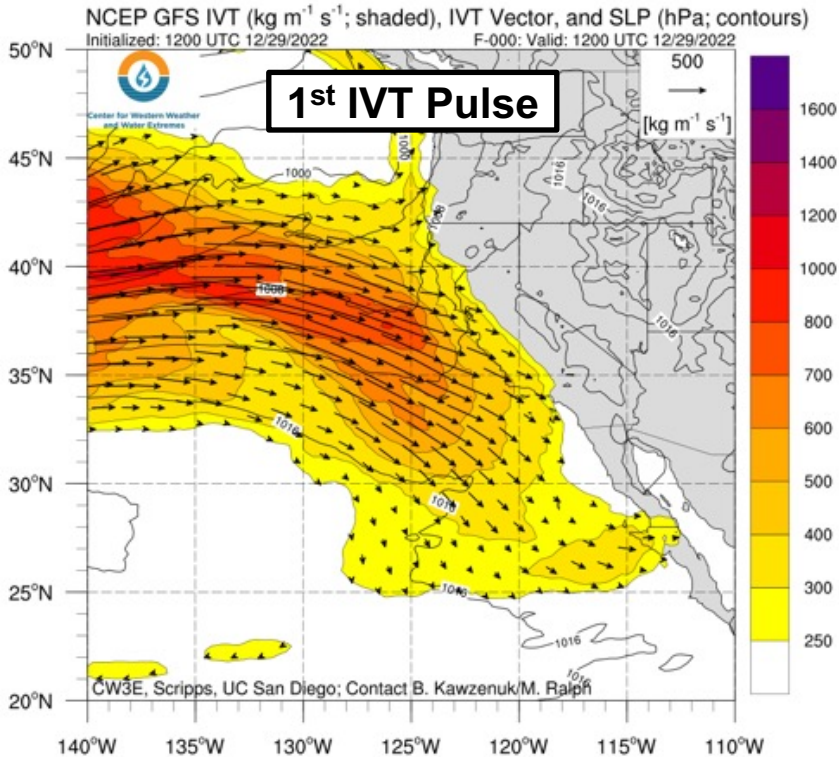


Atmospheric River Brings Record-Breaking Precipitation to California

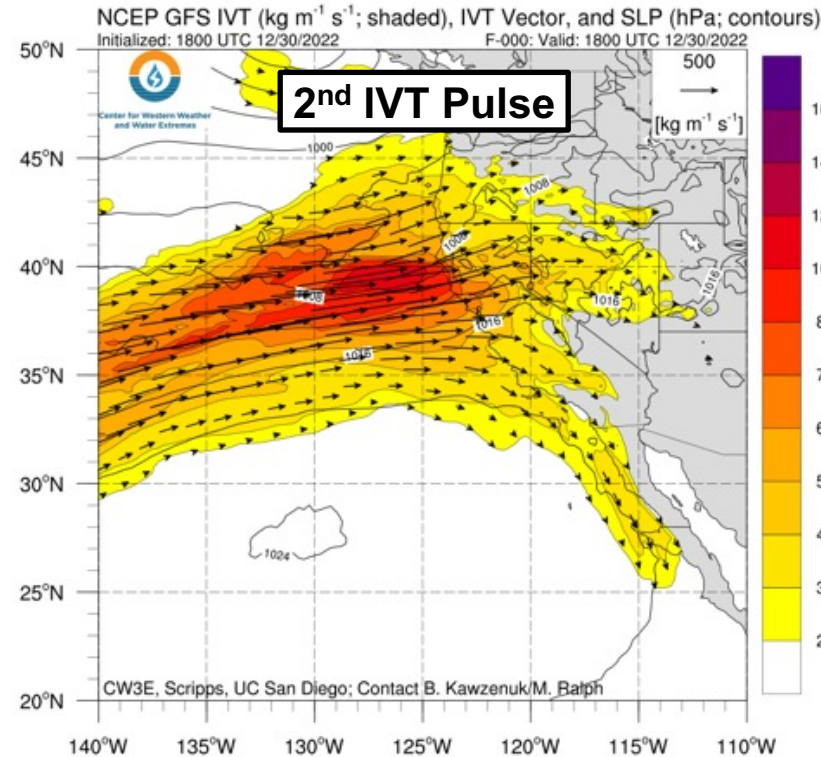
- A strong atmospheric river (AR) made landfall over Northern California on 29 Dec
- AR 1/AR 2 conditions (based on the Ralph et al. 2019 AR Scale) were observed across much of coastal California
- While the initial pulse of moisture transport produced little precipitation, two additional stronger pulses produced heavy precipitation across portions of Northern and Central California on 30–31 Dec
- More than 5 inches of storm-total precipitation fell across the San Francisco Bay Area, while more than 10 inches fell over portions of the Sierra Nevada
- More than 3 feet of snow fell in the higher terrain of the Central and Southern Sierra Nevada
- Warm air associated with this AR limited snowfall accumulations in the Northern Sierra Nevada
- The combination of heavy rainfall and high antecedent soil moisture and streamflow conditions led to riverine and urban flooding
- Multiple levee breaks along the Cosumnes River caused major flooding on Highway 99 and led to water rescues and at least one fatality
- Heavy rain falling on nearly saturated soils triggered mudslides and rockslides in Northern and Central California
- Strong winds downed trees and power lines, resulting in numerous power outages in the Sacramento area
- The severe flooding along the Cosumnes River was poorly forecast at lead times < 48 hours due to large errors in precipitation forecasts, which substantially underestimated the observed precipitation in the Upper Cosumnes watershed

GFS IVT & SLP Analyses

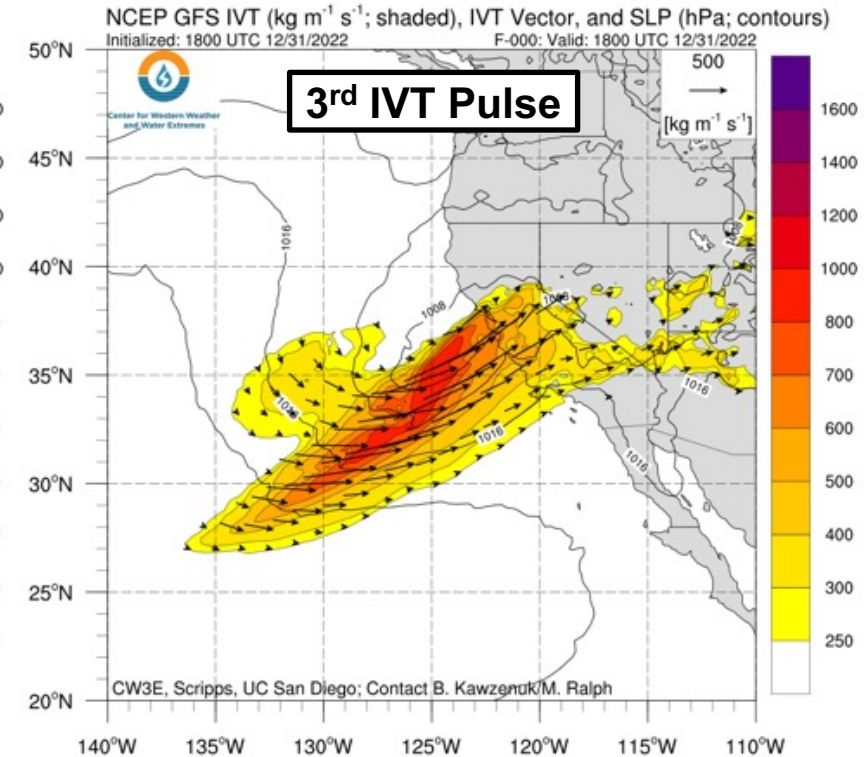
(A) Valid: 4 AM PT 29 Dec



(B) Valid: 10 AM PT 30 Dec

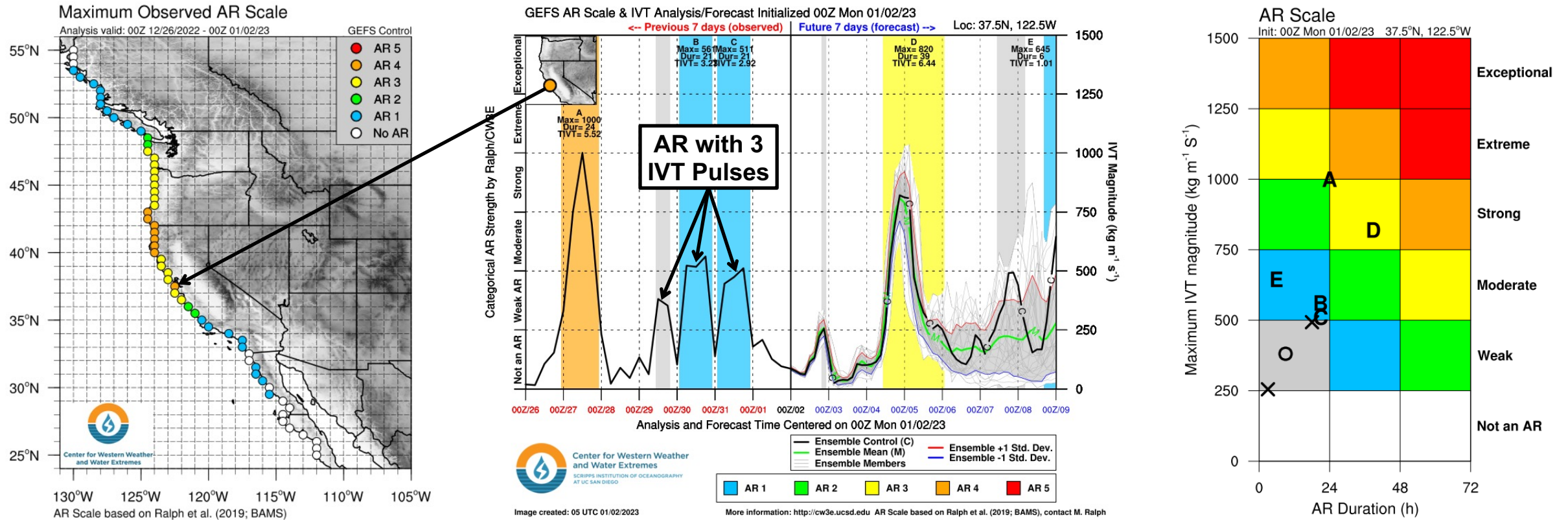


(C) Valid: 10 AM PT 31 Dec



- An AR featuring multiple distinct pulses of moisture transport made landfall over California on 29 Dec
- The first IVT pulse was northwesterly and thus produced little precipitation (Figure A)
- The second IVT pulse brought IVT magnitudes $> 700 \text{ kg m}^{-1} \text{ s}^{-1}$ to Northern California on 30 Dec in association with a weak mesoscale frontal wave (MFW, Figure B)
- The third IVT pulse brought IVT magnitudes $> 600 \text{ kg m}^{-1} \text{ s}^{-1}$ to Central California on 31 Dec in association with a much stronger MFW (Figure C)
- The westerly-to-southwesterly orientation of the second and third IVT pulses were much more favorable for orographic precipitation enhancement

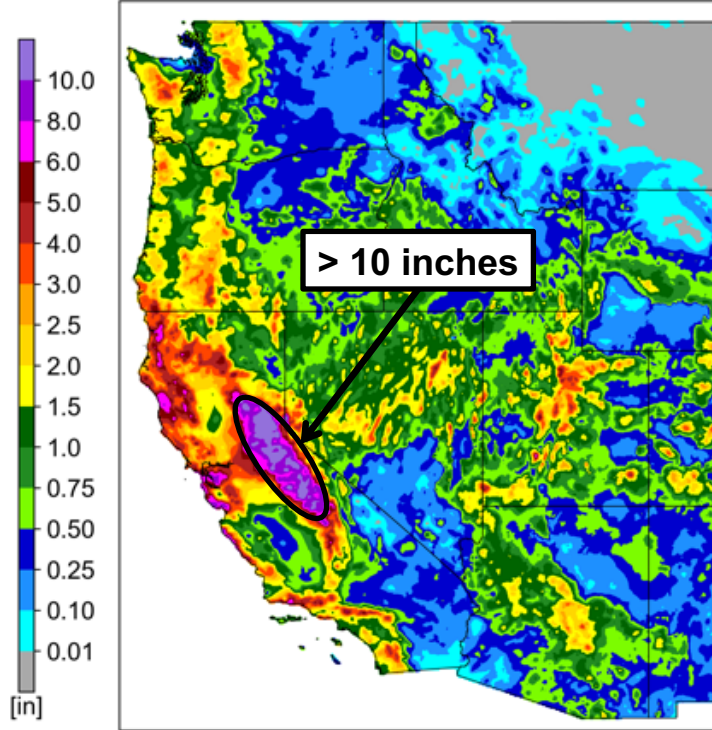
GEFS AR Scale Analysis



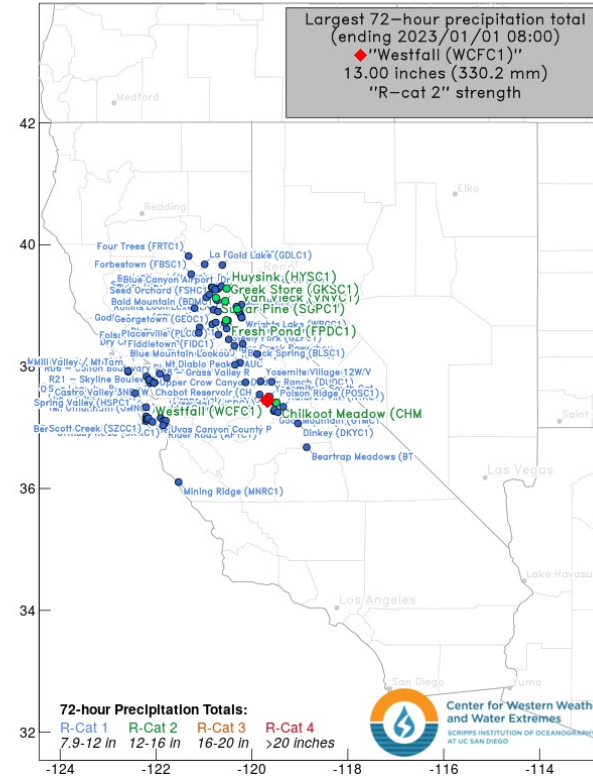
- The AR produced AR 1/AR 2 conditions (based on the Ralph et al. 2019 AR Scale) over much of coastal California
- Three distinct IVT pulses were observed over the San Francisco Bay Area during this AR
- The second and third IVT pulses each brought a moderate-strength AR conditions ($\text{IVT} > 500 \text{ kg m}^{-1} \text{ s}^{-1}$) to the Bay Area
- This AR came right on the heels of a stronger AR that produced AR 3/AR 4 conditions in Northern and Central California

Observed Precipitation

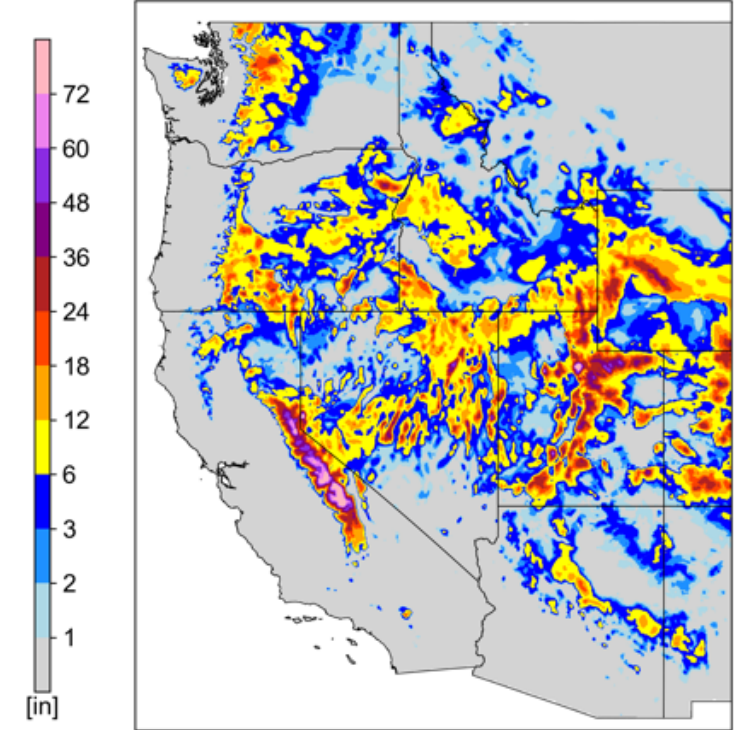
NCEP Stage IV 96-h QPE
Valid: 4 AM PT 2 Jan



R-Cat report produced 2023/01/01 08:22:23



NOHRSC 96-h Snowfall Analysis
Valid: 4 AM PT 2 Jan

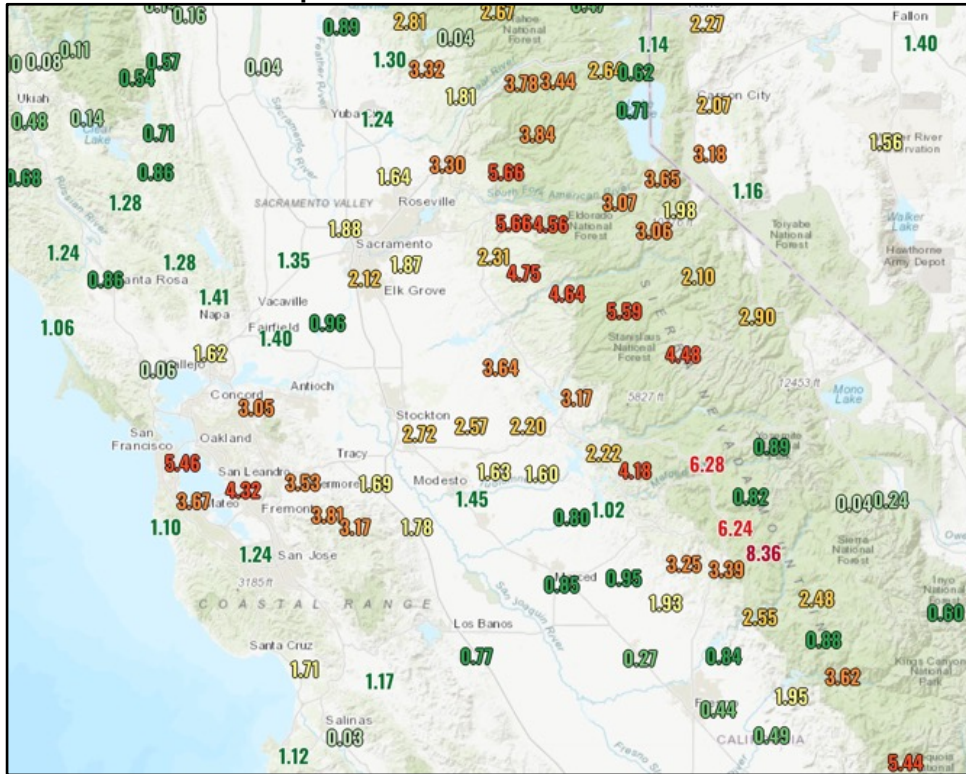


- This AR produced more than 5 inches of precipitation over much of the Bay Area and more than 10 inches of precipitation over the Sierra Nevada
- At least 2–5 inches of precipitation also fell in the eastern Transverse Ranges and Peninsular Ranges in Southern California
- Numerous stations in the Bay Area and along the western side of the Sierra Nevada experienced an R Cat 1 event (≥ 7.9 inches in a 72-hour period), with 7 stations recording an R Cat 2 event (≥ 12 inches in a 72-hour period)
- More than 3 feet of snow fell in the higher terrain of the Central and Southern Sierra Nevada, with 54" reported at the Mammoth Mountain summit
- Inland penetration of this AR produced least 1–3 feet of snow in the higher terrain of the Great Basin

CW3E Event Summary: 29 December 2022 – 1 January 2023

Observed Precipitation

24-h Precipitation: Valid 12 AM PT 1 Jan



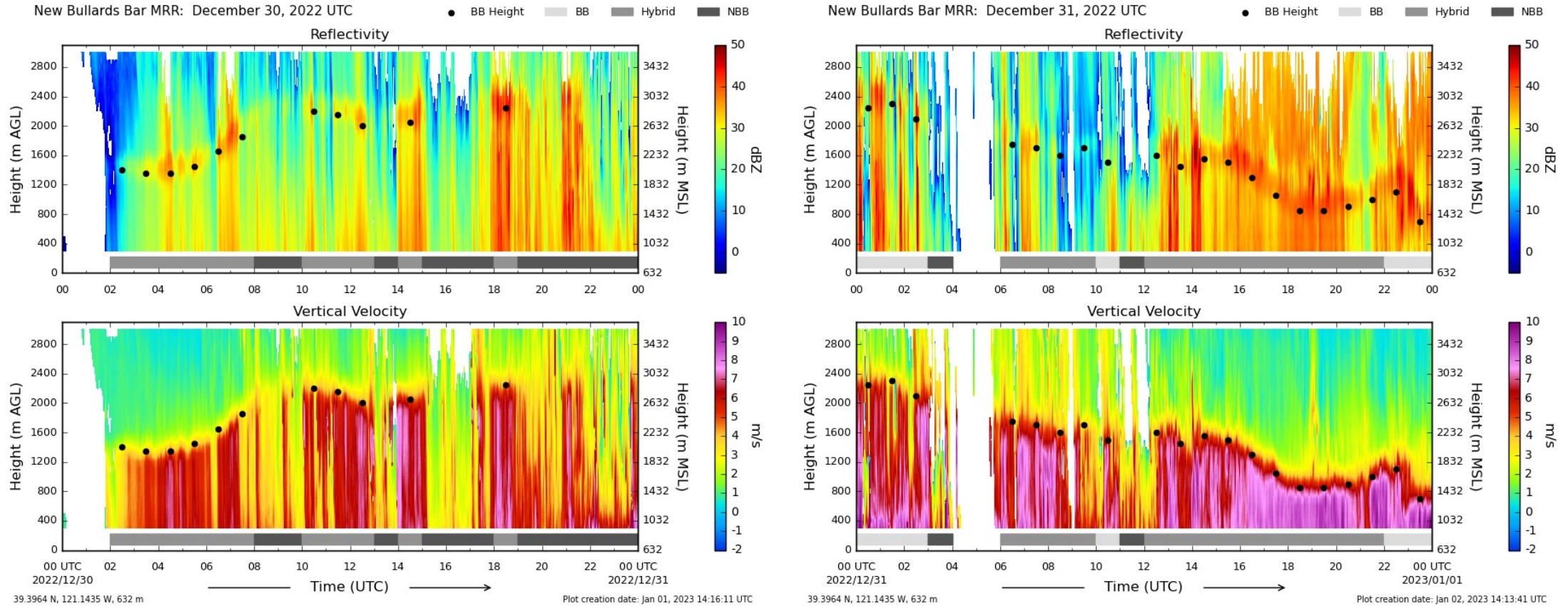
Source: NOAA/NWS Western Region Headquarters

Station	29–31 Dec Precip (in)	Total Dec Precip (in)	Normal Dec Precip (in)	% of Normal Dec Precip
Downtown San Francisco	6.94	11.60	4.76	244
Oakland AP	6.31	11.50	3.84	299
South Lake Tahoe AP	6.16	13.62	3.49	390
Hayward AP	5.59	10.53	3.20	329
San Francisco AP	4.64	9.66	4.14	233
Livermore AP	4.04	8.09	2.80	289
Stockton AP	3.94	8.50	2.41	353
Concord AP	3.60	7.97	3.18	251
Downtown Sacramento	3.57	9.50	3.49	272
Sacramento Executive AP	3.10	7.79	3.43	227
Watsonville AP	2.97	13.42	4.01	335
Modesto AP	1.90	6.94	2.21	314

Source: NWS Bay Area, NWS Sacramento, and NWS Reno

- The heaviest precipitation fell over the Bay Area and Central Sierra Nevada on 31 Dec, with many stations reporting 4–6 inches in a single day
- Oakland Museum set a new all-time daily precipitation record with 4.75 inches (records began in 1970)
- Downtown San Francisco experienced its second-wettest day (5.46 inches) since records began in 1849
- This storm closed out an active December, with many stations in Central California receiving > 200% the normal monthly precipitation
- Oakland Airport, Stockton Airport, and Modesto Airport all experienced their wettest Decembers on record

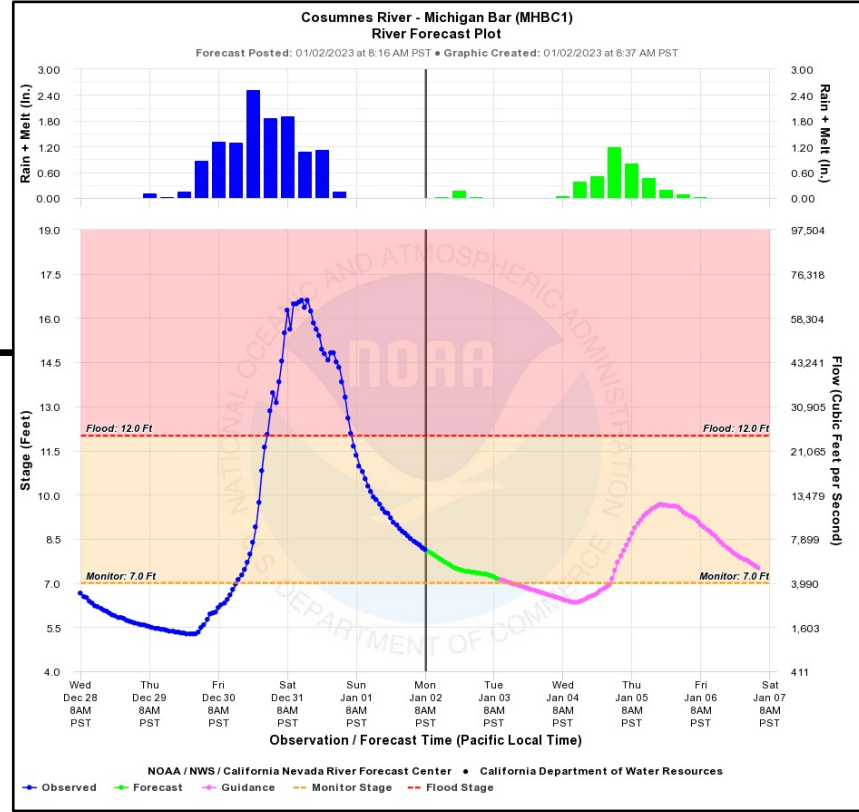
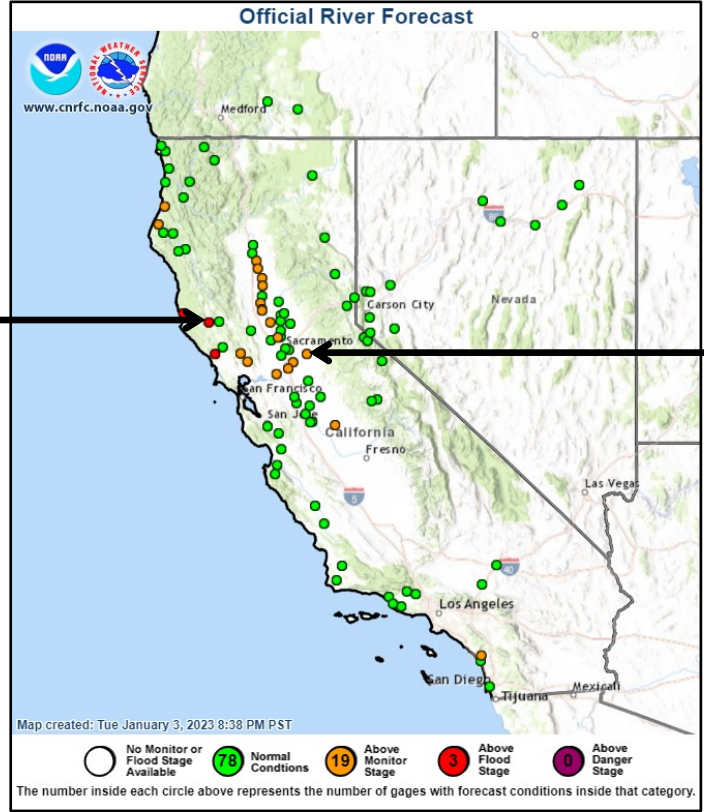
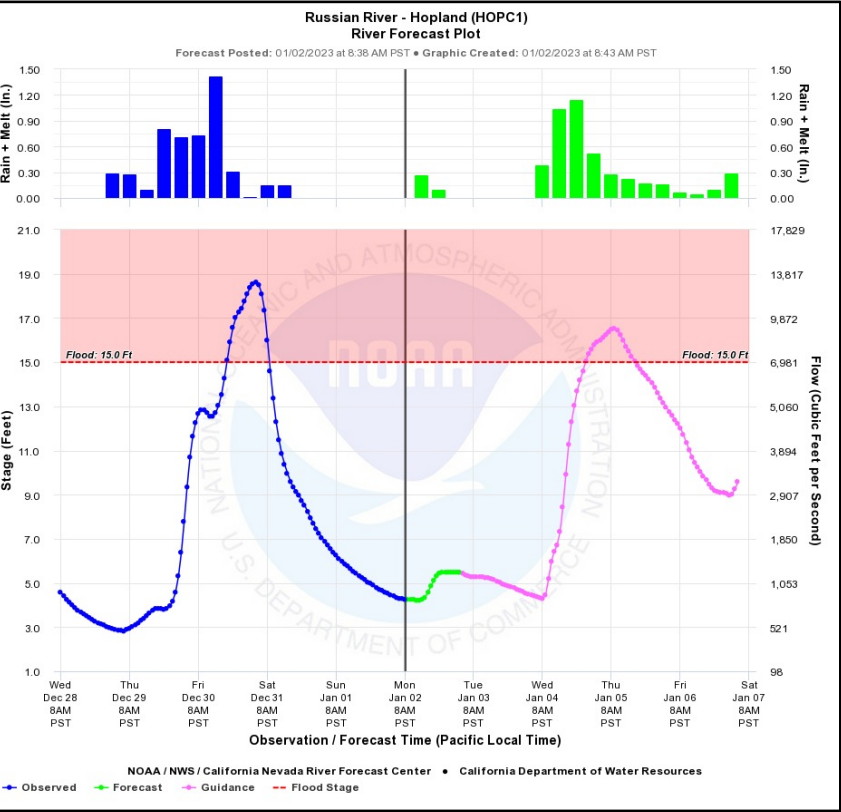
CW3E Observations: New Bullards Bar MRR



- Warm air associated with this AR limited snowfall accumulations over much of the Northern Sierra Nevada
- CW3E's MicroRain Radar (MRR) at New Bullards Bar shows that freezing levels rose above 2500 meters after the initial AR landfall
- Freezing levels eventually fell below 1500 meters on 31 Dec as colder air overspread the region

CW3E Event Summary: 29 December 2022 – 1 January 2023

Impacts



- The combination of heavy rain and antecedent conditions (moist soils and elevated river levels) resulted in riverine flooding along the Russian and Cosumnes Rivers
- The Russian River at Hopland reached a peak stage of 18.64 ft
- The Cosumnes River at Michigan Bar recorded its second-highest peak stage (16.83 ft) since records began in 1907

Impacts



SR 99 near Galt

Source: Caltrans



SR 9 near Boulder Creek

Source: Caltrans



SR 1 near Ragged Point

Source: Caltrans



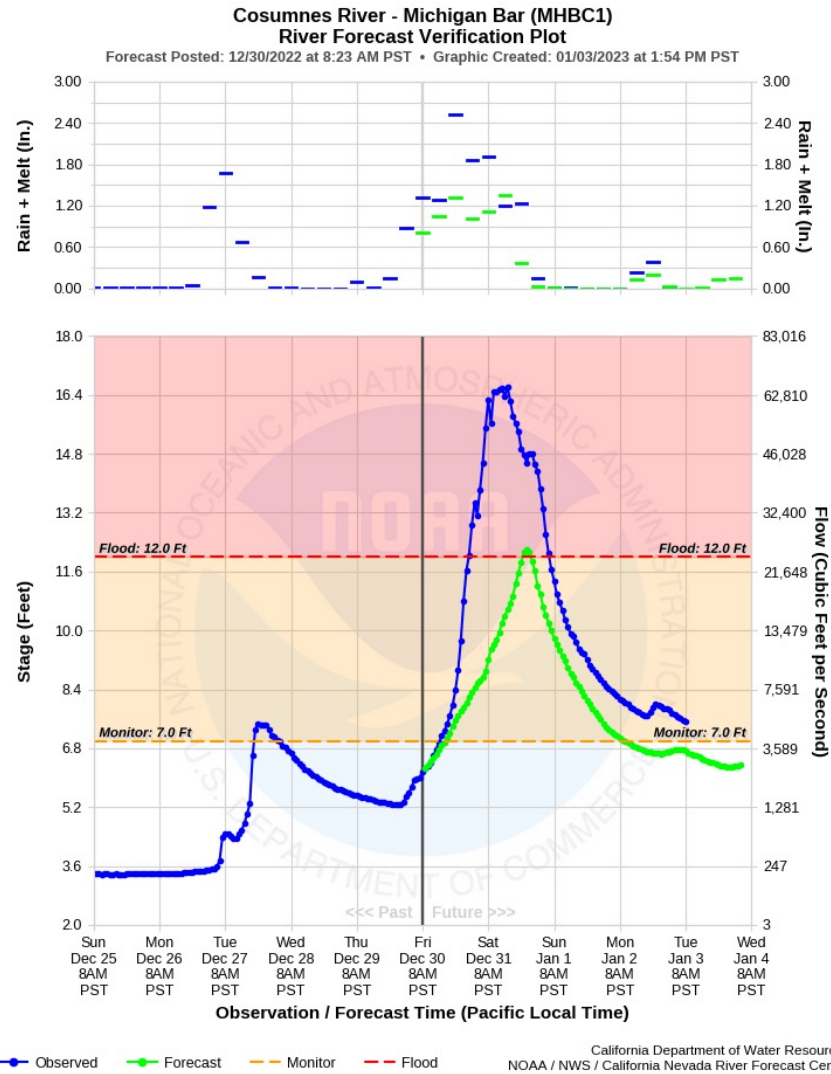
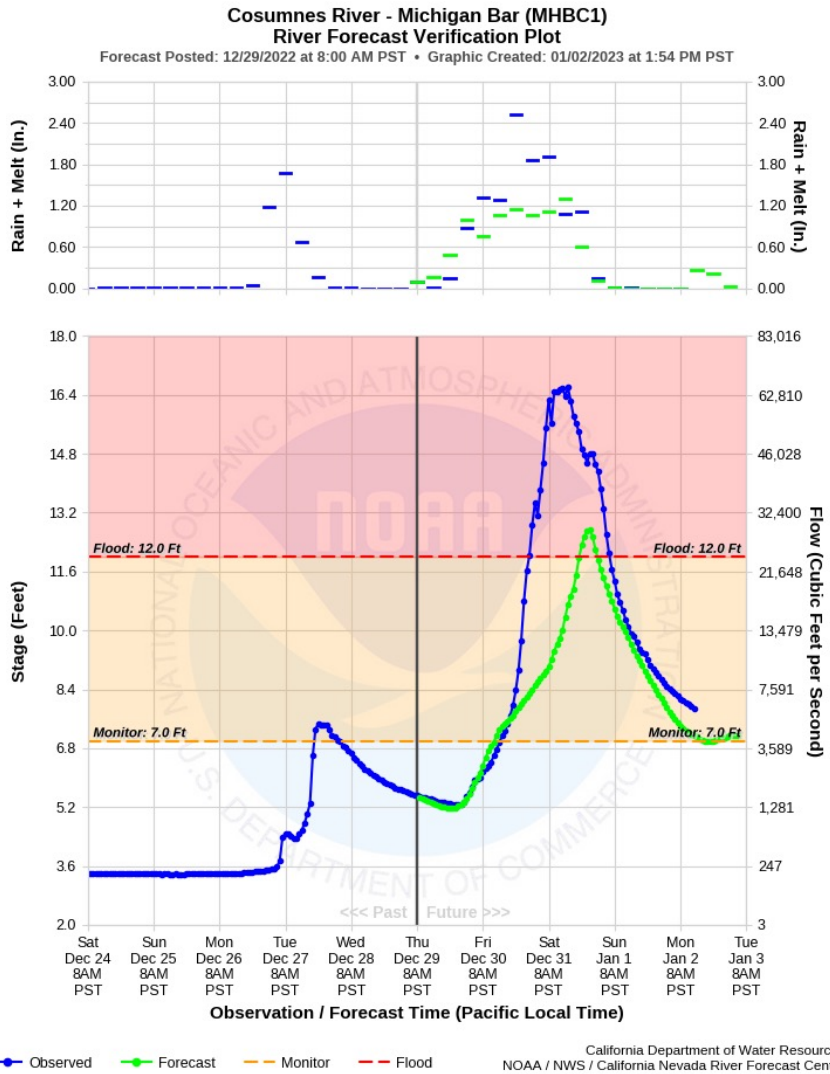
Sacramento

Source: Molly Riehl, CBS Sacramento

- The combination of heavy rain and antecedent conditions resulted in widespread riverine and urban flooding
- High river levels caused multiple levee breaks along the Cosumnes River, leading to a 9-mile closure of Highway 99
- Dozens of water rescues and at least one fatality were reported due to flooding along the Cosumnes and Mokelumne Rivers
- Heavy rain falling on nearly saturated soils triggered mudslides and rockslides throughout Northern and Central California
- Strong winds downed trees and power lines, leaving more than 100,000 customers without power Sacramento area

CW3E Event Summary: 29 December 2022 – 1 January 2023

Streamflow Forecast Verification



- The rapid rise in streamflow on the Cosumnes River at Michigan Bar was forecast quite poorly, even at lead times within 48 hours
- The deterministic streamflow forecast issued at 8 AM PT 30 Dec underestimated the peak stage by more than 4 feet
- In addition, the peak stage occurred more than 6 hours earlier than forecast
- Large precipitation forecast errors over the Upper Cosumnes watershed likely contributed to the large streamflow forecast errors at this location

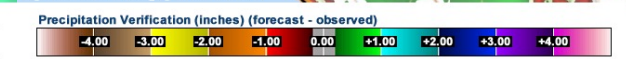
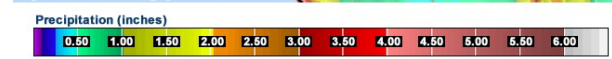
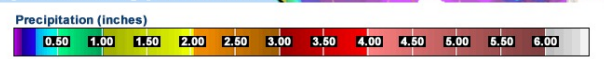
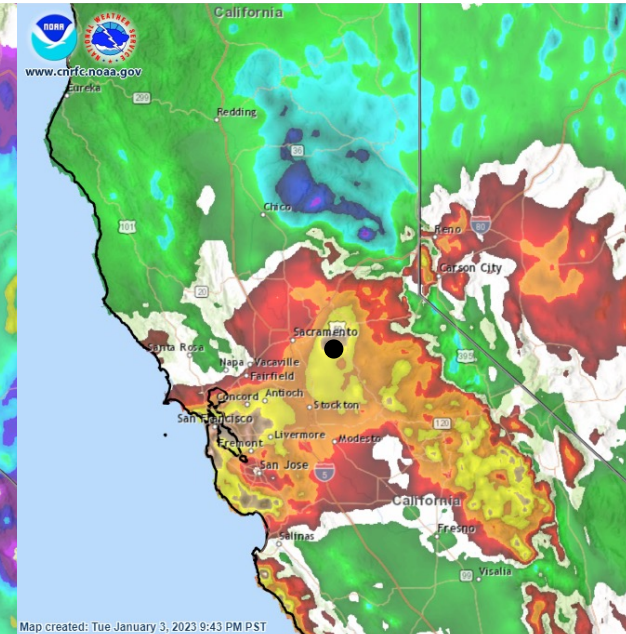
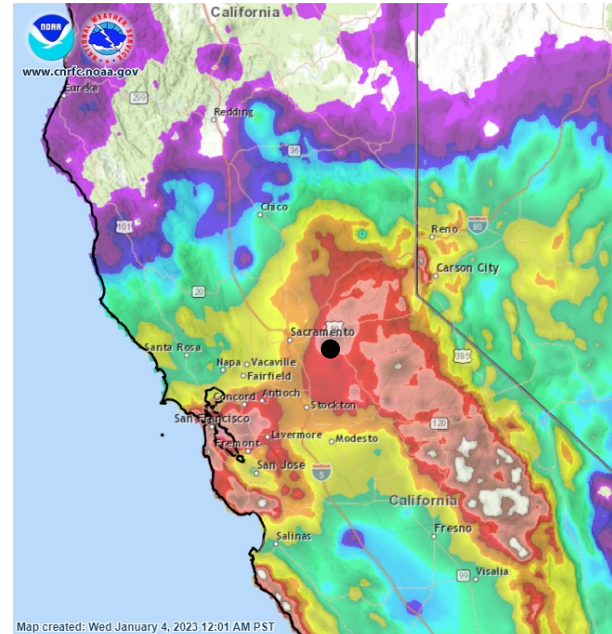
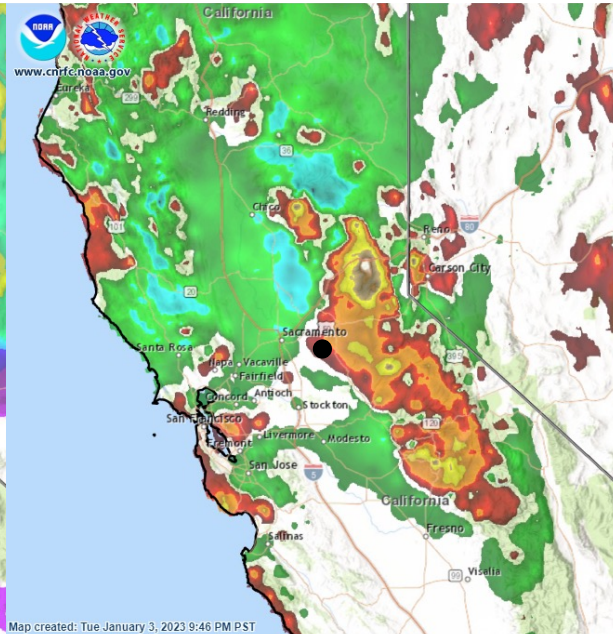
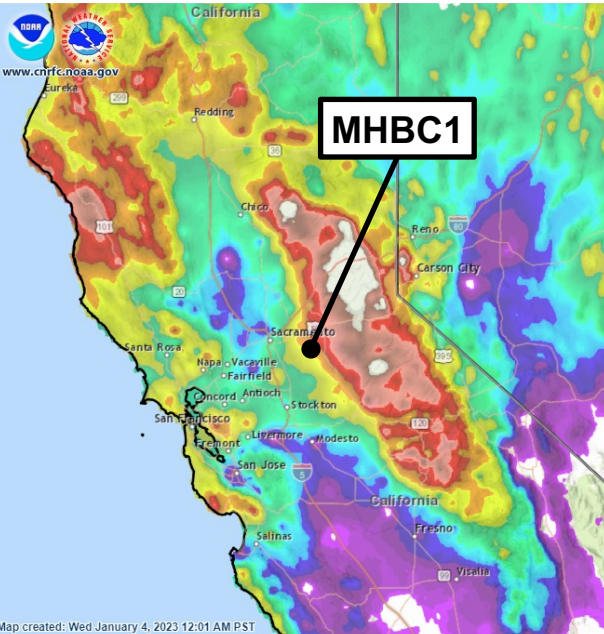
Precipitation Forecast Verification

CNRFC 24-h QPE
Valid 4 AM PT 31 Dec

CNRFC QPF Minus QPE
Forecast Issued 29 Dec

CNRFC 24-h QPE
Valid 4 AM PT 1 Jan

CNRFC QPF Minus QPE
Forecast Issued 30 Dec



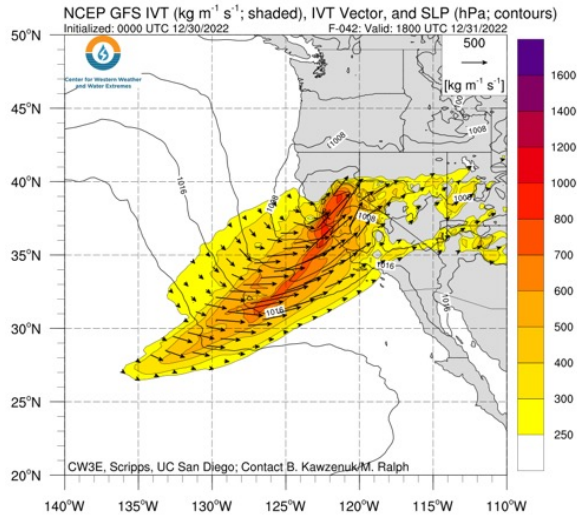
Forecast < Observed Forecast > Observed

Forecast < Observed Forecast > Observed

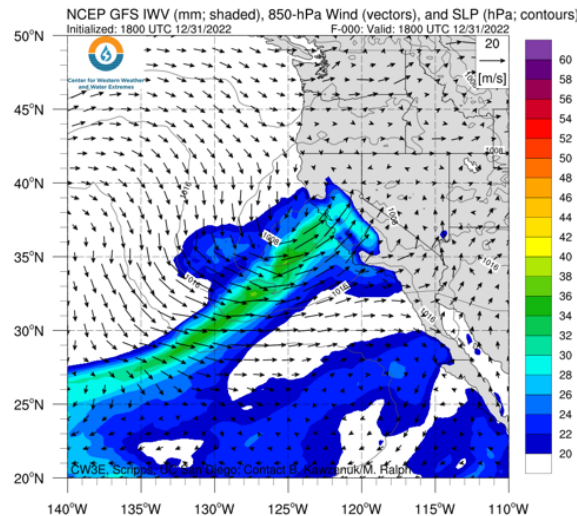
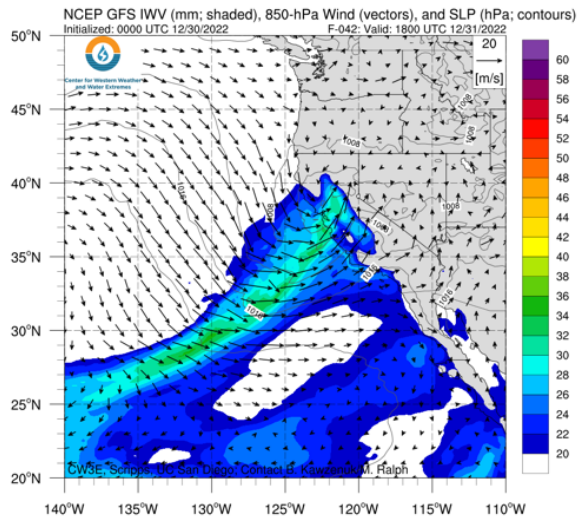
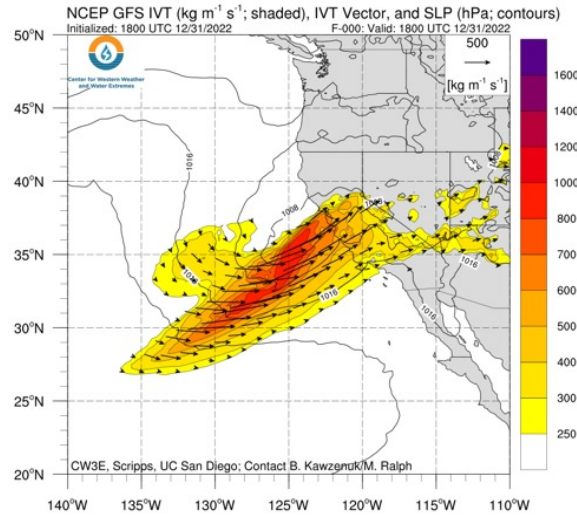
- NWS forecasts significantly underestimated the observed precipitation over portions of the Central and Southern Sierra Nevada, Bay Area, and Central Valley, and overestimated the observed precipitation across much of the Northern Sierra Nevada
- Even at shorter lead times (48 hours), 24-hour precipitation forecast errors were on the order of 2–5 inches in these areas

AR Forecast Verification

Forecast (Initialized 00Z 30 Dec)

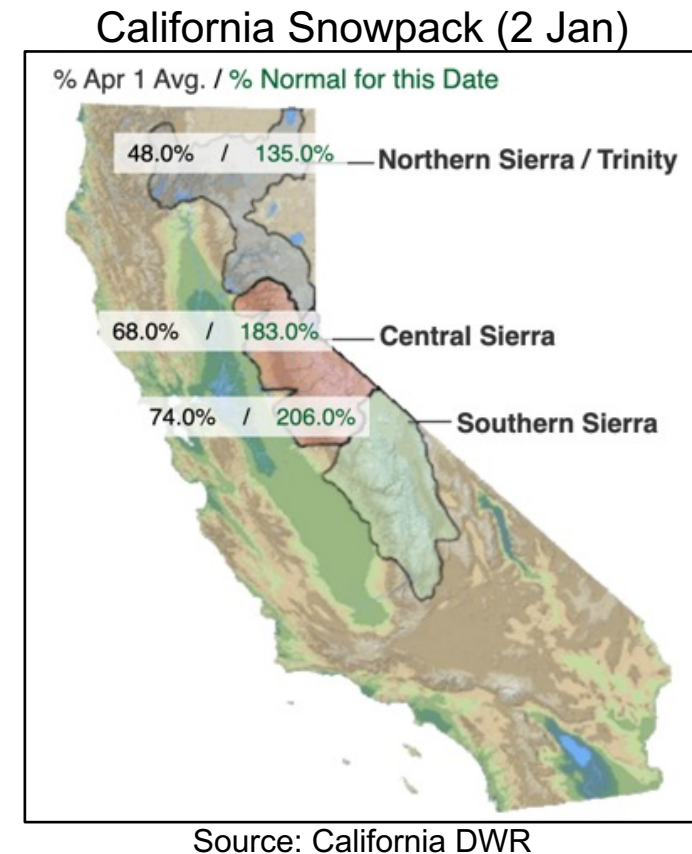
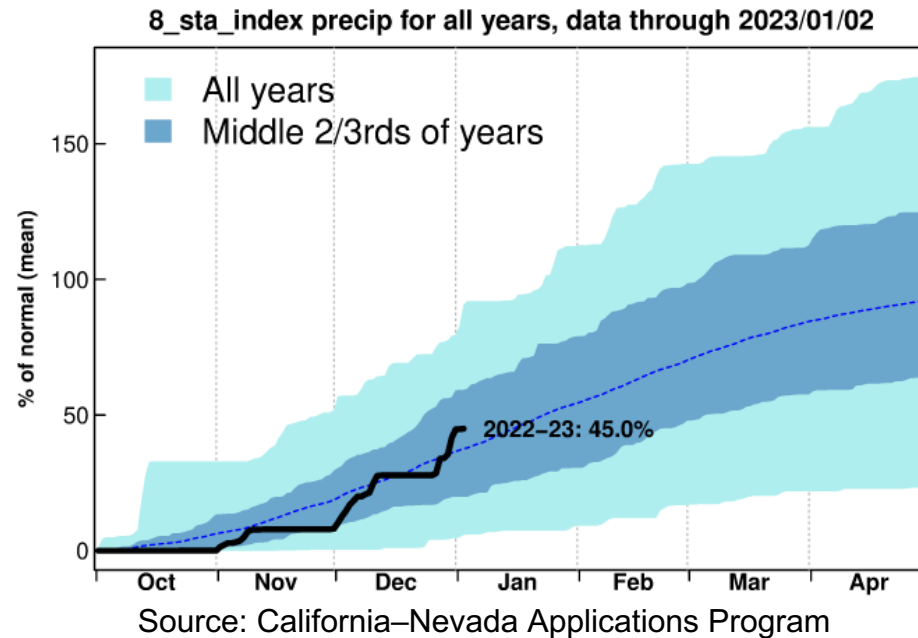
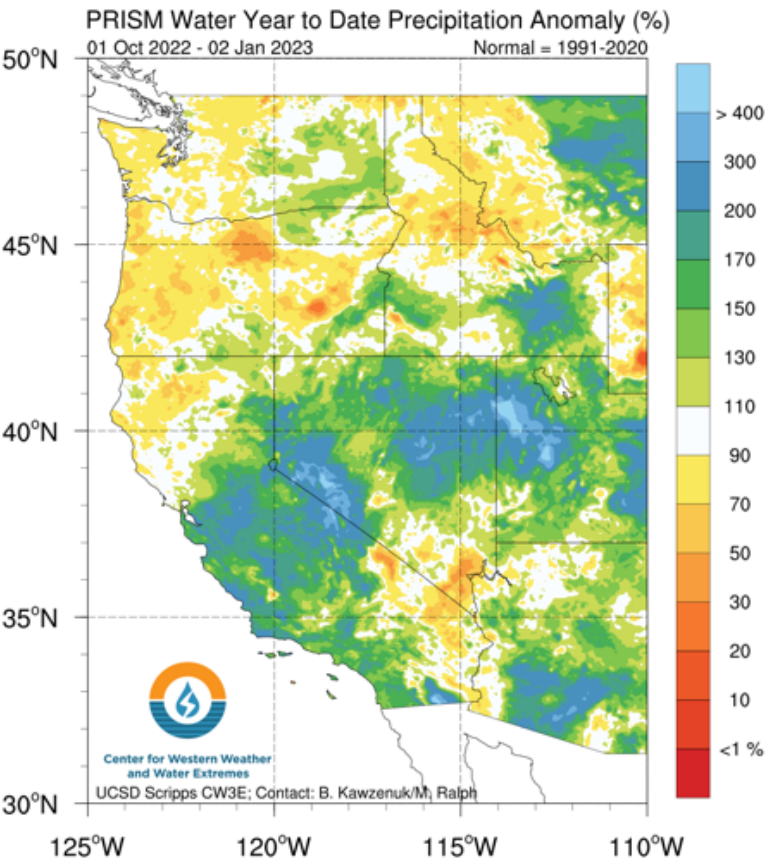


Analysis (Valid 18Z 31 Dec)



- Forecast errors related to the structure of the AR may have contributed to the precipitation forecast errors in the Central and Northern Sierra Nevada
 - Compared to the GFS analysis at 18Z 31 Dec, the GFS forecast initialized at 00Z 30 Dec predicted a narrower, faster-moving AR core with more meridionally-orientated IVT and much higher IVT magnitudes over interior Northern California
 - In addition, the forecast initialized at 00Z 30 Dec predicted strong southwesterly low-level flow over the Sacramento Valley, which is favorable for the development of Sierra barrier jets
 - These errors likely resulted in a displacement of the heaviest precipitation from the Central Sierra Nevada to the Northern Sierra Nevada
- *CW3E is currently working on a more in-depth verification analysis of this event. Stay tuned for updates.*

Water Year 2023 Precipitation and Snowpack



- As of 2 Jan, water-year-to-date precipitation is running above-normal across much of Central California and coastal Southern California
- Some areas in Central California have received more than 200% of normal water-year-to-date precipitation
- Based on the 8-station index, the Northern Sierra Nevada has received 45% of its normal total water year precipitation
- Snowpack continues to run well-above normal throughout California, particularly in the Central and Southern Sierra Nevada, where snowpack is 183% and 206% of normal, respectively