

The image shows a vast, dry, and cracked lake bed in the foreground, with a small, isolated pool of water in the middle ground. In the background, there are rugged, brownish mountains under a clear sky. The overall scene conveys the severity of a drought.

Lessons Learned from the California Drought

Norman Miller
24 April 2015

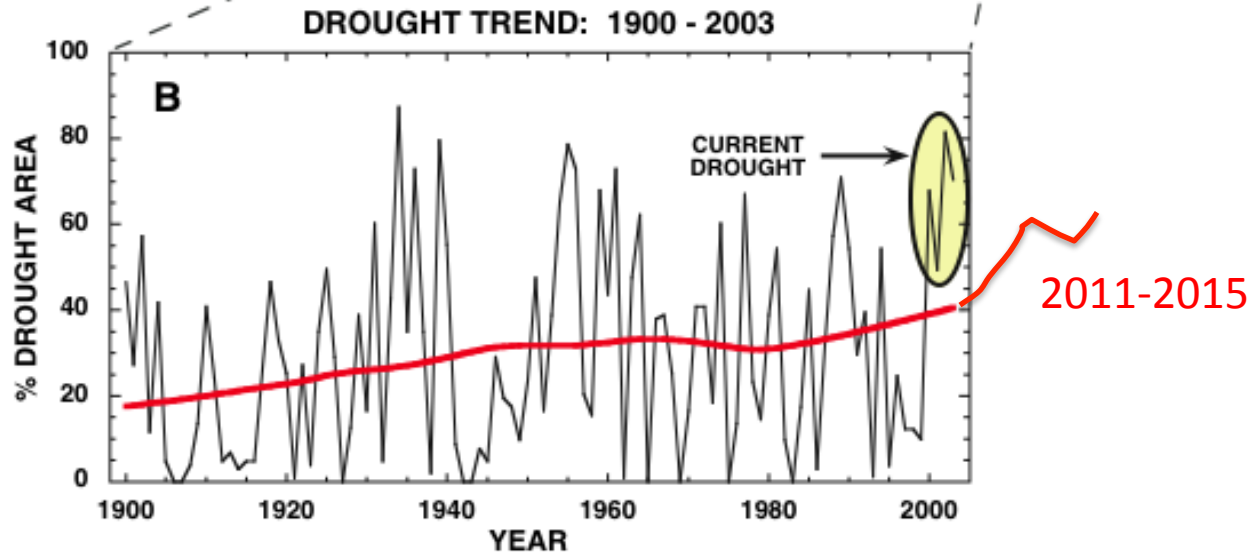
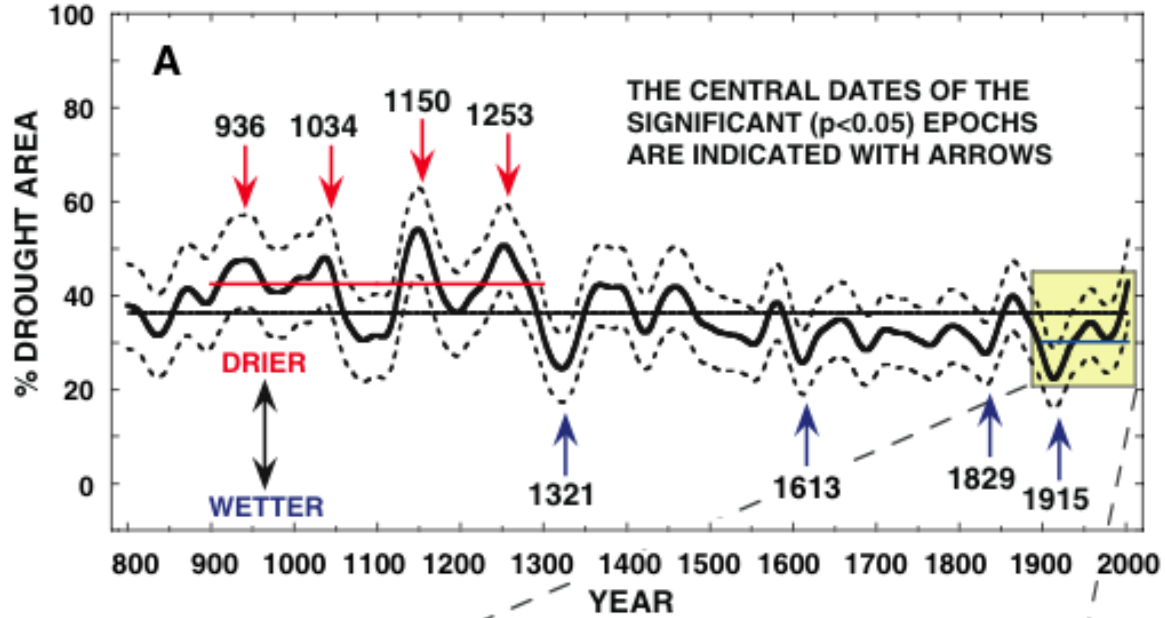
Outline

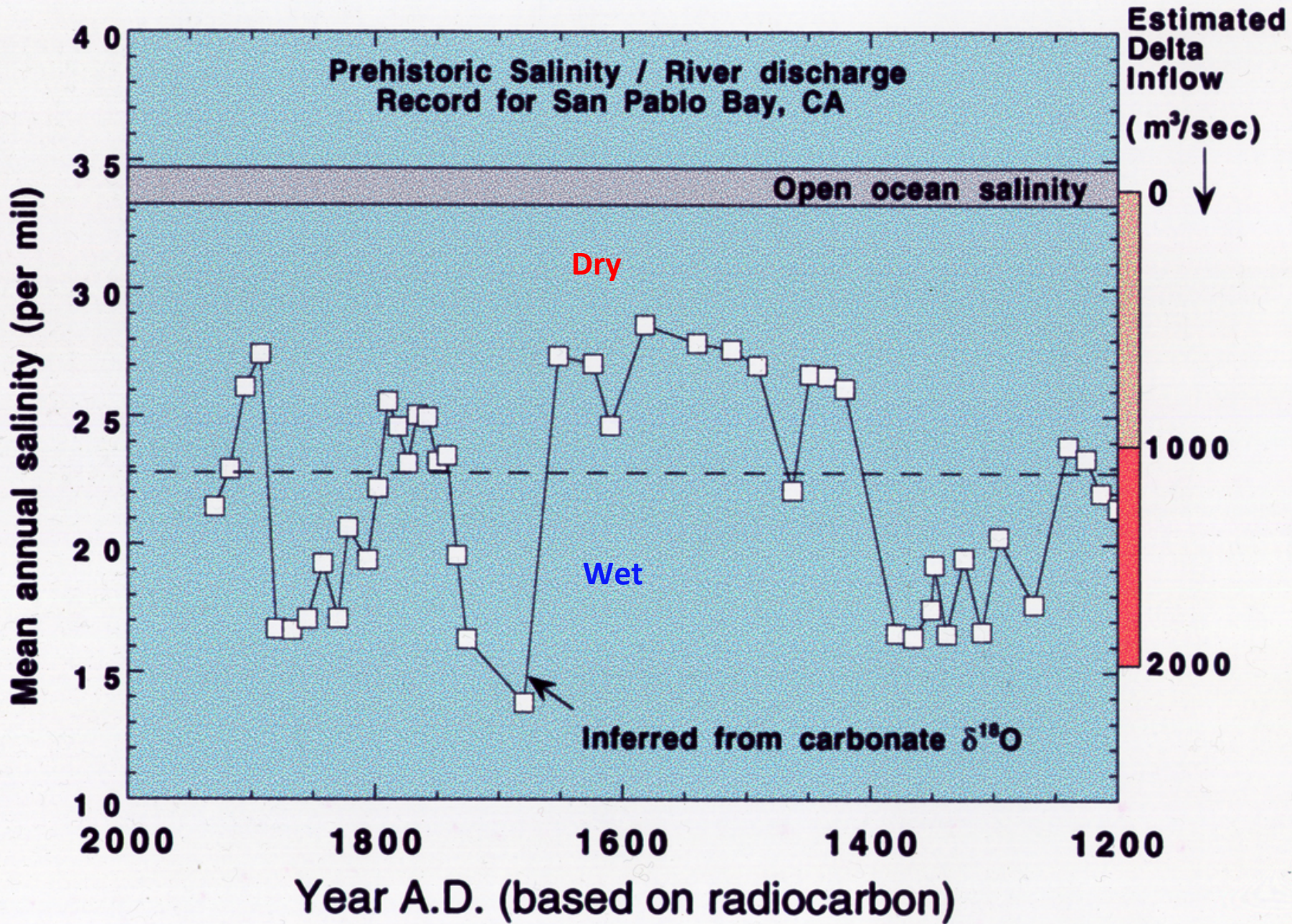
- **Background**
 - **Historic Droughts**
 - **Current Conditions**
 - **Eastern Pacific High Pressure**
- **Drought Mechanisms**
 - **Tropical Pacific Sea Surface Temperature**
 - **Return of the Resilient Ridge?**
- **Drought Breakers**
 - **Closed Low systems from the Northwest**
 - **Atmospheric Rivers from the Southwest**
- **Model-Based Drought Simulations**

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LONG-TERM CHANGES IN DROUGHT AREA IN THE WEST





Palmer Drought Severity Index

Balance between Precipitation and Evaporation as a function of Temperature

Palmer Classifications	
4.0 or more	extremely wet
3.0 to 3.99	very wet
2.0 to 2.99	moderately wet
1.0 to 1.99	slightly wet
0.5 to 0.99	incipient wet spell
0.49 to -0.49	near normal
-0.5 to -0.99	incipient dry spell
-1.0 to -1.99	mild drought
-2.0 to -2.99	moderate drought
-3.0 to -3.99	severe drought
-4.0 or less	extreme drought

**Current
Conditions**

< -5

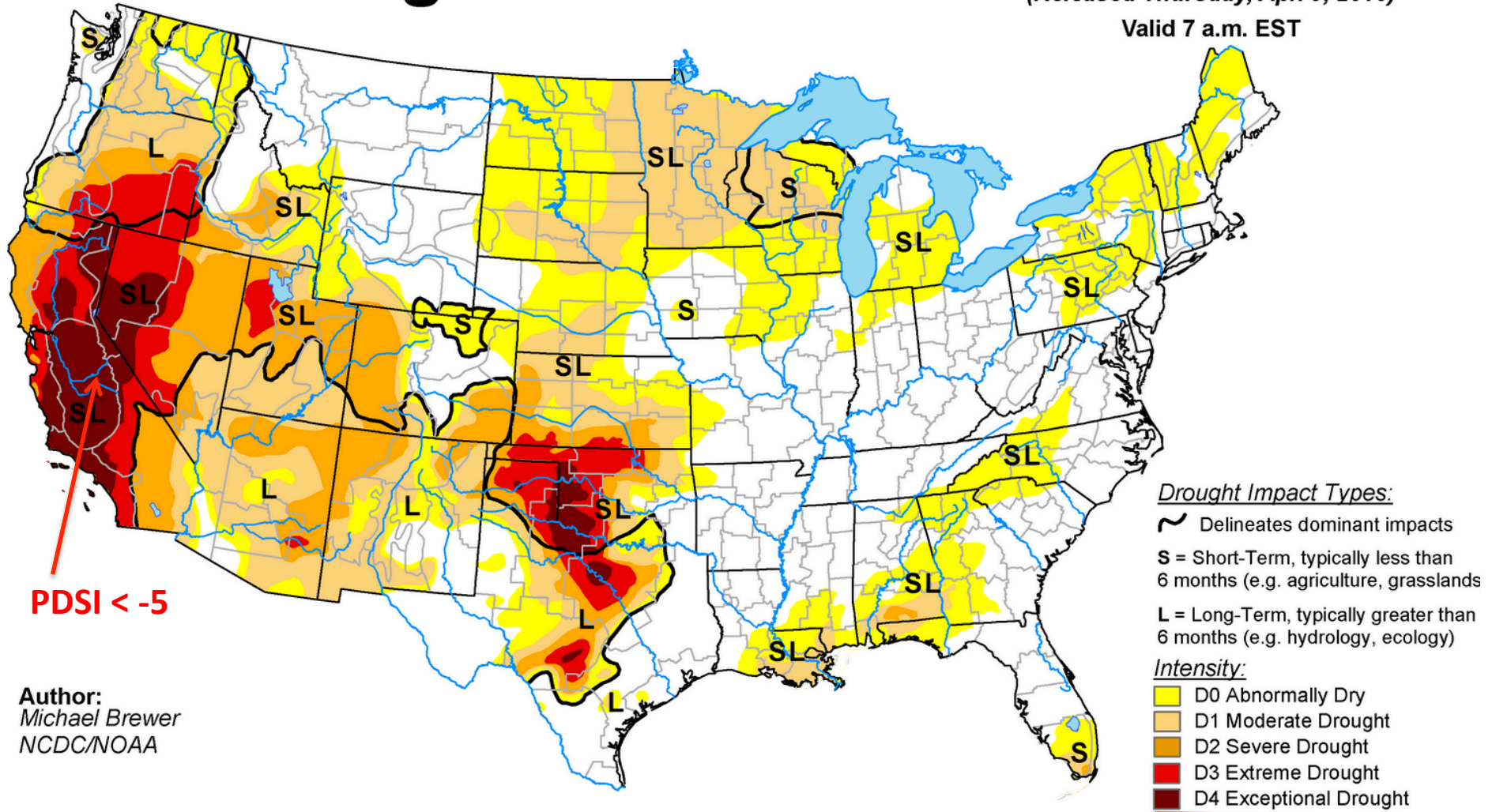
Exceptional

U.S. Drought Monitor

April 7, 2015

(Released Thursday, Apr. 9, 2015)

Valid 7 a.m. EST








41% of California is in Exceptional Drought

May 24, 2011



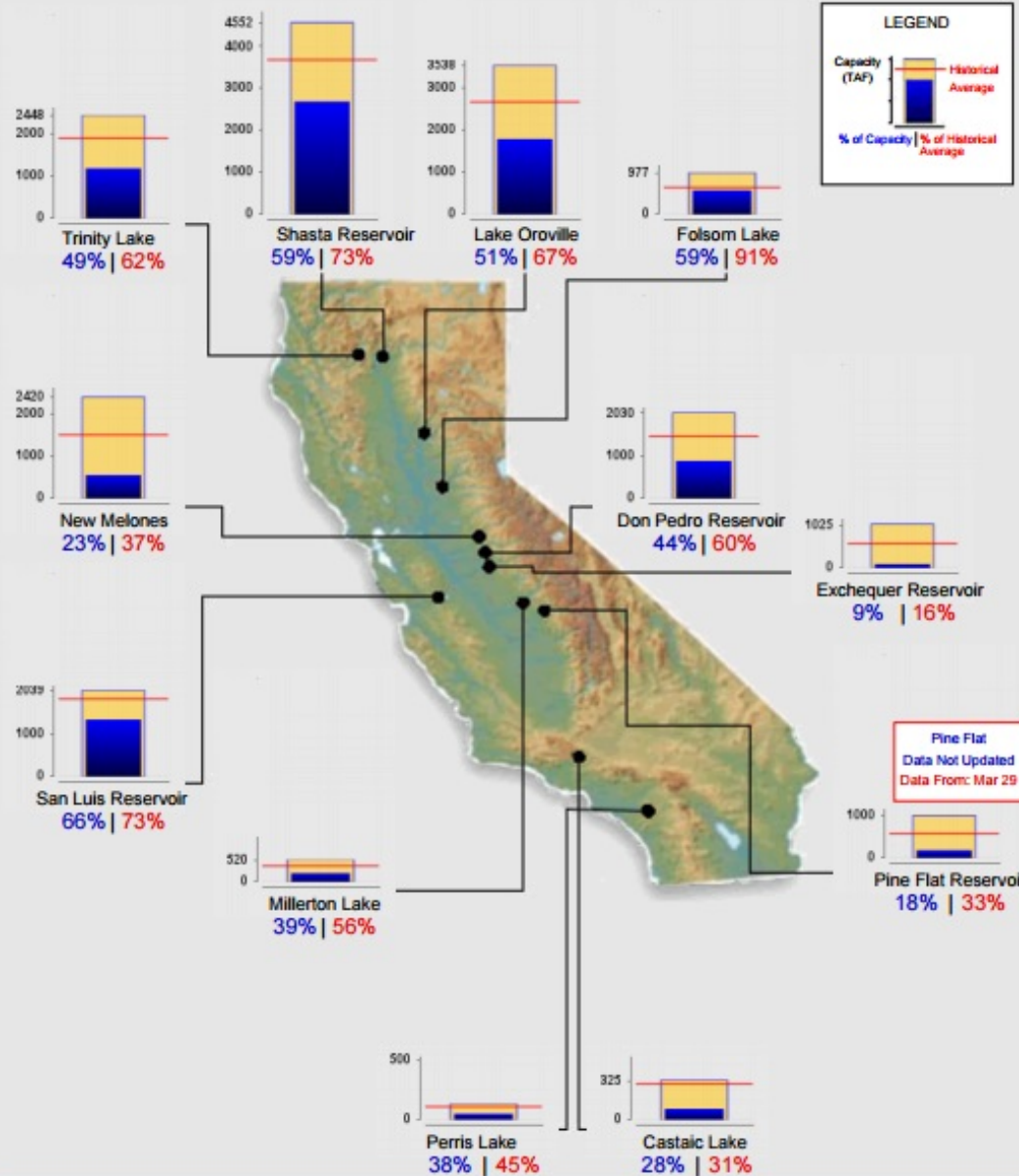
Intensity:

-  D0 Abnormally Dry
-  D1 Moderate Drought
-  D2 Severe Drought
-  D3 Extreme Drought
-  D4 Exceptional Drought

Current Reservoir Conditions

Ending At Midnight - March 30, 2015

CURRENT RESERVOIR CONDITIONS



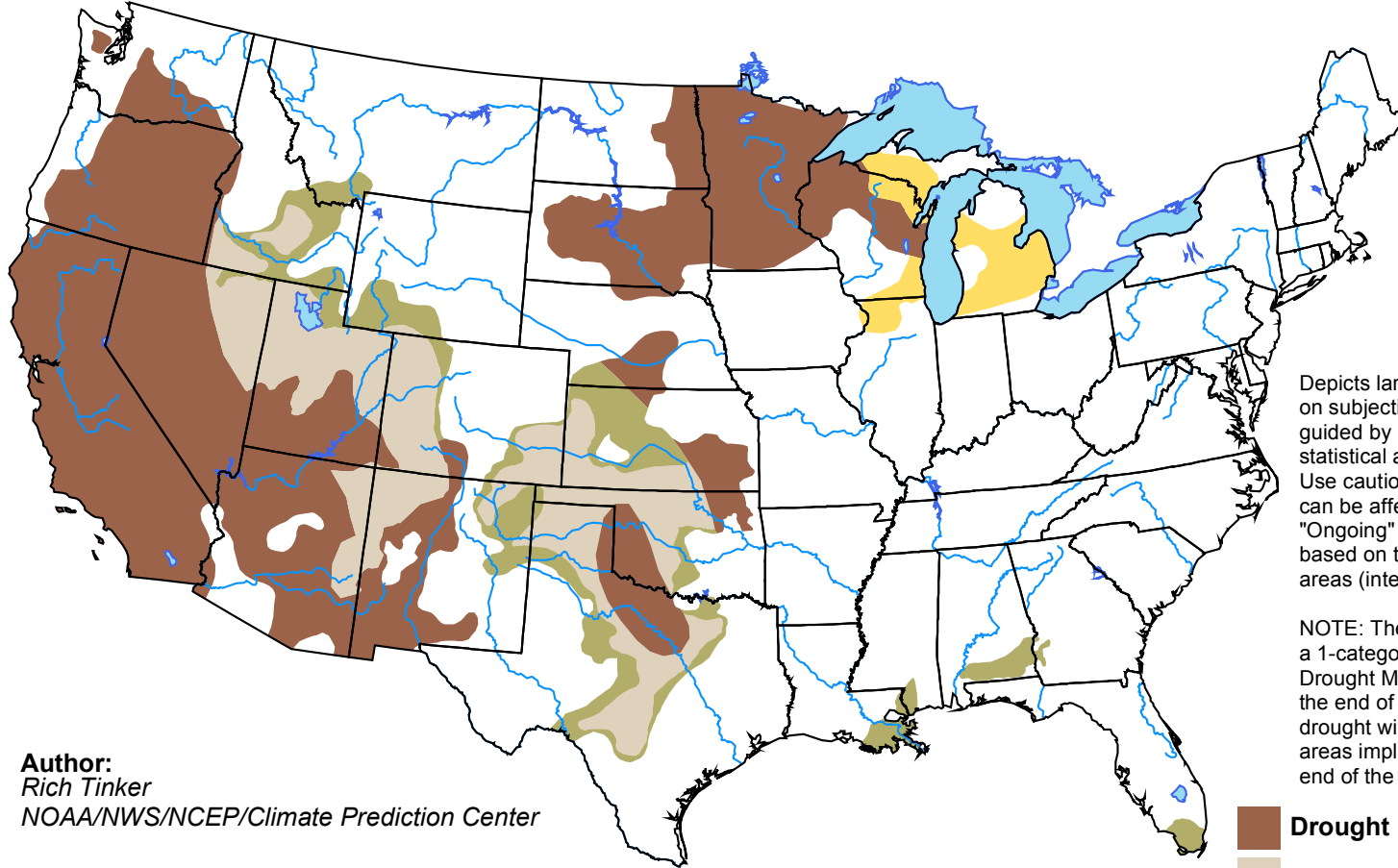
Blue – Current % of capacity

Red – % of Historic Average

U.S. Seasonal Drought Outlook

Drought Tendency During the Valid Period





Valid for April 16 - July 31, 2015
Released April 16, 2015

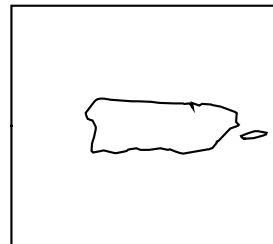
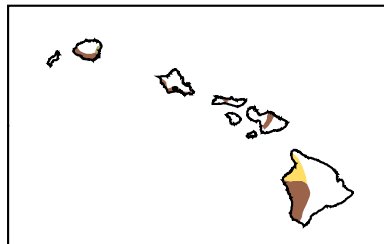
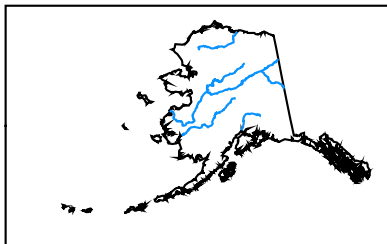


Depicts large-scale trends based on subjectively derived probabilities guided by short- and long-range statistical and dynamical forecasts. Use caution for applications that can be affected by short lived events. "Ongoing" drought areas are based on the U.S. Drought Monitor areas (intensities of D1 to D4).

NOTE: The tan areas imply at least a 1-category improvement in the Drought Monitor intensity levels by the end of the period, although drought will remain. The green areas imply drought removal by the end of the period (D0 or none).

Author:
Rich Tinker
NOAA/NWS/NCEP/Climate Prediction Center

-  **Drought persists/intensifies**
-  **Drought remains but improves**
-  **Drought removal likely**
-  **Drought development likely**



<http://go.usa.gov/hHTe>

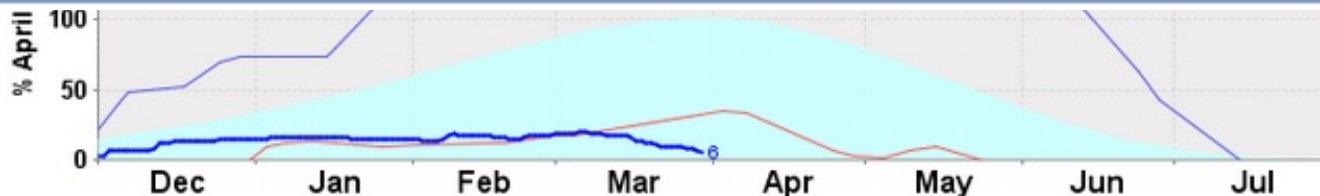
California Snow Water Content - Percent of April 1 Average For: 30-Mar-2015



STATEWIDE SUMMARY

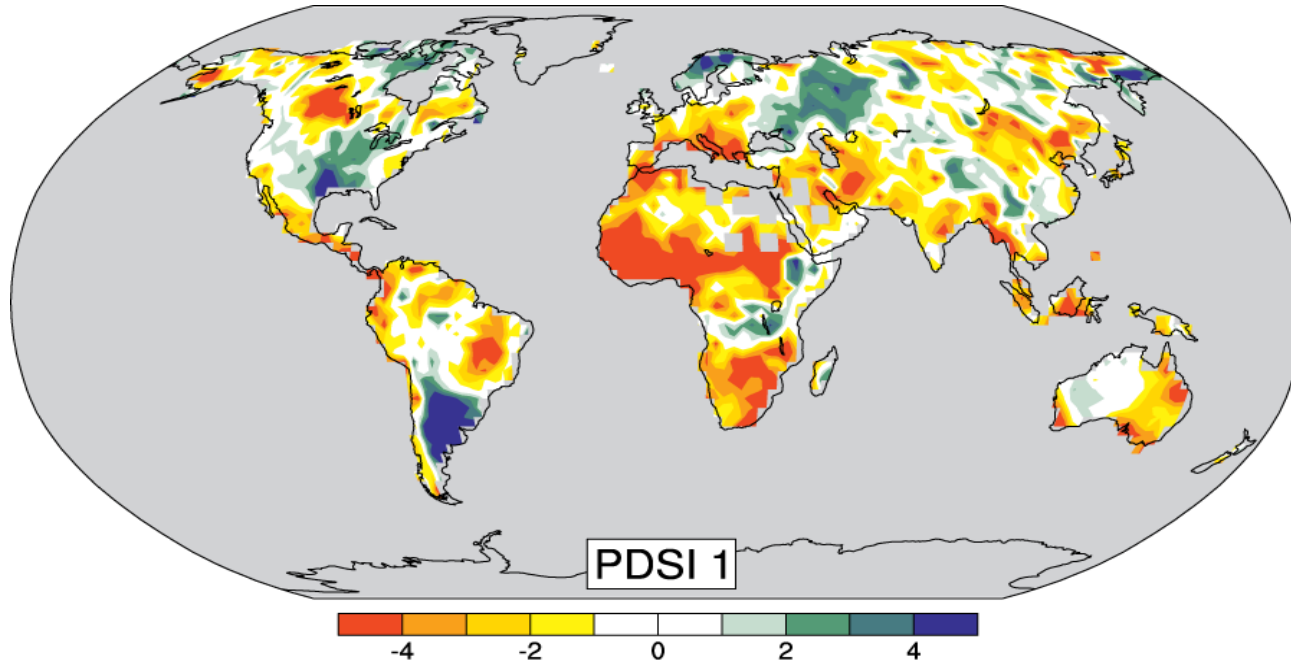
Data For: 14-Apr-2015

Number of Stations Reporting	101
Average snow water equivalent	1.5"
Percent of April 1 Average	5%
Percent of normal for this date	5%

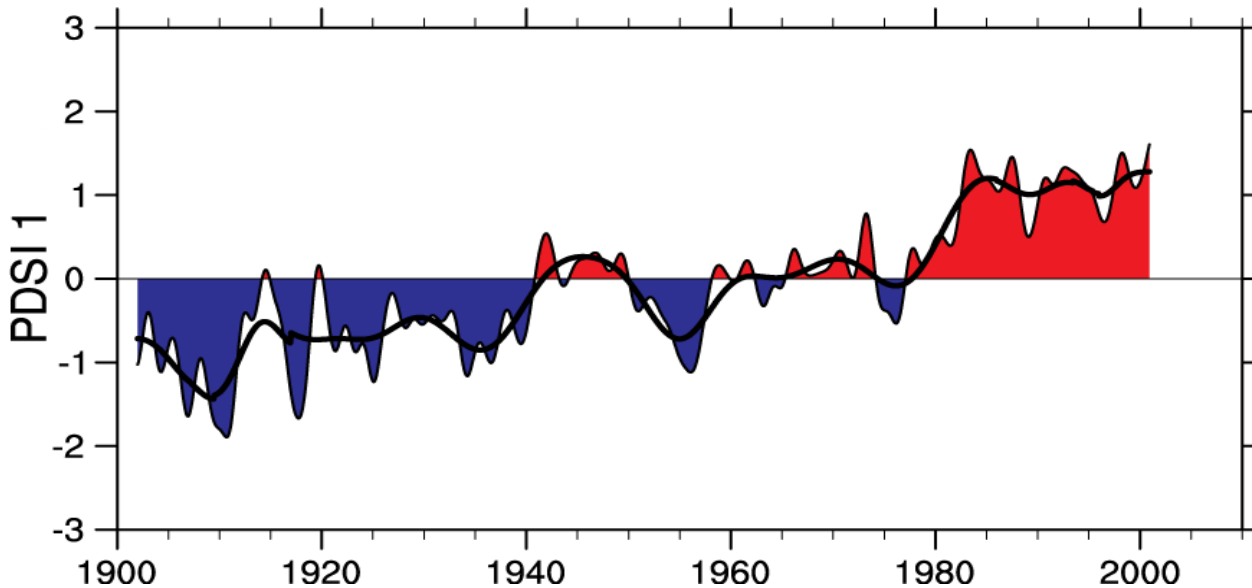


Average — 1976-1977 (min) — 1982-1983 (max) — 2014-2015 (current)

Drought is increasing most places



Drought Severity Index (PDSI) for 1900 to 2002.

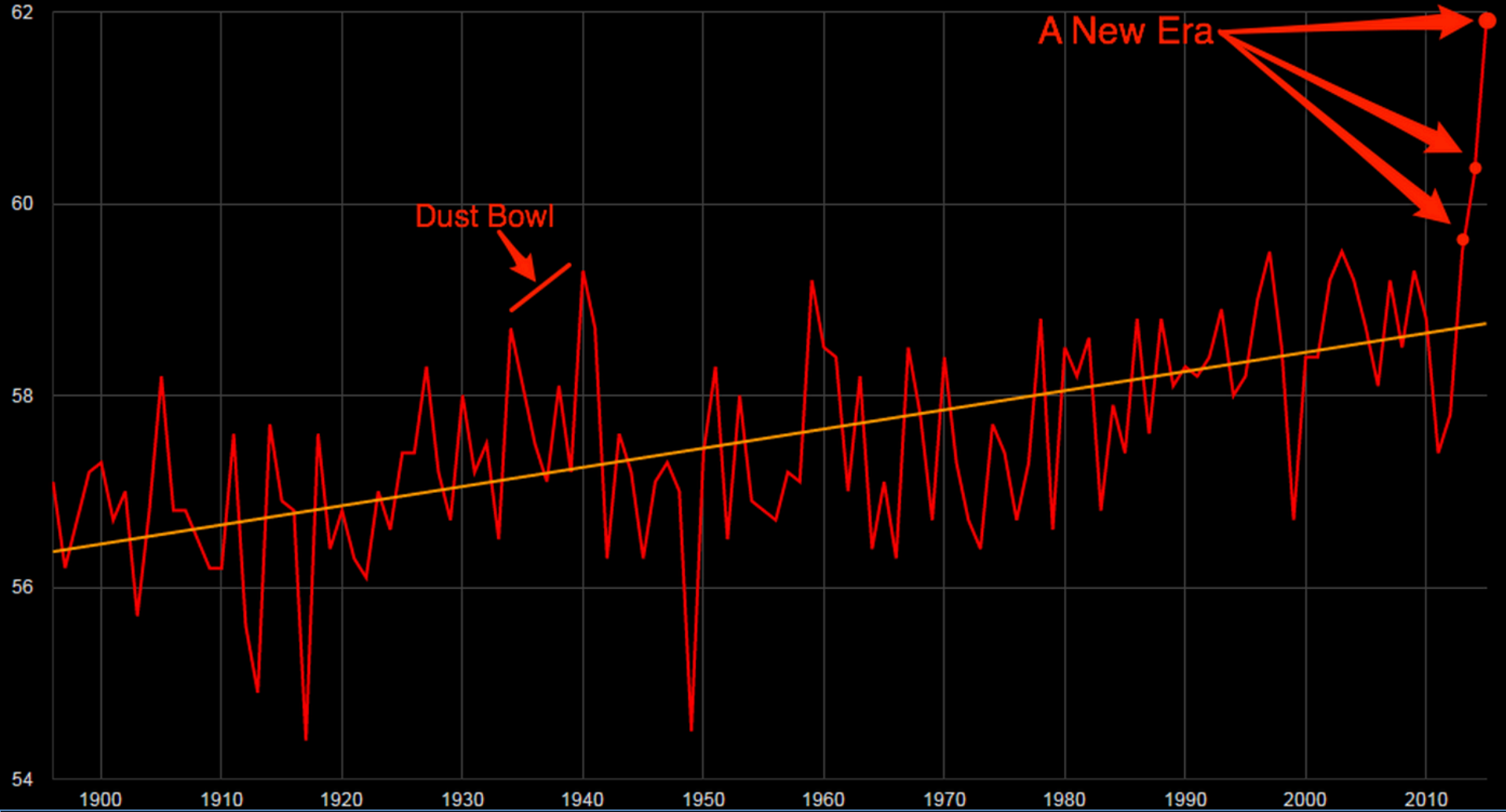


This increasing trend is largely due to global warming and increased evaporation

IPCC AR4

To what extent can the drought be attributed to Global Warming?

California's Heat Pops the Thermometer



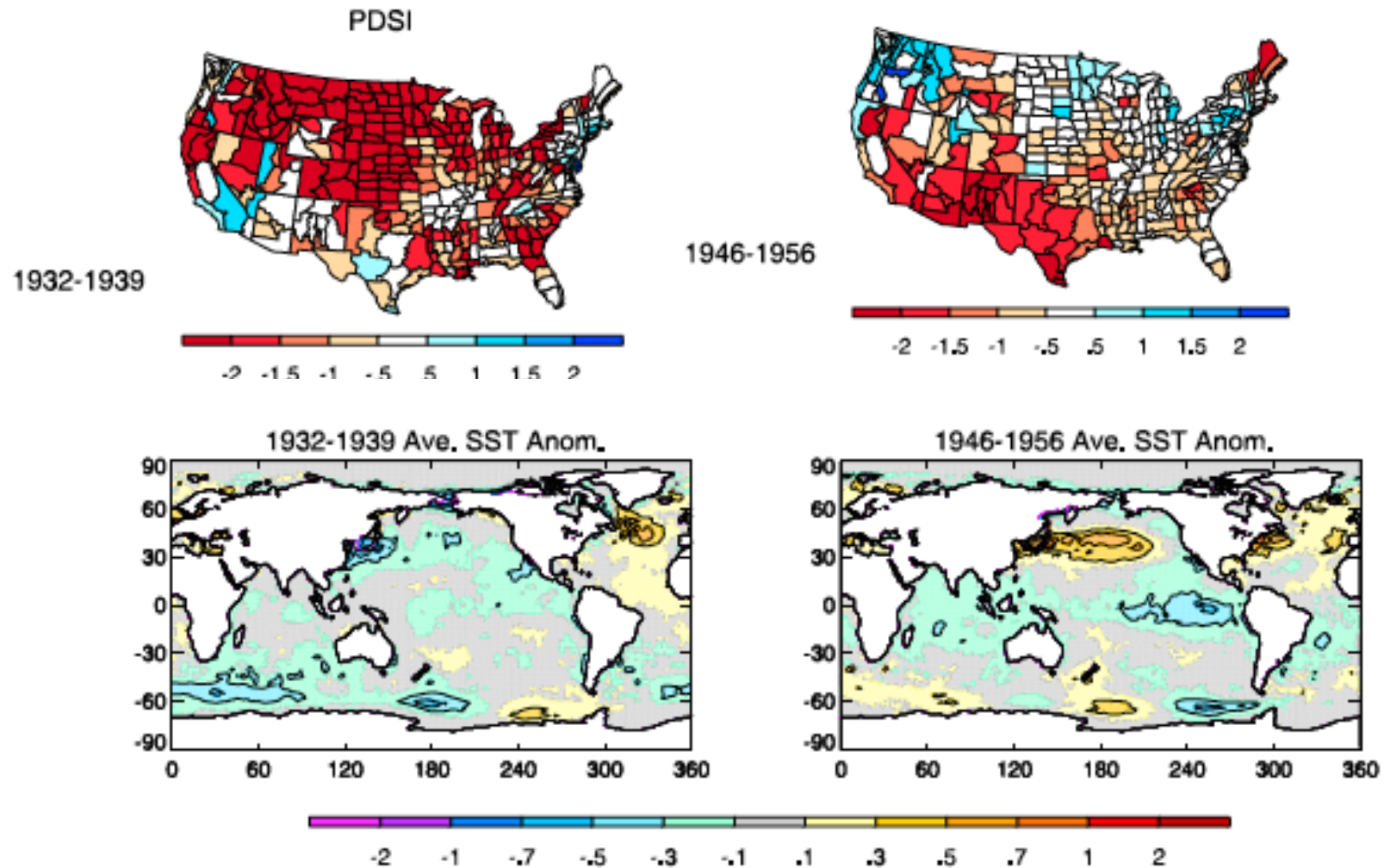
Outline

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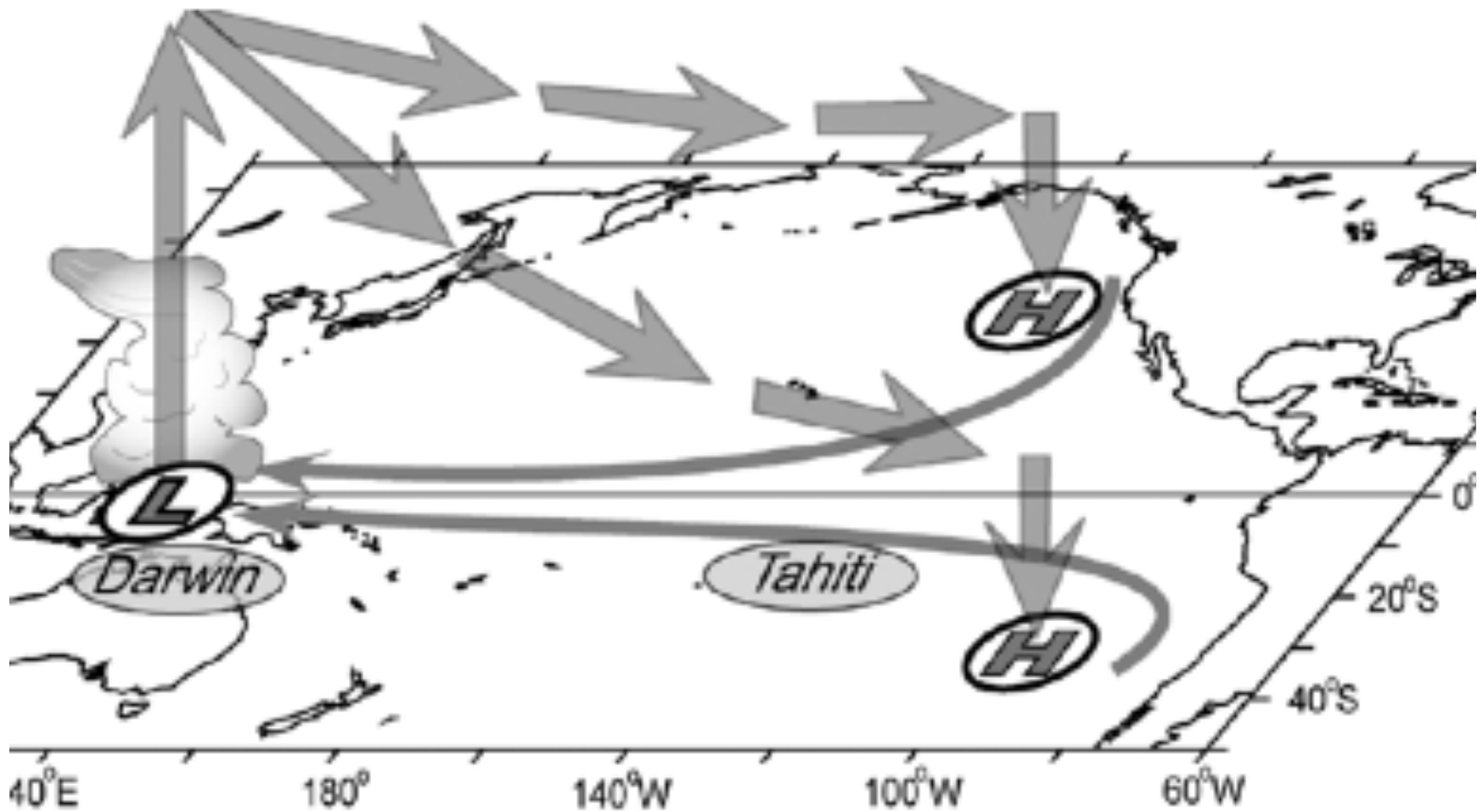
California Drought Mechanisms

- Warm Sea Surface Temperature Anomaly
- Persistent High Pressure Blocking Pattern
- Storm Tracks Divert North of California

Warm North Pacific Sea Surface Temperatures lead to Southwest Drought

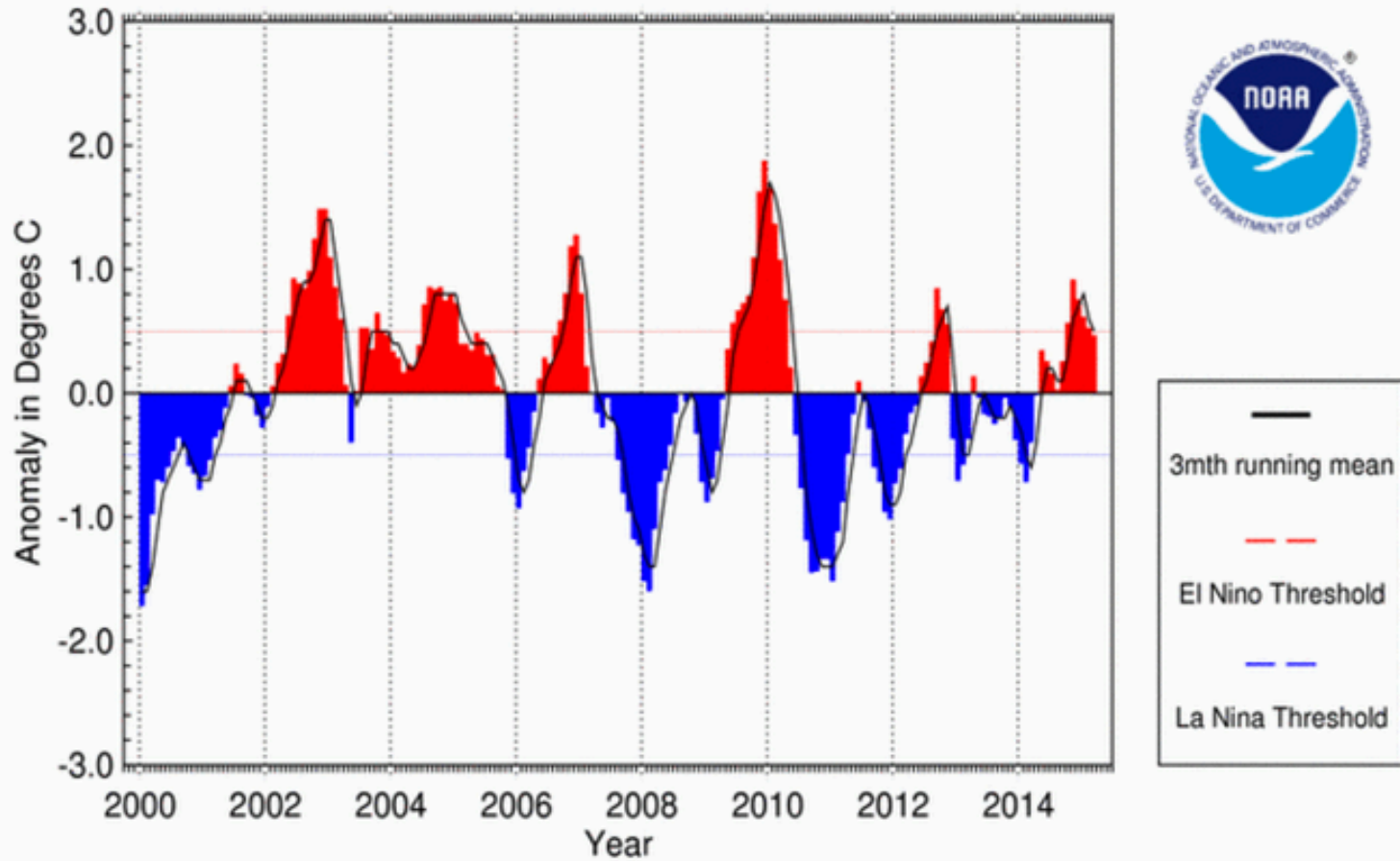


The Hadley-Walker Circulation



El Nino and La Nina 2000-2015

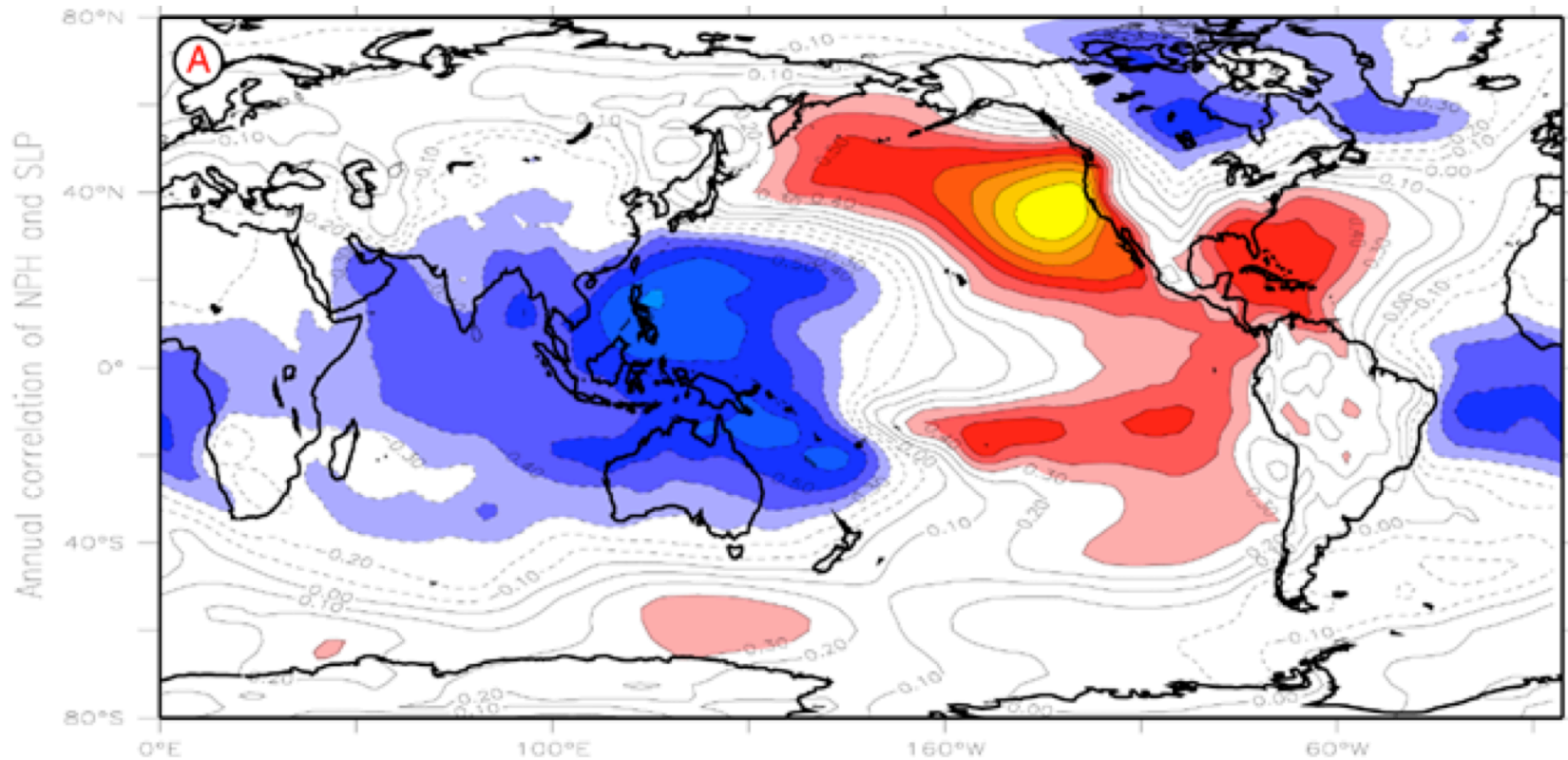
SST Anomaly in Nino 3.4 Region (5N-5S,120-170W)



National Climatic Data Center / NESDIS / NOAA

Warm Western Pacific Sea Surface Temperature Negatively Correlates with Northeastern Pacific Sea Surface Pressure

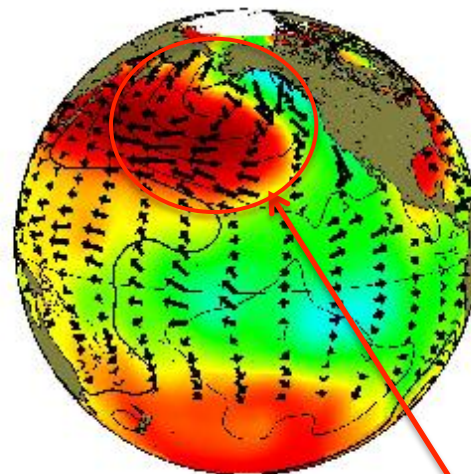
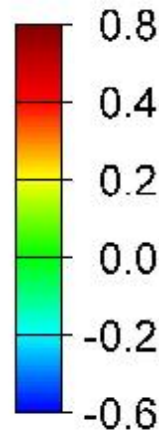
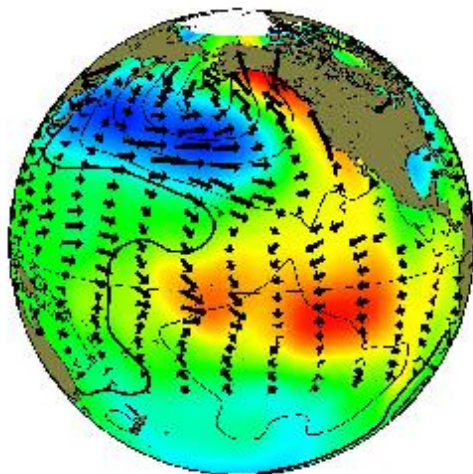
Cool Western Equatorial Pacific Sea Surface Temperatures Leads to High Pressure in the Northeastern Pacific



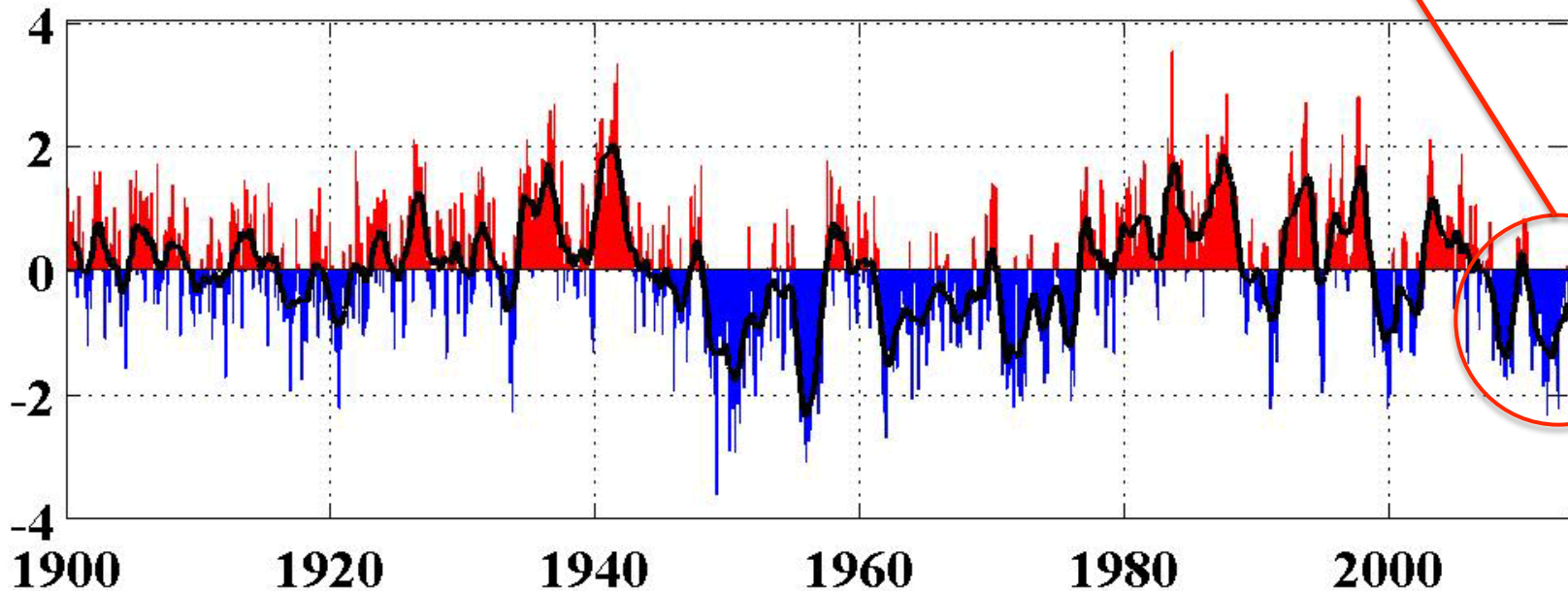
Pacific Decadal Oscillation (PDO)

+ Warm Phase

- Cool Phase

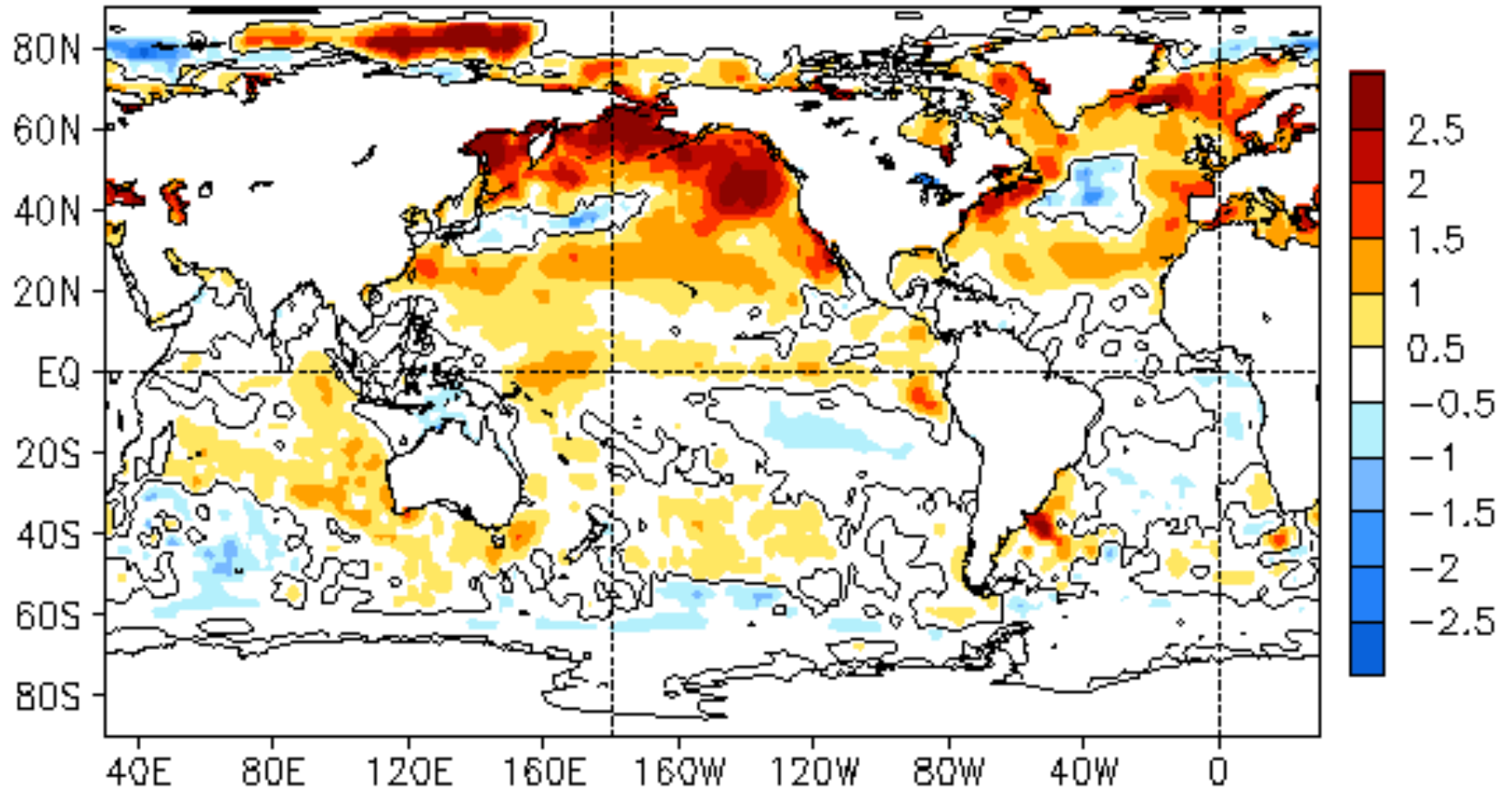


monthly values for the PDO index: 1900-2013



2014 SST Warm North Pacific Anomaly

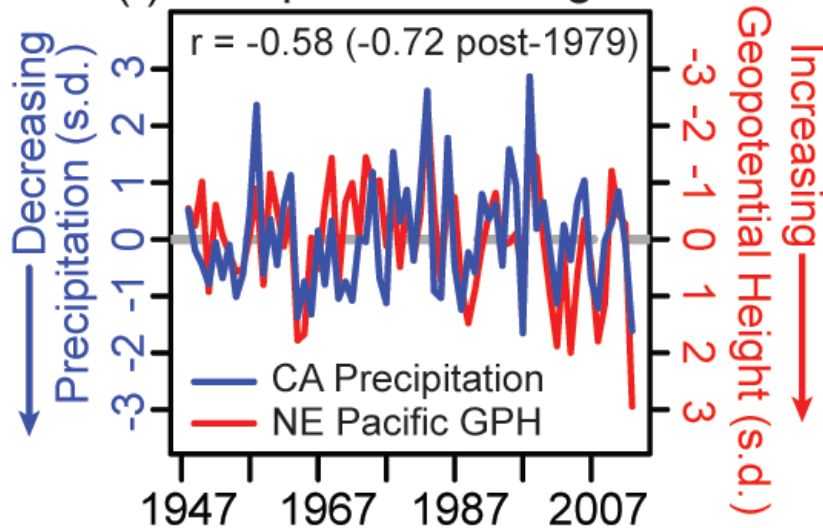
SEP 2014 SST Anomaly ($^{\circ}\text{C}$)
(1981–2010 Climatology)



North Pacific High Pressure (Positive Geopotential Height) Correlates with Decreasing Precipitation

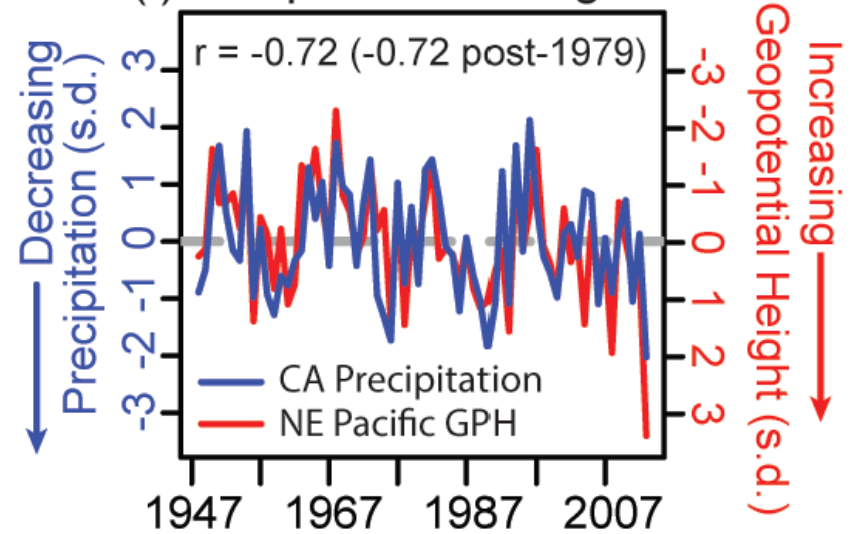
Feb–May Precipitation
and 500-mb

(f) Geopotential Height



Oct–Jan Precipitation
and 500-mb

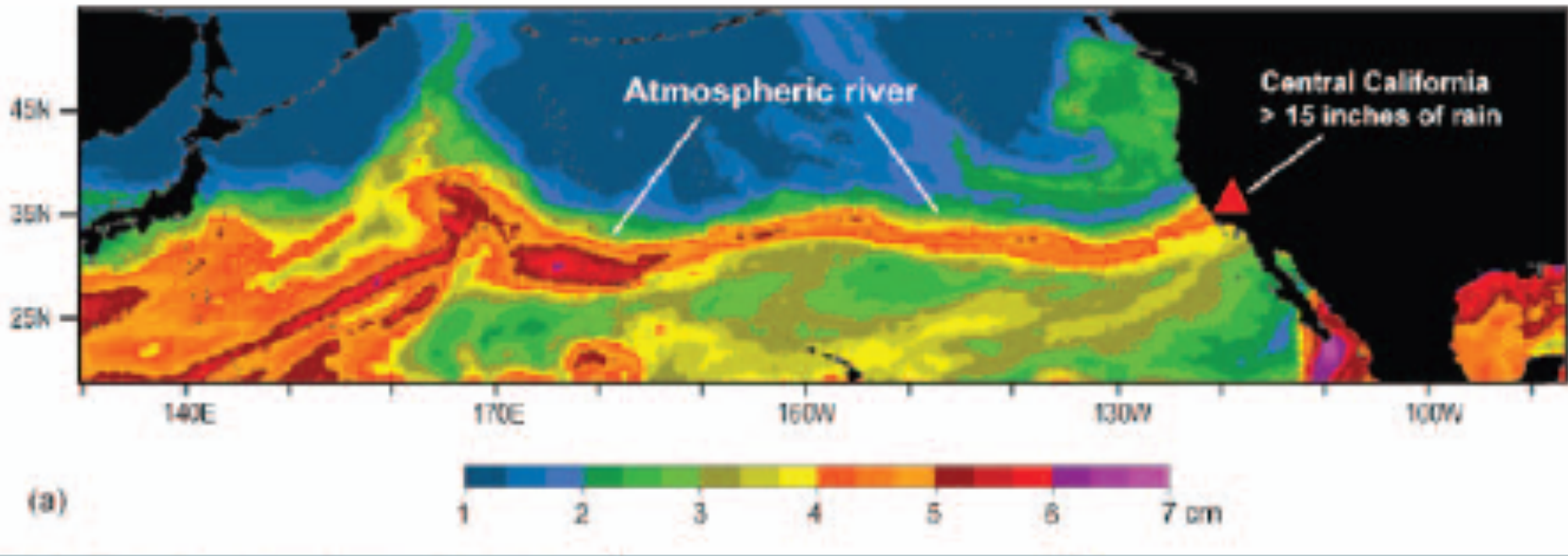
(i) Geopotential Height



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Atmospheric Rivers typically occur during El Nino years and may act as Drought Busters



- California's largest storms and floods are due to Atmospheric Rivers
- ~10 Atmospheric Rivers make landfall per winter

Closed Low Pressure Systems From the North Pacific

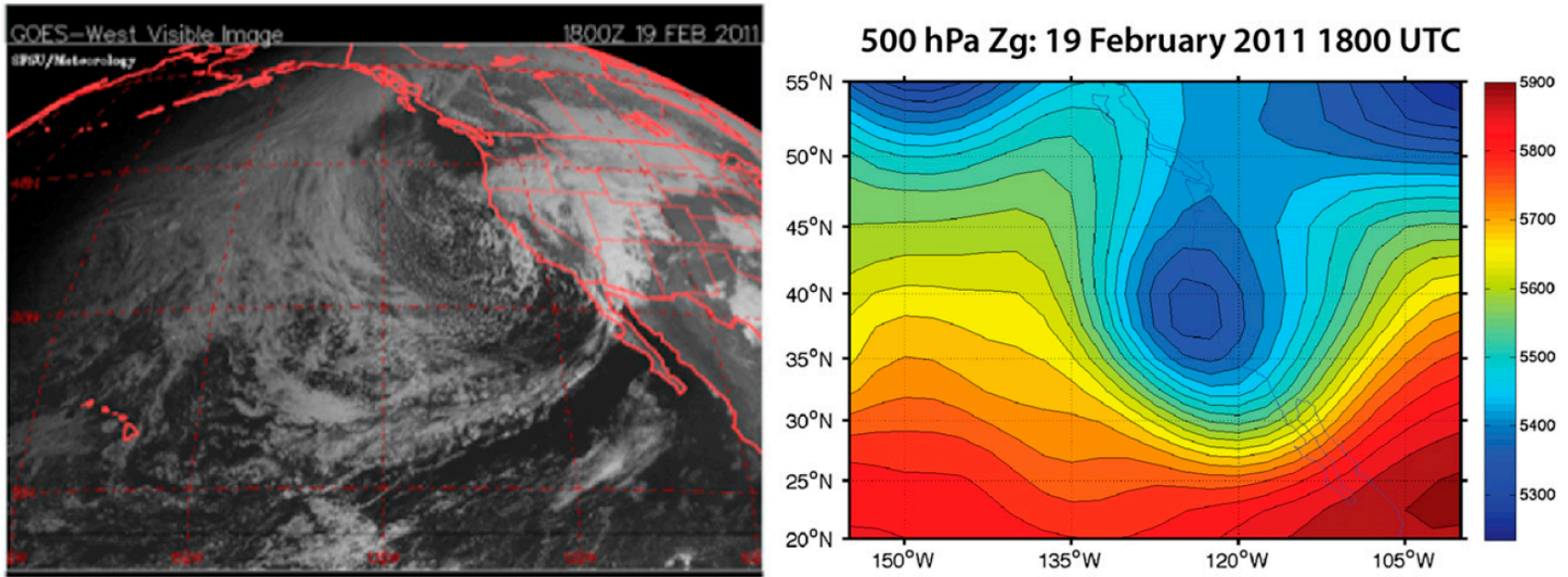
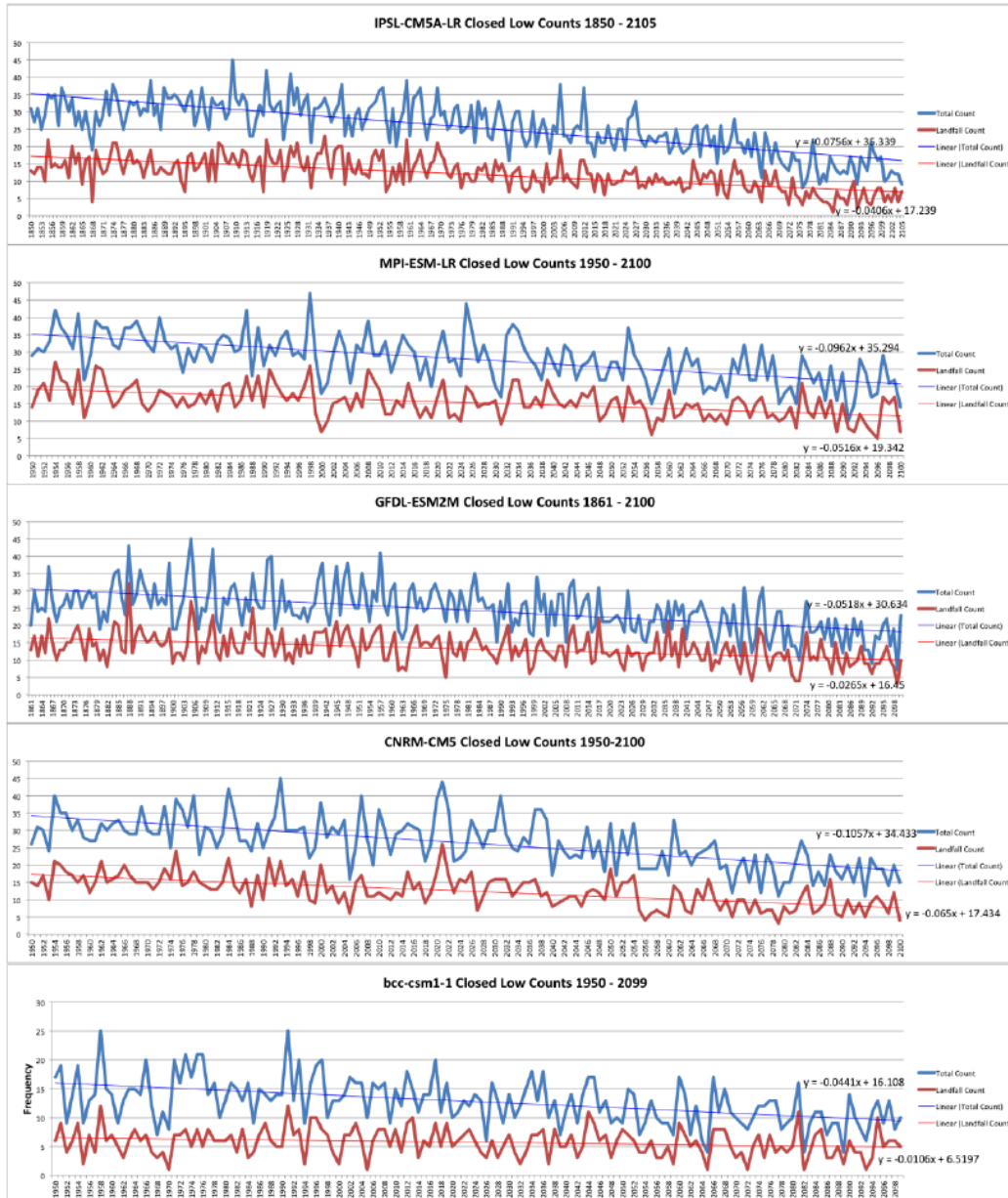


FIG. 1. (left) GOES-West visible satellite image of a closed low approaching the U.S. West Coast and (right) 500-hPa height contours in geopotential meters on 1800 UTC 19 Feb 2011.

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Closed Low are Projected to Decrease

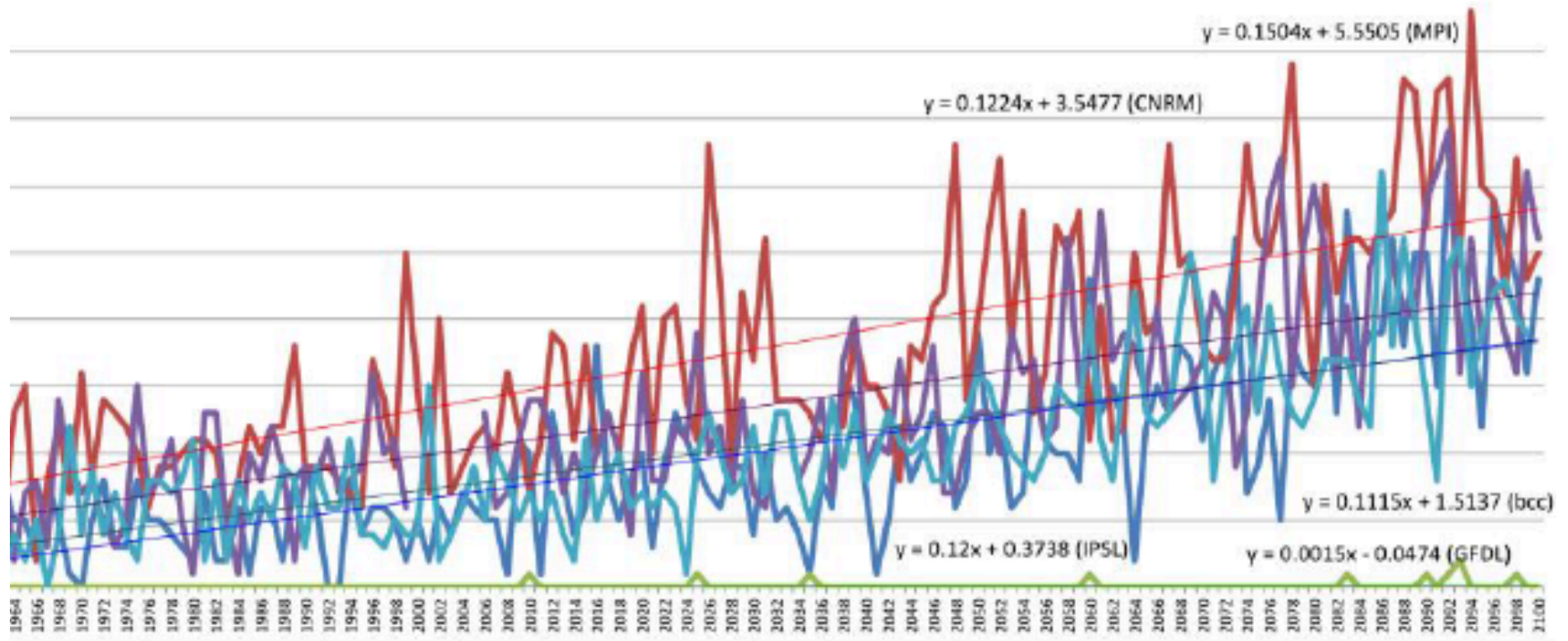


Results from 5 GCMs show a Decreasing trend in Closed Lows for Projections to 2100.

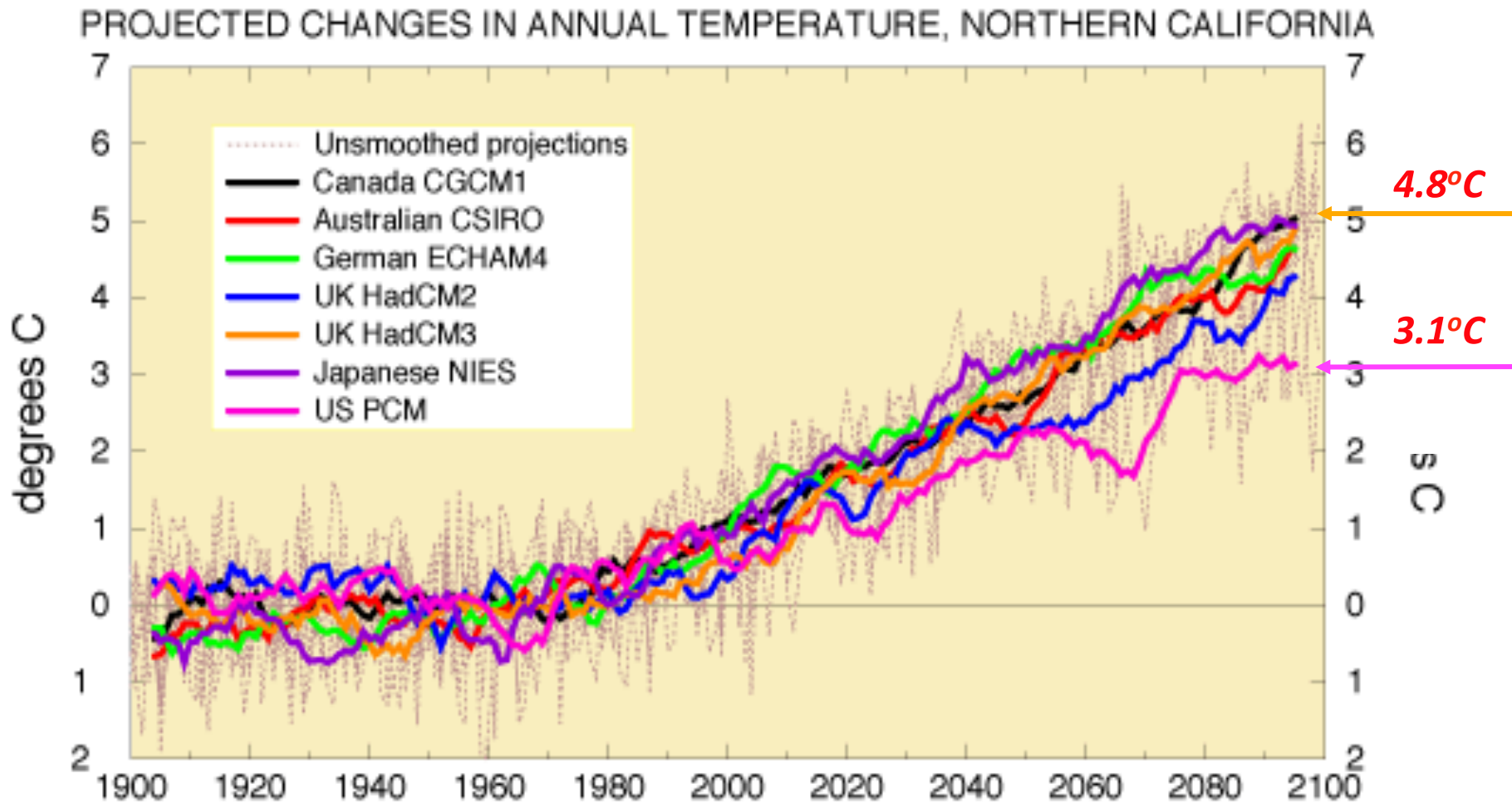
This suggest fewer Extra-Tropical storms from The Gulf of Alaska “Center of Action”

Atmospheric Rivers are Projected to Increase

Atmospheric River Counts per Year 1950 - 2100



Global Climate Model Projections



Temperature Sensitivity: $T_{2070-2099} - T_{1961-1990}$

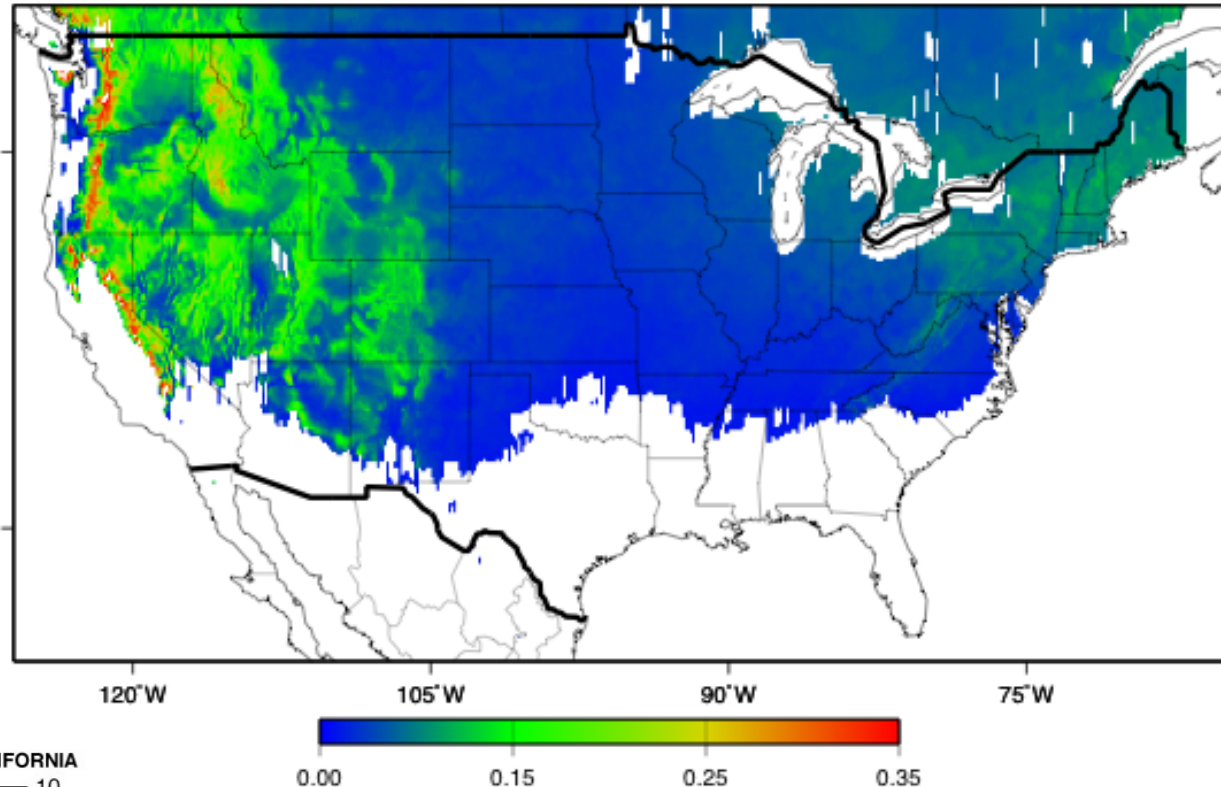
PCM Low Sensitivity HadCM3 High Sensitivity

SENSITIVITY OF SNOWFED HYDROCLIMATE TO A +3°C WARMING ... Rain? or Snow?

FRACTION OF ANNUAL PRECIPITATION FALLING
IN THE DAILY TEMPERATURE RANGE: $-3C < T_{avg} < 0C$
[from 1950-1999 VIC 1/8-degree INPUT DATA]

The fraction of each year's precipitation that historically fell on days with average temperatures just below freezing.

Cascades and Sierra are the most sensitive
To a 3°C increase



120°W 105°W 90°W 75°W

0.00 0.15 0.25 0.35

FRACTION

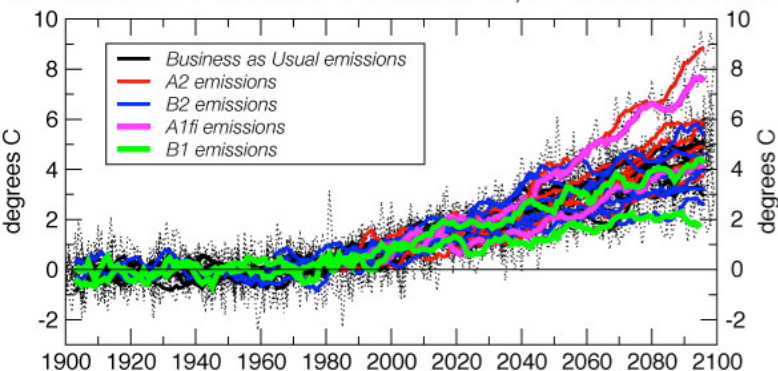
Less vulnerable

More vulnerable

+3

Computed from UW's VIC model daily INPUTS Courtesy Mike Dettinger.

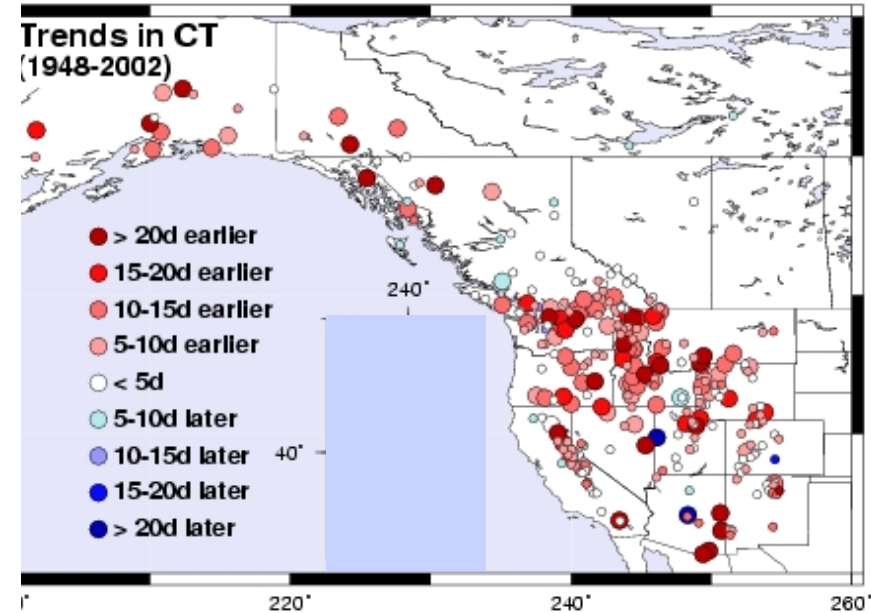
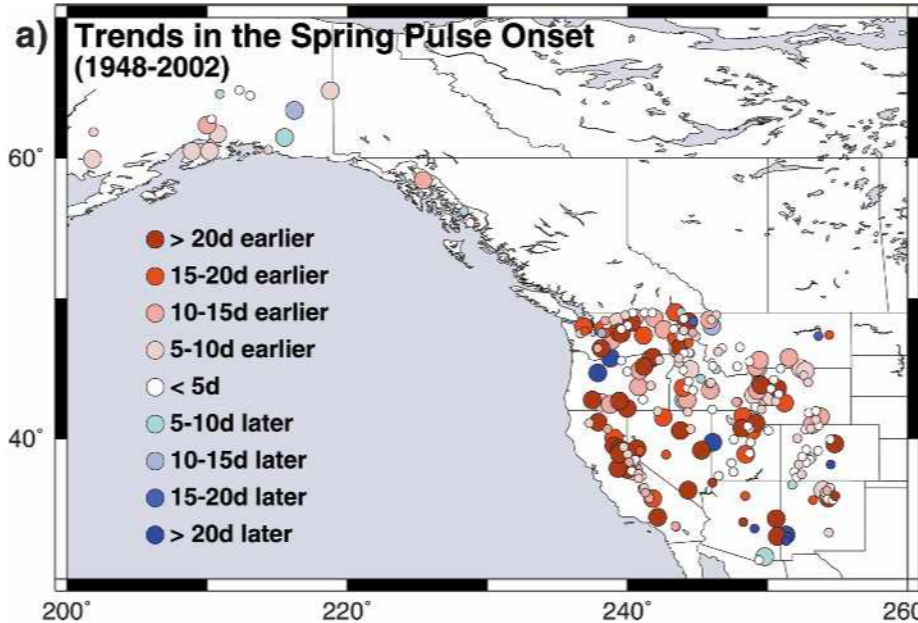
PROJECTED CHANGES IN ANNUAL TEMPERATURE, NORTHERN CALIFORNIA



degrees C

degrees C

Observed 20th Century Hydrologic Timing



Stewart et al. 2005

- Trends in stream flow timing shifted 1-3 weeks earlier over the past ~50 years.
- Timing shift dominated by changes in snowmelt-derived streamflow, partially attributed to warming.

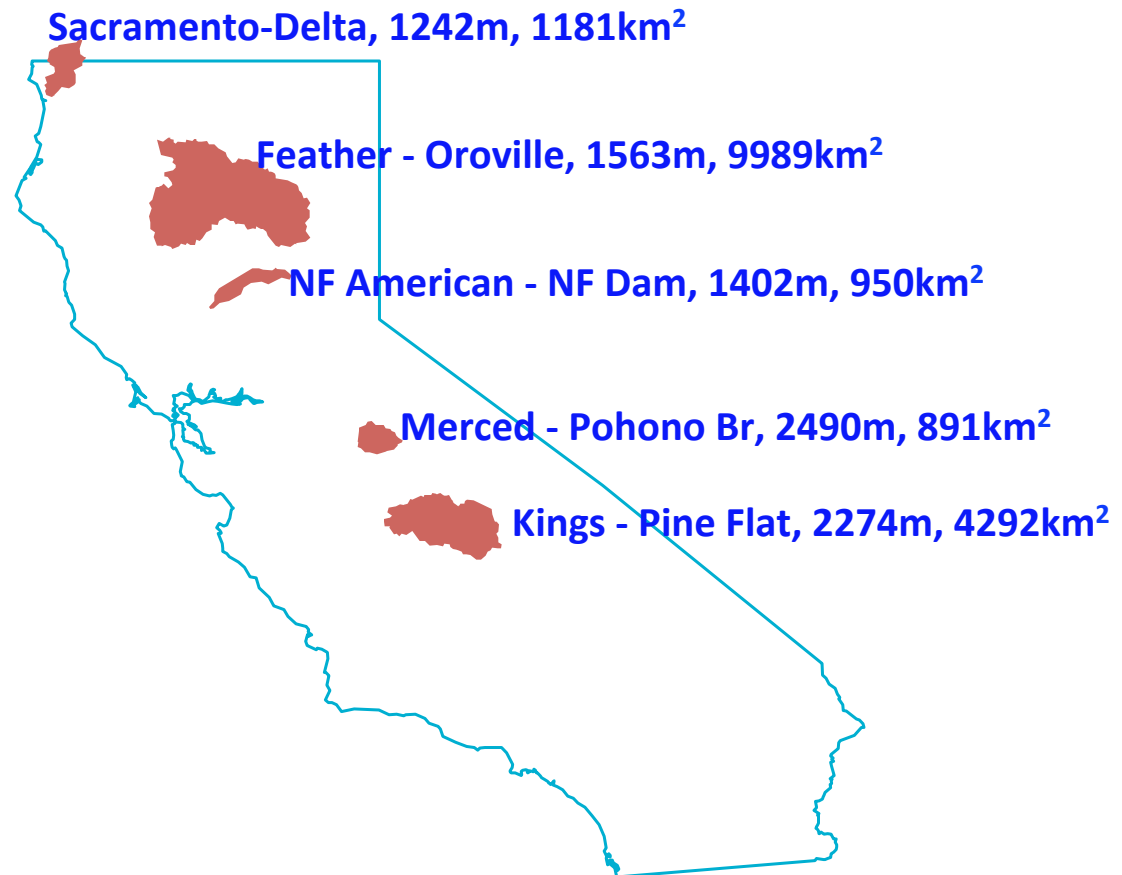
NOAA NWSRFS Operational Forecast Basins



Analysis of the Hydrologic Response

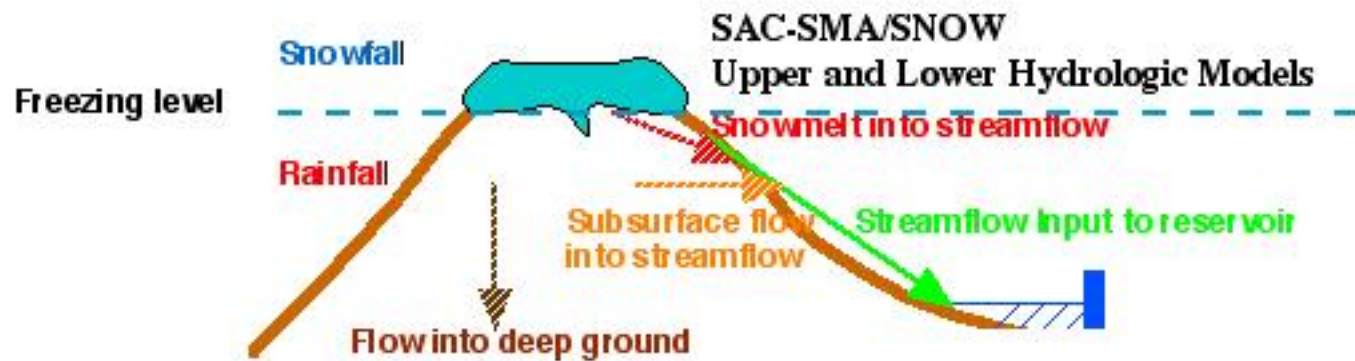
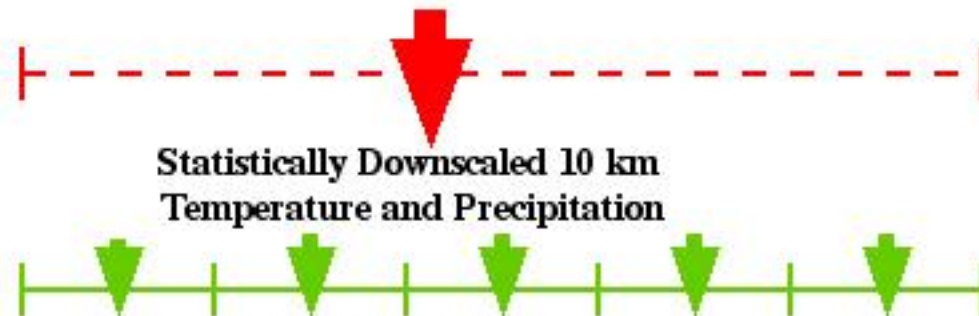
- National Weather Service – River Forecast System Sacramento Soil Moisture Accounting Model (Burnash 1973)

- Anderson Snow Model for computing snow accumulation and ablation (Anderson 1973)

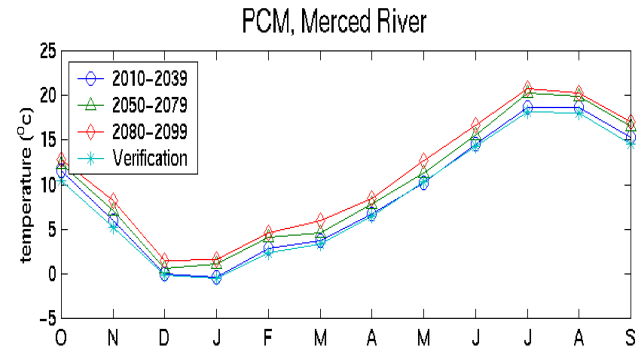
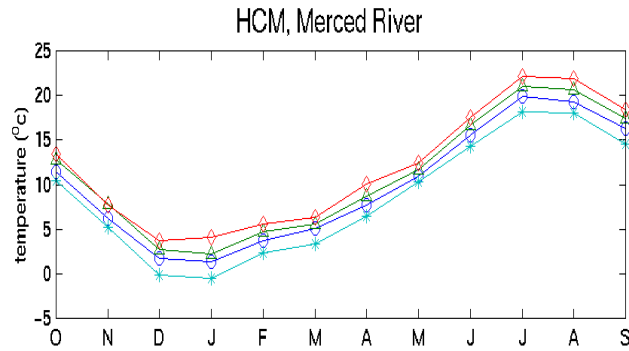
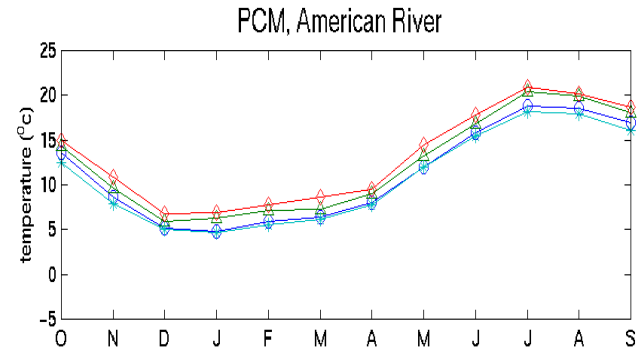
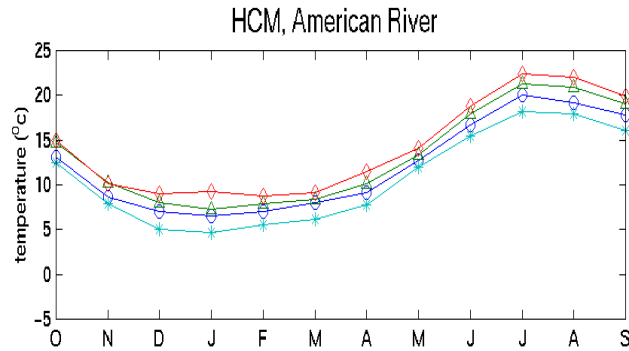
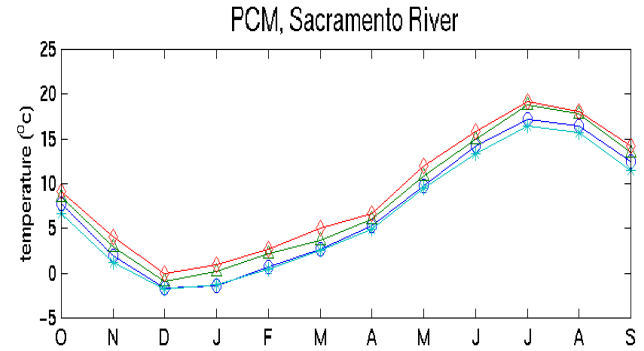
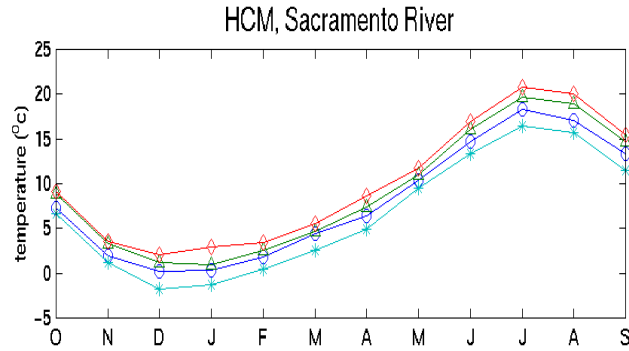


Statistically Downscaled Temperature and Precipitation

GCM-simulated Global-Scale Temperature and Precipitation



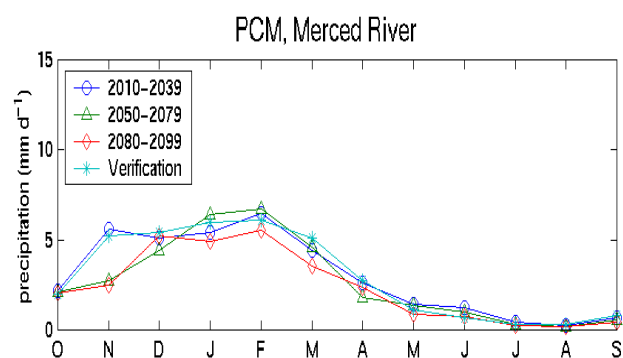
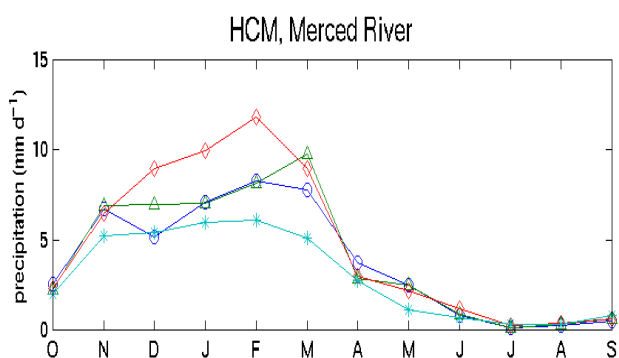
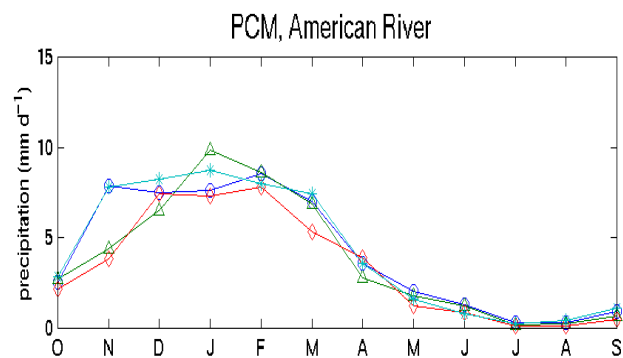
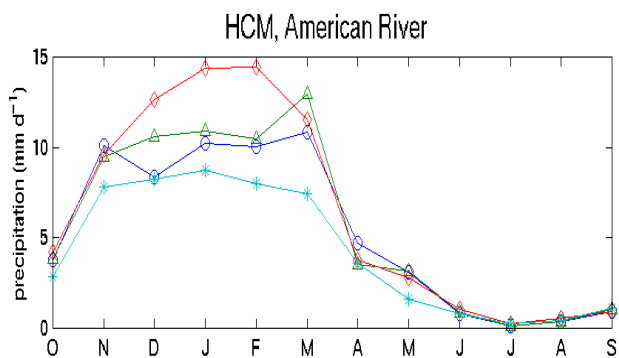
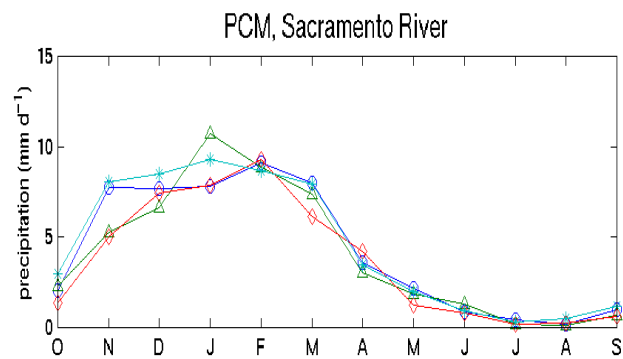
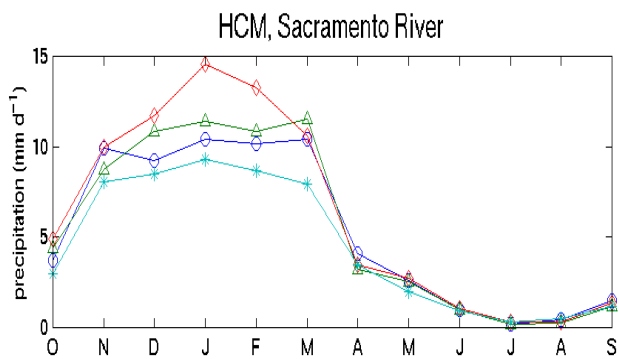
Temperature: GCM-Based



Month

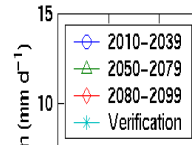
Month

Precipitation: GCM-Based



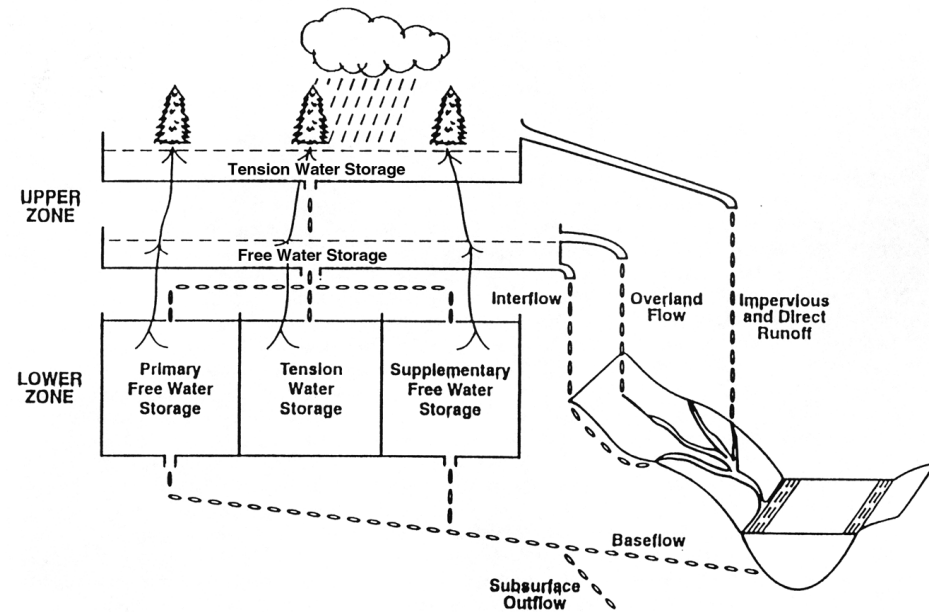
Month

Month

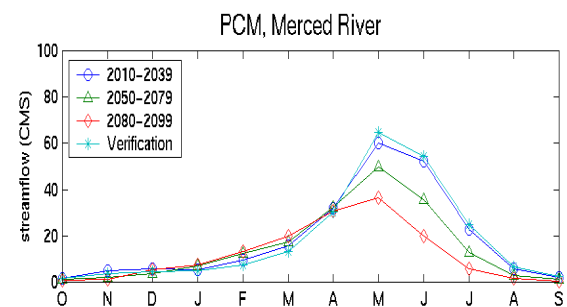
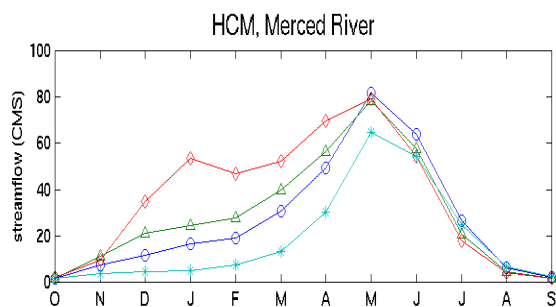
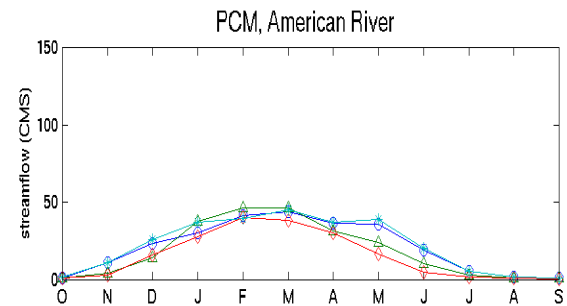
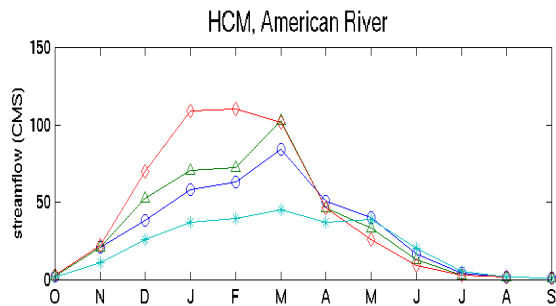
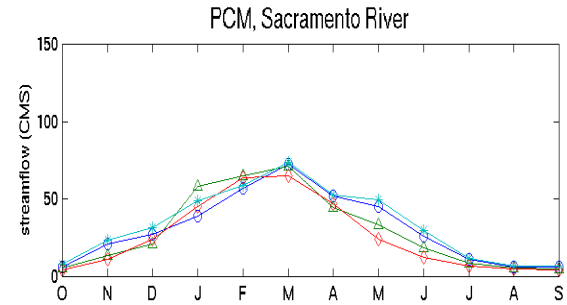
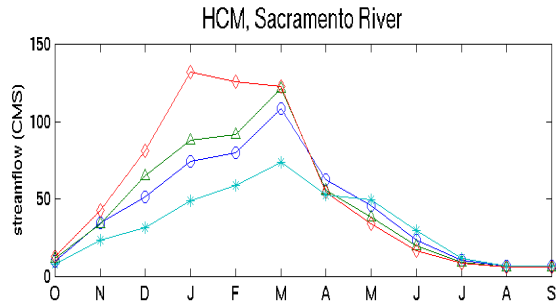


NWS Soil Moisture Accounting and Anderson Snow Model

- **Snow Accumulation and Ablation Energy Balance Model**
 - Anderson Snow Model
 - Air Temperature is an index to energy exchange at the snow-air interface
- **Sacramento Soil Moisture Accounting**
 - Spatially lumped and deterministic
 - 2 vertical layers
 - 5 storage compartments
 - upper and lower tension
 - upper free
 - lower primary and secondary free
 - Inputs:
 - Mean Area Precipitation (MAP)
 - Mean Area Temperature (MAT)



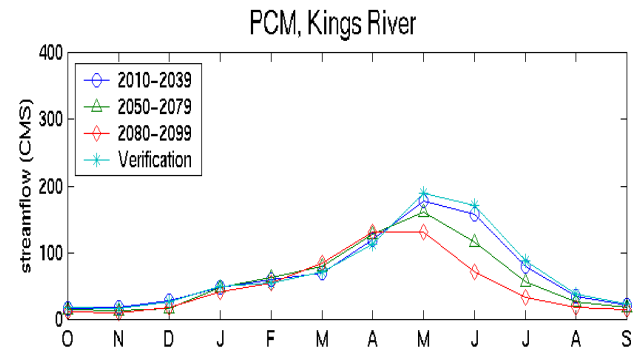
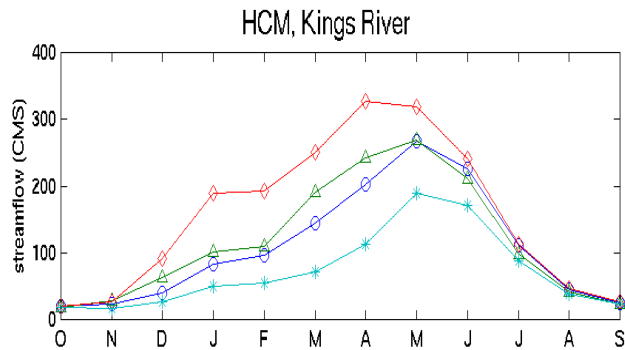
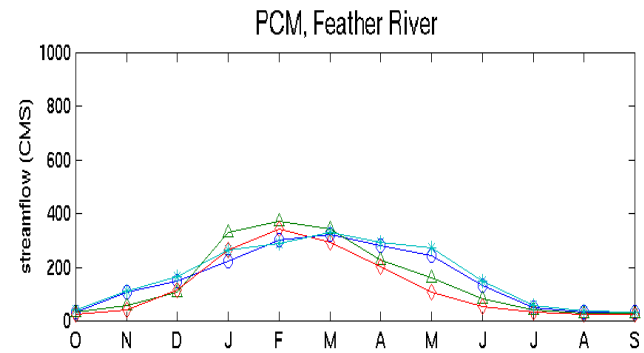
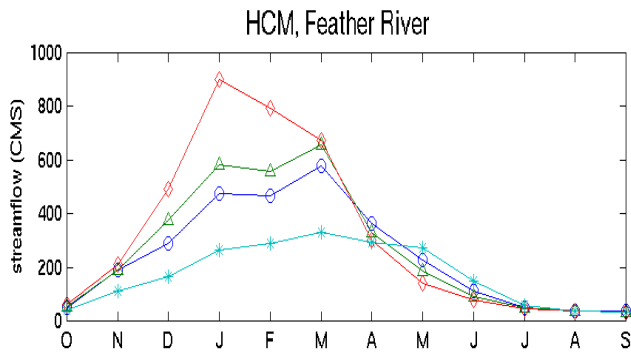
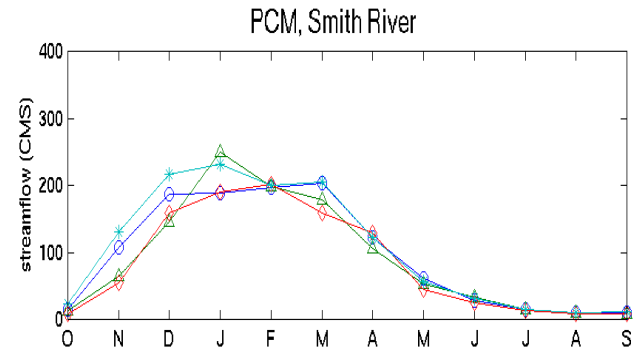
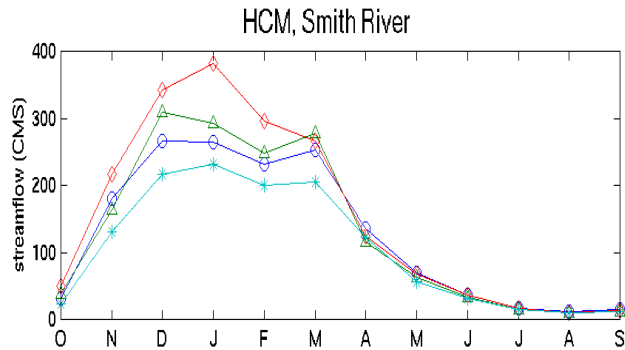
Streamflow: GCM-Based



Month

Month

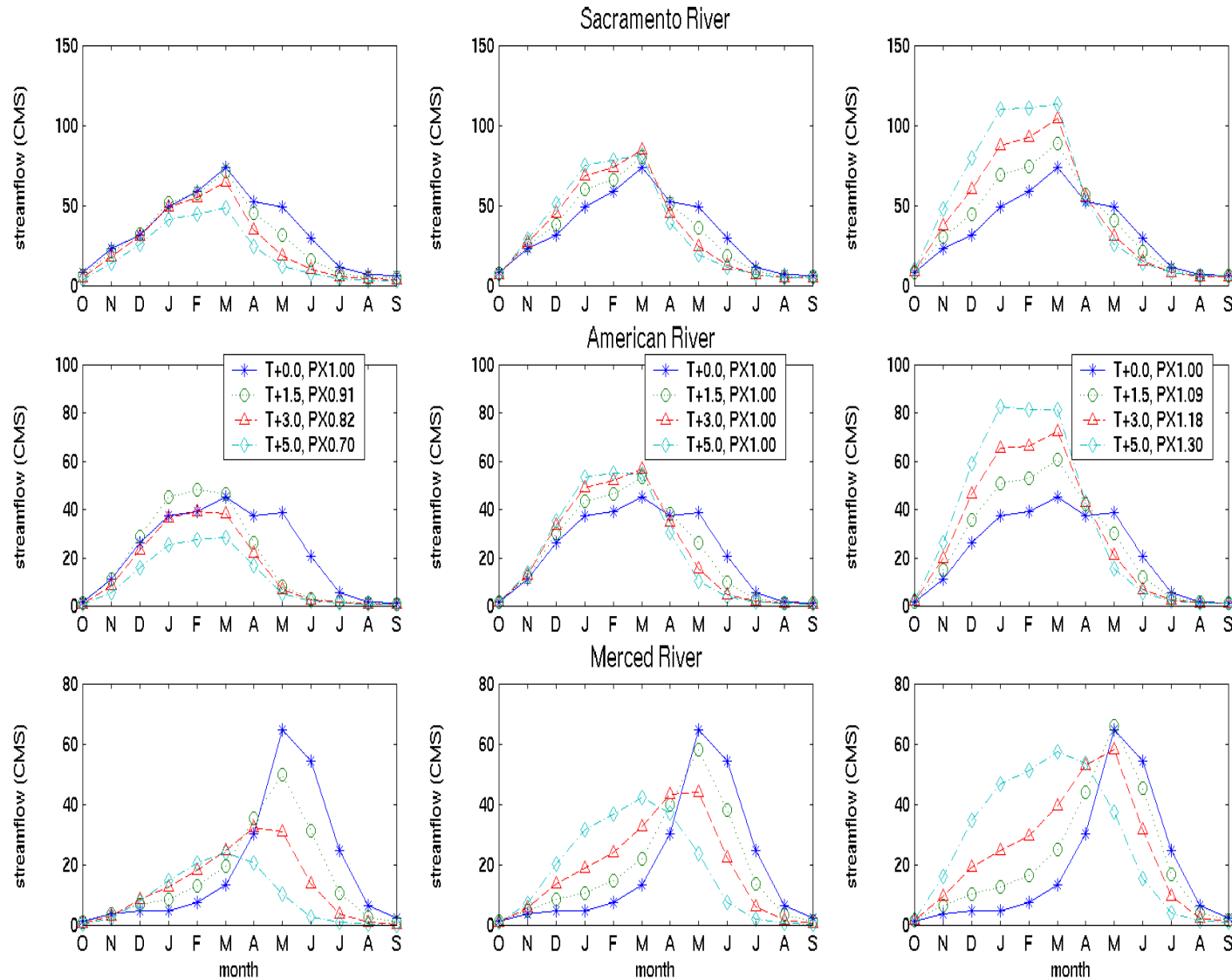
Streamflow: GCM-Based



Month

Month

Mean-Monthly Streamflow



P Decrease

P No Change

P Increase

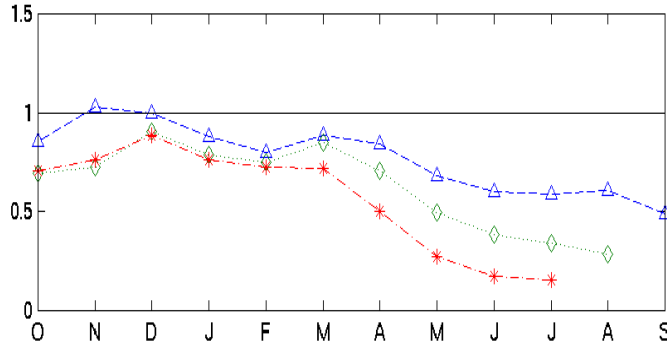
Ratio of Mean-Monthly Projected Snow Melt to Baseline Snow Melt

Warm-Wet

HCM, Sacramento River

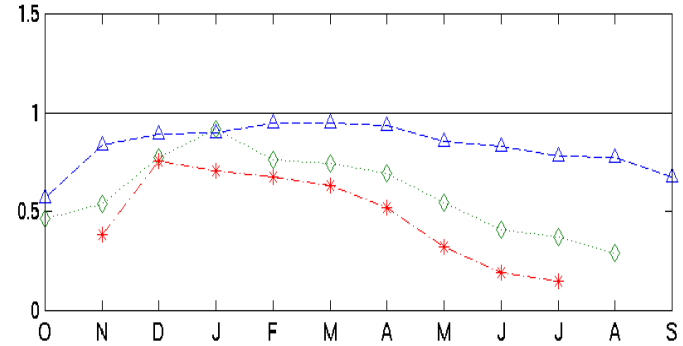
73% Lower: 1036 M, 27% Upper 1798 M

Lat: 41.2



Cool-Dry

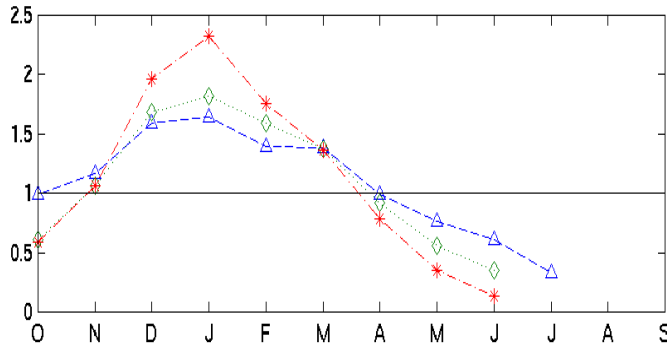
PCM, Sacramento River



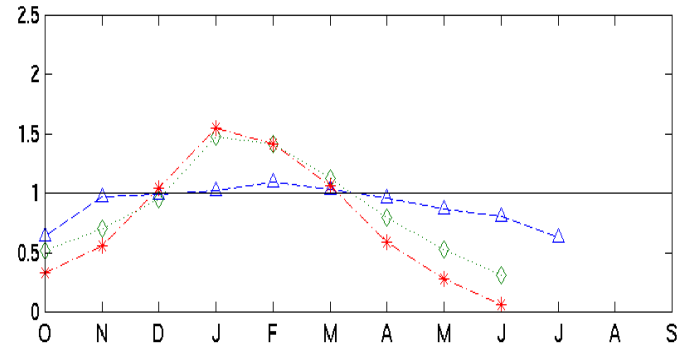
HCM, American River

42% Lower: 1280 M, 58% Upper 1768 M

Lat: 39.9



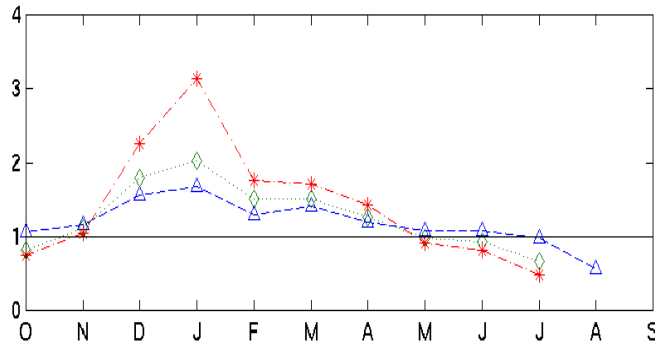
PCM, American River



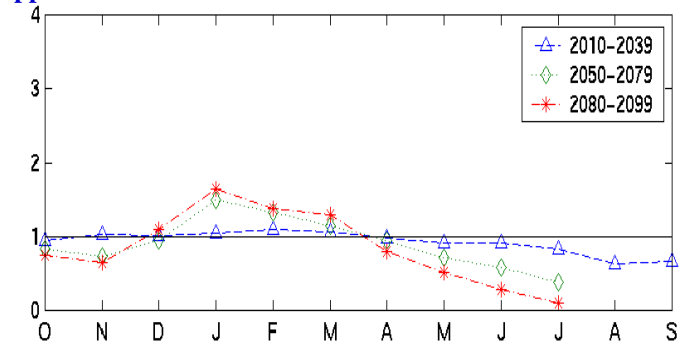
HCM, Merced River

11% Lower: 1676 M, 89% Upper: 2591 M

Lat: 37.8

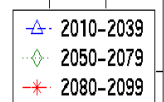


PCM, Merced River

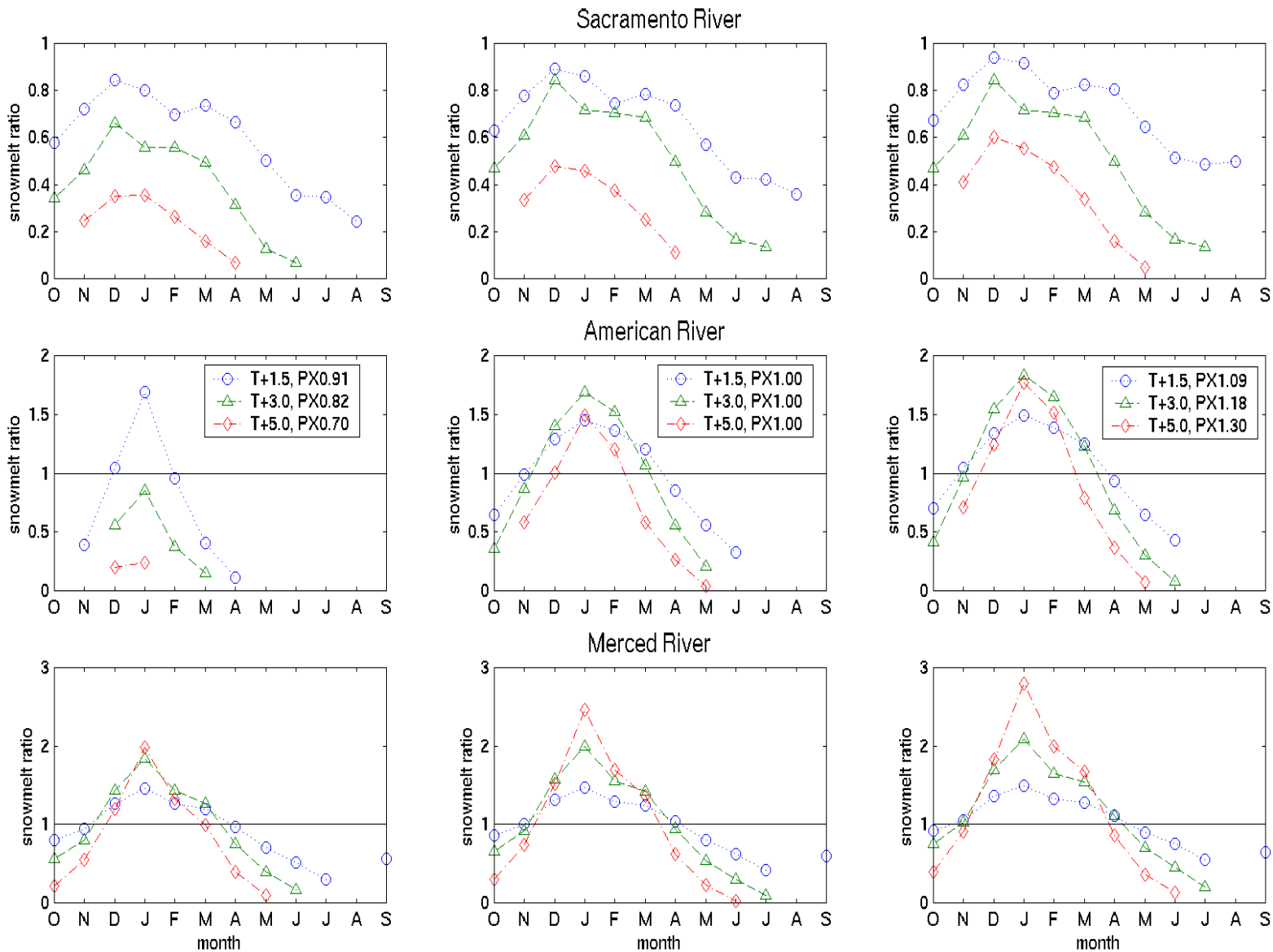


Month

Month



Ratio of Mean-Monthly Projected Snow Melt to Baseline Snow Melt



P Decrease

P No Change

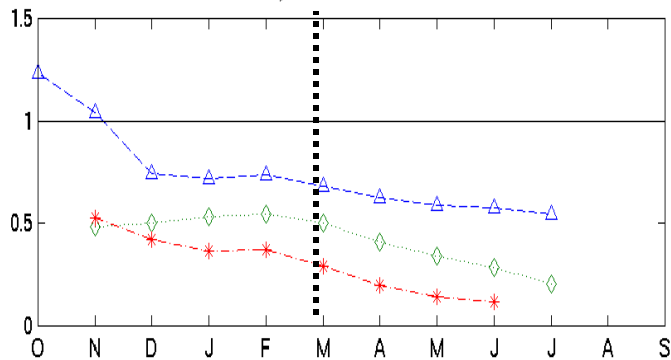
P Increase

Ratio of Mean-Monthly Projected Snow Water Equivalent to Baseline Snow Water Equivalent

Warm-Wet

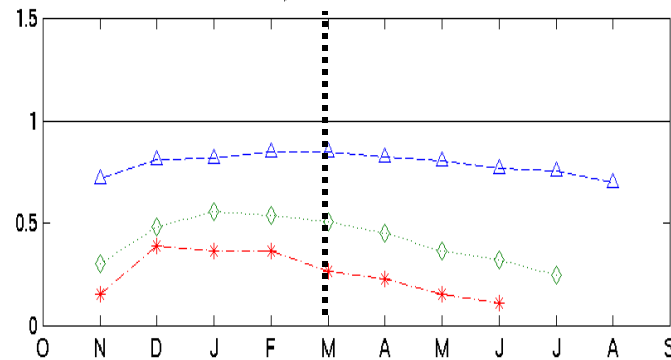
HCM, Sacramento River

73% Lower: 1036 M, 27% Upper 1798 M
Lat: 41.2



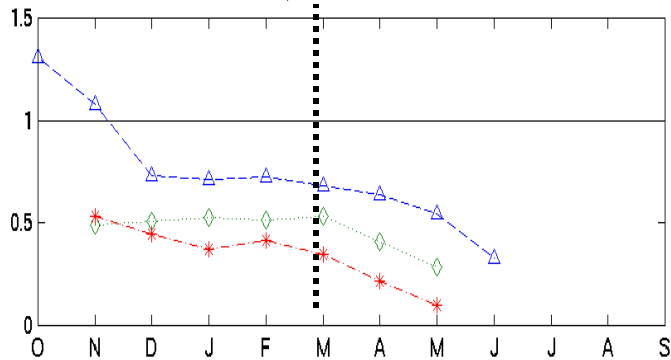
Cool-Dry

PCM, Sacramento River

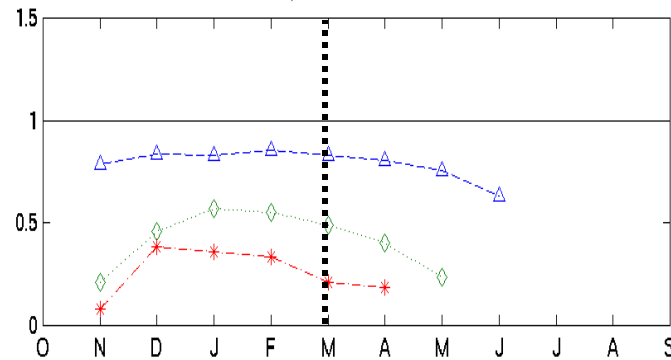


HCM, American River

42% Lower: 1280 M, 58% Upper 1768 M
Lat: 39.9

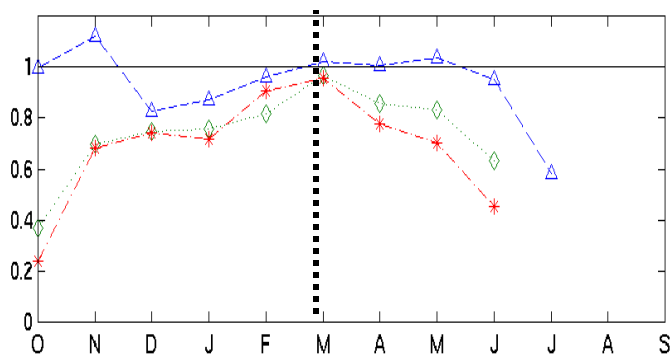


PCM, American River

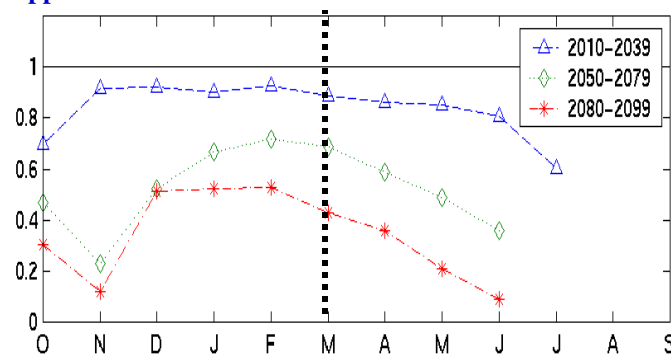


HCM, Merced River

11% Lower: 1676 M, 89% Upper 2591 M
Lat: 37.8

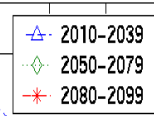


PCM, Merced River



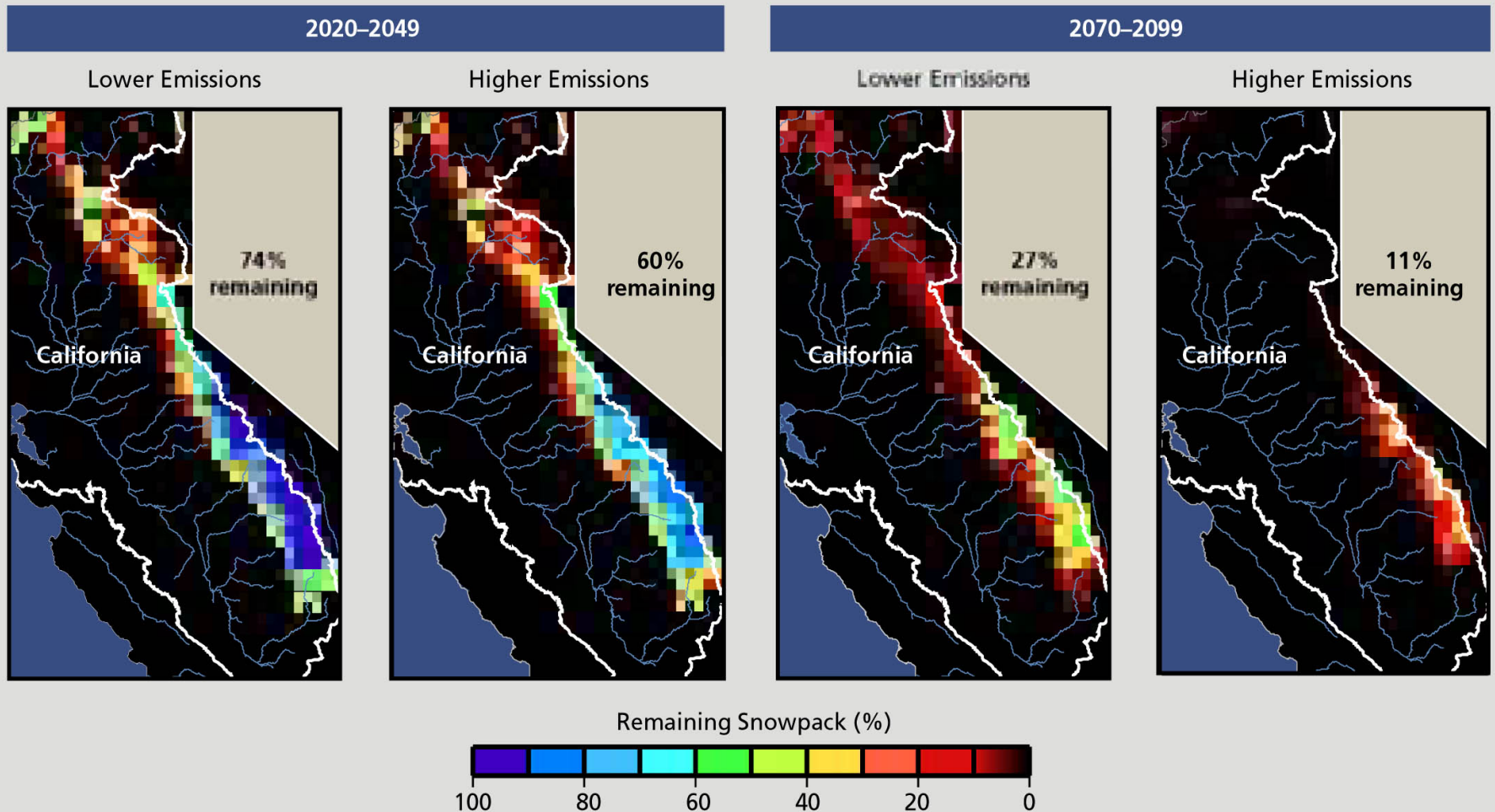
Month

Month

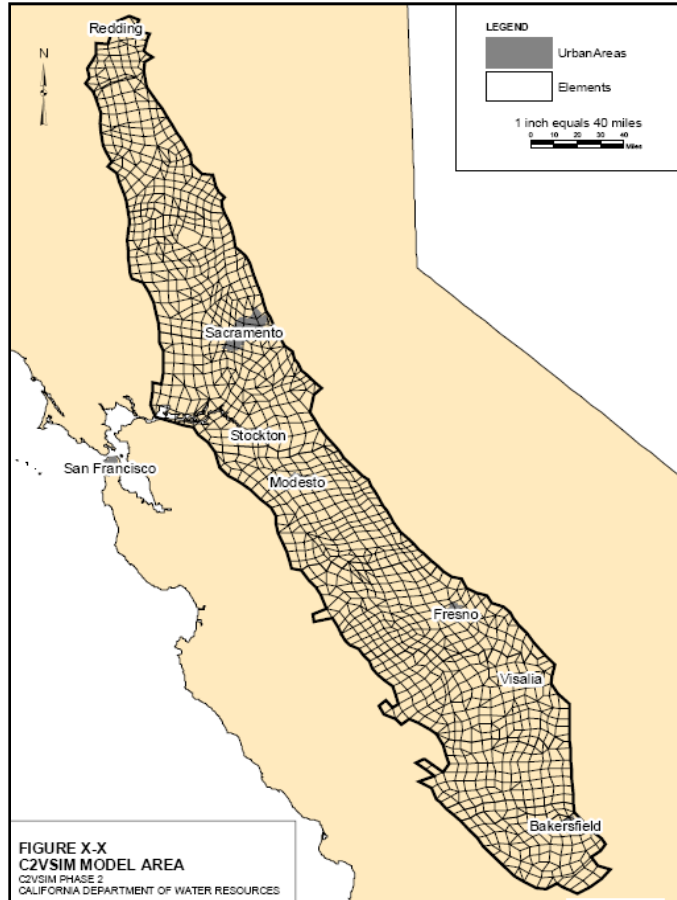


Diminishing Sierra Snowpack

% Remaining, Relative to 1961-1990



Snowpack Reduction Impacts on California Groundwater Water Infrastructure Using C2VSIM



Domain: ~ 20,000 square miles

Drought Experiments

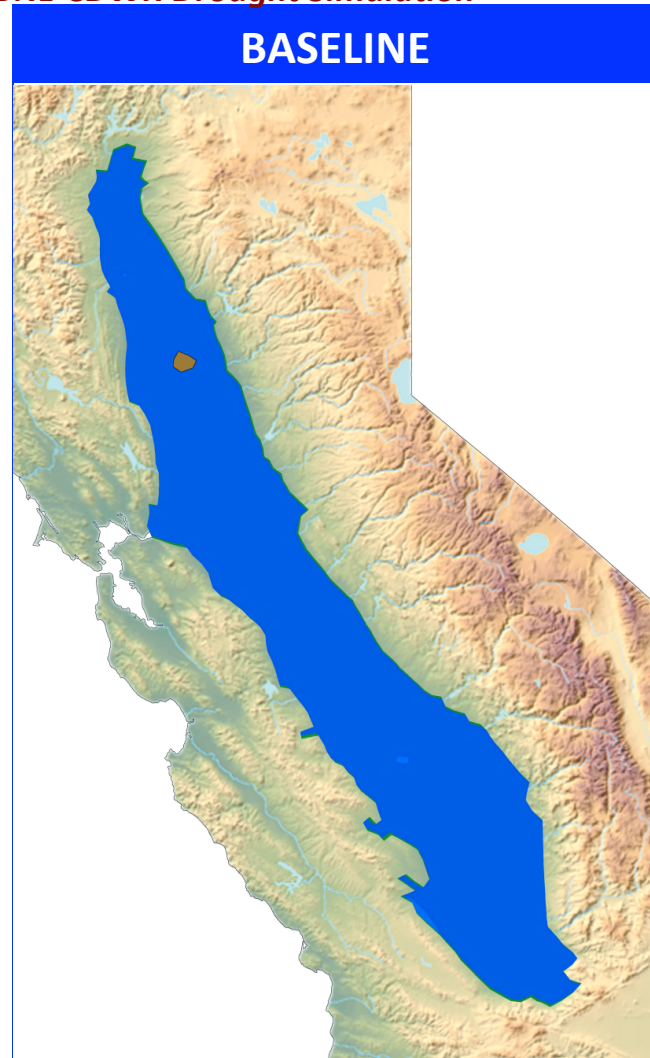
- **Approach:**
 - **Recreate drought scenarios considering historic data**
 - **Managed Surface Water Drought Scenarios**
 - **10 year spin-up;**
 - **Duration: 10, 20, 30, 60 year managed droughts**
 - **Intensity: Dry, Very Dry, Critical 30, 50, 70 effective reduction**
 - **30 year rebound period**
 - **All simulations used fixed 1973-2003 precipitation, urban demands, cropping etc.**

Central Valley Water Table 'Relative' Response

Joint LBNL-CDWR Drought Simulation

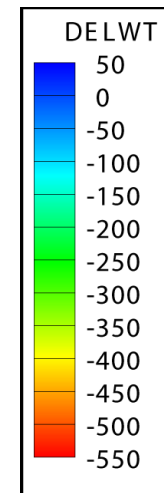
➤ *Climate simulations using the IPCC SRES output indicates California Snowpack will be reduced by 60-90% by 2100.*

➤ *Simulating drought scenarios acts as an analogue to climate warming and provides us with a means to analyze impacts.*



- **Baseline** - no surface water reduction
- **Drought** - 30 - 70 percent surface water reduction
- **All simulations used fixed 1973-2003 precipitation, urban demands, cropping etc.**

Relative WT Change
(Feet)



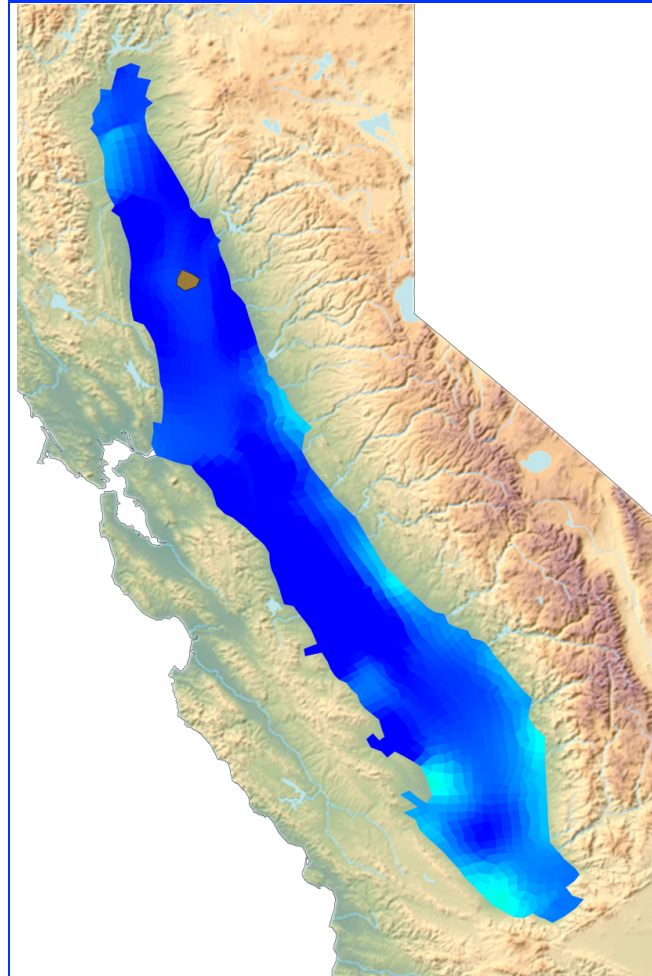
Central Valley Water Table 'Relative' Response

Joint LBNL-CDWR Drought Simulation

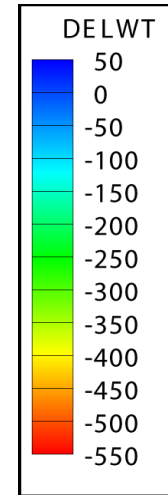
10 YEARS

DRY

*30 PERCENT EFFECTIVE
REDUCTION IN MANAGED SURFACE FLOW.*



Relative WT Change
(Feet)



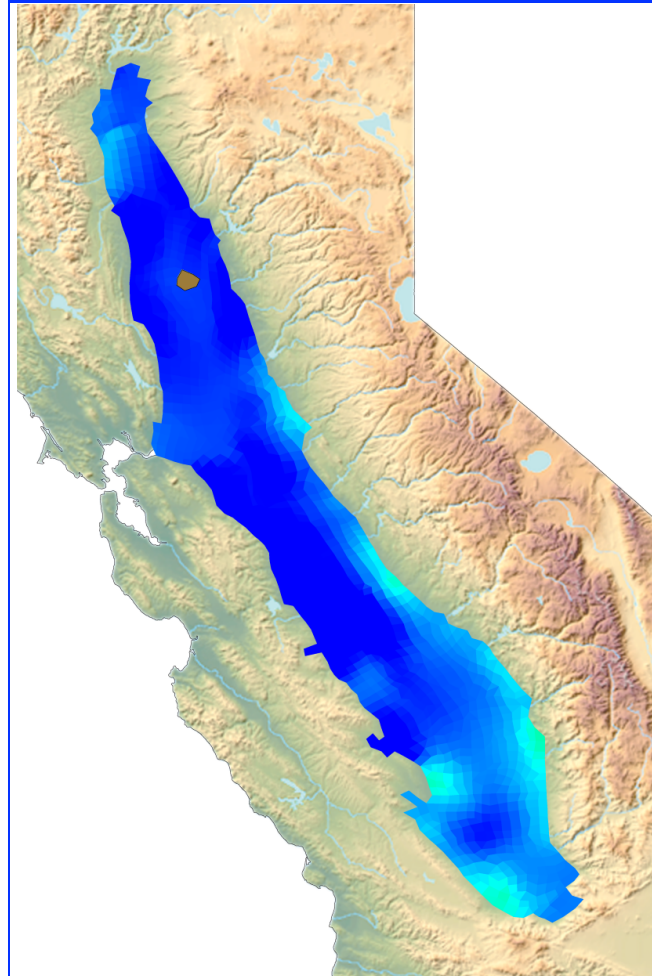
Central Valley Water Table 'Relative' Response

Joint LBNL-CDWR Drought Simulation

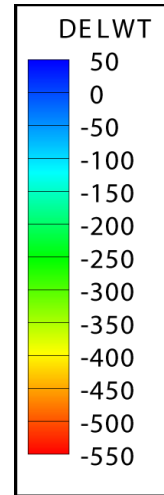
20 YEARS

DRY

*30 PERCENT EFFECTIVE
REDUCTION IN MANAGED SURFACE FLOW.*

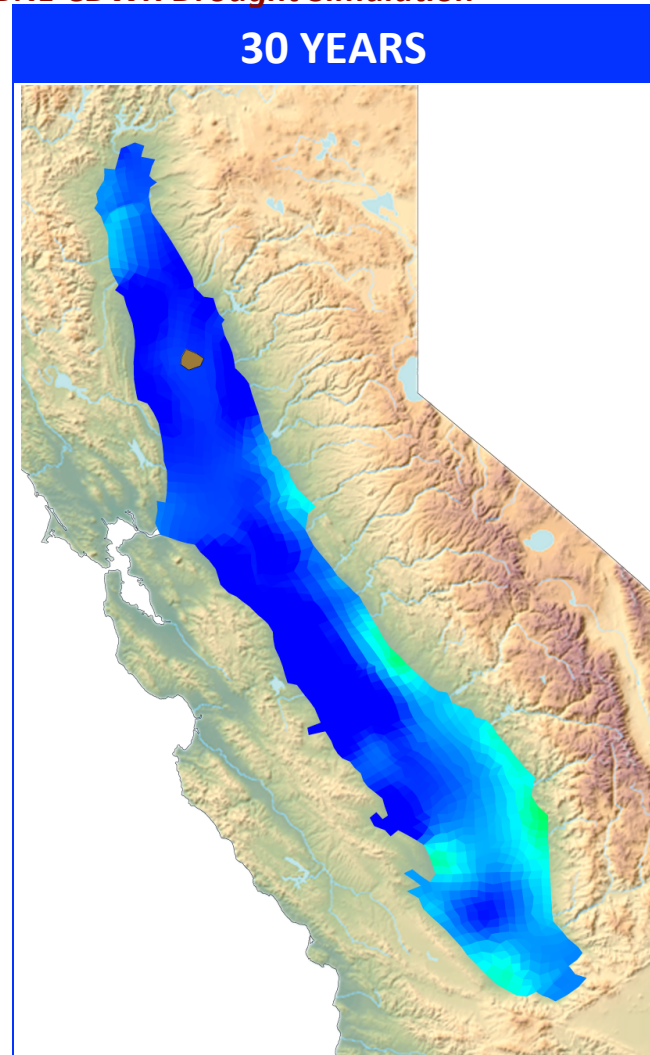


Relative WT Change
(Feet)

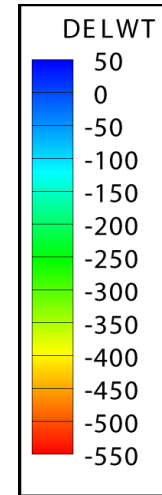


Central Valley Water Table 'Relative' Response

Joint LBNL-CDWR Drought Simulation



Relative WT Change
(Feet)



DRY

*30 PERCENT EFFECTIVE
REDUCTION IN MANAGED SURFACE FLOW.*

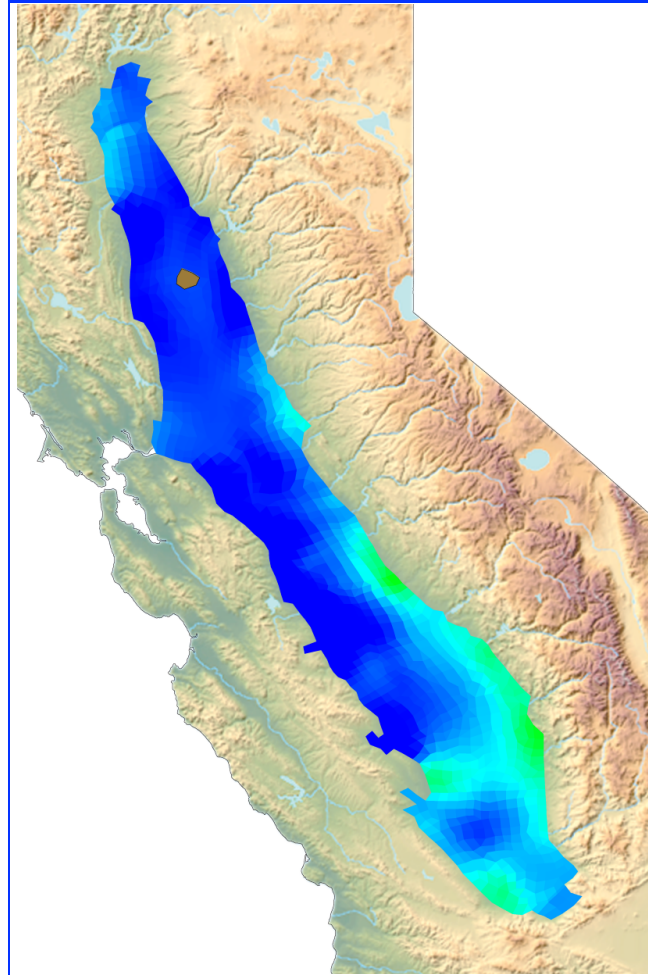
Case II: Initial Central Valley Water Table 'Relative' Response

Joint LBNL-CDWR Drought Simulation

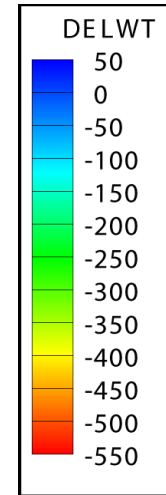
60 YEARS

DRY

*30 PERCENT EFFECTIVE
REDUCTION IN MANAGED SURFACE FLOW.*



Relative WT Change
(Feet)



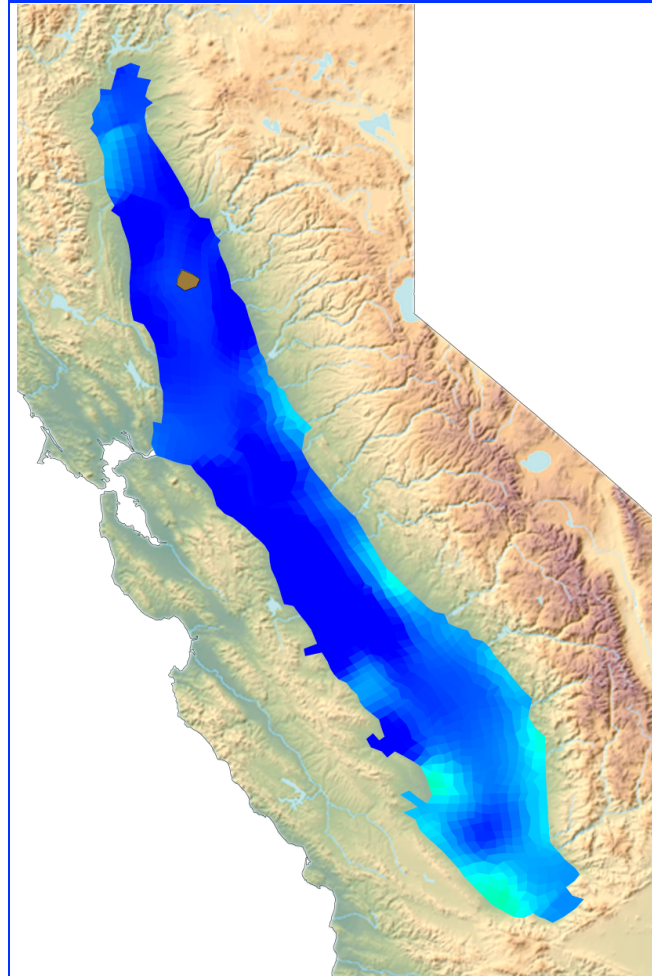
Central Valley Water Table 'Relative' Response

Joint LBNL-CDWR Drought Simulation

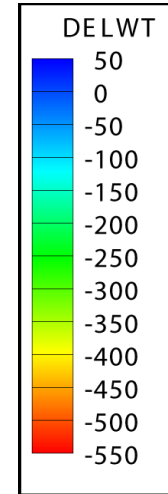
10 YEARS

VERY DRY

*50 PERCENT EFFECTIVE
REDUCTION IN MANAGED SURFACE FLOW.*



Relative WT Change
(Feet)



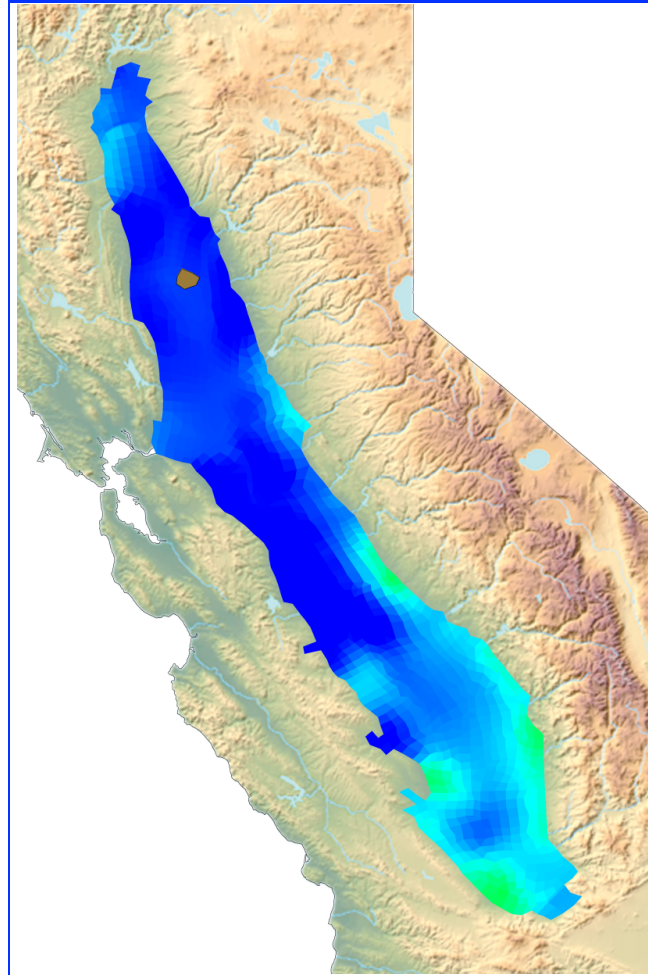
Central Valley Water Table 'Relative' Response

Joint LBNL-CDWR Drought Simulation

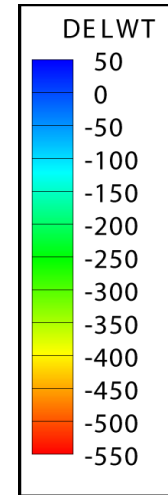
20 YEARS

VERY DRY

*50 PERCENT EFFECTIVE
REDUCTION IN MANAGED SURFACE FLOW.*



Relative WT Change
(Feet)

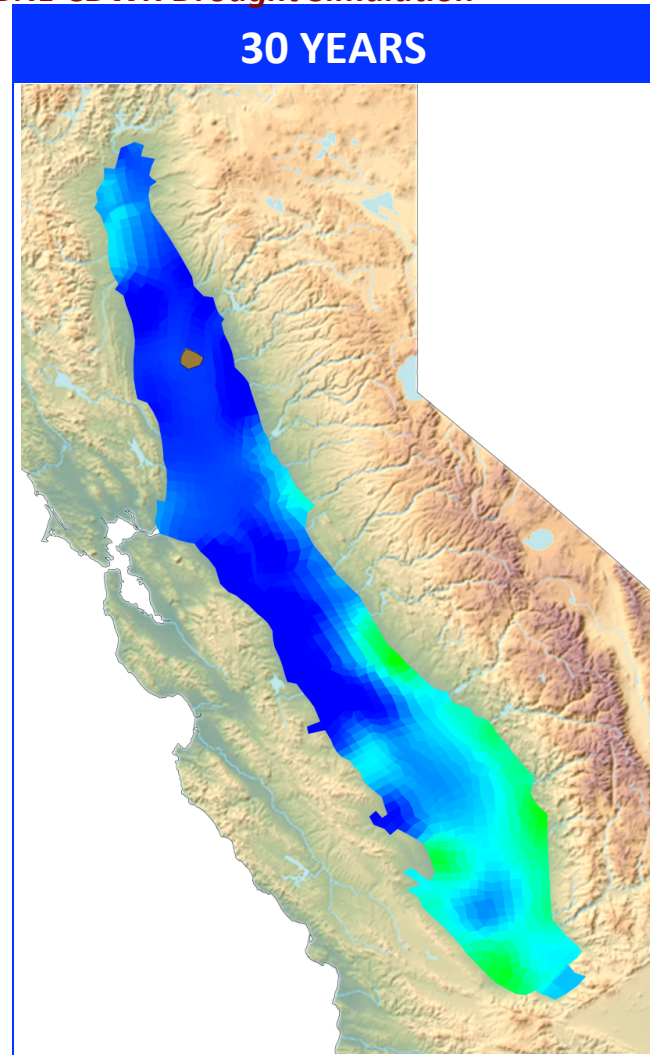


Central Valley Water Table 'Relative' Response

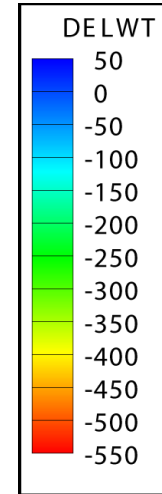
Joint LBNL-CDWR Drought Simulation

VERY DRY

*50 PERCENT EFFECTIVE
REDUCTION IN MANAGED SURFACE FLOW.*



Relative WT Change
(Feet)



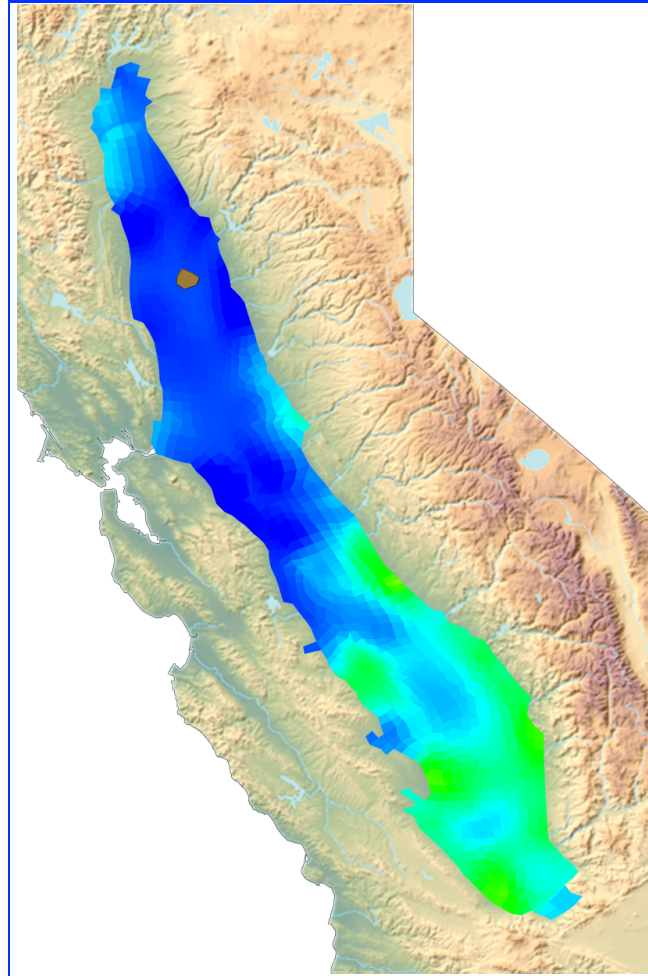
Central Valley Water Table 'Relative' Response

Joint LBNL-CDWR Drought Simulation

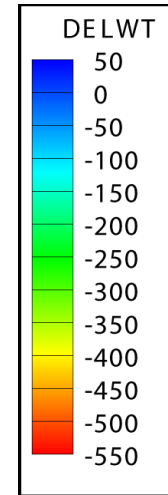
60 YEARS

VERY DRY

*50 PERCENT EFFECTIVE
REDUCTION IN MANAGED SURFACE FLOW.*



Relative WT Change
(Feet)



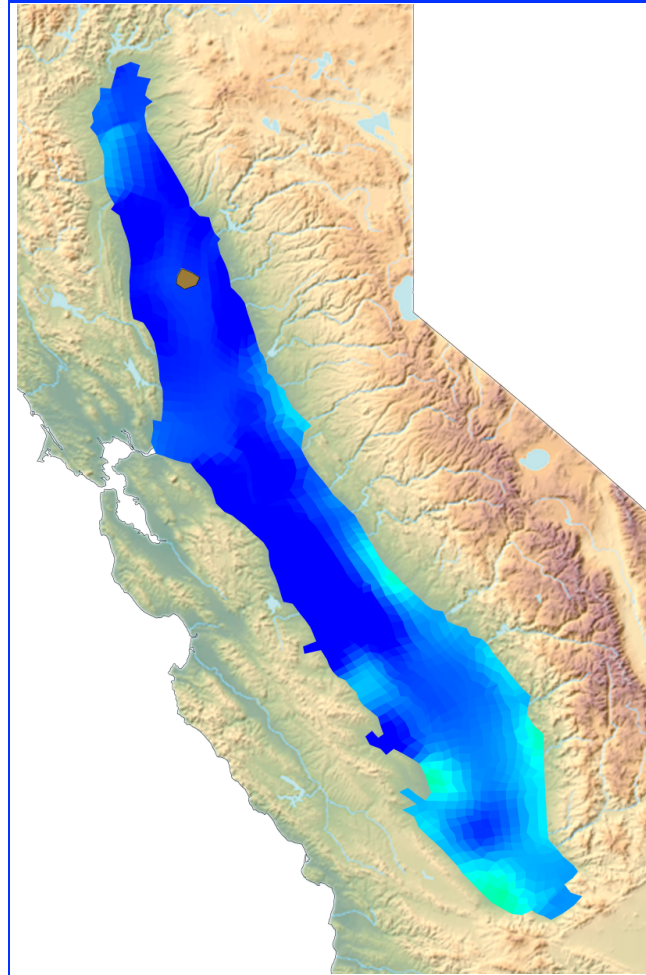
Central Valley Water Table 'Relative' Response

Joint LBNL-CDWR Drought Simulation

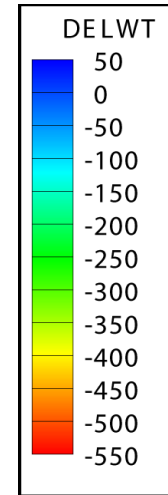
10 YEARS

CRITICAL

*70 PERCENT EFFECTIVE
REDUCTION IN MANAGED SURFACE FLOW.*



Relative WT Change
(Feet)



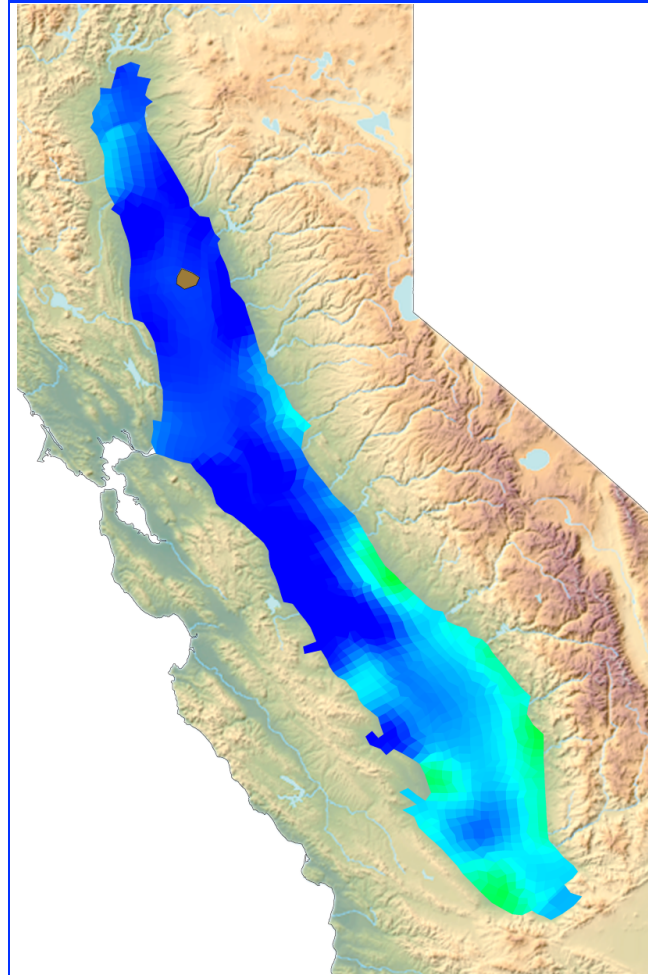
Central Valley Water Table 'Relative' Response

Joint LBNL-CDWR Drought Simulation

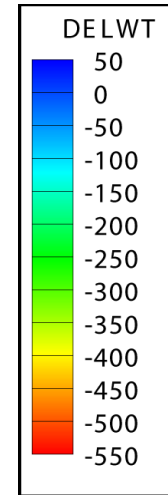
20 YEARS

CRITICAL

*70 PERCENT EFFECTIVE
REDUCTION IN MANAGED SURFACE FLOW.*



Relative WT Change
(Feet)



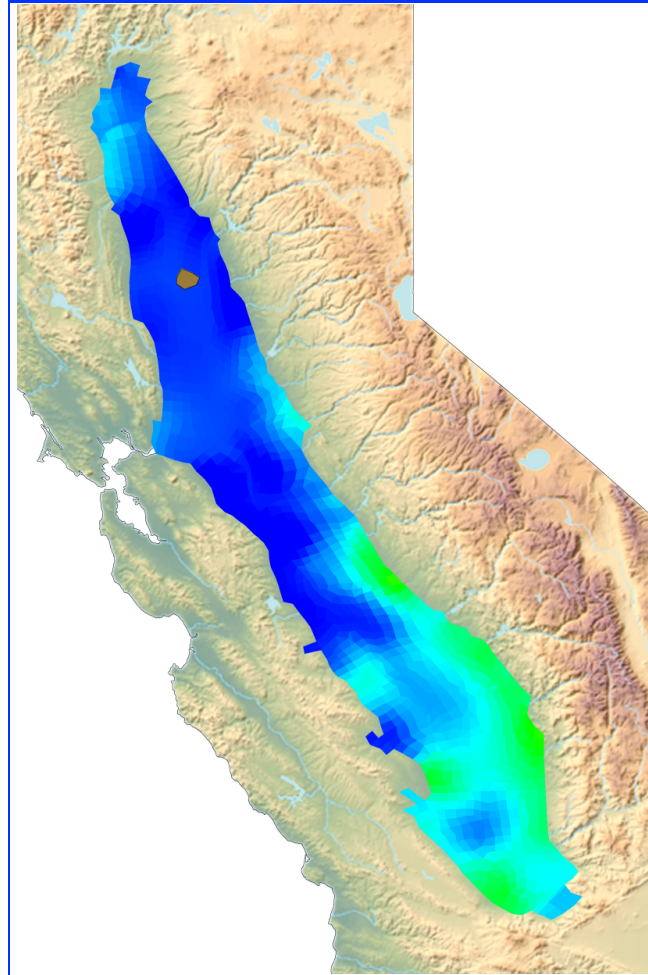
Central Valley Water Table 'Relative' Response

Joint LBNL-CDWR Drought Simulation

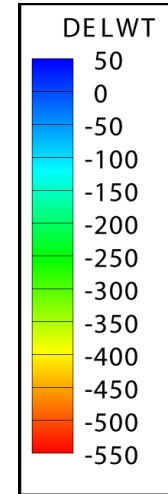
30 YEARS

CRITICAL

*70 PERCENT EFFECTIVE
REDUCTION IN MANAGED SURFACE FLOW.*



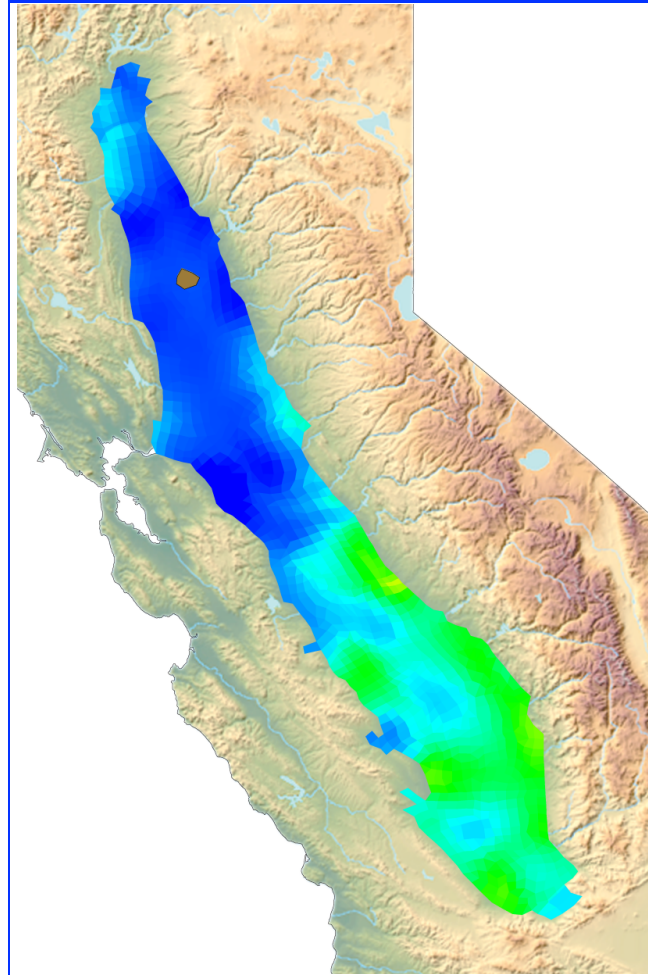
Relative WT Change
(Feet)



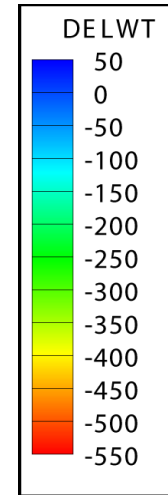
Central Valley Water Table 'Relative' Response

Joint LBNL-CDWR Drought Simulation

60 YEARS



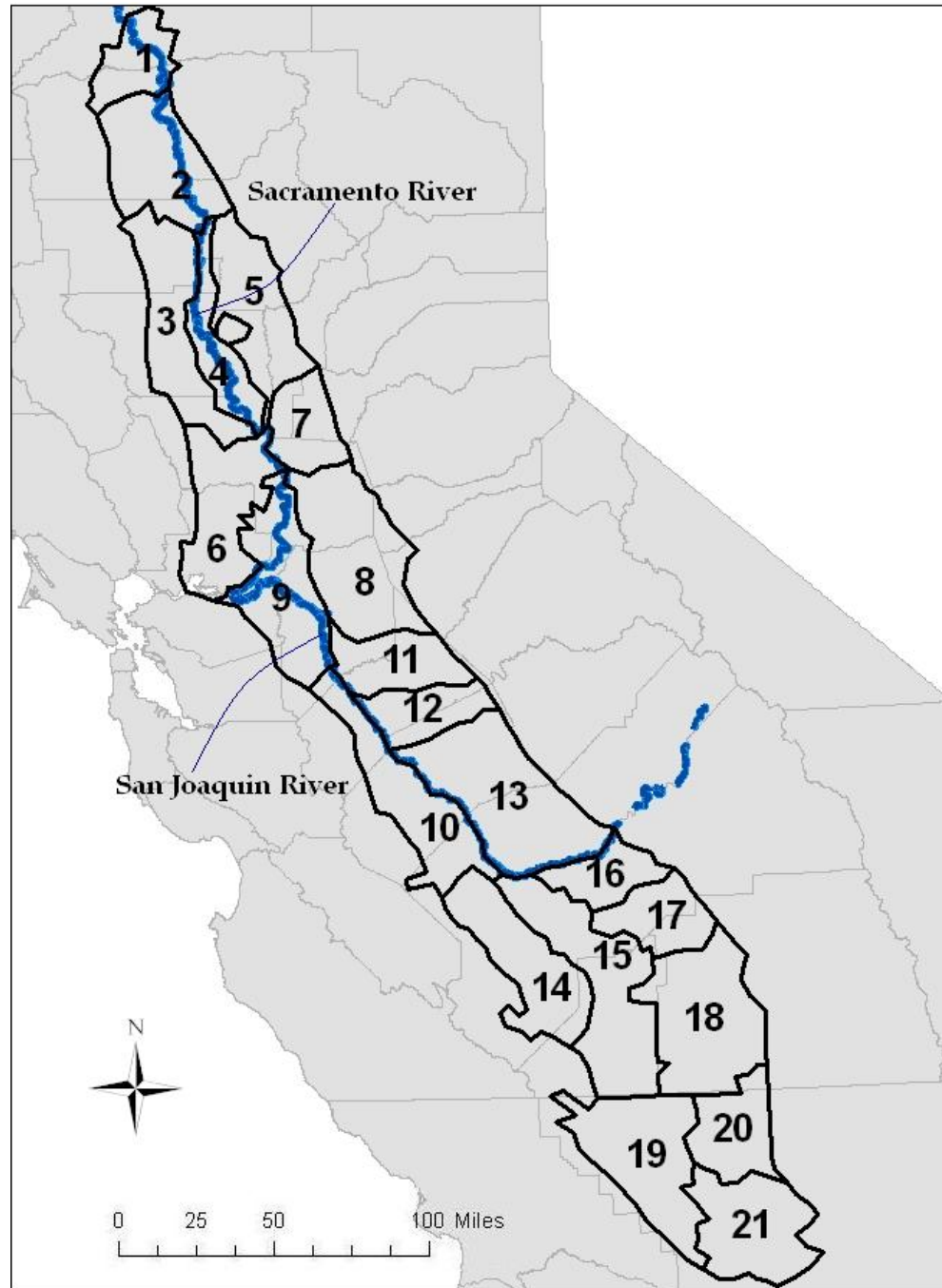
Relative WT Change
(Feet)



CRITICAL

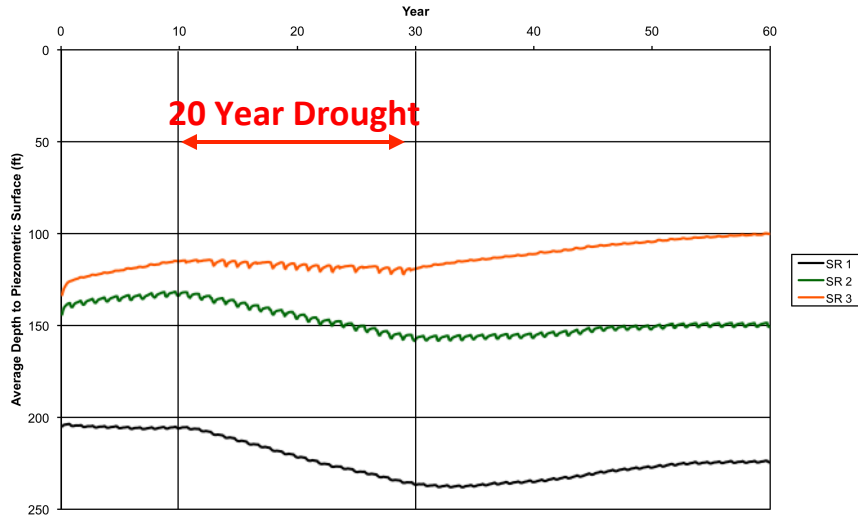
*70 PERCENT EFFECTIVE
REDUCTION IN MANAGED SURFACE FLOW.*

C2VSIM Sub-Regions

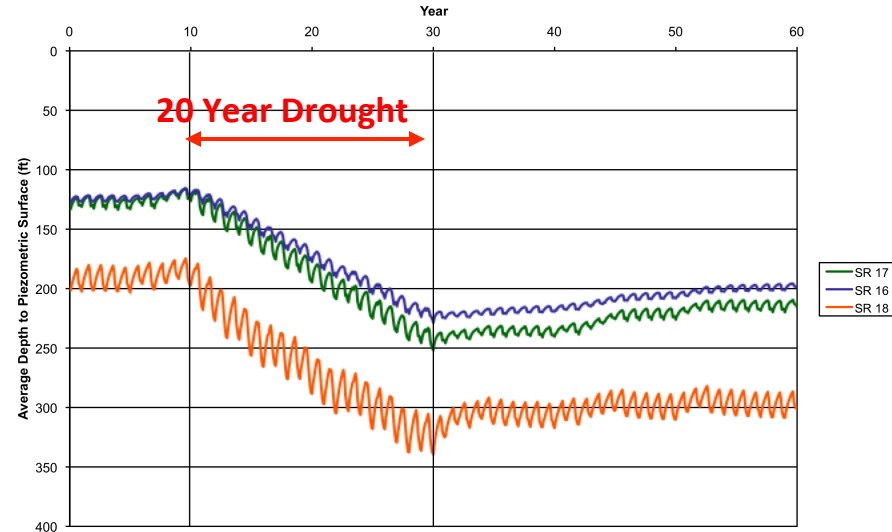


Critical (70 % Reduction)

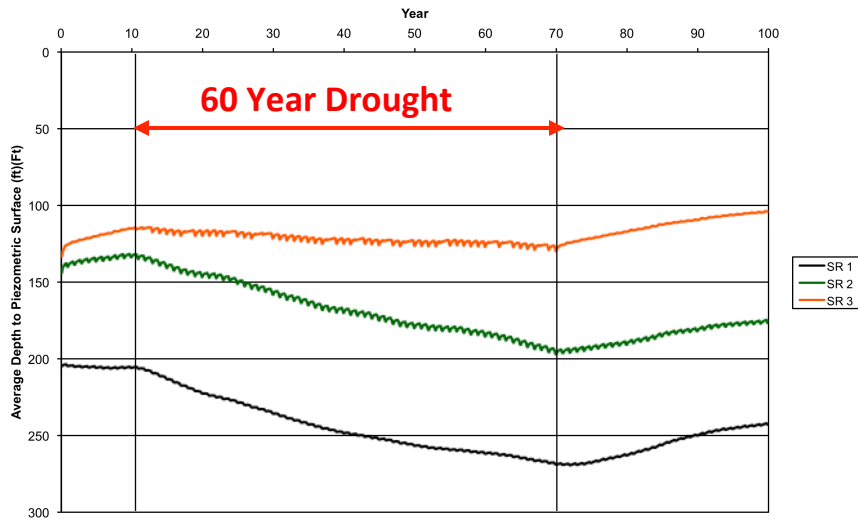
Average Depth to Water in Model Layer 2 - 70% reduction for 20 years



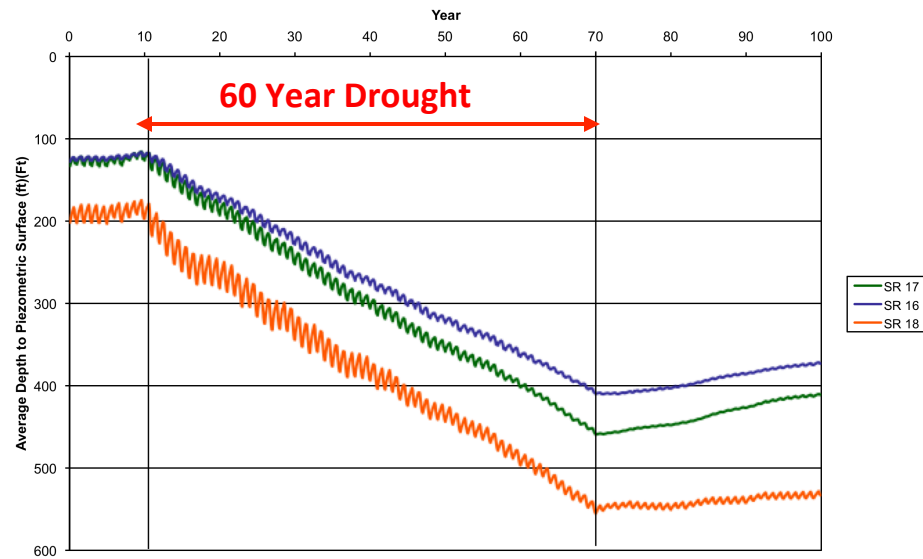
Average Depth to Water in Model Layer 2 - 70% reduction for 20 years



Average Depth to Water in Model Layer 2 - 70% reduction for 60 years



Average Depth to Water in Model Layer 2 - 70% reduction for 60 years



Qualifiers

- **C2VSIM and ALL water allocation models are only partially verified. Many empirical parameters are tuned.**
- **The groundwater processes lack sufficient physical descriptions.**
- **Groundwater total mass and variation is not known.**
- **Pumping is based on a limited available demand record.**
- **Demand is fixed and agriculture does not shift with change in supply.**

Summary

- California and the SW have experienced multi-decadal droughts in the past.
- The present exceptional drought is in its fourth year. Many, many new wells are being drilled to tap groundwater.
- Warm North Pacific SSTs have contributed to the presence of the persistent high which blocks storms to the north of California.
- It will take years to recover if there is above average precipitation.
- At this point in time we cannot say definitively that this is directly caused by global warming, but it is CERTAINLY made worse through increased evaporation and shifts in storm tracks.
- Drought impacts have become very serious in part due to the *population* growth and resource demands that go with it.