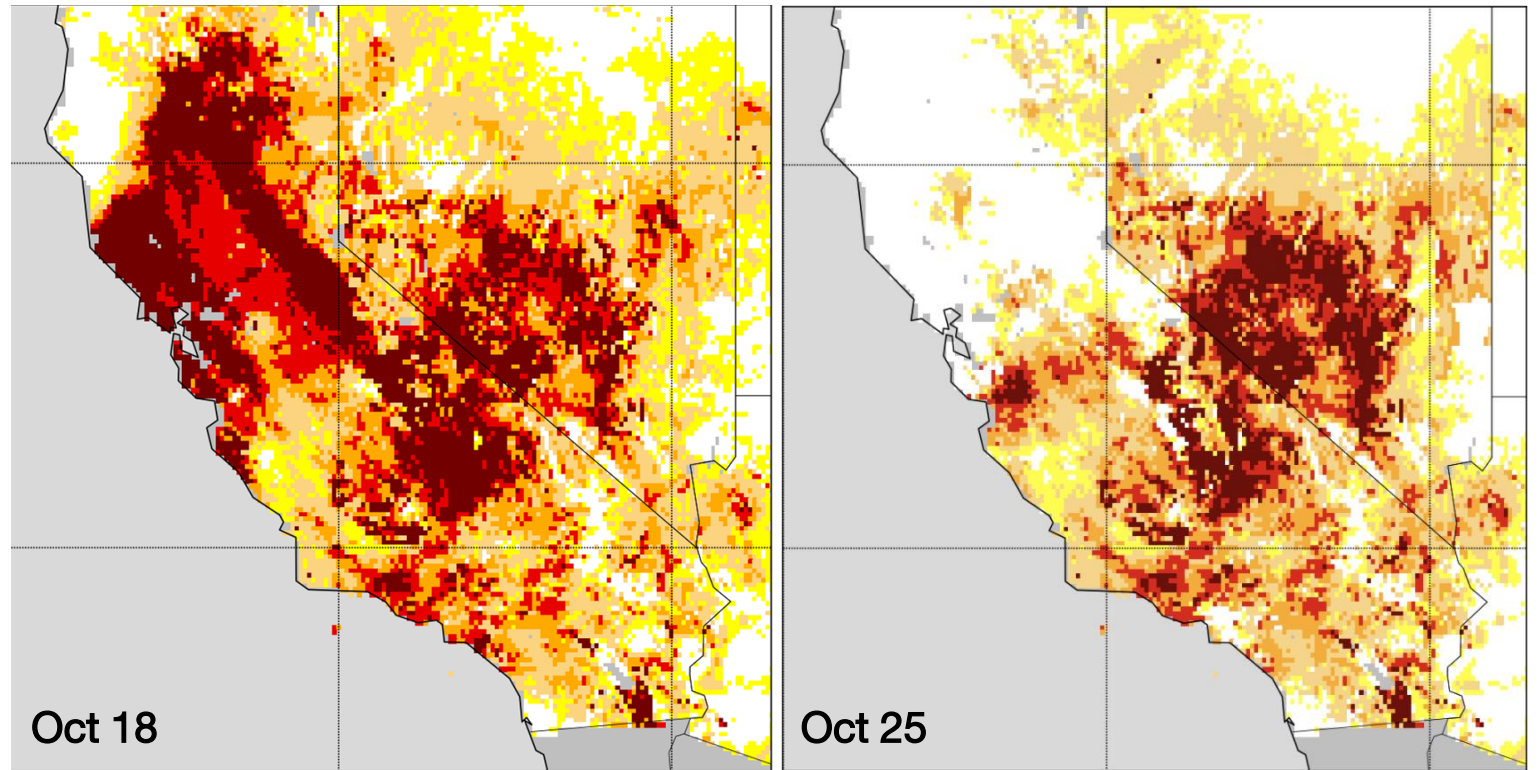
# CW3E Event Summary: 19–26 Oct 2021

## Major Improvement in Soil Moisture Condition across Northern California

Based on the UCLA Soil Moisture Drought Monitor:

- Areas of extreme and exceptional soil moisture deficits droughts are largely relieved across Northern California
- Some areas surrounding the Southern Sierra Nevada and the Southern Central Valley saw improvements, but dry soil moisture largely persist in this region

UCLA Soil Moisture Drought Monitor



[http://www.hydro.ucla.edu/SurfaceWaterGroup/forecast/monitor\\_ca/index.html](http://www.hydro.ucla.edu/SurfaceWaterGroup/forecast/monitor_ca/index.html)

# CW3E Event Summary: 19–26 Oct 2021

## Observed Soil Moisture & Streamflow Responses in the Russian River

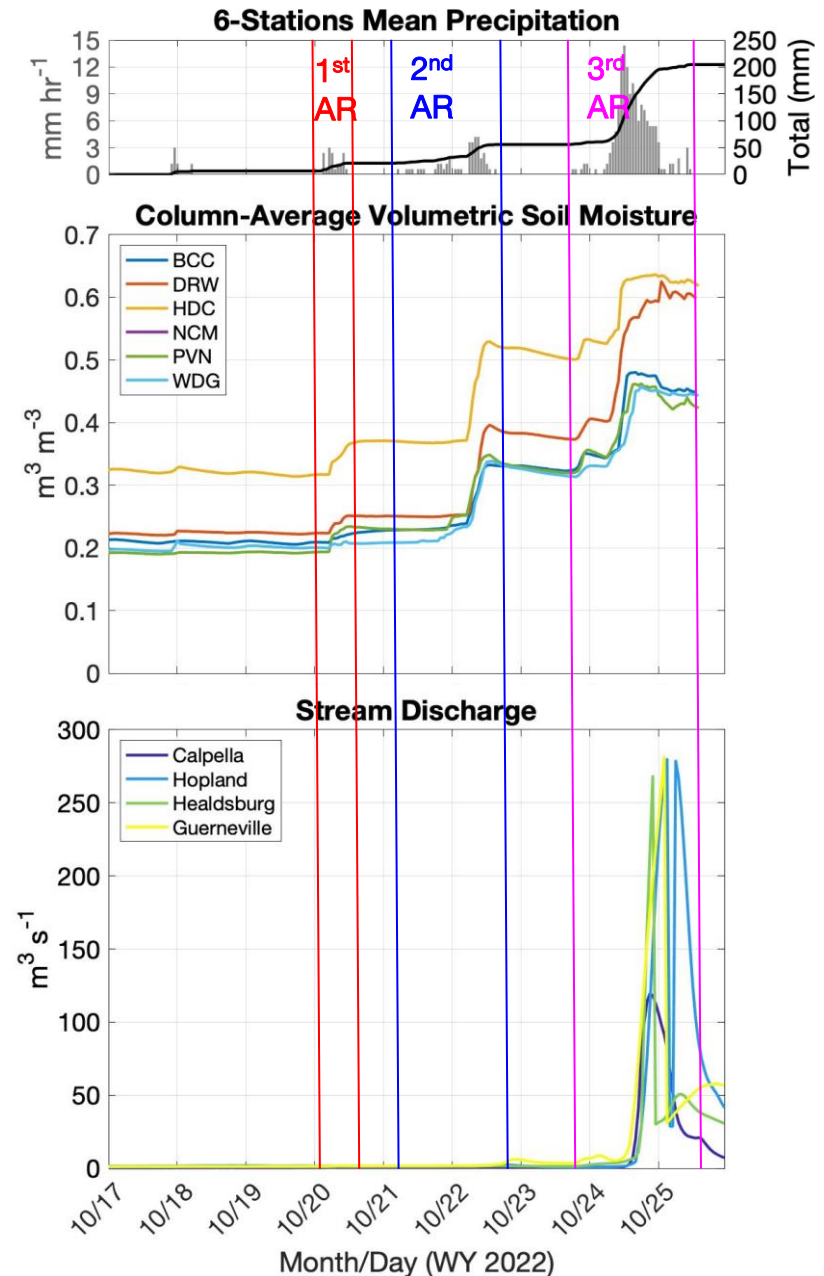
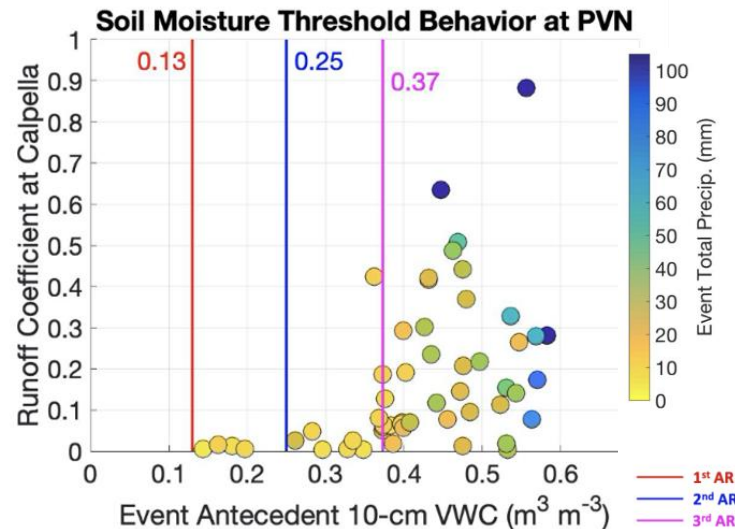
- *The first AR resulted in:*
  - Avg. total precip. of ~14 mm over the six CW3E stations
  - Minimal soil wet-up across & virtually no streamflow response

### *The second AR resulted in:*

- Avg. total precip. of ~35 mm over the six stations
- Rapid soil wet-up to its “runoff-generation threshold” levels at near-surface depths ( $\leq 20$  cm)  $\rightarrow$  *Prime condition for rapid runoff generation in the 3<sup>rd</sup> event*
- Minimal and relatively delayed streamflow responses with peak flows of  $< 7$   $\text{m}^3 \text{s}^{-1}$  at all gauges

### • *The third AR resulted in:*

- Avg. total precip. of ~149 mm over the six stations
- Rapid soil wet-up t/o the column (5-100 cm) leading to soil saturation
- Rapid streamflow responses with peak flows of 119 (Calpella)-281 (Guerneville)  $\text{m}^3 \text{s}^{-1}$





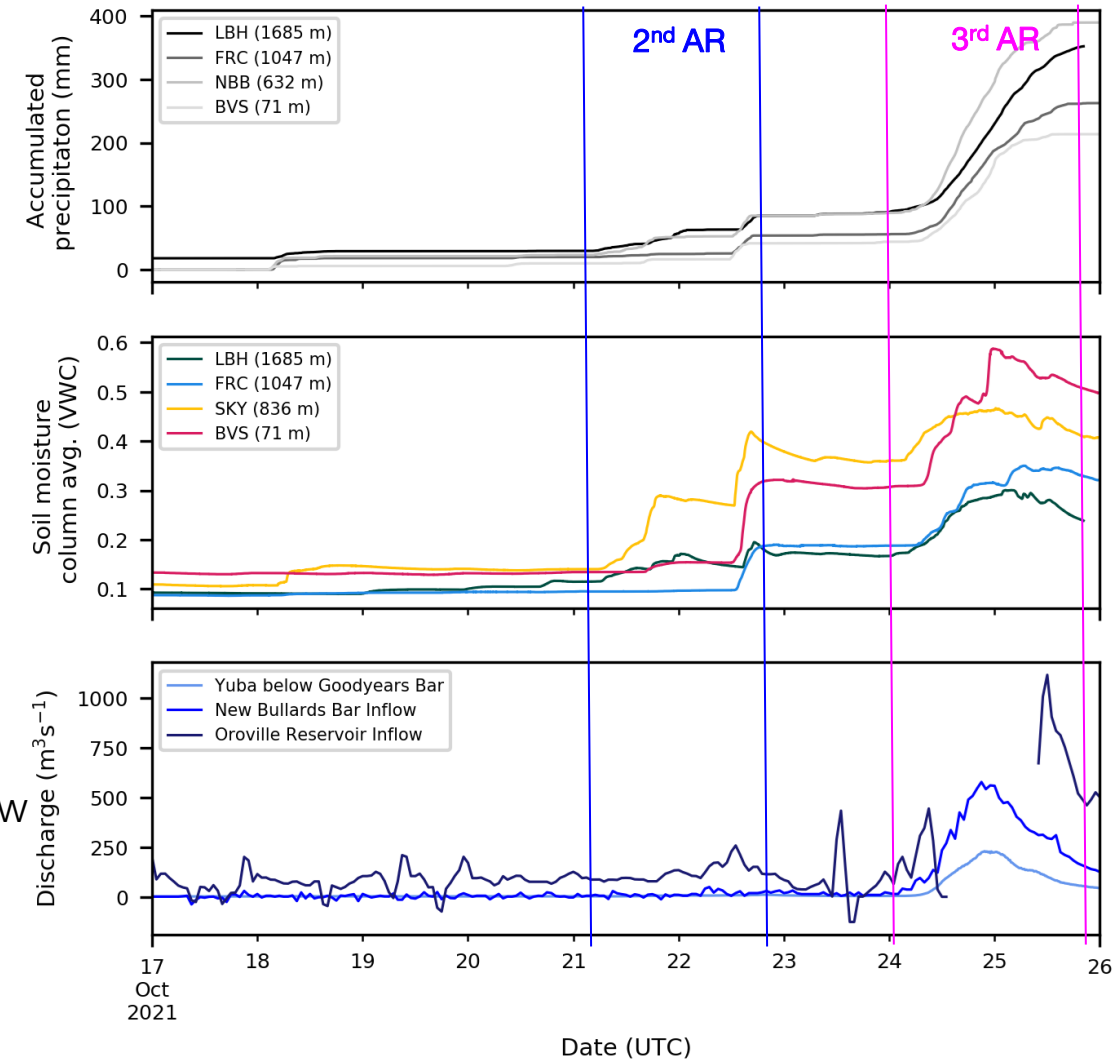
# CW3E Event Summary: 19–26 Oct 2021

## Observed Soil Moisture and Streamflow Responses in the Yuba and Feather Watersheds

- *The second AR resulted in:*
  - Avg. total precip. of ~49 mm over the four stations
  - Rapid soil wet-up at near-surface depths ( $\leq 20$  cm) across the six stations
  - Minimal and relatively delayed streamflow response

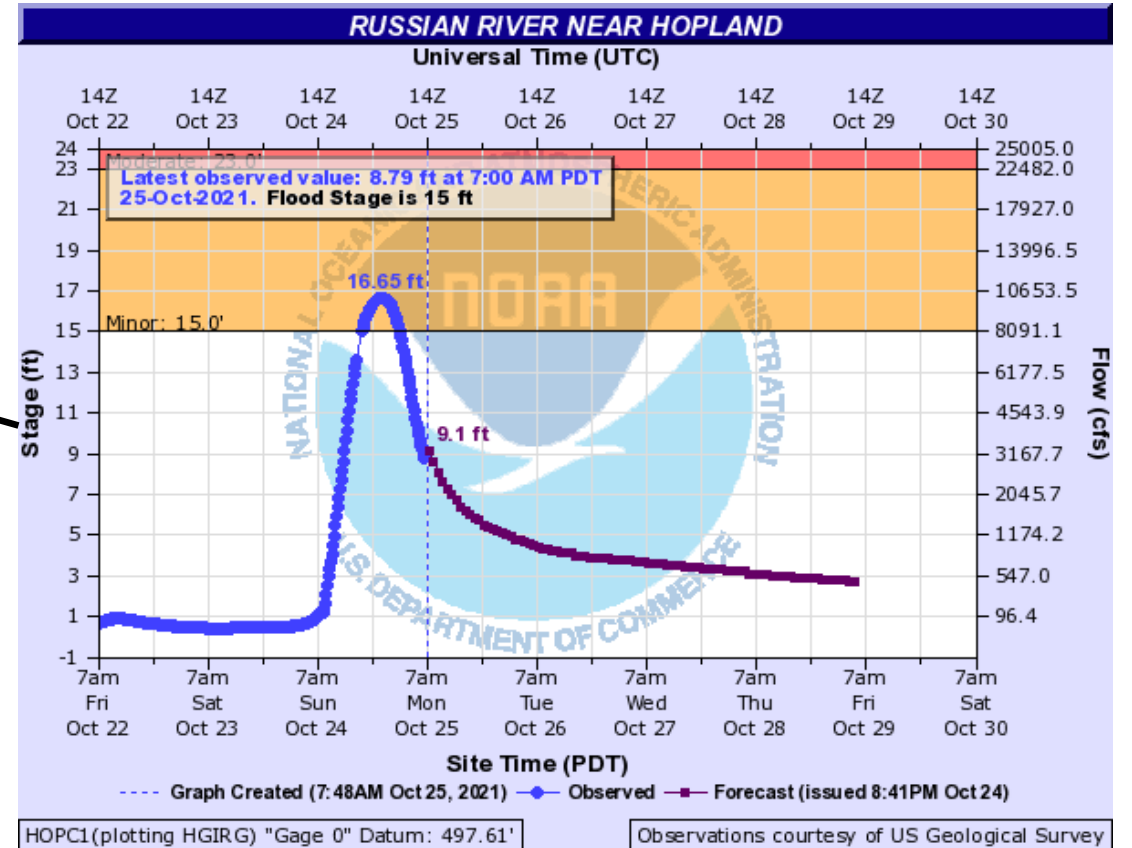
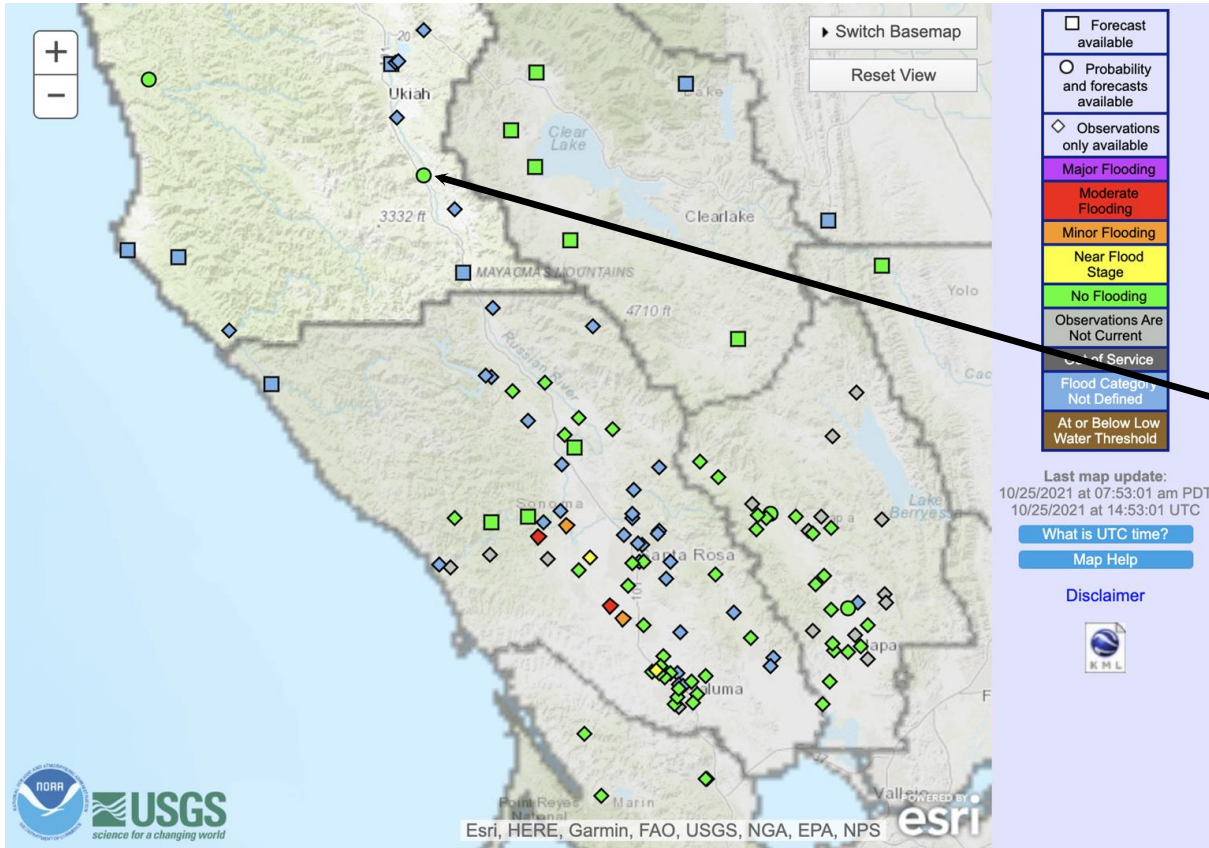
### *The third AR resulted in:*

- Avg. total precip. of ~235 mm over the four stations
- Rapid soil wet-up t/o the column (5-100 cm) leading to soil saturation across the four stations
- Diminished soil response at LBH due to snowfall
- Rapid streamflow response at N. Yuba below Goodyears Bar and resulting increases in New Bullards Bar and Oroville Reservoir inflow



\*SKY precipitation unavailable due to clogged tipping bucket

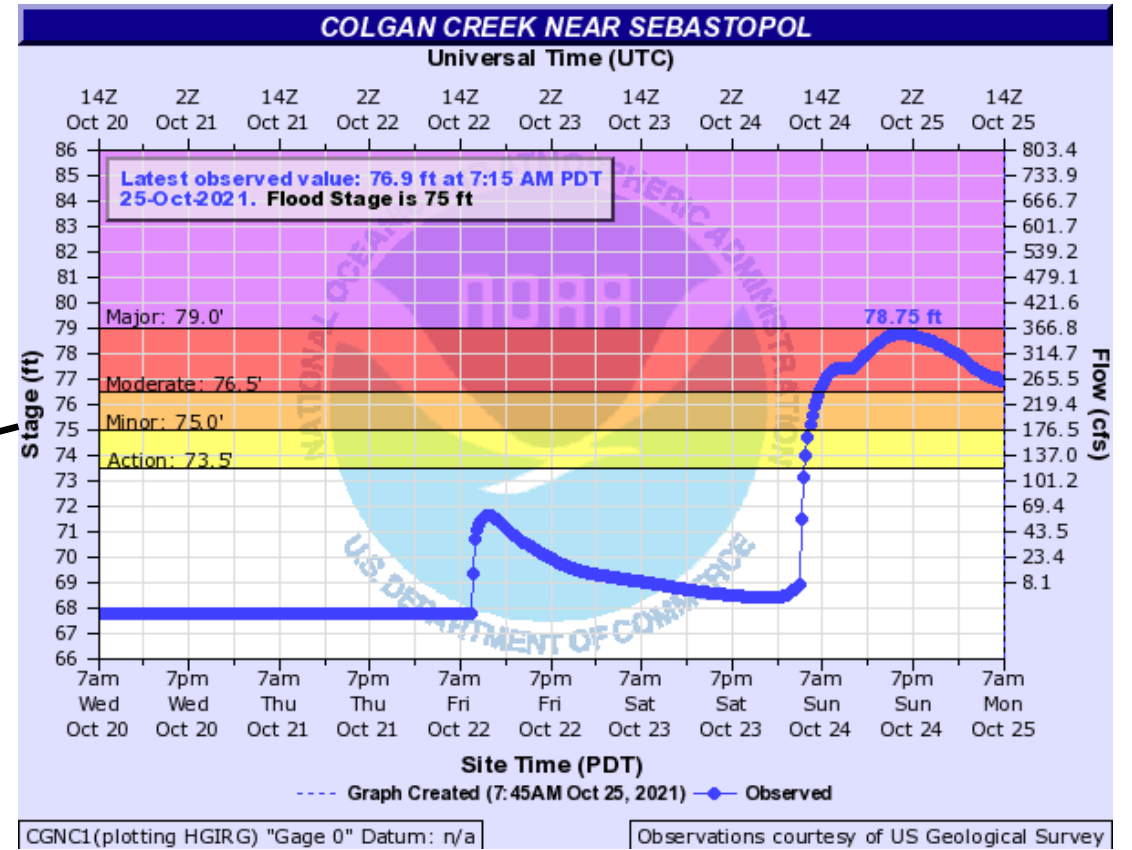
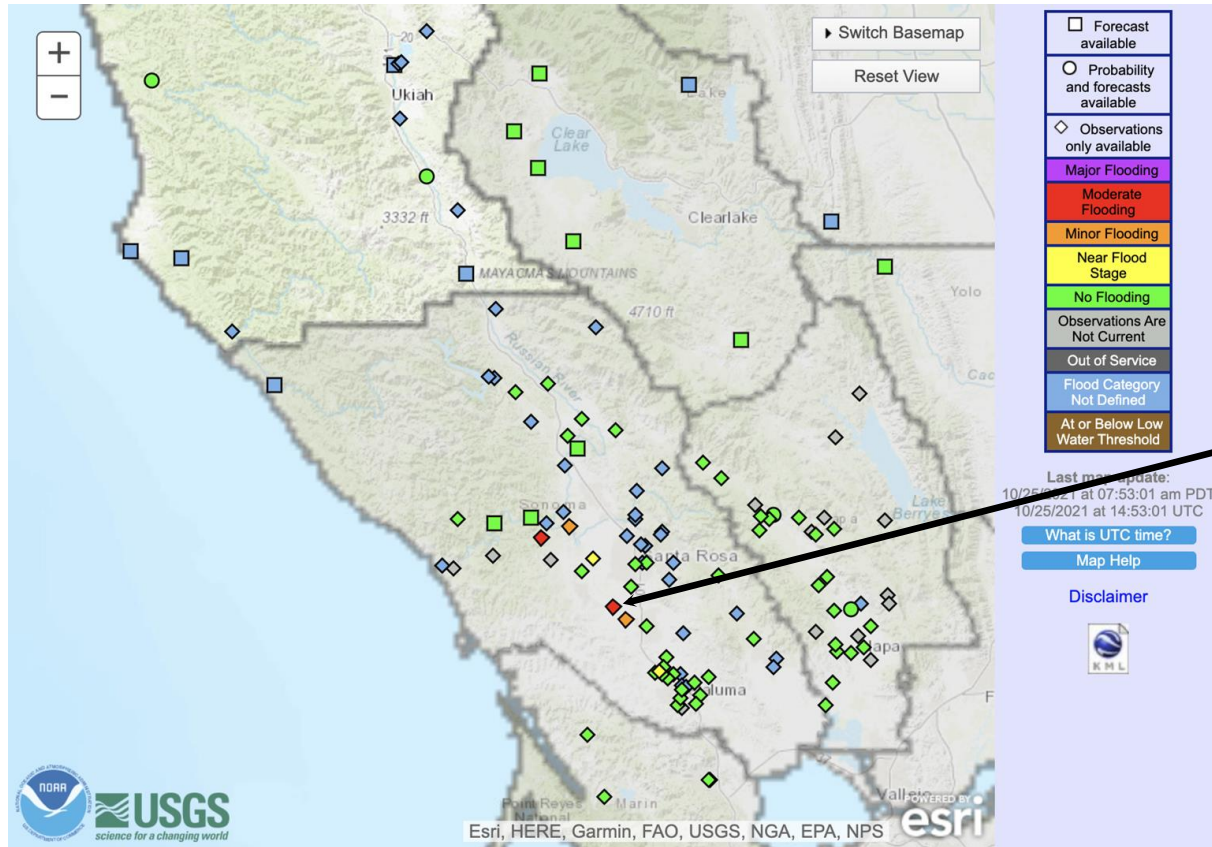
# CW3E Event Summary: 19–26 Oct 2021



Source: NWS Advanced Hydrologic Prediction Service

- Heavy rain during the morning of 24 Oct triggered a rapid streamflow response in the Russian River watershed
- The Russian River near Hopland, CA, rose more than 15 feet in a 12-hour period, reaching minor flood stage (15 ft) by late afternoon
- A peak stage height of 16.65 ft was recorded at 9:30 PM PT on 24 Oct

# CW3E Event Summary: 19–26 Oct 2021



Source: NWS Advanced Hydrologic Prediction Service

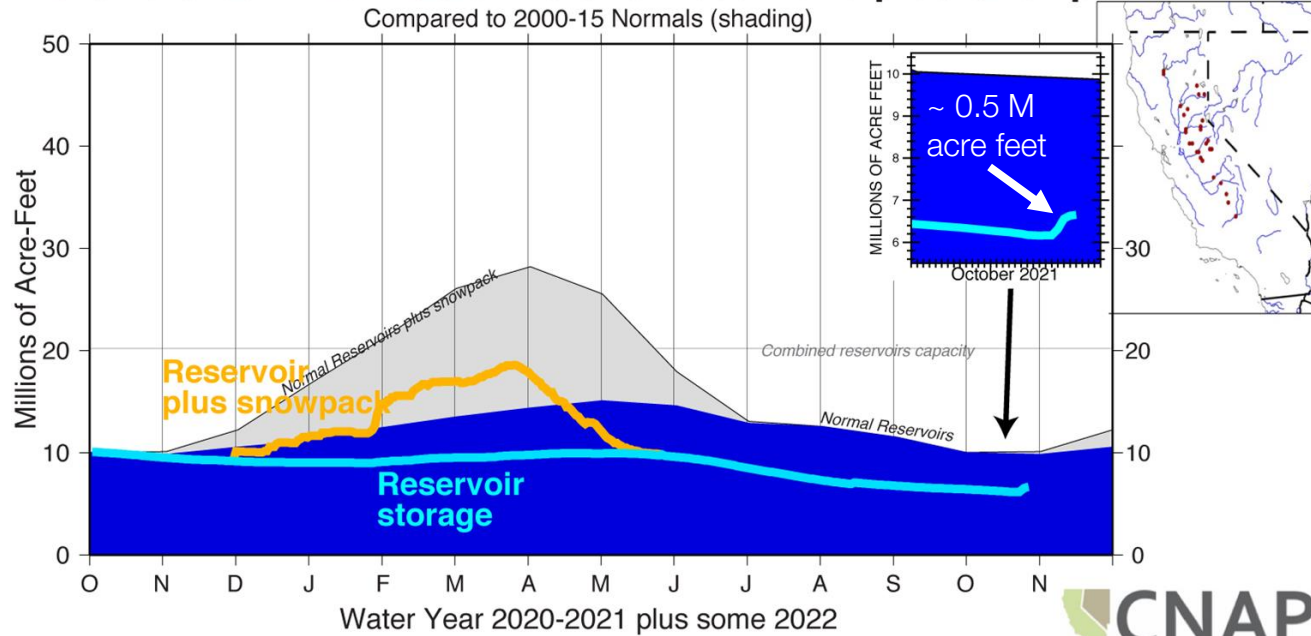
\*Note: Gauge height at Colgan Creek presented from NAVD88, not local elevation

- Intense rainfall rates (> 0.50 inches/hour) during the morning of 24 Oct caused riverine flooding in Sonoma County
- By 8 AM PT 24 Oct, several gauges near Santa Rosa, CA, had exceeded flood stage
- Colgan Creek (near Sebastopol, CA) reached a maximum stage height of 78.75 ft (just below major flood stage) at 5:30 PM PT 24 Oct and exceeded moderate flood stage (76.5 ft) for more than 24 consecutive hours

# CW3E Event Summary: 19–26 Oct 2021

- Reservoir levels did increase throughout California, though the increases were modest for an AR 5 due to dry antecedent conditions.

## Water Stored in 28 Western Sierra Reservoirs plus Snowpack



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, FRD, DAV, BUL, ENG, FOL, UNV, LON, ICH, NAT, CMN, PAR, DON, BRD, TUL, NML, DNP, HTH, CHV, EXC, MIL, PNF, TRM, SCC, ISB



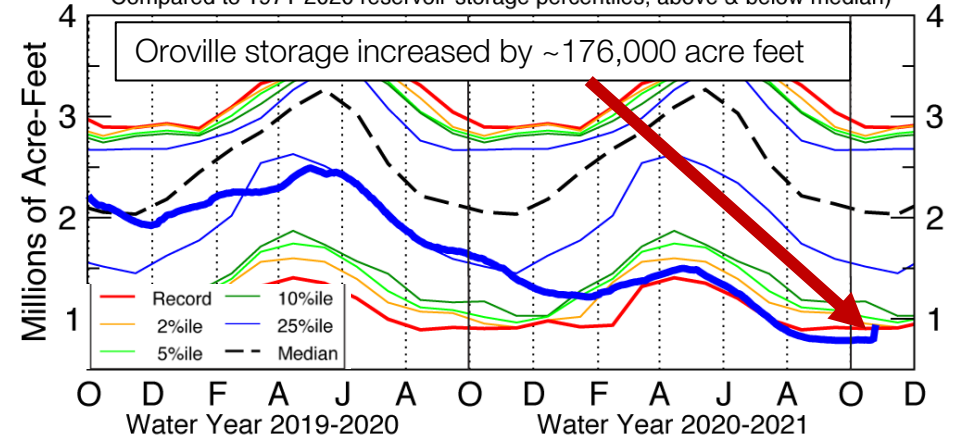
California-Nevada Climate Applications Program  
 A NOAA RISA team

For info: mddettinger at gmail.com

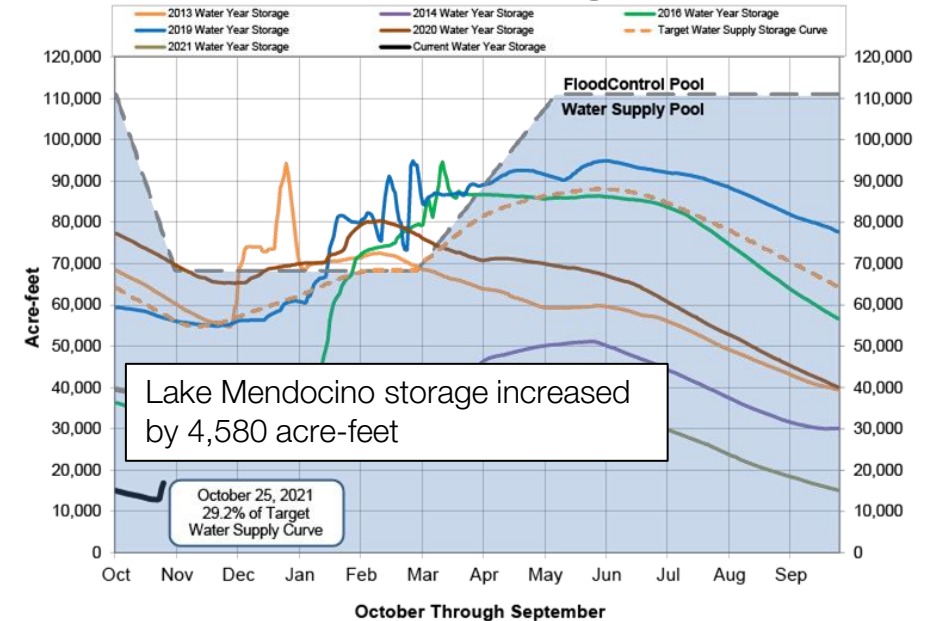
<https://cnap.ucsd.edu>

## Water Stored in Oroville Lake (Feather River)

Compared to 1971-2020 reservoir-storage percentiles, above & below median

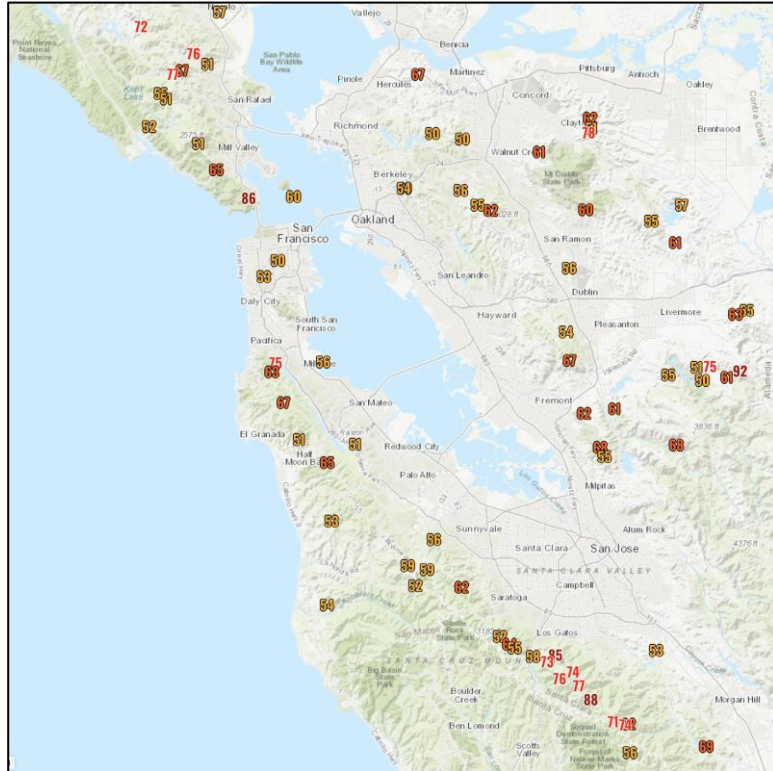


## Lake Mendocino Storage



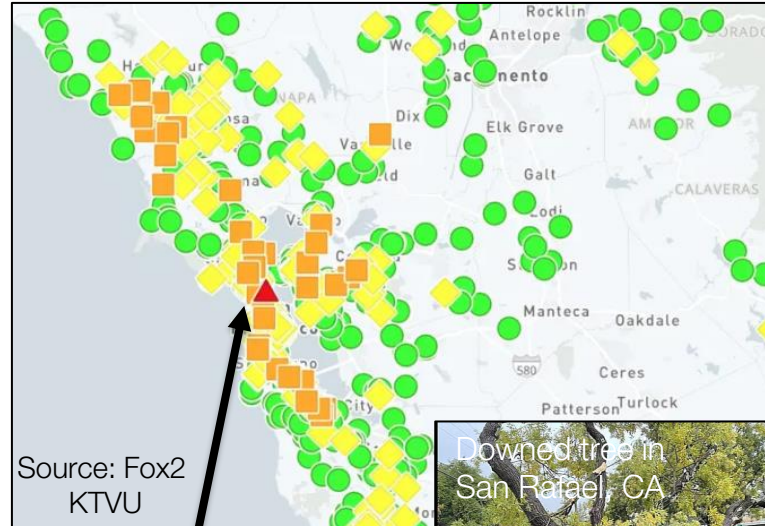
# CW3E Event Summary: 19–26 Oct 2021

24-h Maximum Wind Gust:  
Valid 11:59 PM PT 24 Oct



Source: NWS Western Region

## PG&E Power outage map

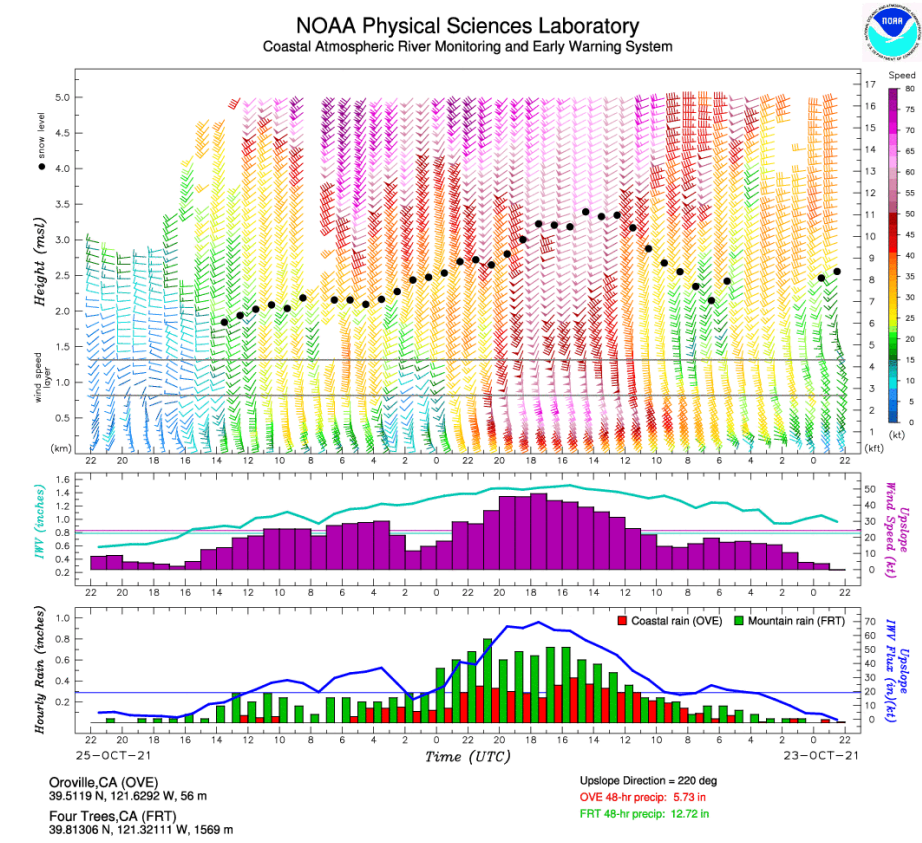


Source: Fox2  
KTVU

As many as  
150,000 customers  
affected



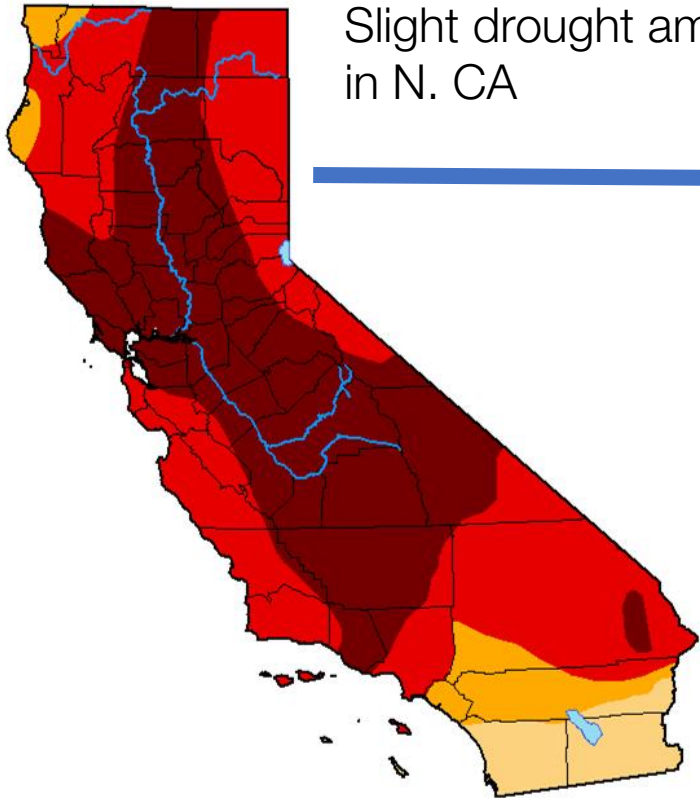
Source: CBS San Francisco Bay Area KPIX



- The combination of heavy rain and high winds downed trees and caused thousands of power outages in the Bay Area
- Several Pacific Gas & Electric stations recorded peak wind gusts > 70 mph in the Marin Headlands and Santa Cruz Mountains
- Wind gusts > 50 mph were also observed in the Sacramento Valley and western foothills of the Northern Sierra Nevada
- Profiler data from Oroville, CA (OVE), shows the development of a low-level Sierra Barrier jet during the time of strongest moisture transport, with southerly winds approaching 70 kts

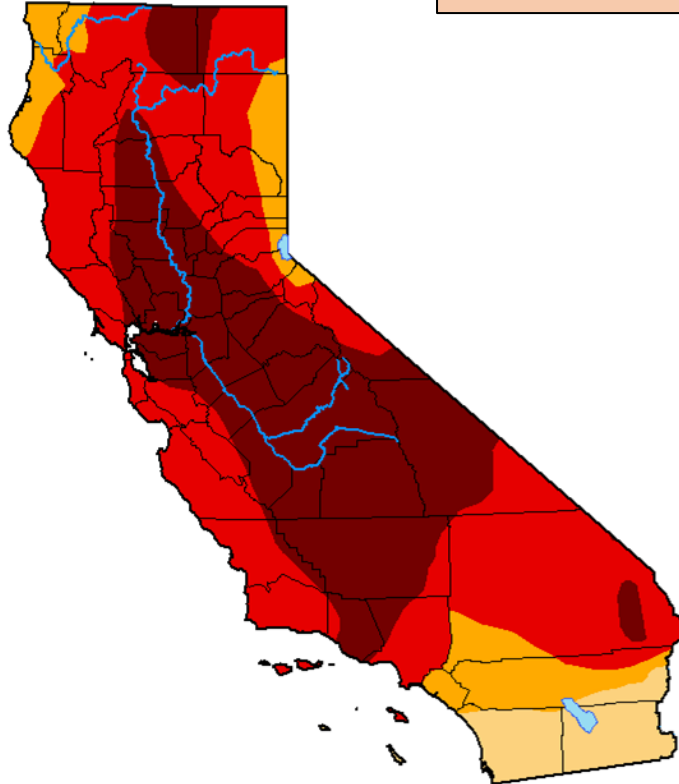
## US Drought Monitor

October 19, 2021



Slight drought amelioration in N. CA

October 26, 2021



Improvements due to ARs

Drought Conditions (Percent Area)

	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
<b>Current</b>	0.00	100.00	100.00	93.81	83.33	38.74
<b>Last Week</b> 10-19-2021	0.00	100.00	100.00	93.81	87.18	45.66
<b>3 Months Ago</b> 07-27-2021	0.00	100.00	100.00	95.09	88.59	46.49
<b>Start of Calendar Year</b> 12-29-2020	0.00	100.00	95.17	74.34	33.75	1.19
<b>Start of Water Year</b> 09-28-2021	0.00	100.00	100.00	93.93	87.88	45.66
<b>One Year Ago</b> 10-27-2020	15.40	84.60	67.54	35.61	12.74	0.00

Intensity:

- None
- D0 Abnormally Dry
- D1 Moderate Drought
- D2 Severe Drought
- D3 Extreme Drought
- D4 Exceptional Drought

The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. For more information on the Drought Monitor, go to <https://droughtmonitor.unl.edu/About.aspx>

Author:

Richard Heim  
NCEI/NOAA

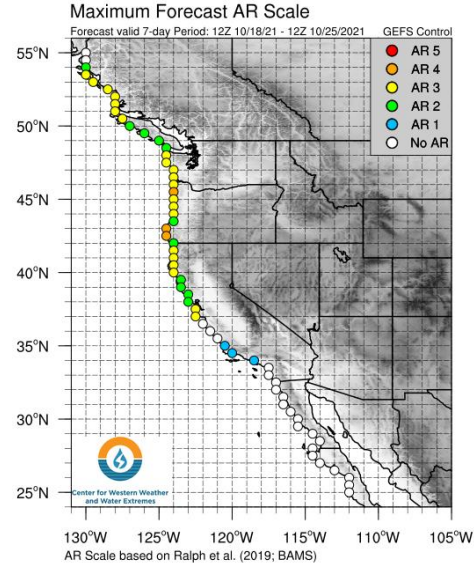


[droughtmonitor.unl.edu](https://droughtmonitor.unl.edu)

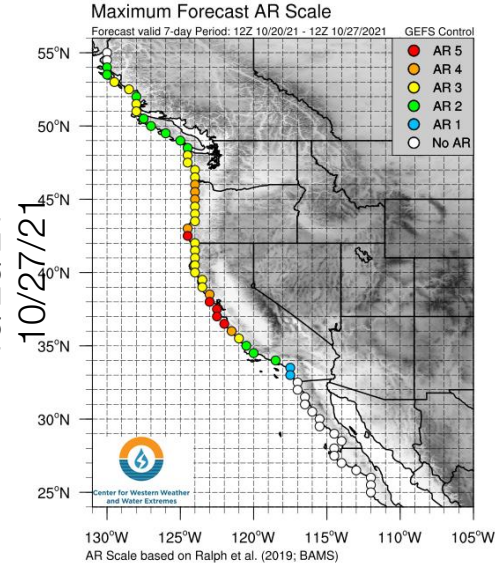
# CW3E Event Summary: 19–26 Oct 2021

## GEFS Coastal AR Scale Forecast and Observations

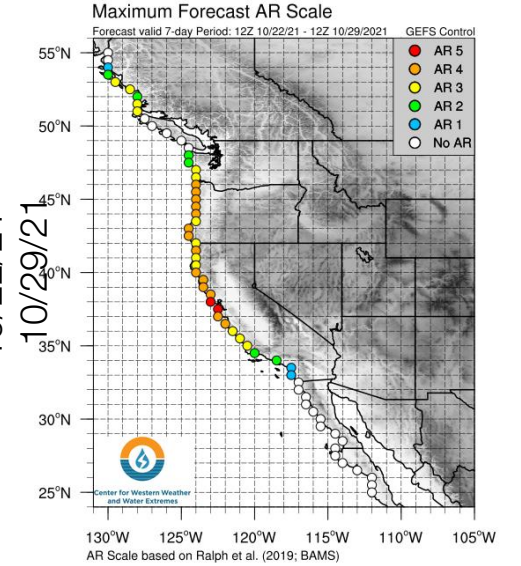
Forecast valid 12Z  
10/18/21 – 10/25/21



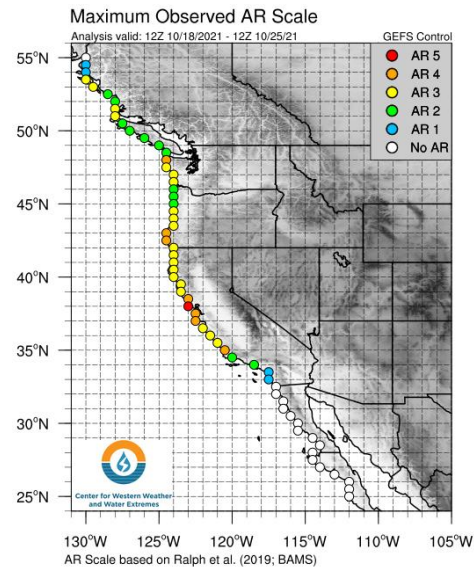
Forecast valid 12Z  
10/20/21 – 10/27/21



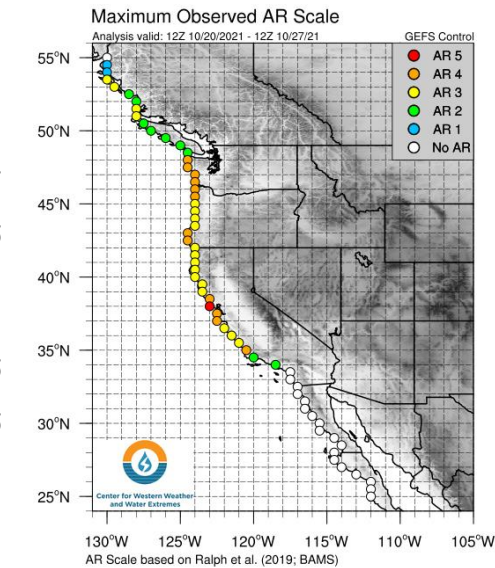
Forecast valid 12Z  
10/22/21 – 10/29/21



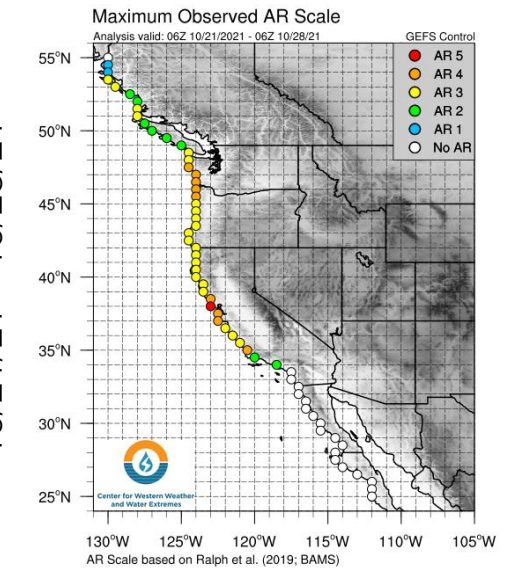
Observations valid 12Z  
10/18/21 – 10/25/21



Observations valid 12Z  
10/20/21 – 10/27/21

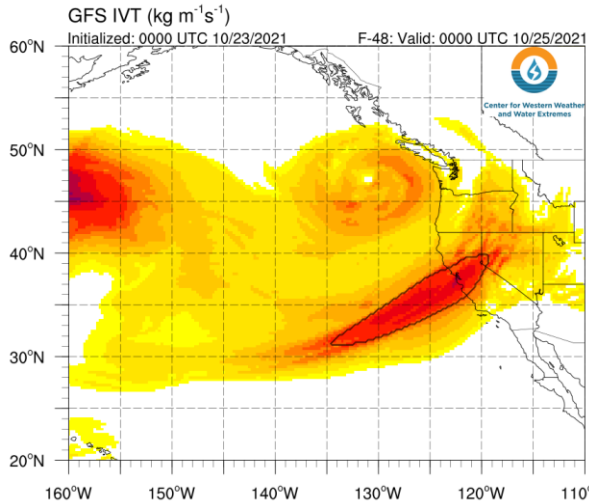


Observations valid 12Z  
10/21/21 – 10/28/21

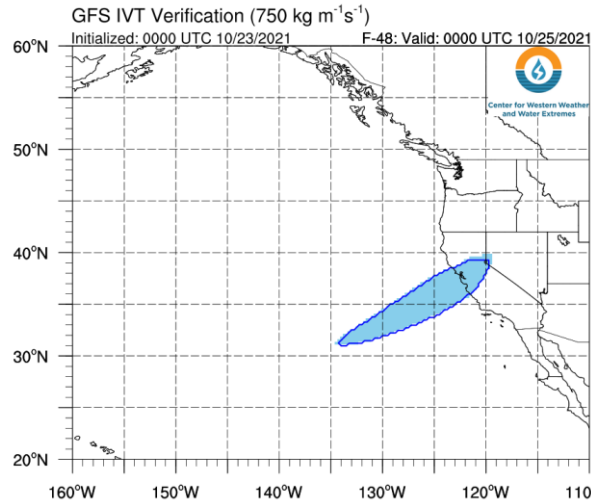


## GFS Analysis and Forecasts Valid: 00 UTC 25 Oct 2021

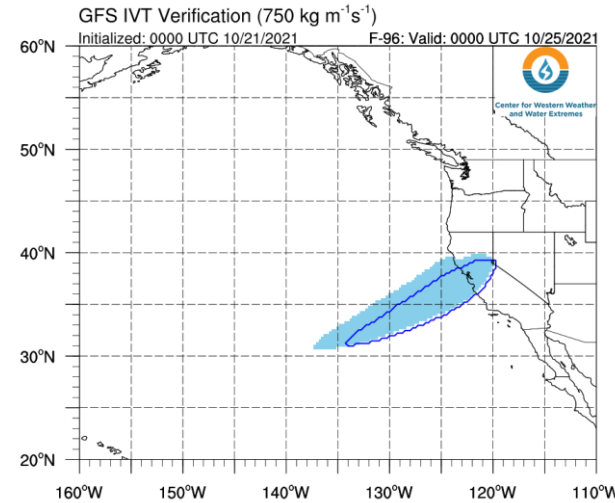
Model Analysis



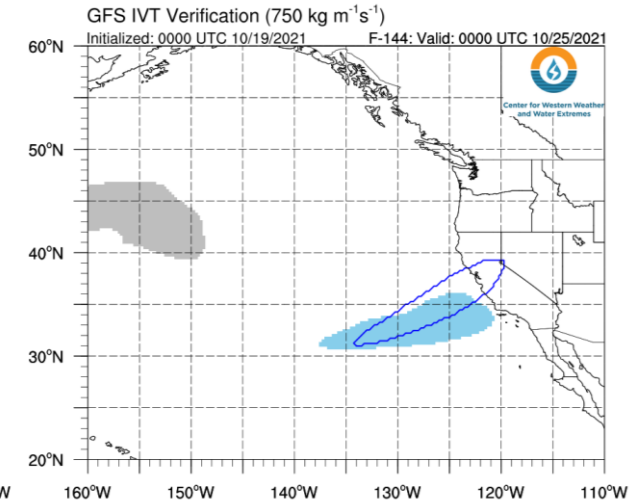
48-hr Forecast



96-hr Forecast



144-hr Forecast



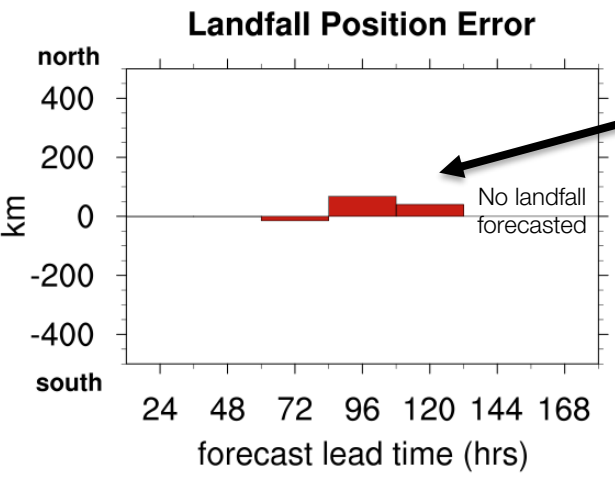
*Forecast objects shaded  
Observed objects contoured  
Objects defined based on  $IVT > 750 \text{ kg m}^{-1} \text{ s}^{-1}$*

- Using the Method for Object-Based Diagnostic Evaluation (MODE) with a  $750 \text{ kg m}^{-1} \text{ s}^{-1}$  IVT threshold shows the locations of the core of the AR was nearly perfectly forecasted at a 48-hour lead time with only a small area of inland penetration over the Northern Sierra Nevada and Nevada over forecasted
- At 96-hours lead time the AR was still present over Northern California with the core well forecasted, however the propagation of the AR was slightly slower resulting in the Northern extent of the AR being over forecasted at this time
- At 144-hours lead time the AR was still present in the forecast, but had propagated south much quicker, potentially due to an under forecasted deepening of the parent cyclone
- There was no landfalling AR at this time from the 168-hour lead time forecast (not shown)

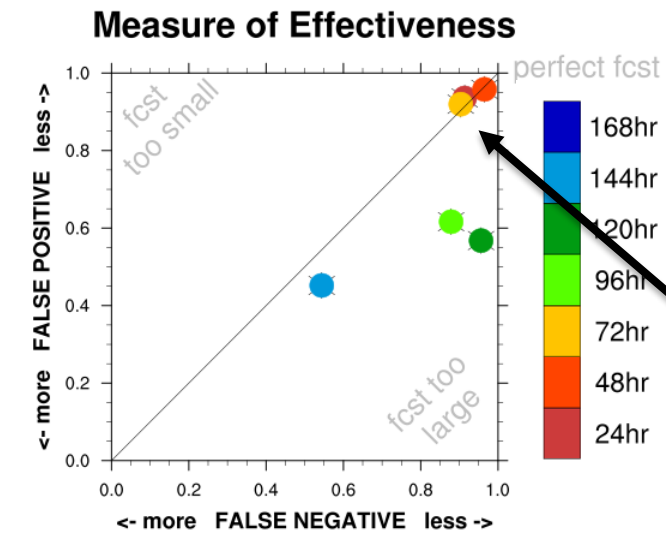


## GFS Analysis and Forecasts Valid: 00 UTC 25 Oct 2021

### AR object angle and 90th percentile intensity

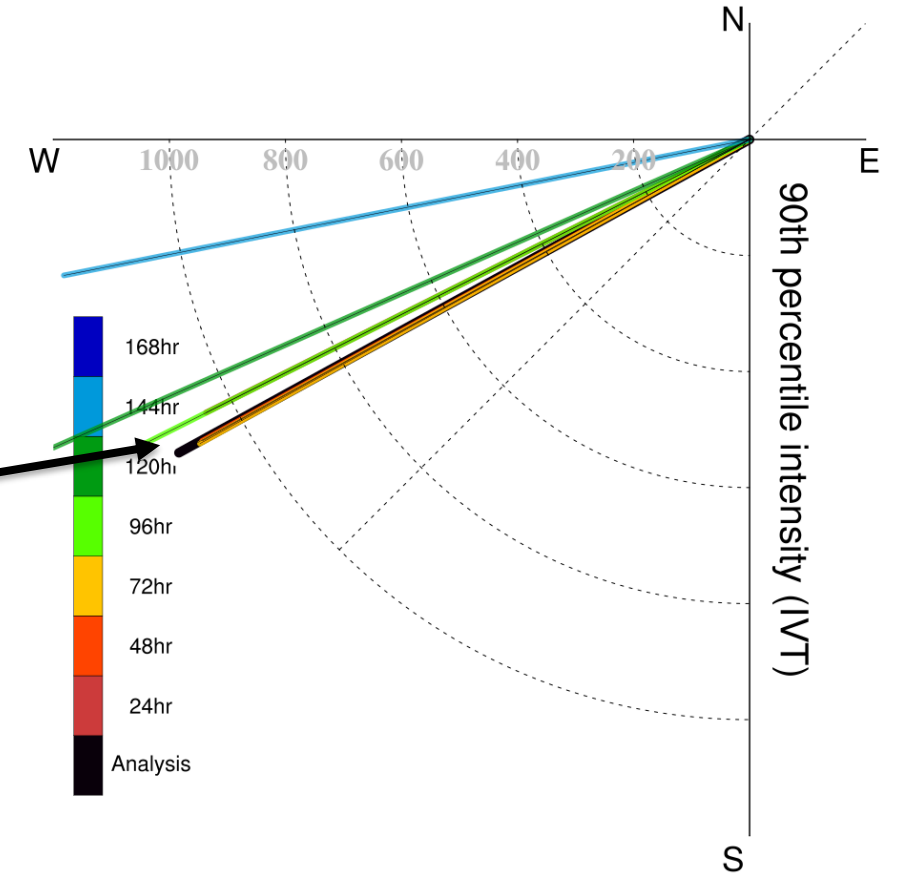


- The landfall position was perfectly forecasted at 24 and 48-hour lead times. At lead times out to 120 hours the position error was less than 100 km



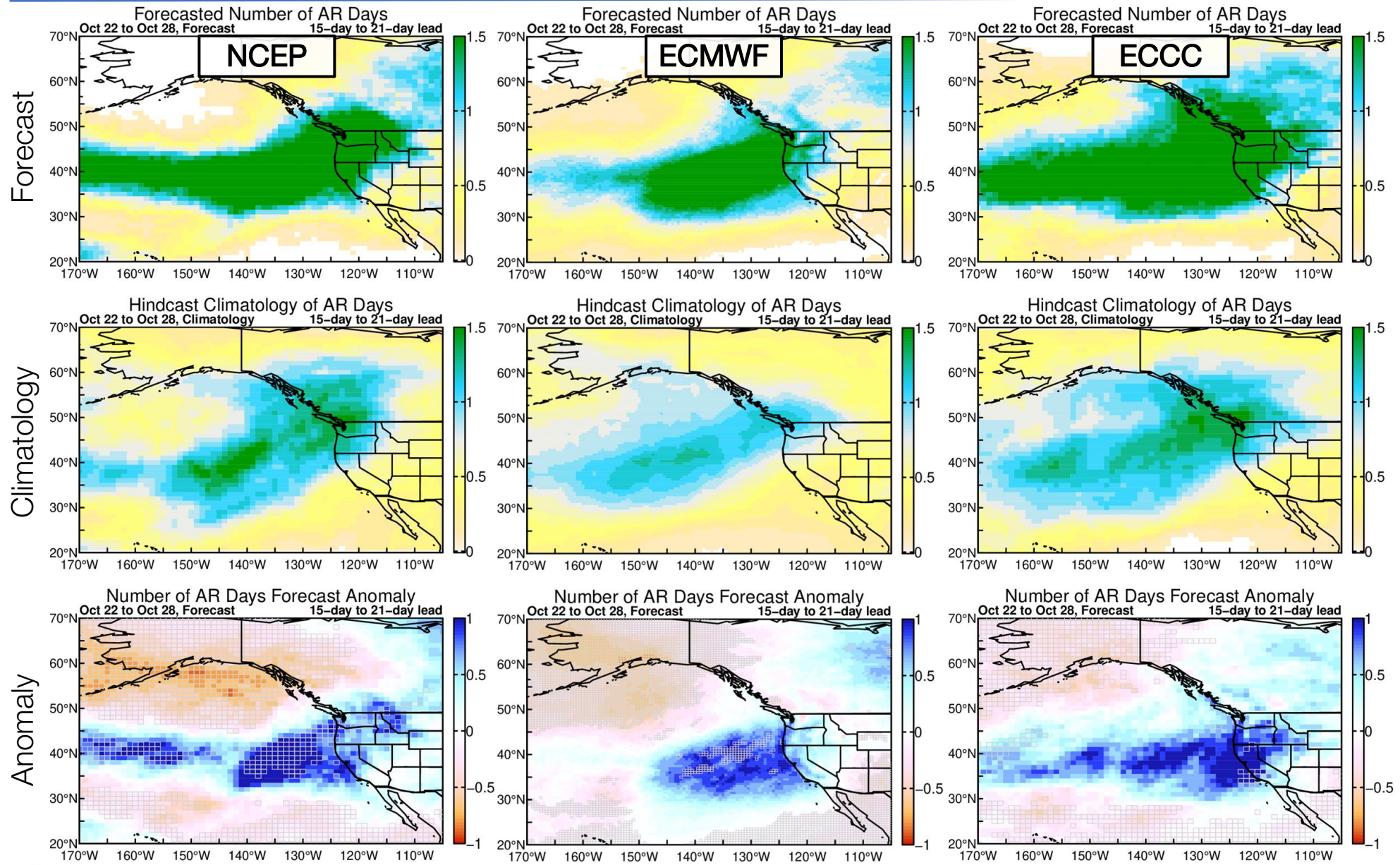
- The 90<sup>th</sup> percentile intensity and orientation of the AR was nearly perfectly forecasted at 24 and 48-hour lead times
- At lead times beyond 48-hours the intensity was slightly over forecasted with an orientation too westerly

- The size and position of the AR core was nearly perfectly forecasted out to 72-hour lead times. For lead times 96, 120, and 144-hours the objects were too large



Objects defined based on  $IVT > 750\ kg\ m^{-1}\ s^{-1}$

# AR Week-3 Outlook – Initialized: Oct 7; Valid: Oct 22-28



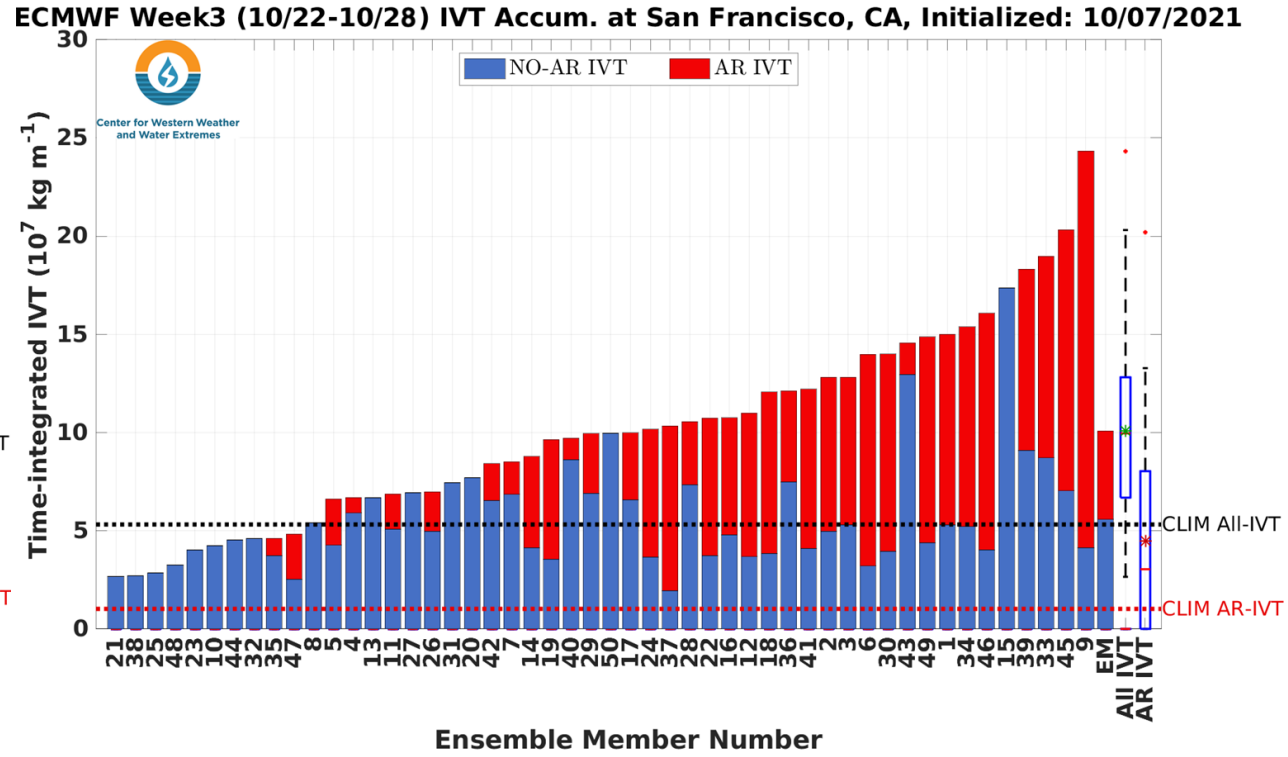
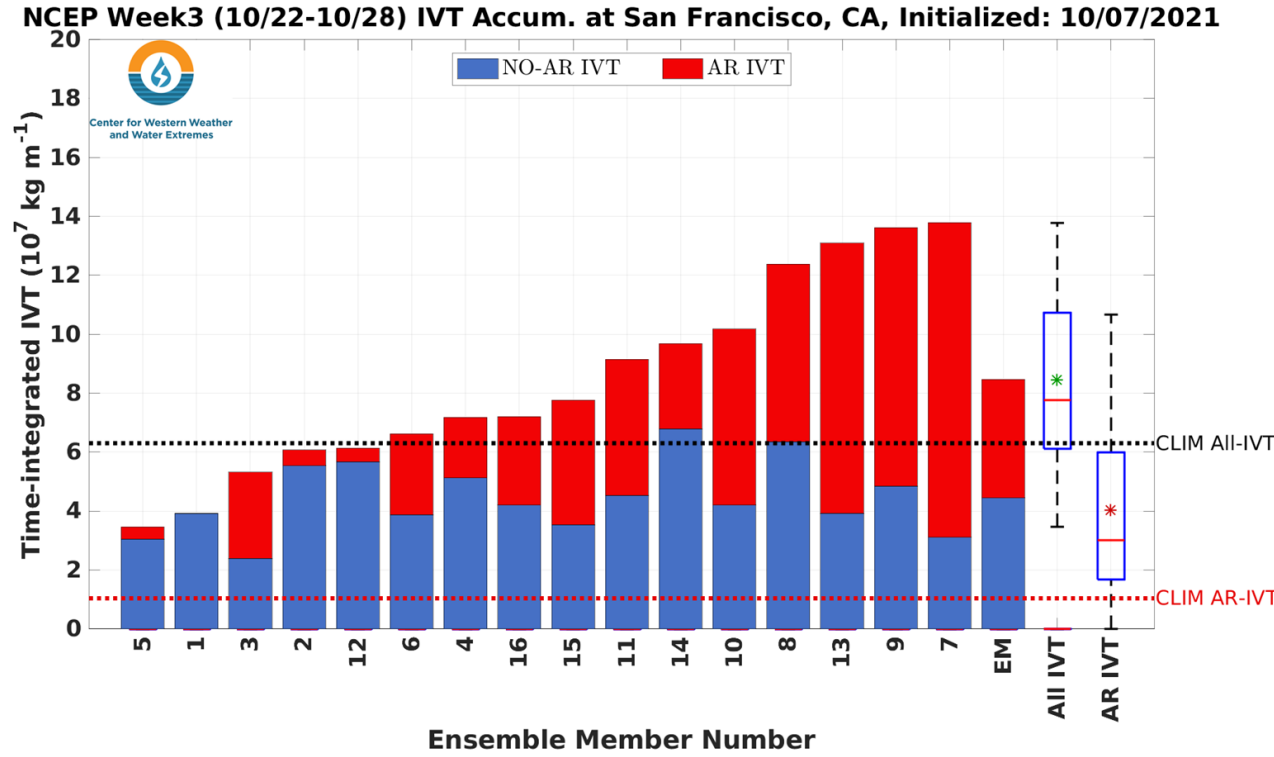
- All the three models capture this major AR event at 15-day to 21-day lead time.
- The forecasted anomaly of weekly AR days at San Francisco is ~0.9 day in ECMWF and ~1 day in ECCC and NCEP.

# AR Week-3 Outlook – Initialized: Oct 7; Valid: Oct 22-28

Time-Integrated IVT (T-IVT) at San Francisco in the Week of Oct 22-28

NCEP

ECMWF



## Ensemble Mean AR T-IVT at San Francisco in the Week of Oct 22-28

- In NCEP (left panel):  $\sim 4.0 \times 10^7 \text{ kg m}^{-1}$ , nearly 300% higher than the model climatology.
- In ECMWF (right panel):  $\sim 4.5 \times 10^7 \text{ kg m}^{-1}$ ,  $\sim 350\%$  higher than the model climatology.