

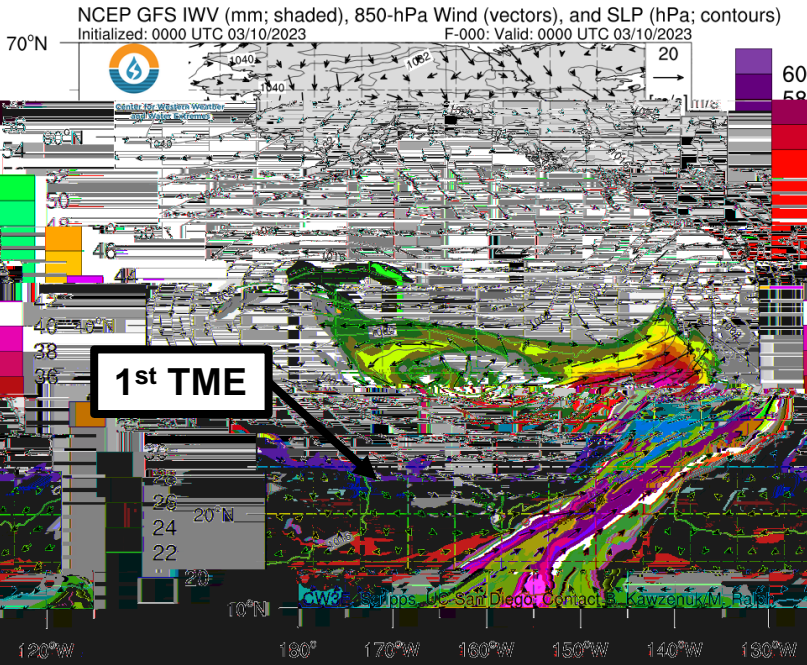
CW3E Event Summary: 9–15 March 2023

Atmospheric Rivers Produce Heavy Precipitation and Flooding in California

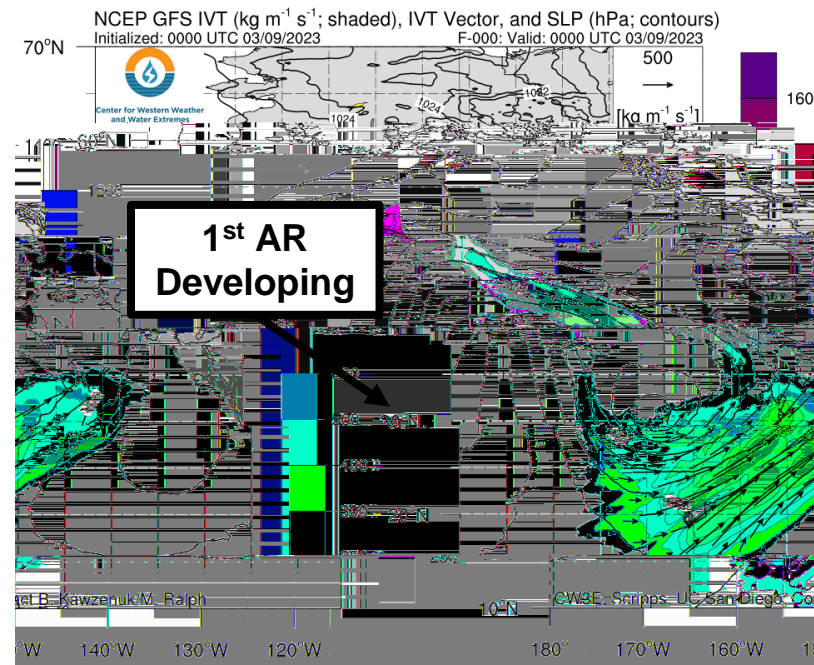
- Two atmospheric rivers (ARs) made landfall over California during 9–15 Mar
- These ARs were characterized by the transport of very warm, moist air from the tropical North Pacific into the midlatitudes
- The first AR brought AR3 conditions (based on the Ralph et al. 2019 AR Scale) and IVT magnitudes $> 750 \text{ kg m}^{-1} \text{ s}^{-1}$ to Monterey and Santa Cruz Counties
- The second AR brought AR2 conditions and IVT magnitudes $> 500 \text{ kg m}^{-1} \text{ s}^{-1}$ to Central and Southern California
- The heaviest precipitation fell during the first AR in the Central and Southern Sierra Nevada, with some locations recording > 12 inches in a 3-day period and sustained precipitation rates > 0.5 inches/hour
- High freezing levels limited snowfall accumulations below 7,000 feet in both storms
- Snow survey stations located above 7,000 feet recorded 7-day SWE increases > 12 inches
- High reservoir inflows prompted dam operators to open the main spillway and increase releases to $> 15,000$ cfs at Oroville Dam after the first AR
- The combination of heavy rainfall and melting snowpack led to widespread riverine flooding across Northern and Central California
- The most destructive flooding occurred along the Pajaro River in the community of Pajaro, CA, and along the Kern River in Kernville, CA
- An EF-1 tornado caused structural damage to mobile homes and farms in Tuolumne County

GFS Analyses of First AR: Valid 4 PM PT 8 March 2023

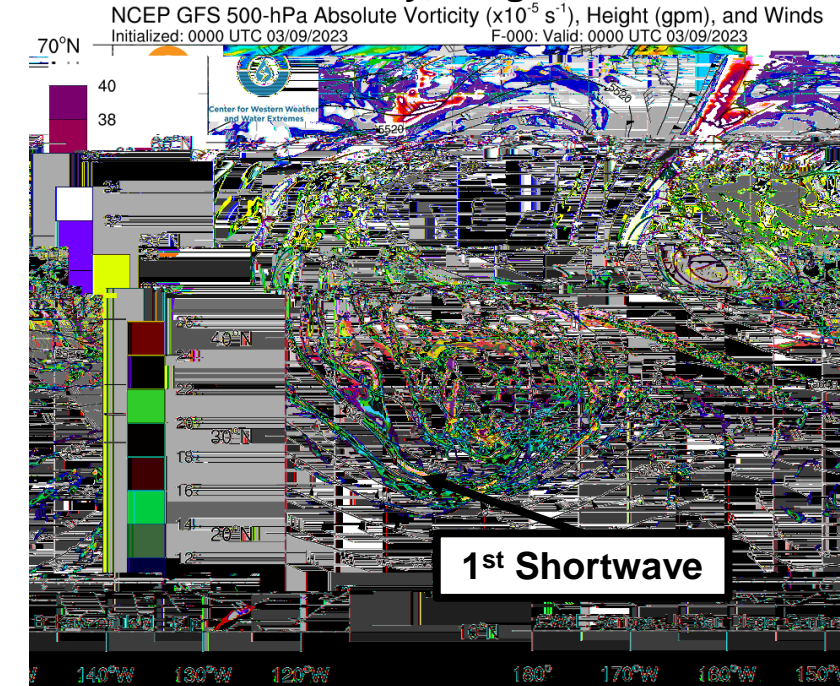
IWV and 850-hPa Wind



IVT and SLP



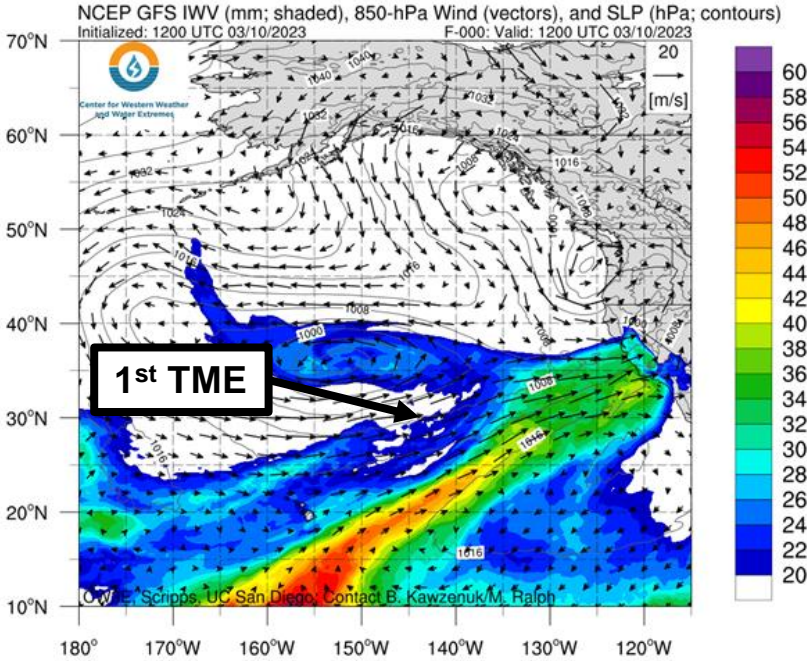
500-hPa Vorticity, Height, and Wind



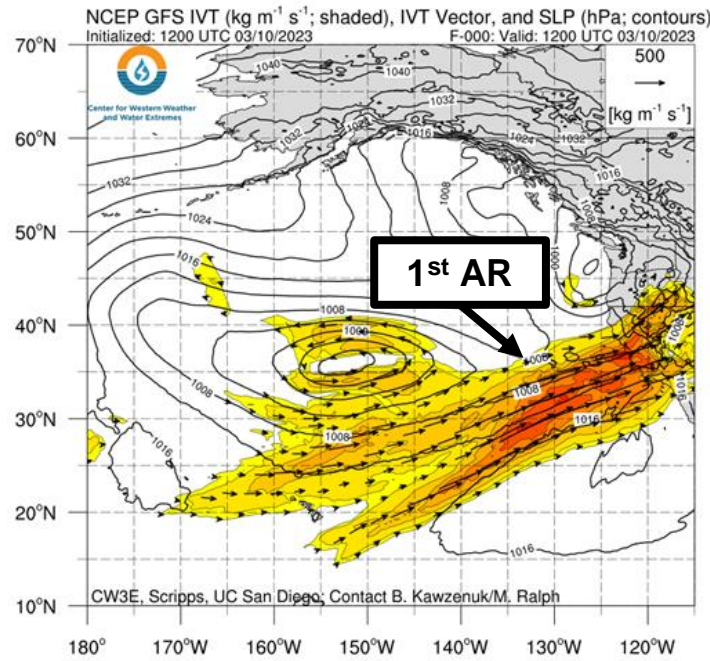
- A robust tropical moisture export (TME) developed over the eastern North Pacific with substantial moisture transport out of the tropics containing IWV values > 45 mm within the core of the TME
- The first AR developed to the northeast of Hawaii with corridor of IVT with $> 1000 \text{ kg m}^{-1} \text{ s}^{-1}$ in the core of the AR
- Cyclogenesis associated with this AR occurred along a broad shortwave trough positioned to the north of Hawaii, providing upper-level support for surface cyclone development in the region of the parent low-pressure center

GFS Analyses of First AR: Valid: 4 AM PT 10 March 2023

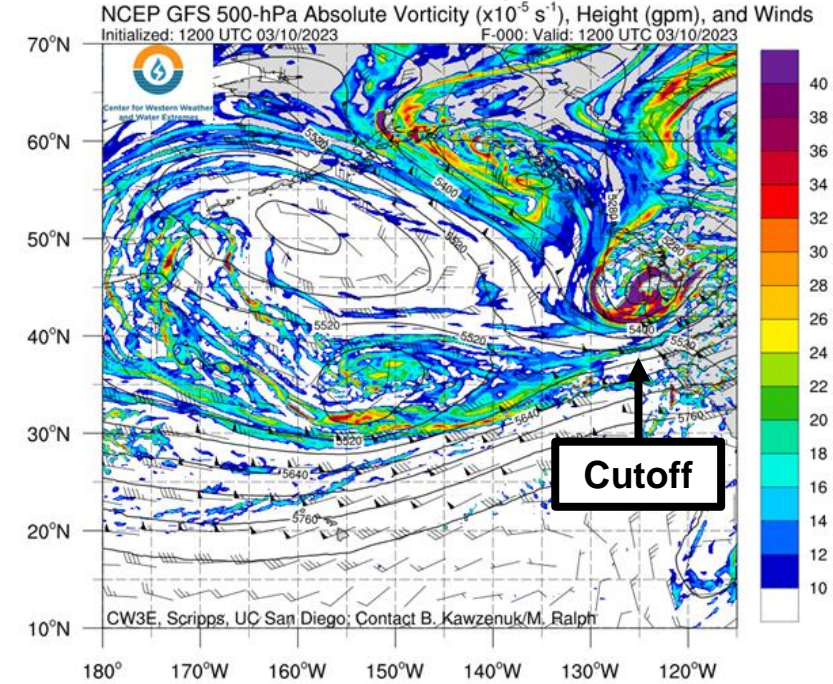
IWV and 850-hPa Wind



IVT and SLP



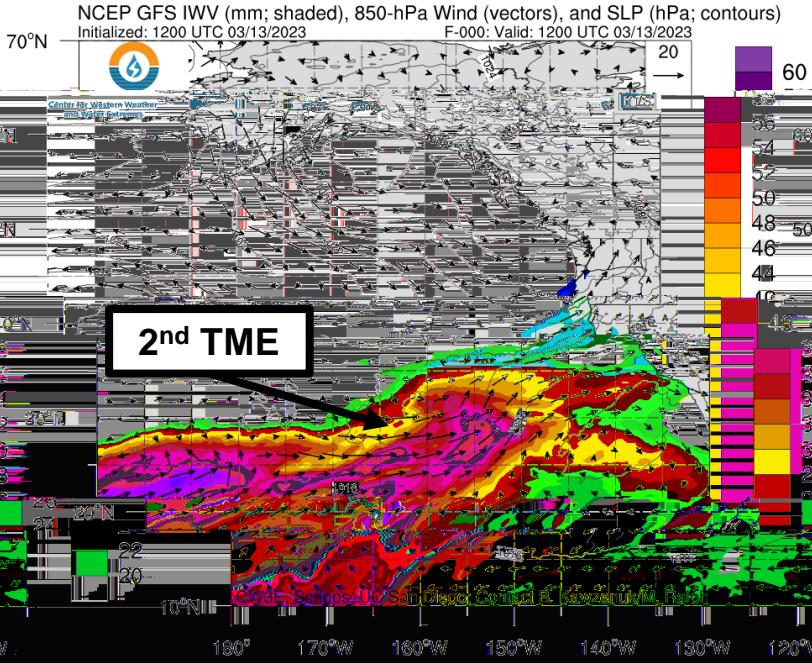
500-hPa Vorticity, Height, and Wind



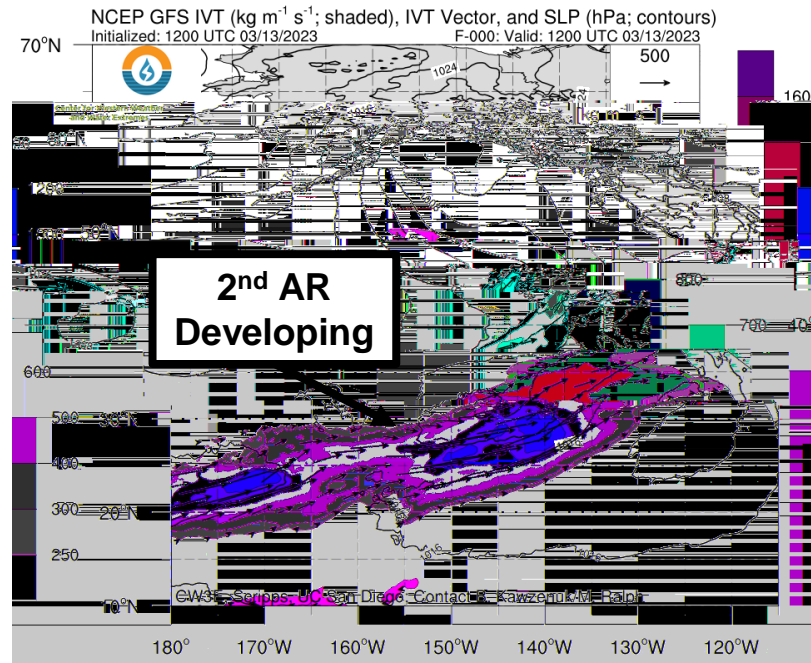
- The TME shifted to the east, bringing IWV values > 36 mm to the US West Coast, resulting in a warm storm for California
- The first AR made landfall late on Thursday 9 Mar, with southwesterly IVT values $> 800 \text{ kg m}^{-1} \text{ s}^{-1}$ in the core of the AR over coastal Northern and Central California
- A cutoff low shifted south from Alaska, providing additional forcing for ascent along the US West Coast, to the north of the AR

GFS Analyses of Second AR: Valid: 5 AM PT 13 March 2023

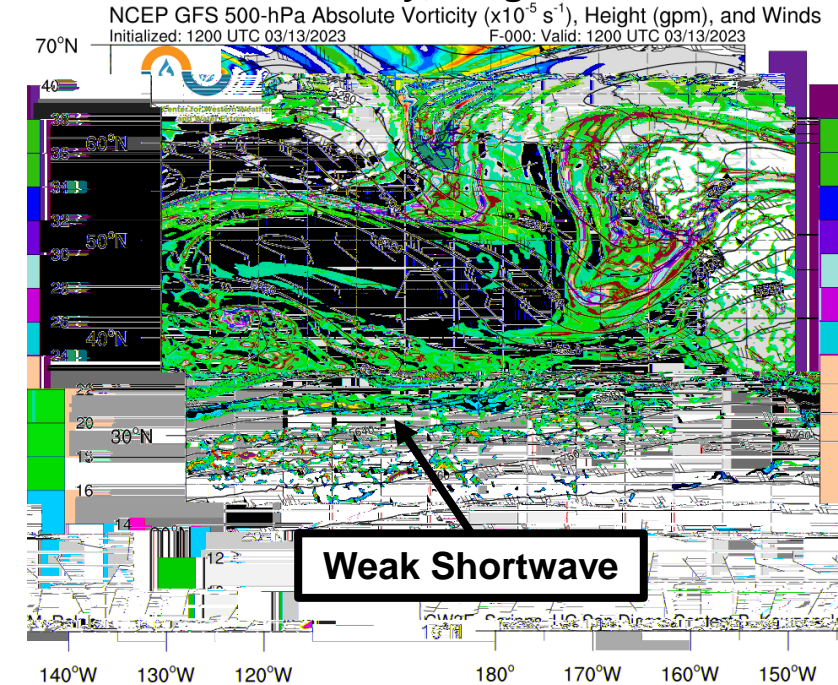
IWV and 850-hPa Wind



IVT and SLP



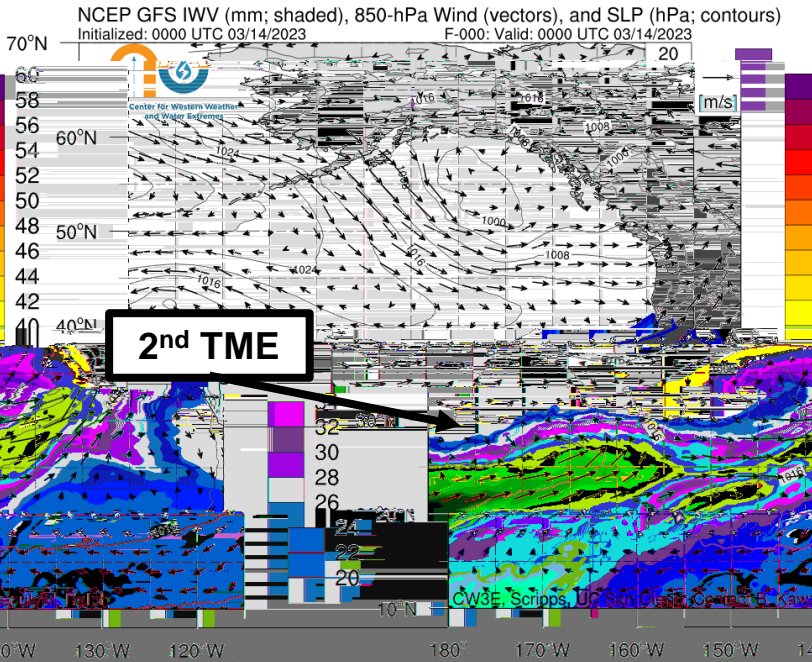
500-hPa Vorticity, Height, and Wind



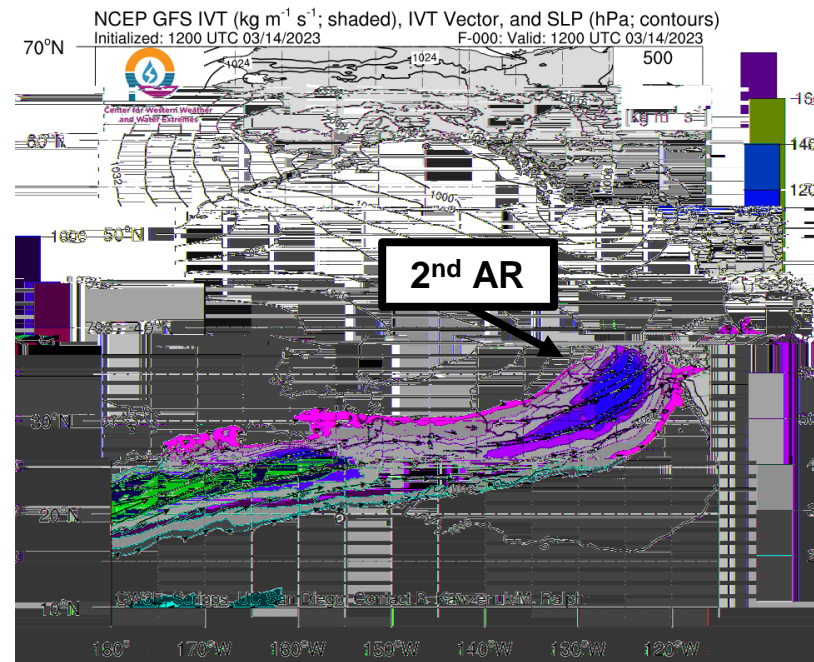
- A second, less well defined TME developed further west over the central North Pacific with IWV values > 40 mm extending from the tropics poleward to the west of Hawaii
- The second AR, with an IVT core $> 800 \text{ kg m}^{-1} \text{ s}^{-1}$ developed over the eastern North Pacific with a southwesterly orientation
- AR development occurred in association with an extremely broad, weak shortwave positioned to the northeast of Hawaii

GFS Analyses of Second AR: Valid: 5 AM PT 14 March 2023

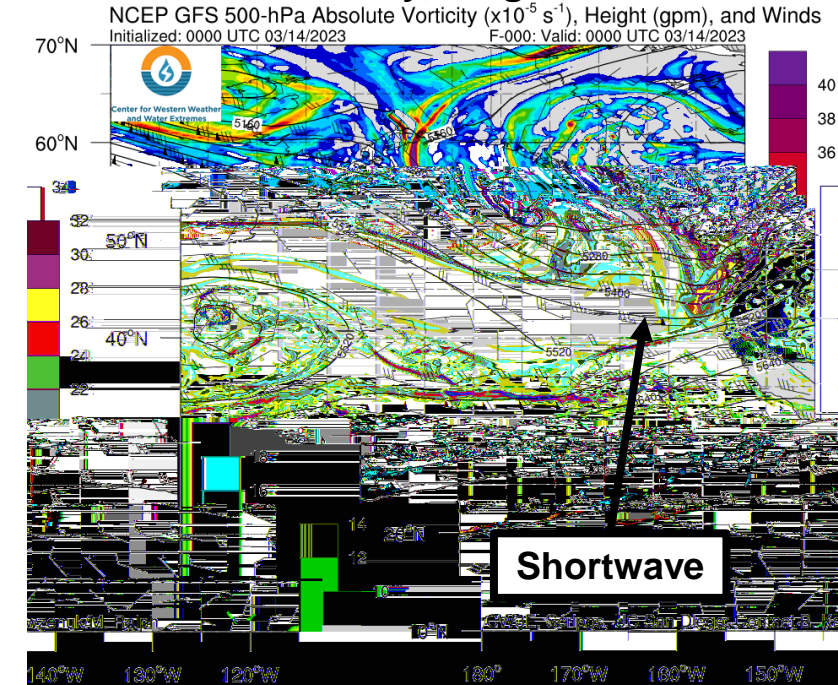
IWV and 850-hPa Wind



IVT and SLP



500-hPa Vorticity, Height, and Wind



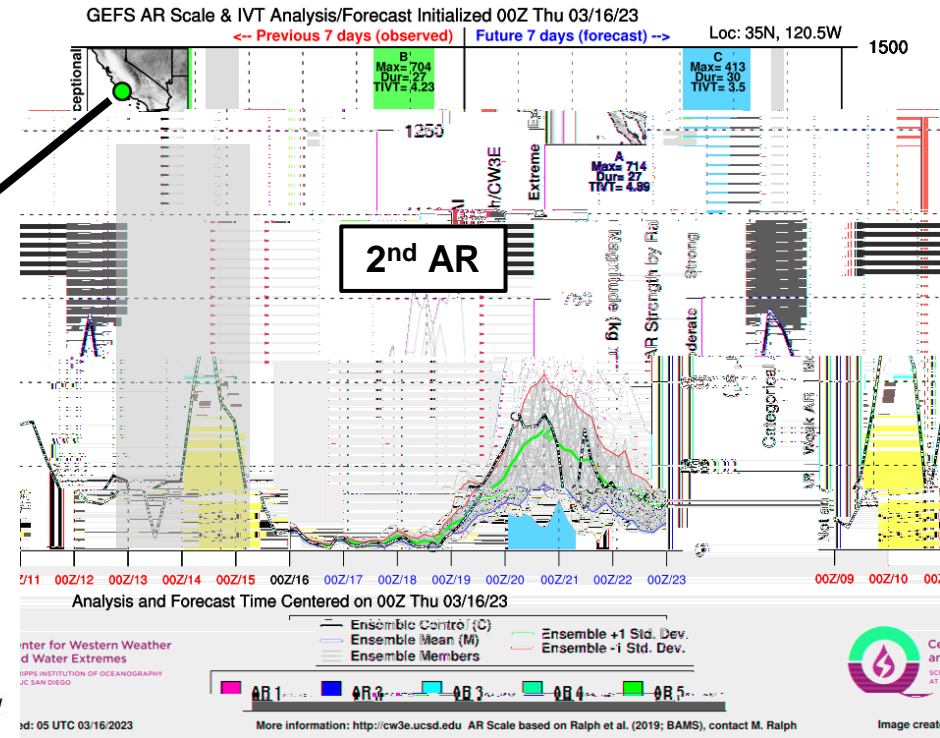
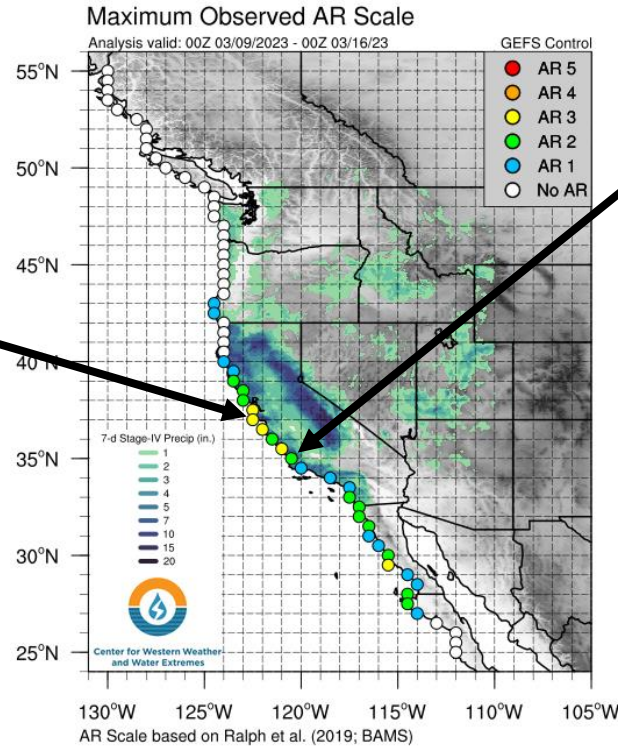
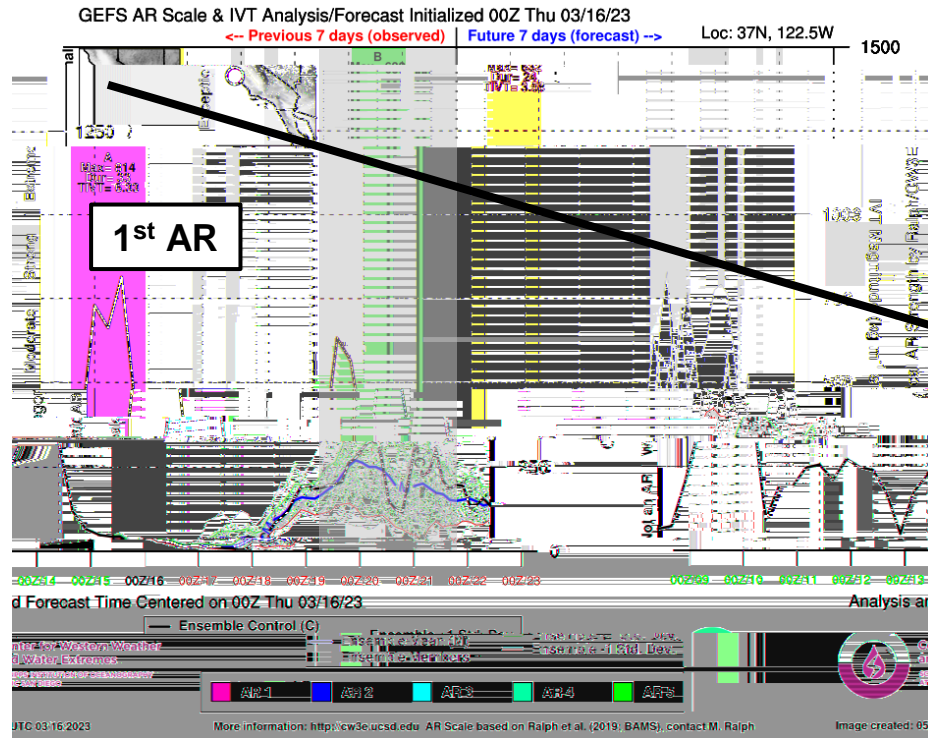
- The second TME continued to provide warm, moist air during this storm, with a narrow southwesterly corridor of IWV > 30 mm
- This second AR made landfall early Tuesday 14 Mar, with south-to-southwesterly IVT > 700 $\text{m}^{-1} \text{s}^{-1}$ over the coast of California
- A second, sharp shortwave trough descended to the south from the Gulf of Alaska, providing additional favorable synoptic forcing for ascent over the US West Coast, along the northern flank of the AR in Northern California

CW3E Event Summary: 9–15 March 2023

GEFS AR Scale Analysis

First AR Max: 37.0° N, 122.5° W

Second AR Max: 35.0° N, 120.5° W

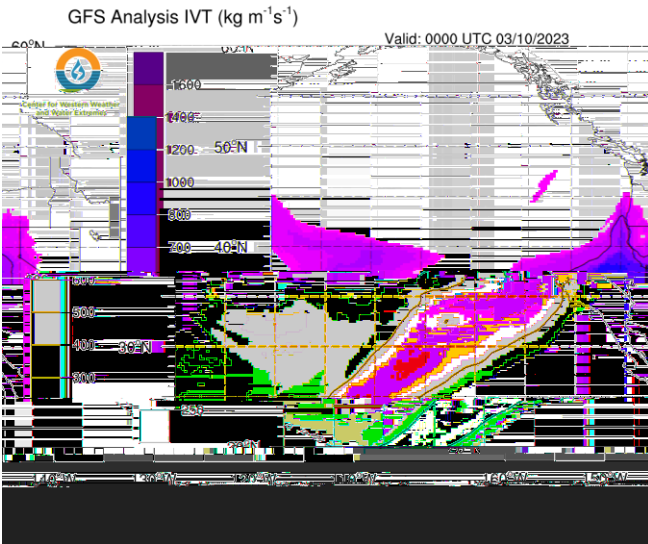


- The first AR produced a maximum of AR 3 conditions just south of the San Francisco Bay Area with IVT > 800 kg m⁻¹ s⁻¹
- The second AR produced AR 2 conditions near Morro Bay, CA, with IVT > 700 kg m⁻¹ s⁻¹ observed along the coast
- Both ARs made landfall in Northern California and propagated to the south, bringing AR conditions to much of California

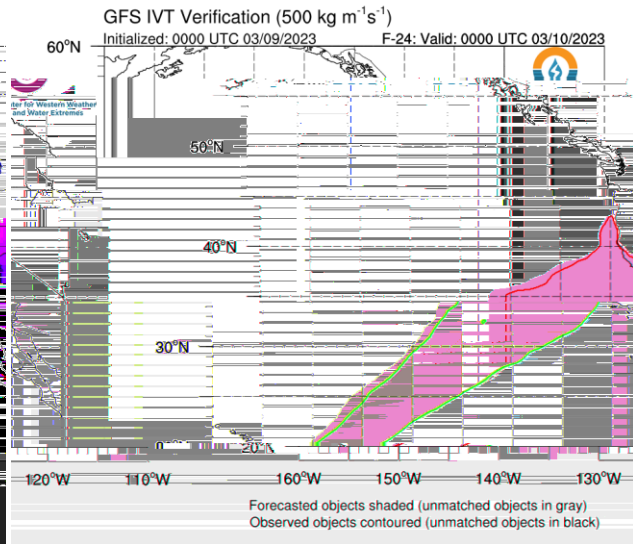
CW3E Event Summary: 9–15 March 2023

AR/IVT Forecast Verification: Valid 00Z 10 March

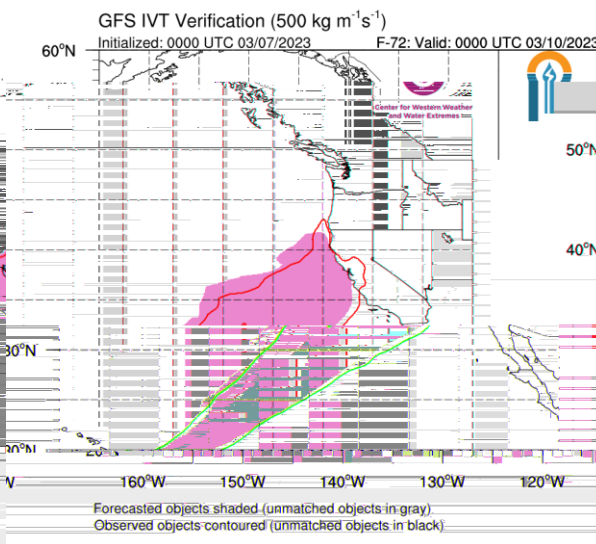
GFS Model Analysis



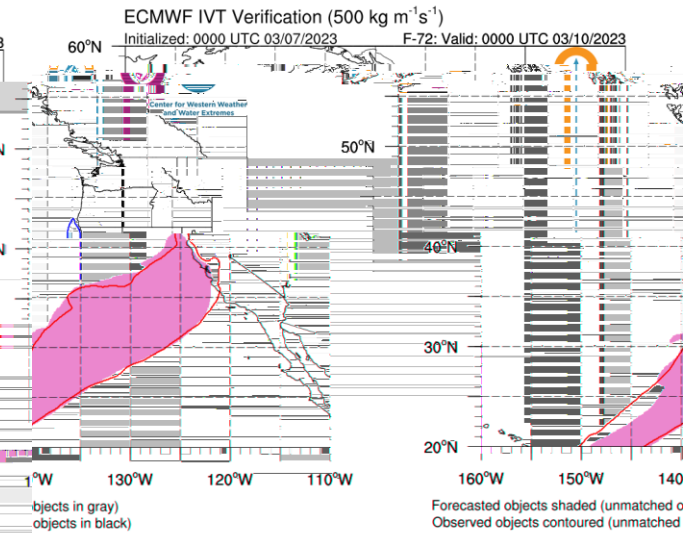
24-h GFS Forecast



72-h GFS Forecast



72-h ECMWF Forecast



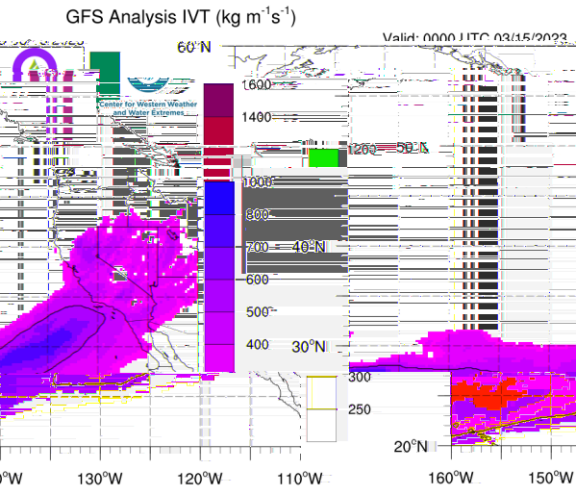
*Forecast objects shaded (unmatched objects in gray)
Observed objects contoured (unmatched objects in black)
Objects defined based on $IVT > 250 \text{ kg m}^{-1} \text{ s}^{-1}$*

- The Method for Object-Based Diagnostic Evaluation (MODE) with a $500 \text{ kg m}^{-1} \text{ s}^{-1}$ IVT threshold shows that the location of the first AR in Central and Northern California was well forecasted in the GFS model at a 24-hour lead time, but the northern extent of the IVT threshold extended slightly further north as compared to the analysis
- Examination of the 72-hour forecast in both the GFS shows that the eastern portion of the AR was rotated in a slight counterclockwise direction and the nose of the AR had not quite made landfall
- The 72-hour ECMWF forecast was very similar to the 72-hour GFS forecast. However, the tail of the AR was not as wide

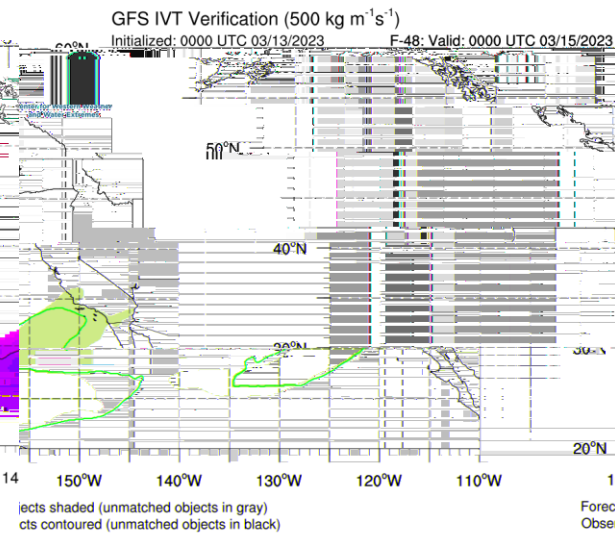
CW3E Event Summary: 9–15 March 2023

GFS AR/IVT Forecast Verification: Valid 00Z 15 March

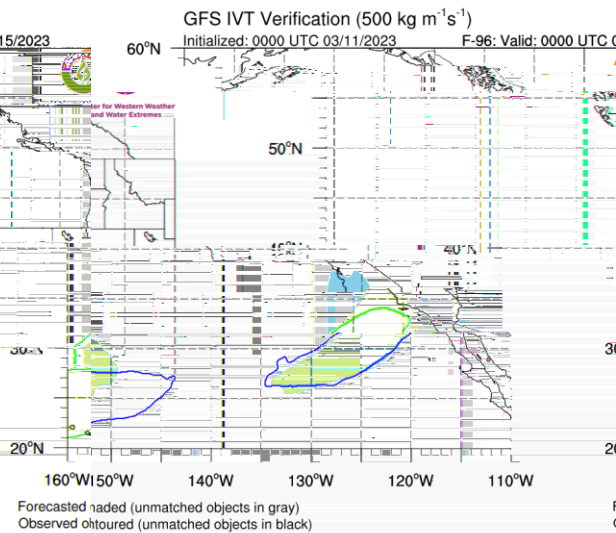
GFS Model Analysis



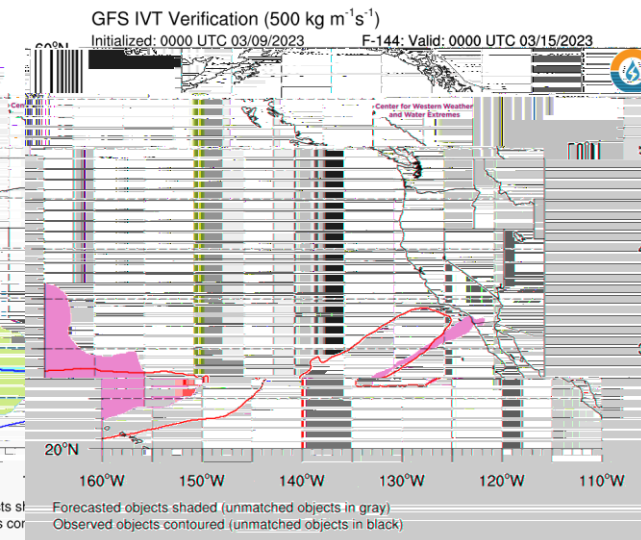
48-h Forecast



96-h Forecast



144-h Forecast

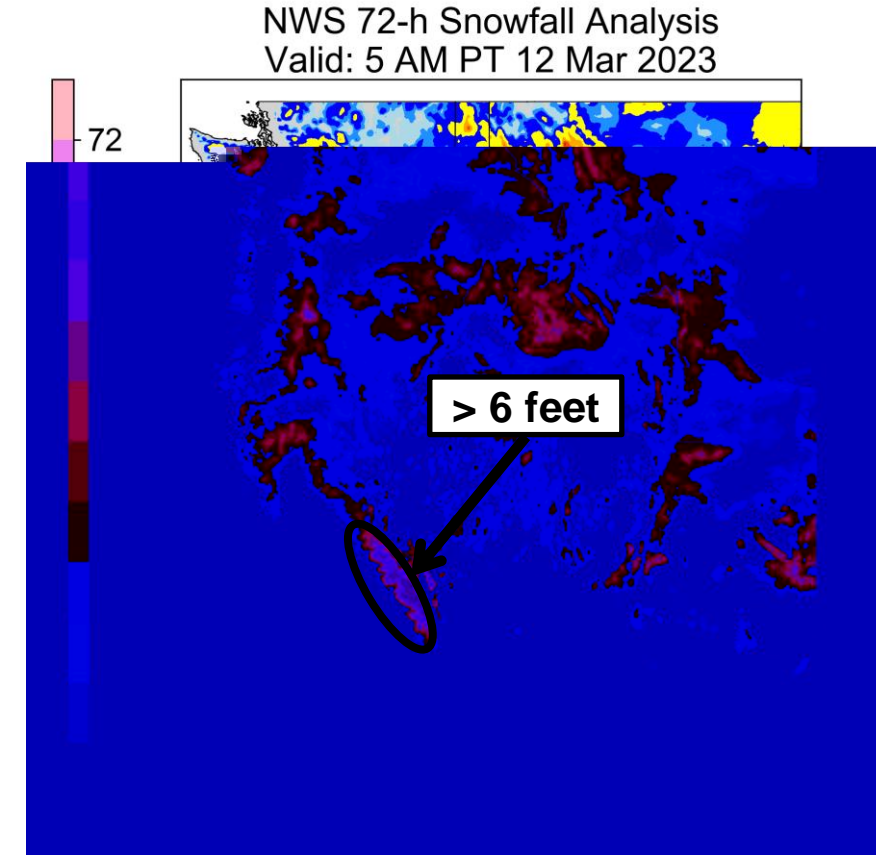
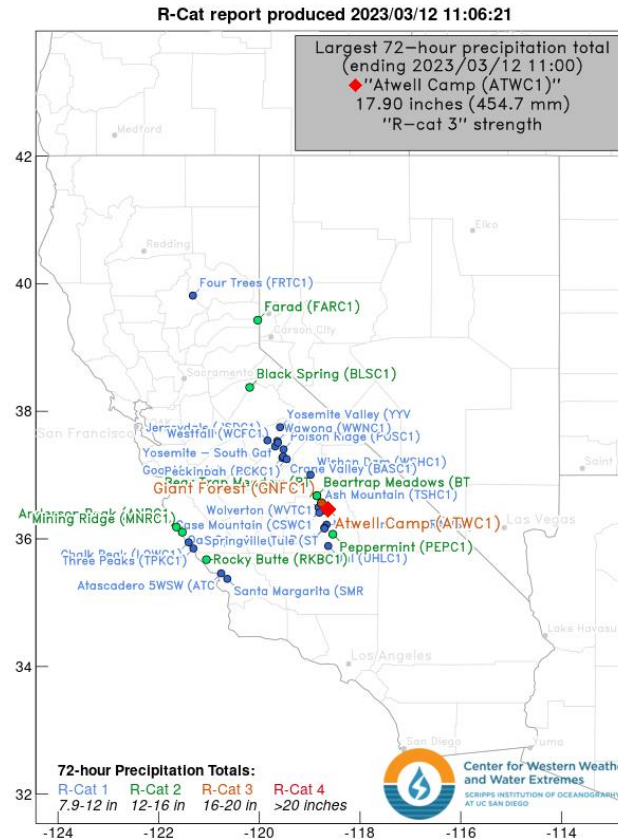
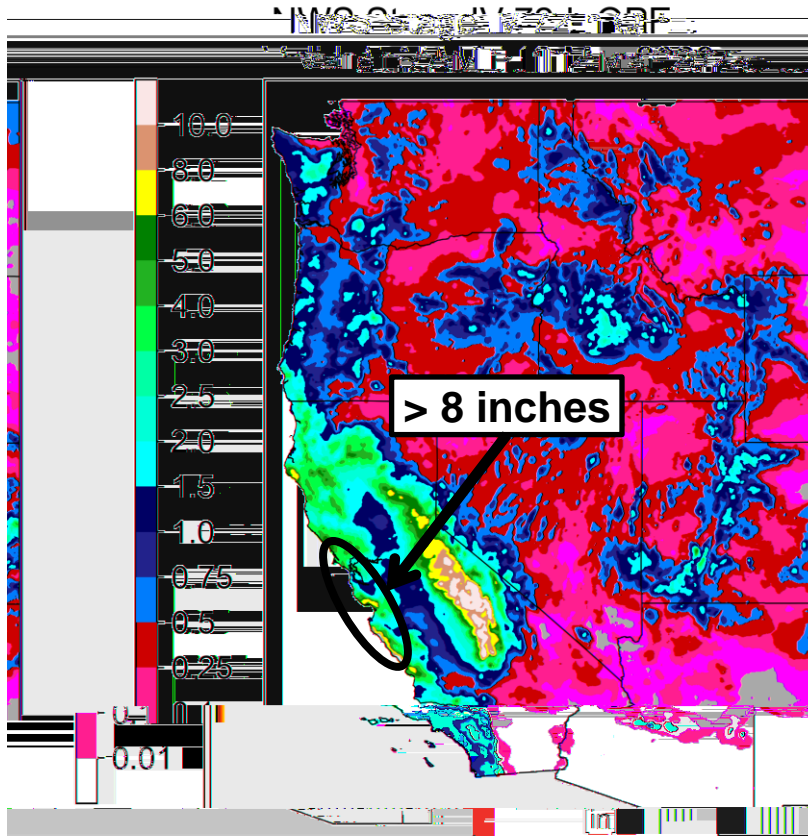


*Forecast objects shaded (unmatched objects in gray)
Observed objects contoured (unmatched objects in black)
Objects defined based on $IVT > 250 \text{ kg m}^{-1} \text{ s}^{-1}$*

- Using the Method for Object-Based Diagnostic Evaluation (MODE) with a $500 \text{ kg m}^{-1} \text{ s}^{-1}$ IVT threshold shows the location of the core of the second AR in Southern California was decently forecasted by the GFS at a 48-hour lead time. However, the forecast had the 500-unit threshold further east and already making landfall. In addition, the 500-unit threshold also extended further west at the tail of the AR with a slight orientation shift towards the middle of the AR
- Examination of the 96-hour GFS forecast shows the head of the AR was misaligned with the analysis and extended northward with landfall over Central California
- At the 144-hour lead time there was a small sliver of the 500-unit IVT threshold along the southern edge of the analysis object

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Observed Precipitation (First AR)

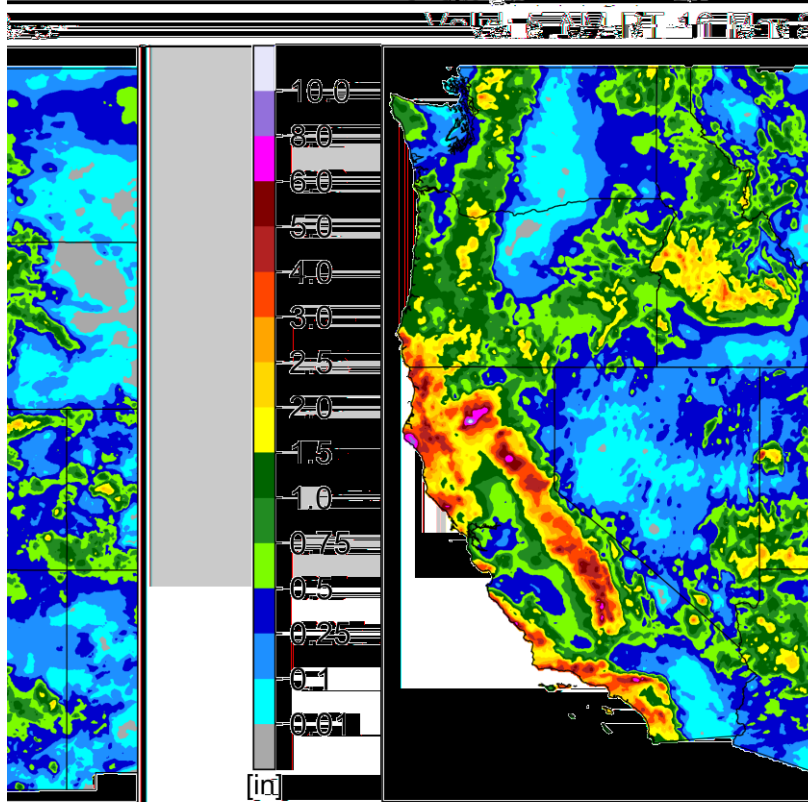


- The first AR produced more than 8 inches of precipitation in portions of the Central/Southern Sierra Nevada and Big Sur Coast
- Several stations in these areas recorded an R-Cat 2 event (> 12 inches in a 72-hour period), and two stations (Giant Forest and Atwell Camp) recorded an R-Cat 3 event (> 16 inches in a 72-hour period)
- An estimated more than 6 feet of snow fell in the highest elevations of the Central and Southern Sierra Nevada
- The warm nature of this storm limited snowfall accumulations below 8,000 feet

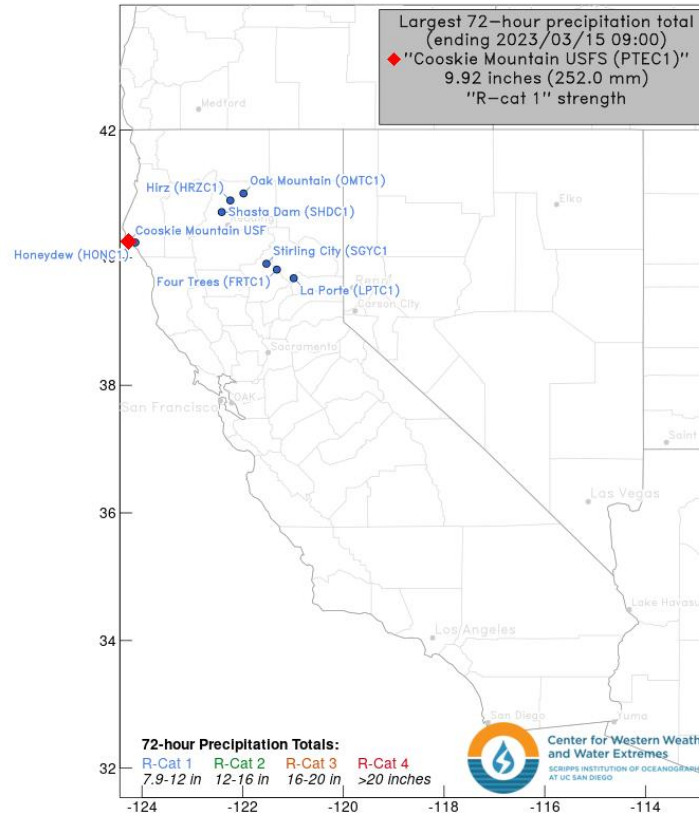
CW3E Event Summary: 9–15 March 2023

Observed Precipitation (Second AR)

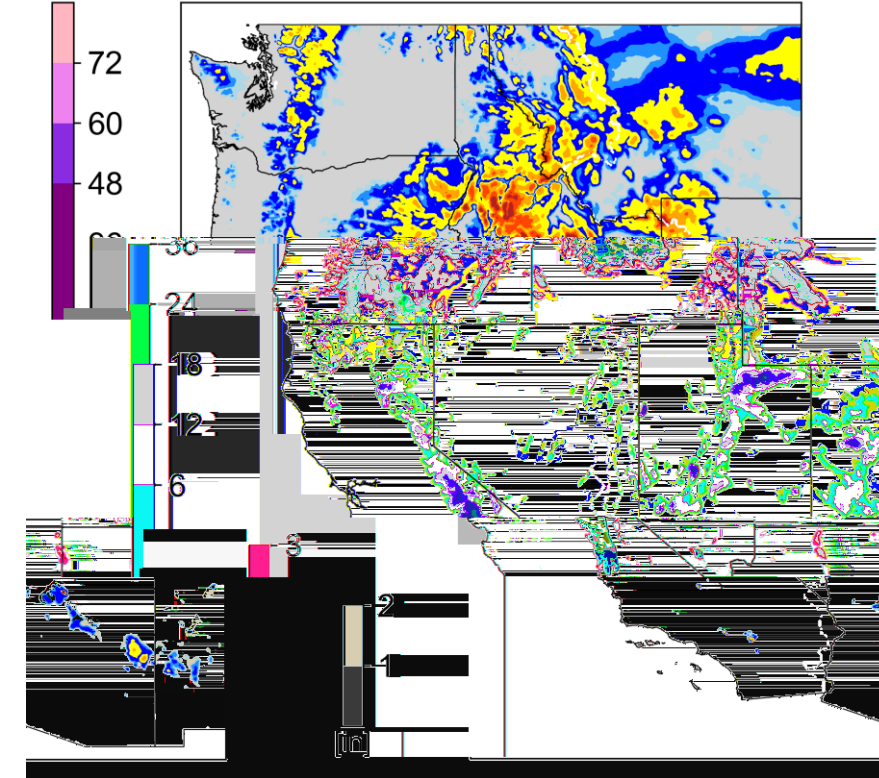
NWS Stage IV 72-h QPF



R-Cat report produced 2023/03/15 09:52:21



NWS 72-h Snowfall Analysis
Valid: 5 AM PT 16 Mar 2023

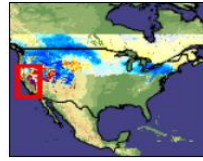
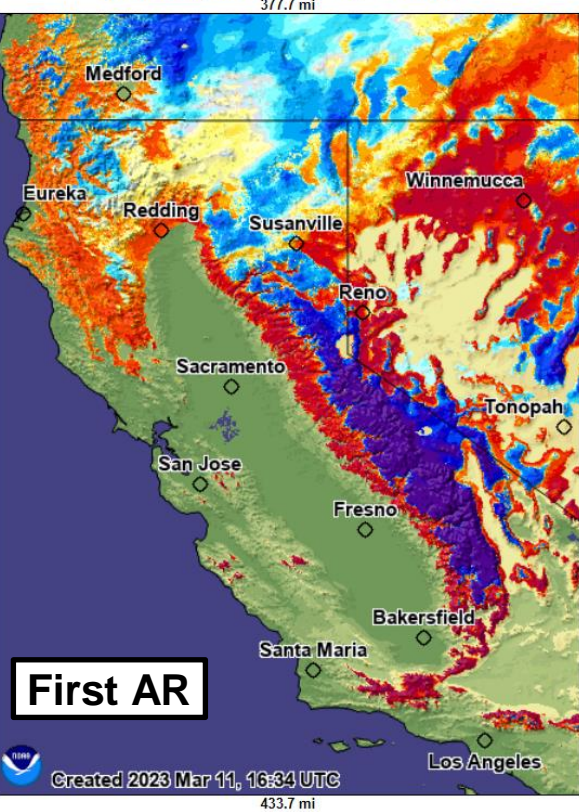


- The second AR produced 4–8 inches of precipitation in portions of the California Coast Ranges, southern Cascades, Sierra Nevada, and Transverse Ranges, and 2–4 inches of precipitation along the coast of southern California
- Inland penetration of this AR resulted in widespread precipitation amounts of 0.5–2 inches in the Lower Colorado Basin
- An estimated 1–3 feet of snow fell in the highest elevations of the Central and Southern Sierra Nevada
- High freezing levels once again limited snowfall accumulations below 8,000 feet

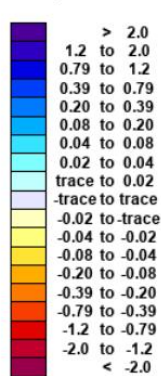
CW3E Event Summary: 9–15 March 2023

Changes in Snowpack

Change in Modeled Snow Water Equivalent during 24h preceding 2023 March 11, 12:00 UTC

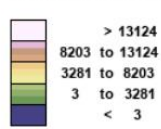


Inches of water equivalent

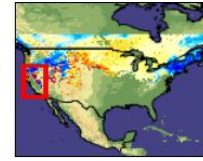
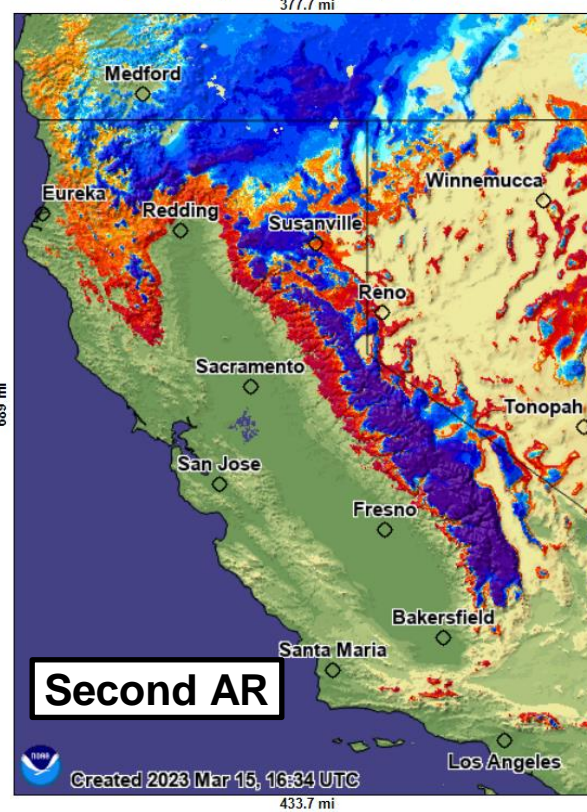


Not Estimated

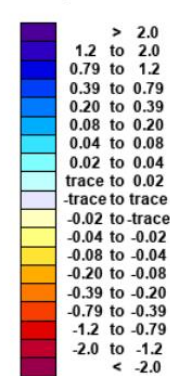
Elevation in feet



Change in Modeled Snow Water Equivalent during 24h preceding 2023 March 15, 12:00 UTC

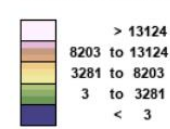


Inches of water equivalent

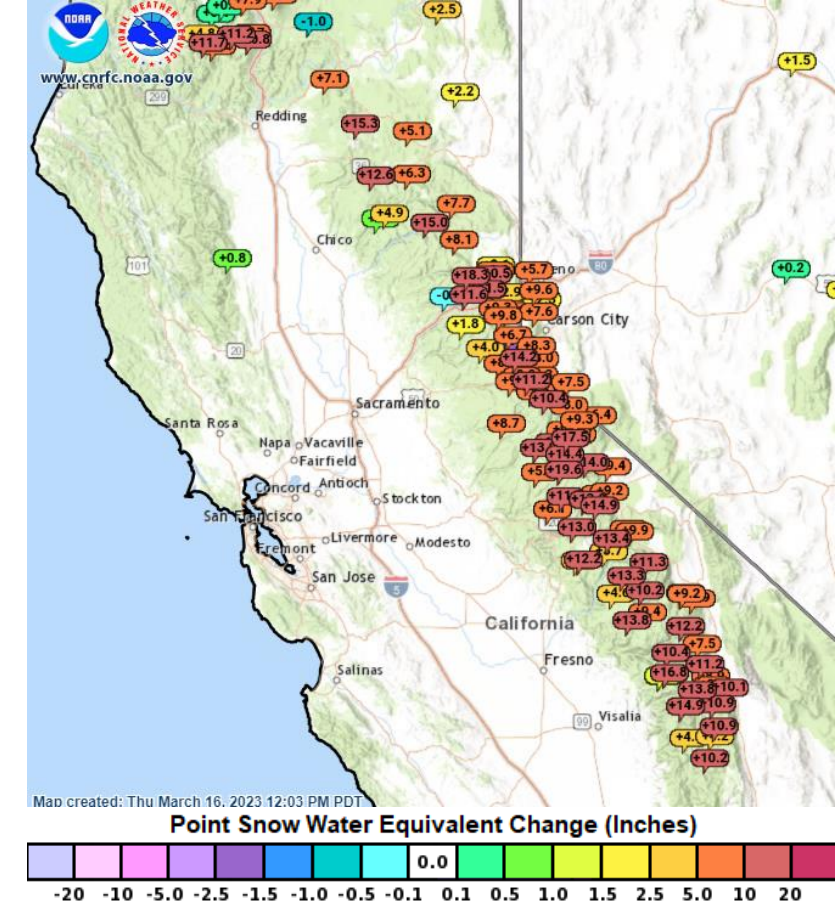


Not Estimated

Elevation in feet



7-day SWE Change: Valid 5 AM PT 16 Mar

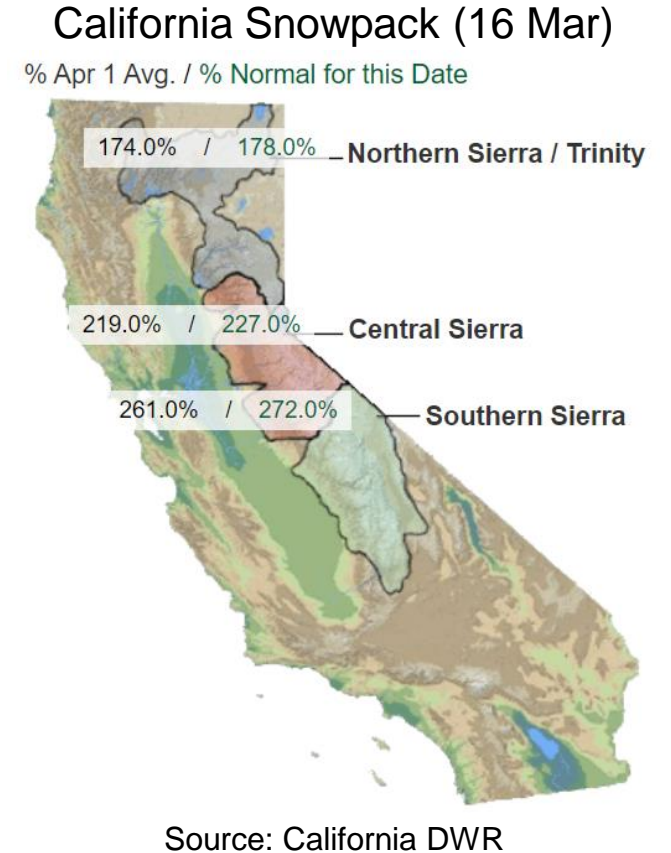
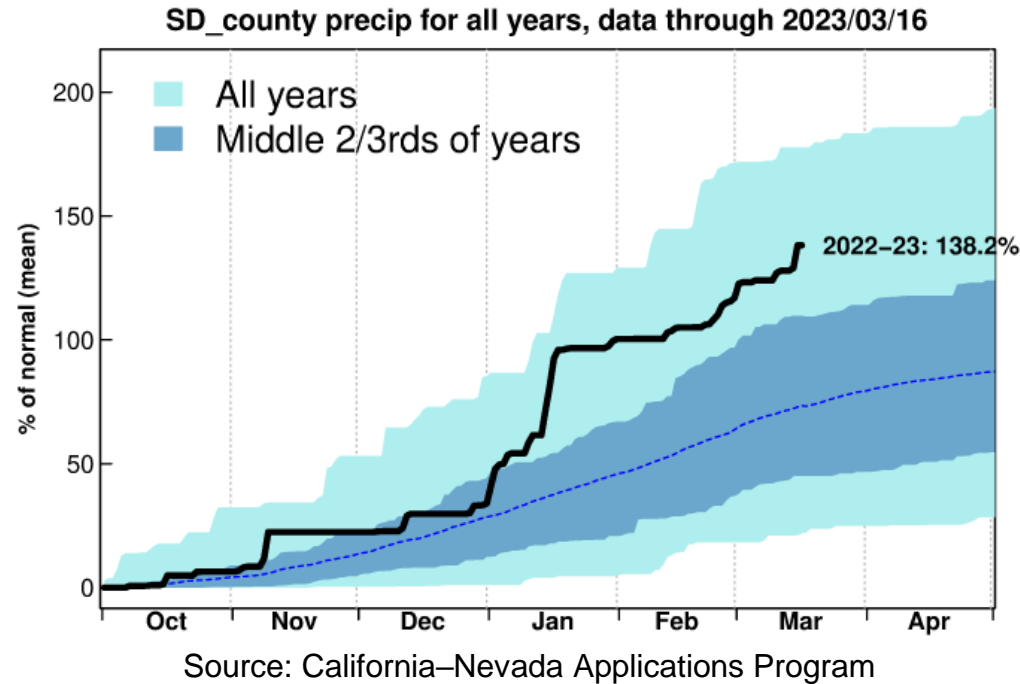
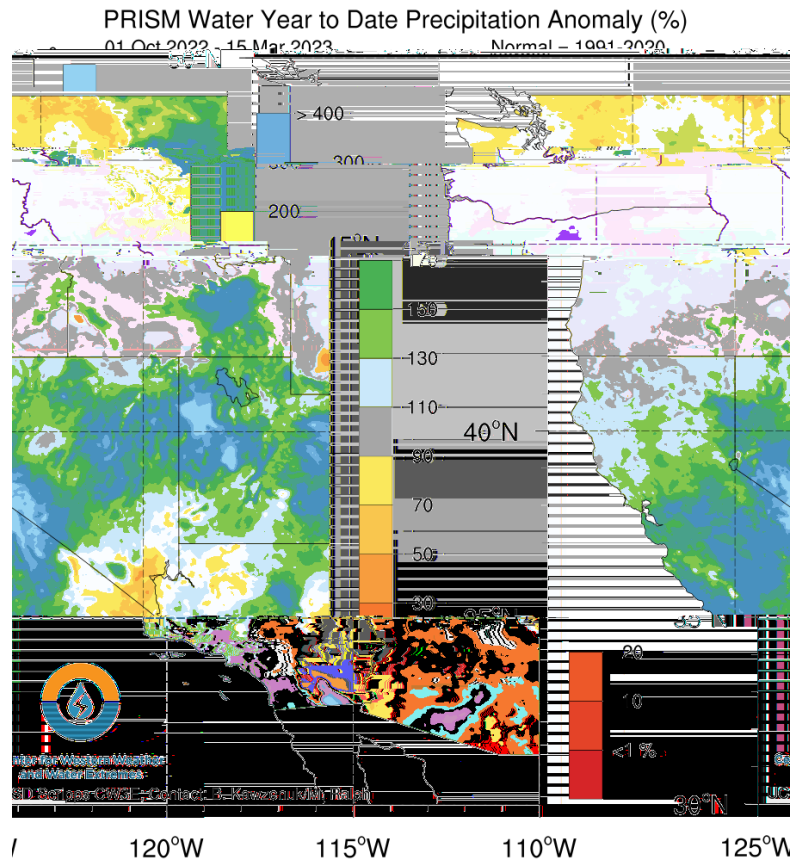


Source: National Operational Hydrologic Remote Sensing Center

- The National Operational Hydrologic Remote Sensing Center (NOHRSC) is showing large estimated decreases in snowpack below 5,000 feet and increases in snowpack above 7,000 feet in the Sierra Nevada during both ARs
- Many California cooperative snow survey stations located above 7,000 feet have recorded 7-day SWE increases > 12 inches

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Water Year 2023 Precipitation and Snowpack



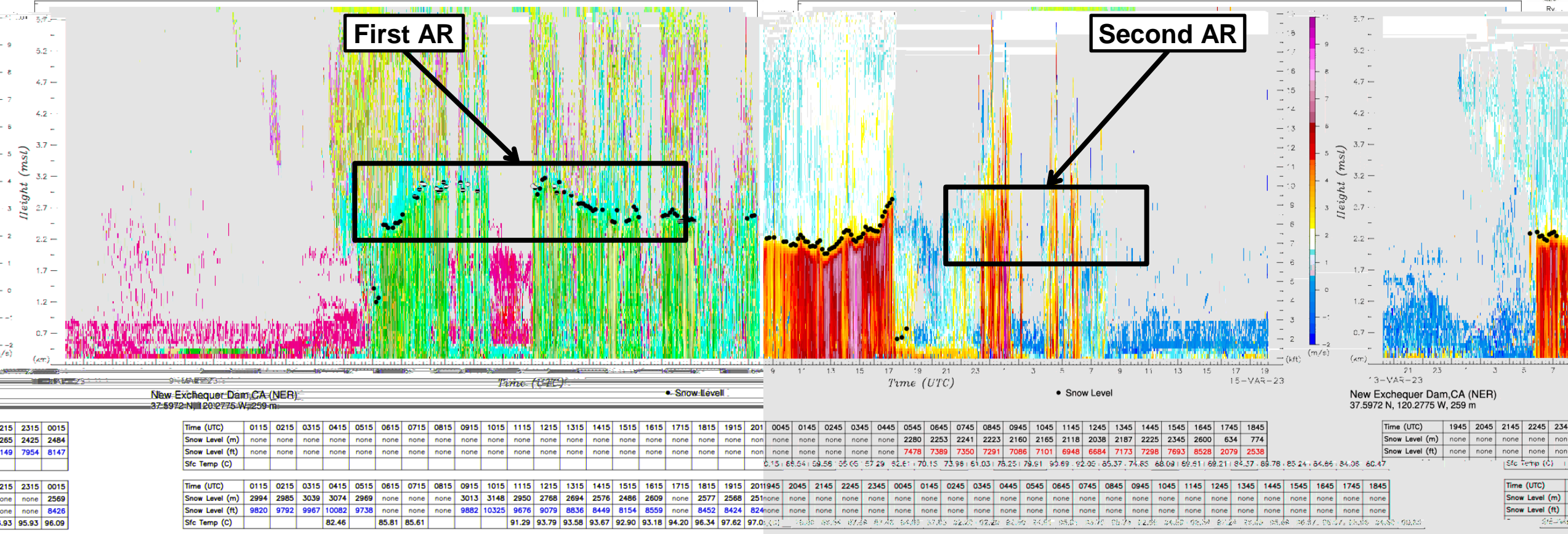
- As of 15 Mar, water-year-to-date precipitation is more > 150% of normal across much of Central California and coastal Southern California
- San Diego County has already received 138% of its normal total water year precipitation
- Current snowpack is 272% of normal in the Southern Sierra Nevada and 223% of normal statewide for this time of year

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Snow Level Radar: New Exchequer Dam

NOAA Physical Sciences Laboratory
FMCW S-band Snow Level Radar

NOAA Physical Sciences Laboratory
FMCW S-band Snow Level Radar



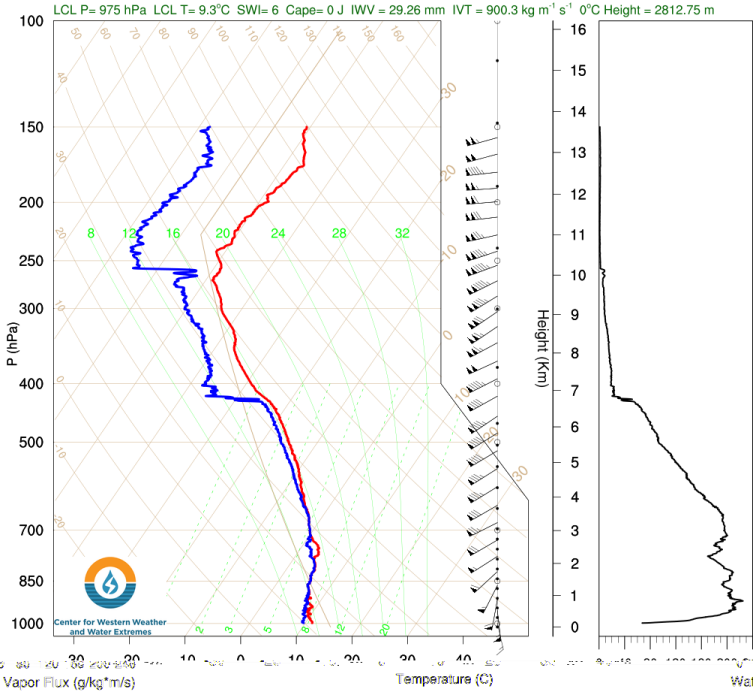
- Both ARs were associated with warm, subtropical air masses and very high snow levels (> 7,000 feet)
- The S-band radar at New Exchequer Dam (Lake McClure) estimated snow levels as high as 10,300 feet during the first AR and as high as 8,500 feet during the second AR

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CW3E Soundings (First AR)

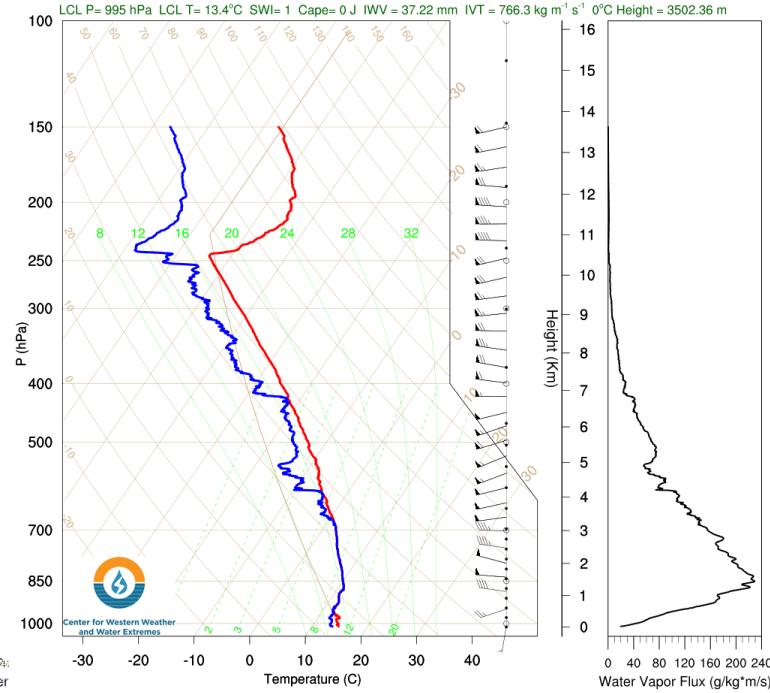
Marysville (39.2°N, 121.5°W)

USYUB: 09:00 UTC 03/10/2023

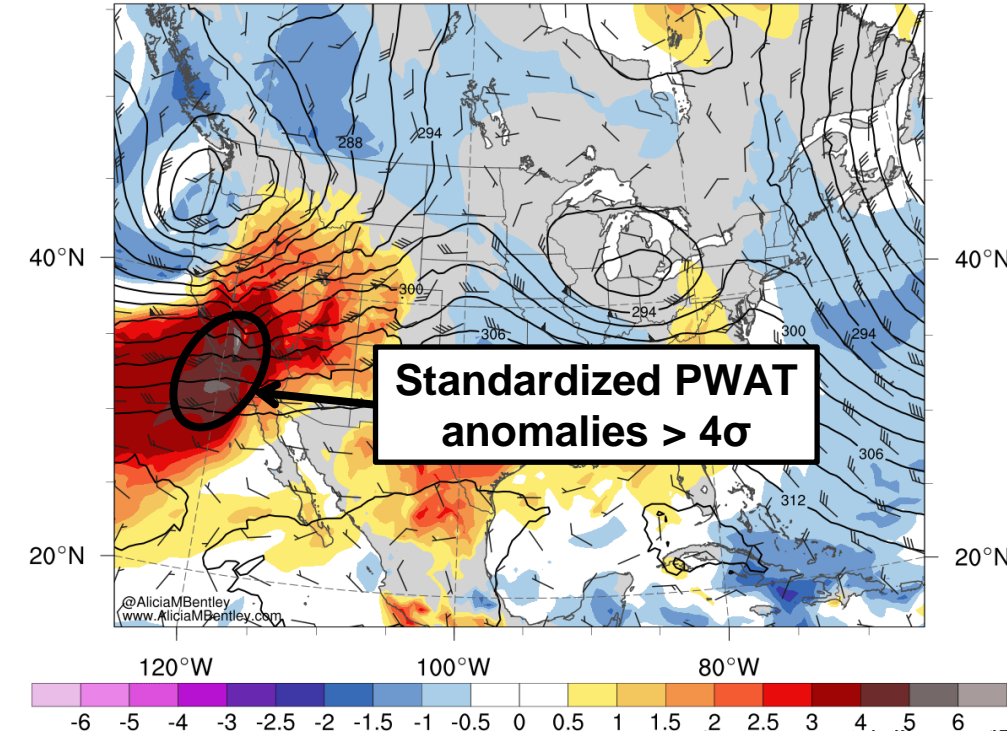


Catalina Island (33.4°N, 118.4°W)

USCAT: 00:00 UTC 03/11/2023



700-hPa geo. height (black, dam), wind (barbs, kt), standardized precip. water anomaly (shaded, sigma)
Initialized: 1200 UTC 10 Mar 2023 | Forecast hour: 0 | Valid: 1200 UTC 10 Mar 2023



Source: Alicia Bentley's Real-Time GFS Maps

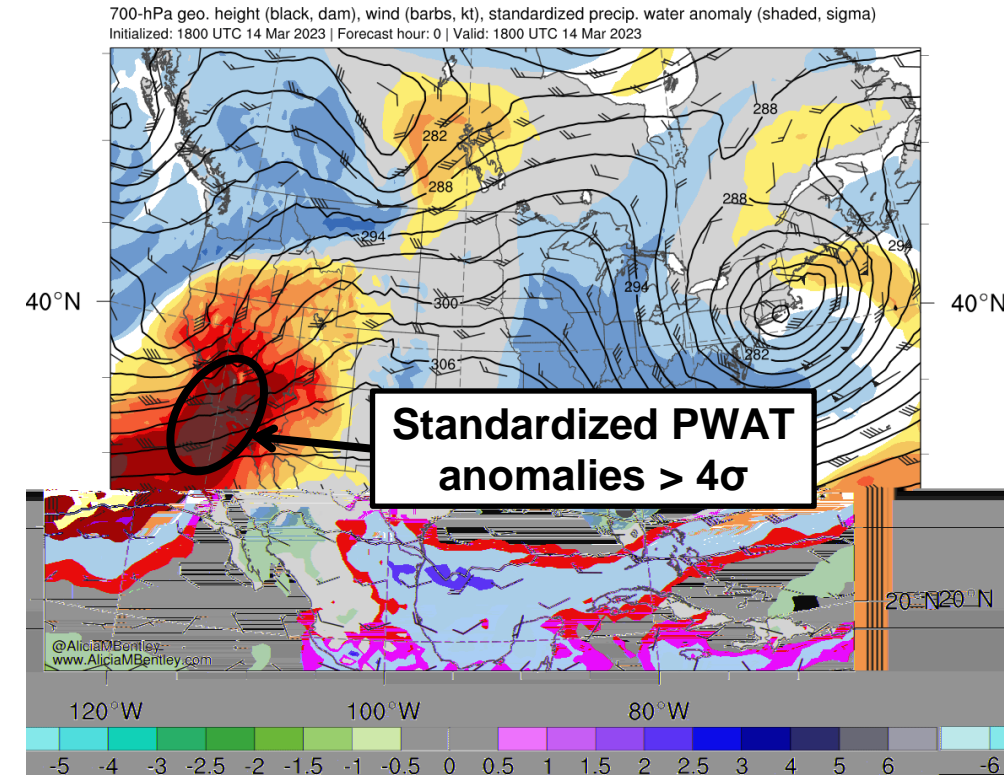
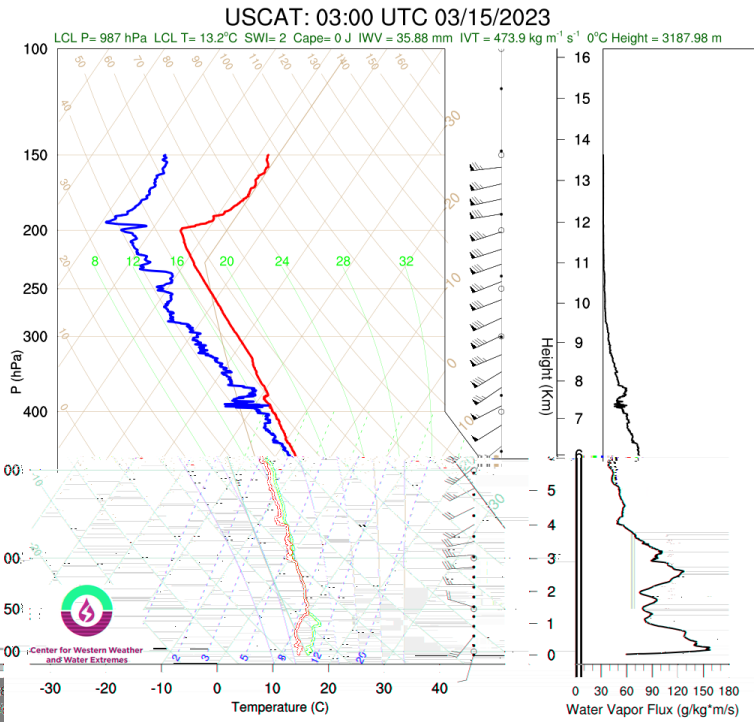
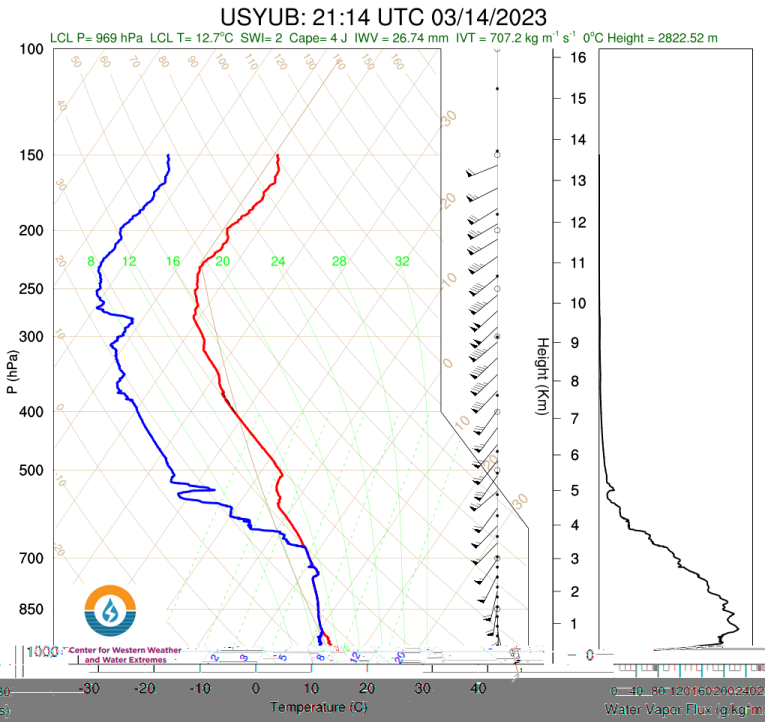
- CW3E teams launched radiosondes during both AR events at Bodega Bay (USBOD), Marysville (USYUB), Catalina Island (USCAT), and Seven Oaks Dam (USSOD)
- These soundings observed a max IVT of 900.3 kg m⁻¹ s⁻¹ at USYUB and a max IWV of 37.22 mm at USCAT during the first AR
- The strongest water vapor flux at USYUB was observed at an altitude of ~900 meters, just above a Sierra barrier jet (SBJ)
- The USCAT sounding shows a sharp peak in water vapor flux ~1500 meters above sea level
- GFS analyses show precipitable water values as high as 4–6 standard deviations above climatology during the first AR

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CW3E Soundings (Second AR)

Marysville (39.2°N, 121.5°W)

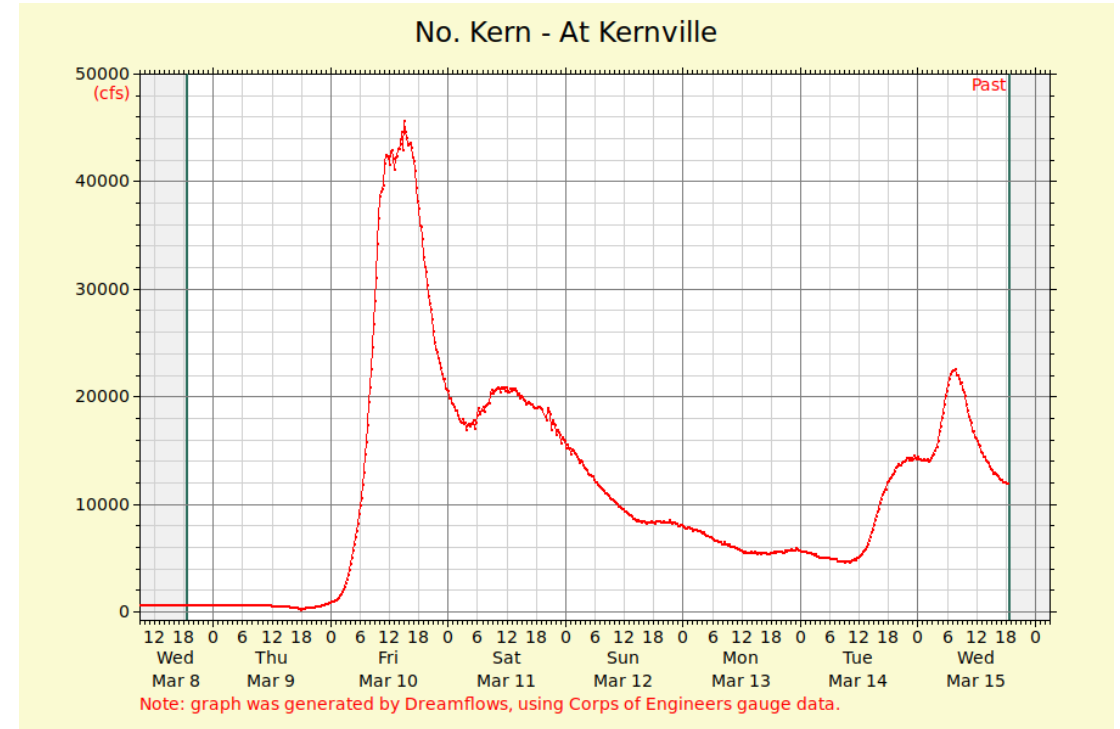
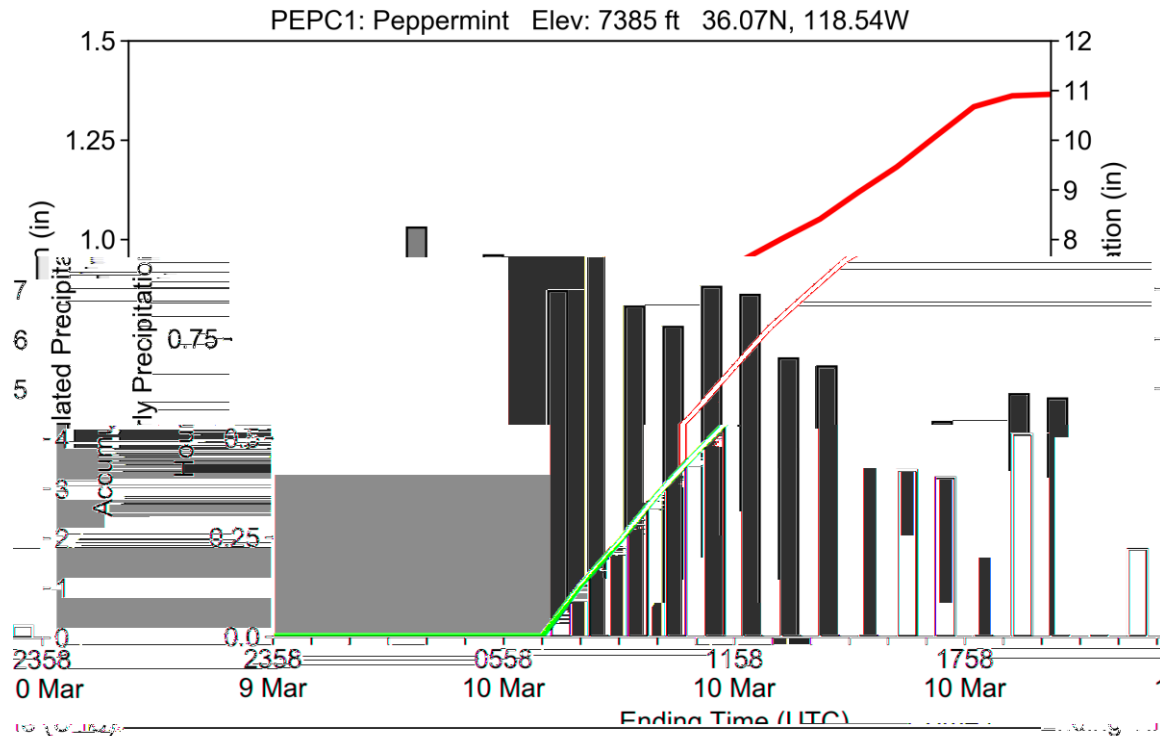
Catalina Island (33.4°N, 118.4°W)



- Soundings from the second AR observed a max IVT of 707.2 kg m⁻¹ s⁻¹ at USYUB and a max IWV of 35.88 mm at USCAT
- Similar to the first AR, the strongest water vapor flux at USYUB was observed at an altitude of ~900 meters, just above a Sierra barrier jet (SBJ)
- The USCAT sounding shows a sharp peak in water vapor flux just above the surface and nearly saturated conditions throughout the entire troposphere
- GFS analyses show precipitable water values as high as 4 standard deviations above climatology during the second AR

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Observed Precipitation and Streamflow (10 Mar)



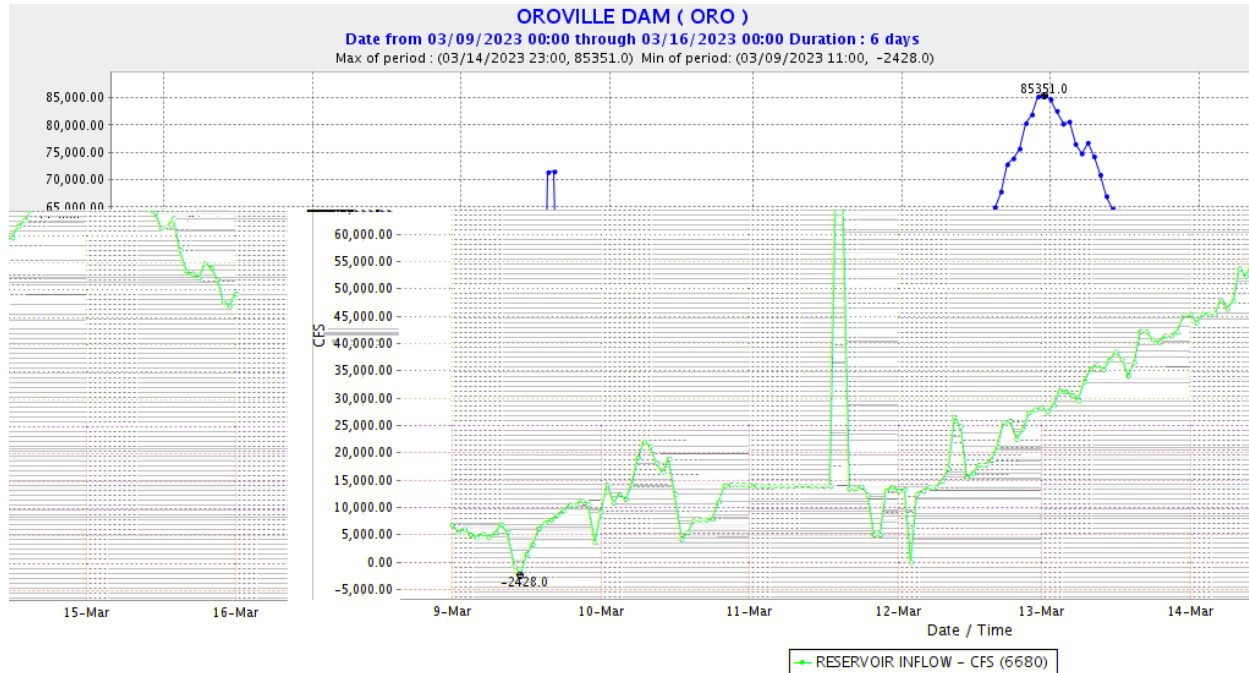
Source: Chris Shackleton, Dreamflows

- The first AR produced very heavy precipitation in the Southern Sierra Nevada on 10 Mar
- Peppermint, located just west of the Kern River, recorded precipitation rates > 0.5 inches/hour for 9 consecutive hours and 10.92 inches of total precipitation in the 24-hour period ending 4 PM PT 10 Mar
- Sustained moderate-intensity rainfall and melting of existing snowpack caused rapid increases in streamflow on the Kern River
- The Kern River at Kernville reached a peak discharge of nearly 46,000 cfs on 10 Mar, the highest peak discharge at this stream gage since Jan 1997

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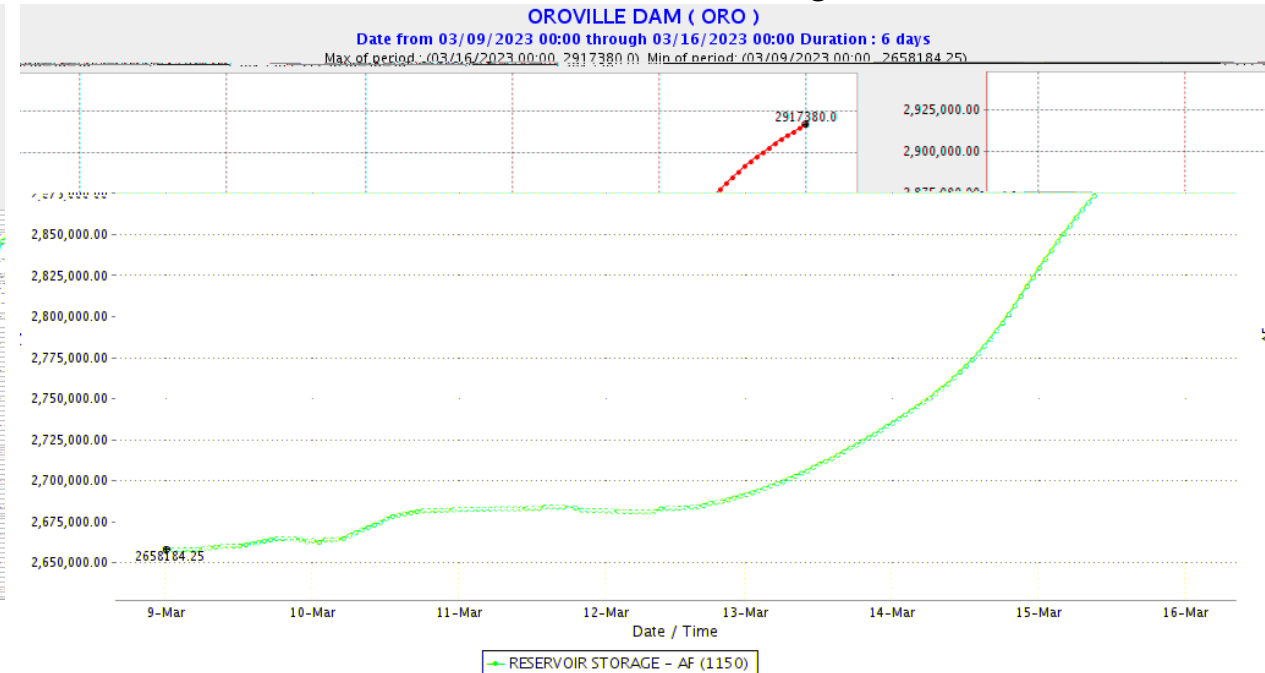
Reservoir Operations

Oroville Dam: Inflow



Source: California Department of Water Resources

Oroville Dam: Storage

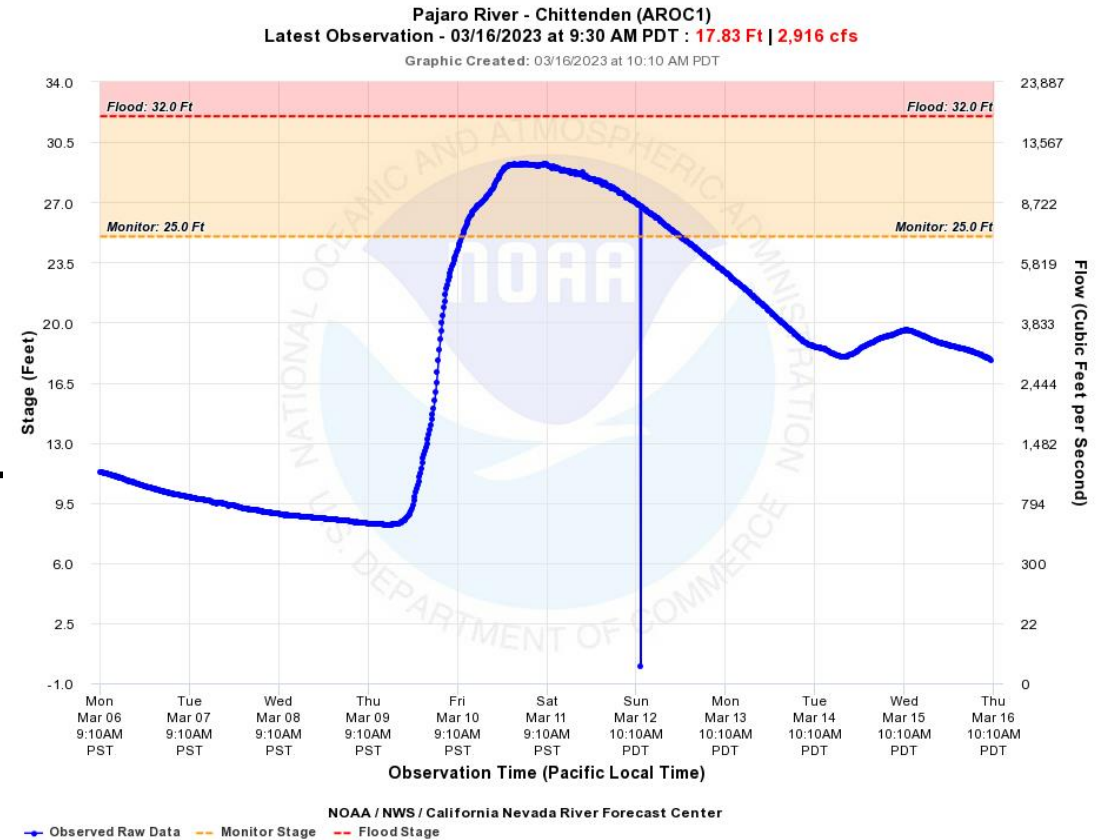


Source: California Department of Water Resources

- Heavy rain and snowmelt in the Feather River system led to large increases in inflow at Lake Oroville, especially during the second AR, with peak hourly inflow reaching 85,000 cfs
- (Not shown) Releases at Lake Oroville increased to 14,000–16,000 cfs following the first AR landfall, and have been as high as 21,000 cfs following the second AR landfall
- Over the past 7 days, storage at Lake Oroville has increased by nearly 260,000 AF and is now at 82% of capacity (~3.5 million AF)

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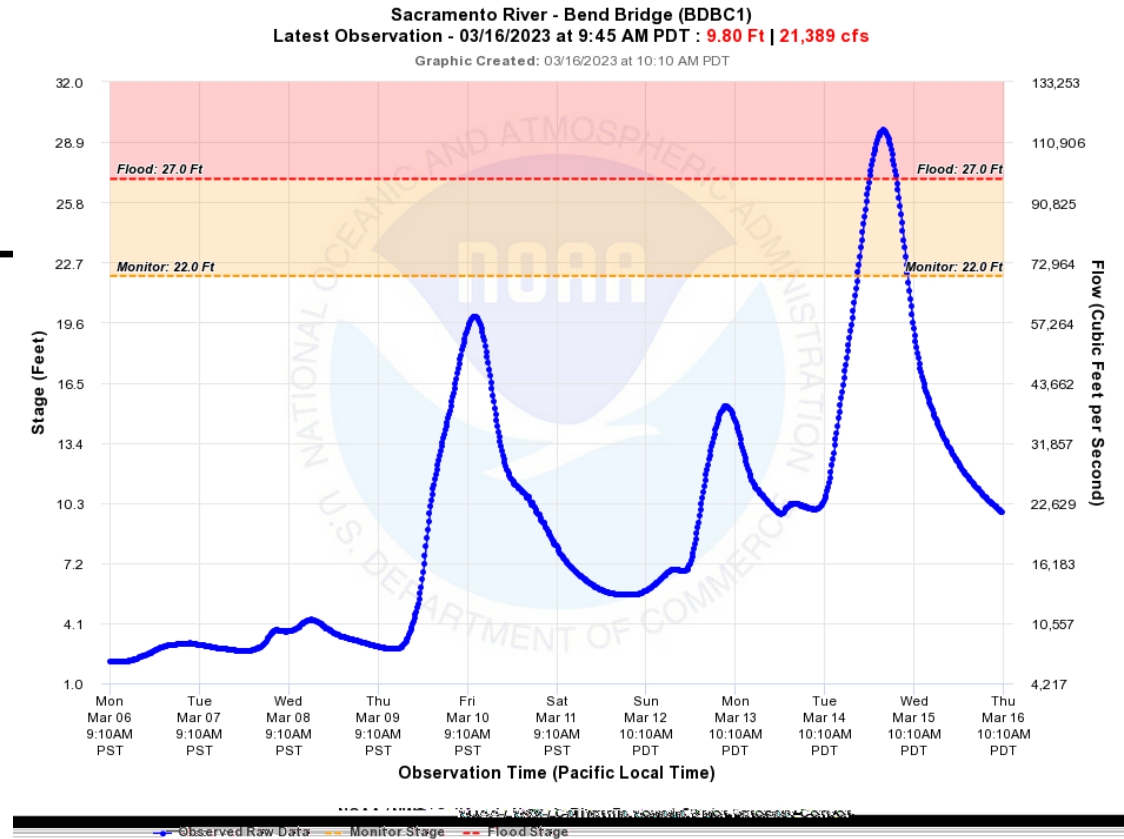
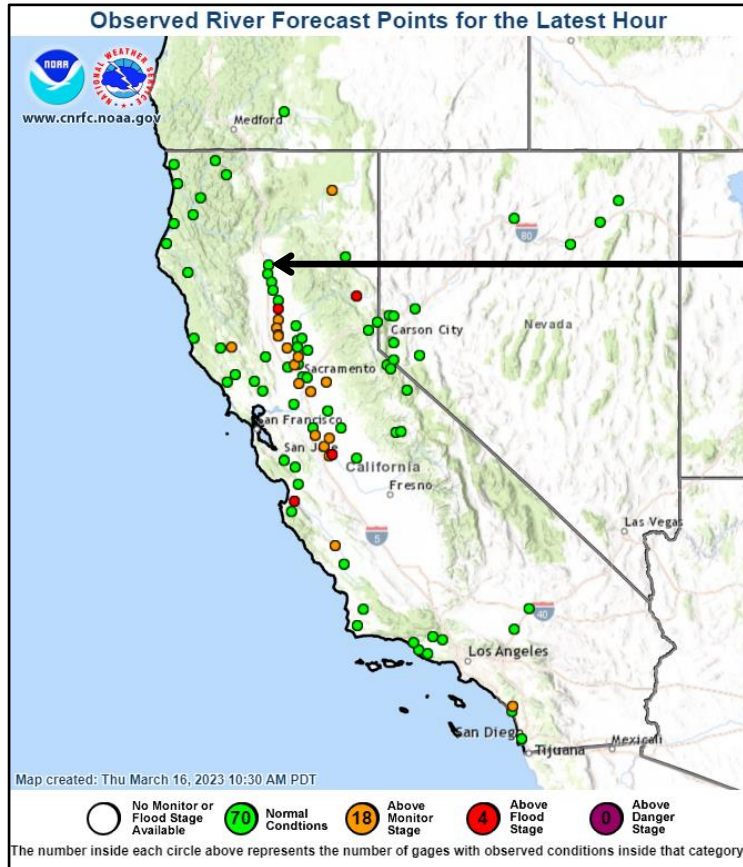
Hydrologic Impacts



- Heavy rain during the first AR triggered a rapid streamflow response on the Pajaro River in northern Monterey County
- The Pajaro River at Chittenden rose more than 19 feet in a 24-hour period, eventually cresting above monitor/action stage
- The peak stage of 29.22 feet was the 7th highest peak stage at this location since records began in 1938
- High river levels caused a levee breach and triggered evacuation orders in Pajaro, CA

CW3E Event Summary: 9–15 March 2023

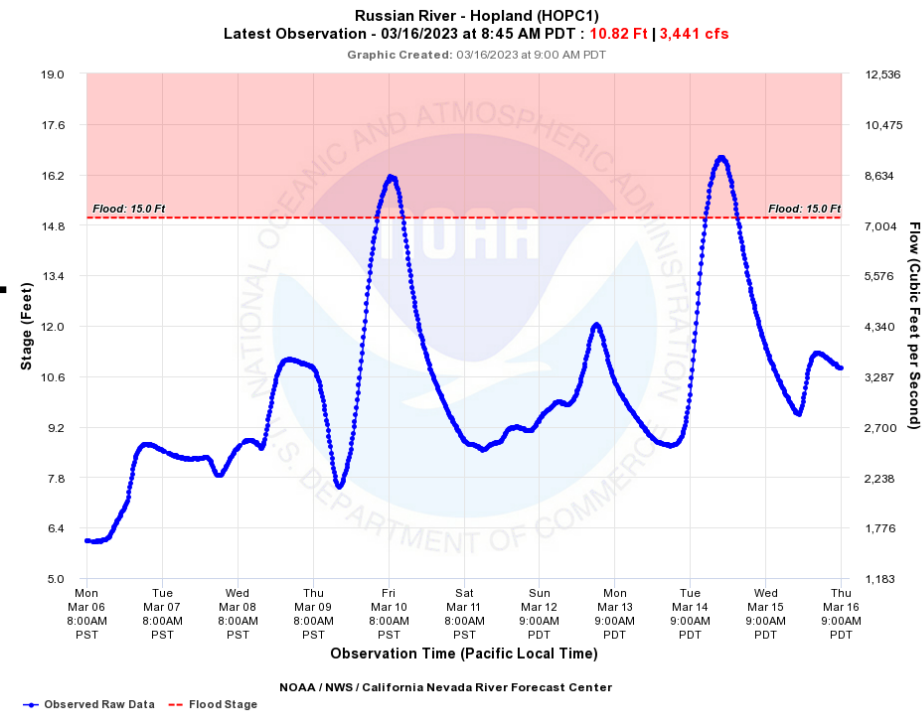
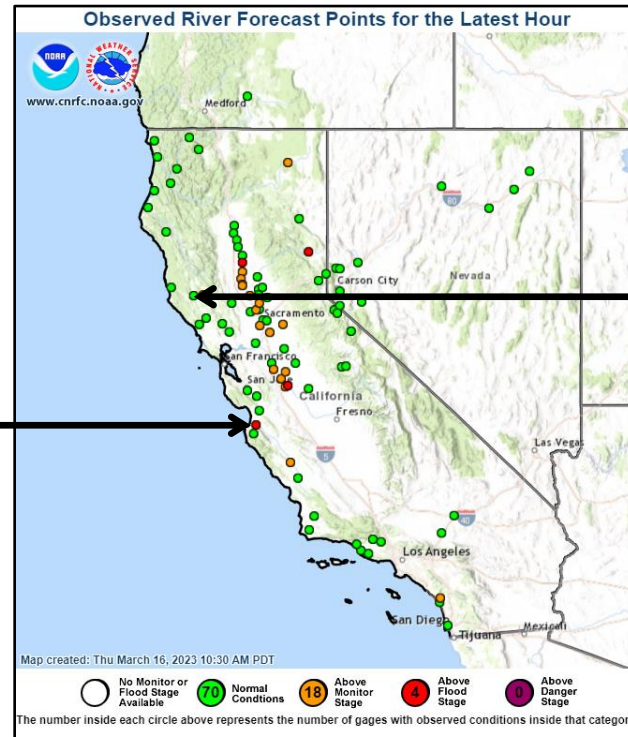
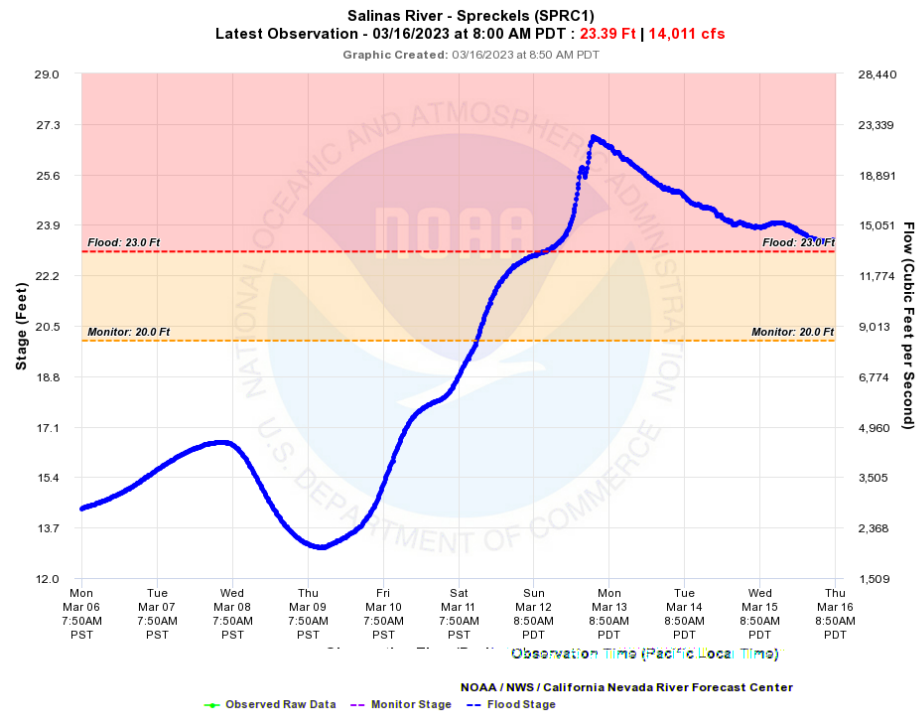
Hydrologic Impacts



- Heavy rain during the second AR caused flooding along the Sacramento River
- The Sacramento River above Bend Bridge reached moderate flood stage (29.5 feet) on 15 Mar
- The peak stage of 29.53 feet was the highest peak stage observed at this location since Dec 2005

CW3E Event Summary: 9–15 March 2023

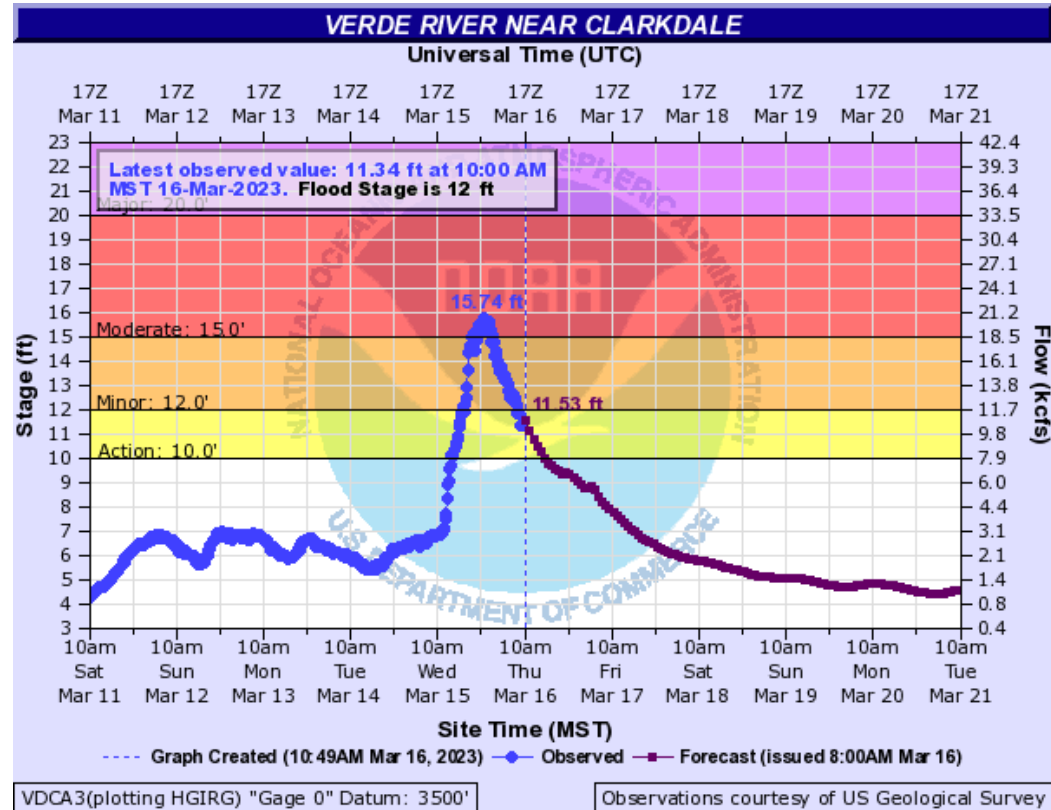
Hydrologic Impacts



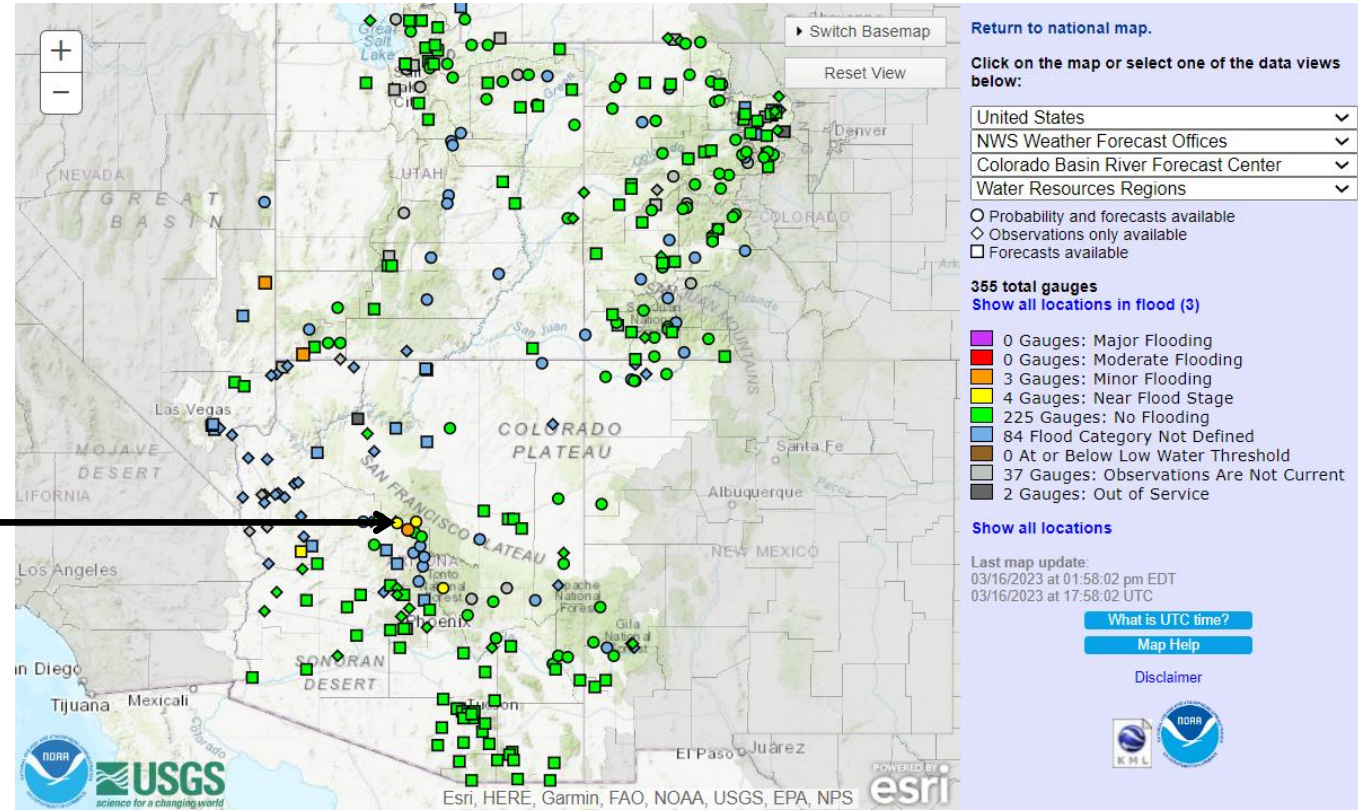
- The Salinas River at Spreckels rose above flood stage on 13 Mar and crested at 26.9 feet, the 2nd highest peak stage recorded at this location since continuous records began in 1929
- The Russian River at Hopland rose above flood stage twice over the past 6 days, peaking at 16.1 feet on 10 Mar, and 16.7 feet on 14 Mar

CW3E Event Summary: 9–15 March 2023

Hydrologic Impacts



Source: NOAA/NWS Advanced Hydrologic Prediction Service



Source: NOAA/NWS Advanced Hydrologic Prediction Service

- Heavy rain and snowmelt also led to flooding in portions of the Lower Colorado River Basin
- The Verde River near Clarkdale, AZ, reached moderate flood stage (15.0 feet) on 15 Mar
- The peak stage of 15.74 feet was the 7th highest peak stage observed at this location since continuous records began in 1965

CW3E Event Summary: 9–15 March 2023

Impacts Photos



Levee break on the Pajaro River
California DWR Twitter



Flooding in Pajaro, CA on 11 March
Josh Edelson / AFP



Major Flooding Along the Kern River on 10 March
Kern Valley Search and Rescue Facebook page

- A levee break along the Pajaro River, ~60 miles Southeast of San Francisco, caused major flooding in agricultural areas
- More than 8,500 people were forced to evacuate, and around 50 people had to be rescued from the flood
- Heavy precipitation along the Kern River caused major flooding and evacuations in Kernville, CA.

CW3E Event Summary: 9–15 March 2023

Impacts Photos



Homes buried under feet of snow in Mammoth
Mario Tama/Getty Images



Snowpack depth near Central Sierra Snow Lab
Karl Mondon via Twitter



Home in Alpine Meadows
Karl Mondon / Bay Area News Group

- Even though these latest ARs were much warmer than previous storms this year, mountain towns like Mammoth Lakes, and Lake Tahoe continue to see snow piling up
- According to the Central Sierra Snow Lab Facebook page, as of 15 Mar the lab has accumulated 668 inches of snow since the beginning of the water year, just 3 inches shy of the 1982–1983 record
- Homes in some locations have 10+ feet of snow on roofs and decks which dramatically increases the risk of collapse

CW3E Event Summary: 9–15 March 2023

Impacts Photos



EF-1 tornado in Tuolumne County
www.cbsnews.com



Tornado damage at Woods Creek
Mobile Home Park in Jamestown
Kim Sutton via www.cbsnews.com



Tornado damage to a 17-stall horse barn
kcranews Twitter

- NWS Sacramento confirmed that an EF-1 tornado touched down in Tuolumne County about 6 miles west of Tuttletown
- According to the Modesto Bee, 'Its estimated peak winds were 90 mph. It traveled a path of about 0.8 miles and had a maximum width of about 100 yards. It was on the ground only about one minute, starting about 2:52 p.m.' on 11 March
- No injuries were reported but high winds caused damage to a mobile home park, and knocked down several trees and power poles

CW3E Event Summary: 9–15 March 2023

Impacts Photos



Lake Oroville Spillway
www.resources.ca.gov

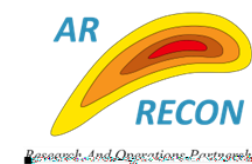


Folsom Dam Auxiliary Spillway
Ken James / California Department of Water Resources)

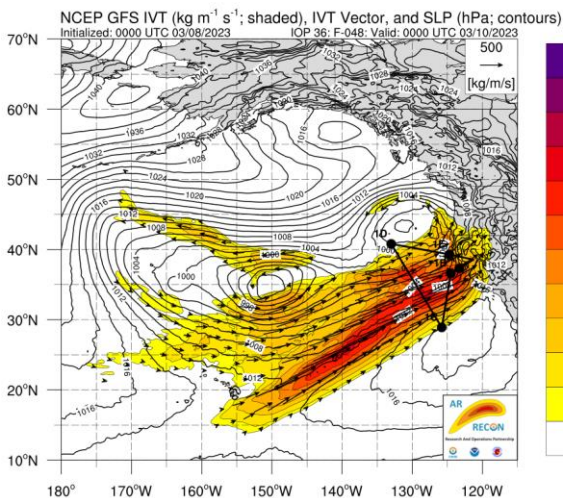
- The California Department of Water Resources began releasing water from the Lake Oroville Spillway ahead of the AR that made landfall on 10 March
- It was the first time the spillway had been used since April 2019 and only the second time since it was rebuilt after the 2017 spillway emergency
- Water was also released from Folsom Dam ahead of the storm

CW3E Event Summary: 9–15 March 2023

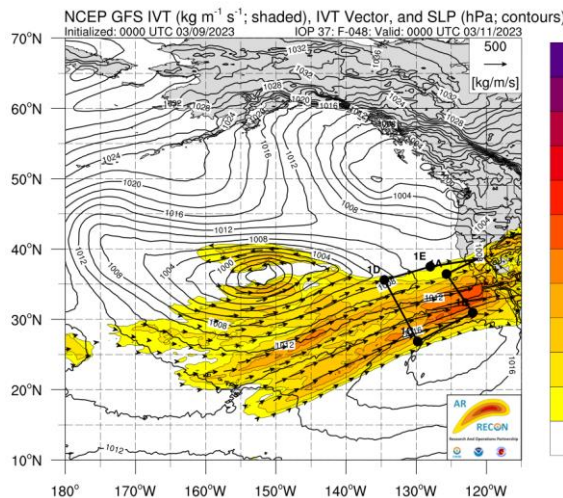
Atmospheric River Reconnaissance – Planned Missions



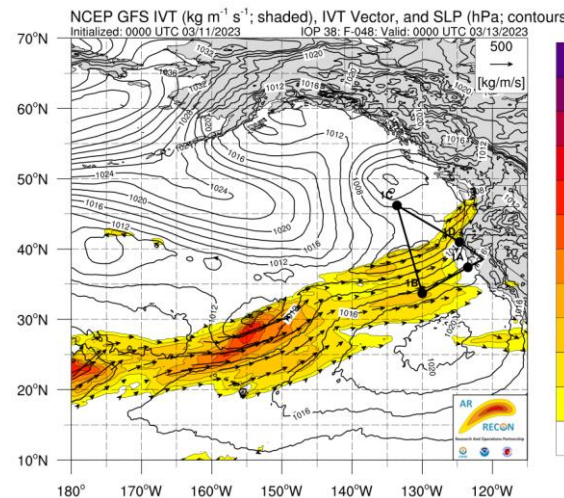
IOP36 – Centered at 00Z 10 Mar



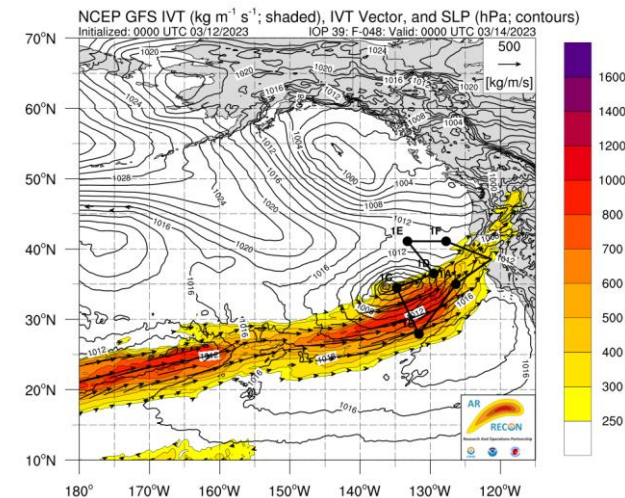
IOP37 – Centered at 00Z 11 Mar



IOP38 – Centered at 00Z 13 Mar



IOP39 – Centered at 00Z 14 Mar



- During this time period the 53rd Weather Reconnaissance Squadron continued to provide observational support over the North Pacific as part of CW3E's Atmospheric River Reconnaissance field campaign
- CW3E planned 4 IOPs (100 planned dropsondes) with a total of 98 successful dropsondes providing additional observations for global forecast models and collecting valuable data for future research
- IOP = Intensive Observation Period