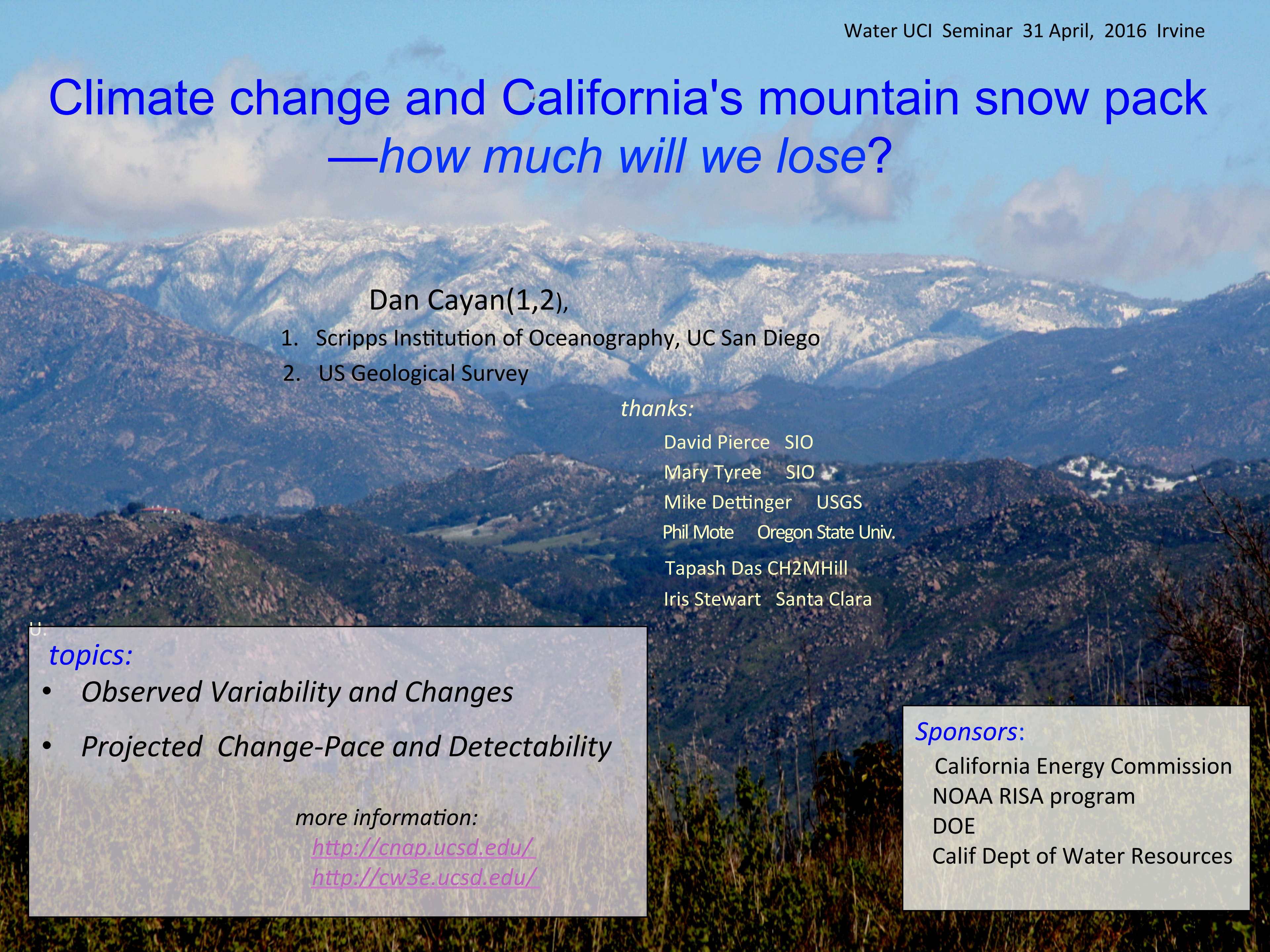


Water UCI Seminar 31 April, 2016 Irvine

Climate change and California's mountain snow pack —*how much will we lose*?

Dan Cayan(1,2),

1. Scripps Institution of Oceanography, UC San Diego
2. US Geological Survey

thanks:

David Pierce	SIO
Mary Tyree	SIO
Mike Dettinger	USGS
Phil Mote	Oregon State Univ.
Tapash Das	CH2MHill
Iris Stewart	Santa Clara

U.

topics:

- *Observed Variability and Changes*
- *Projected Change-Pace and Detectability*

more information:

http://cnap.ucsd.edu/

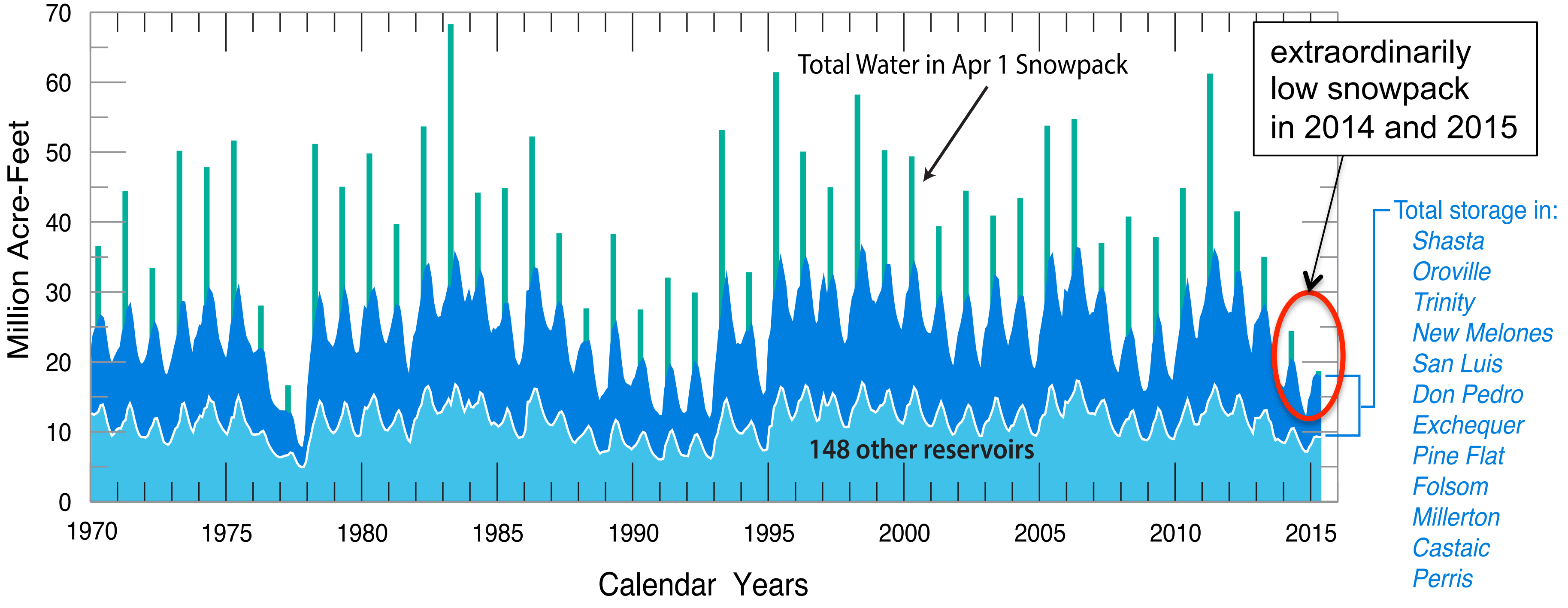
http://cw3e.ucsd.edu/

Sponsors:

California Energy Commission
NOAA RISA program
DOE
Calif Dept of Water Resources

Spring snowpack water varies greatly from year to year
but on average contains about 70% of the water stored in California’s Reservoirs

TOTAL WATER STORED *(monthly)*
in 12 major & 148 other California Reservoirs
with Statewide April 1 Snow-water contents
(stacked atop each other)



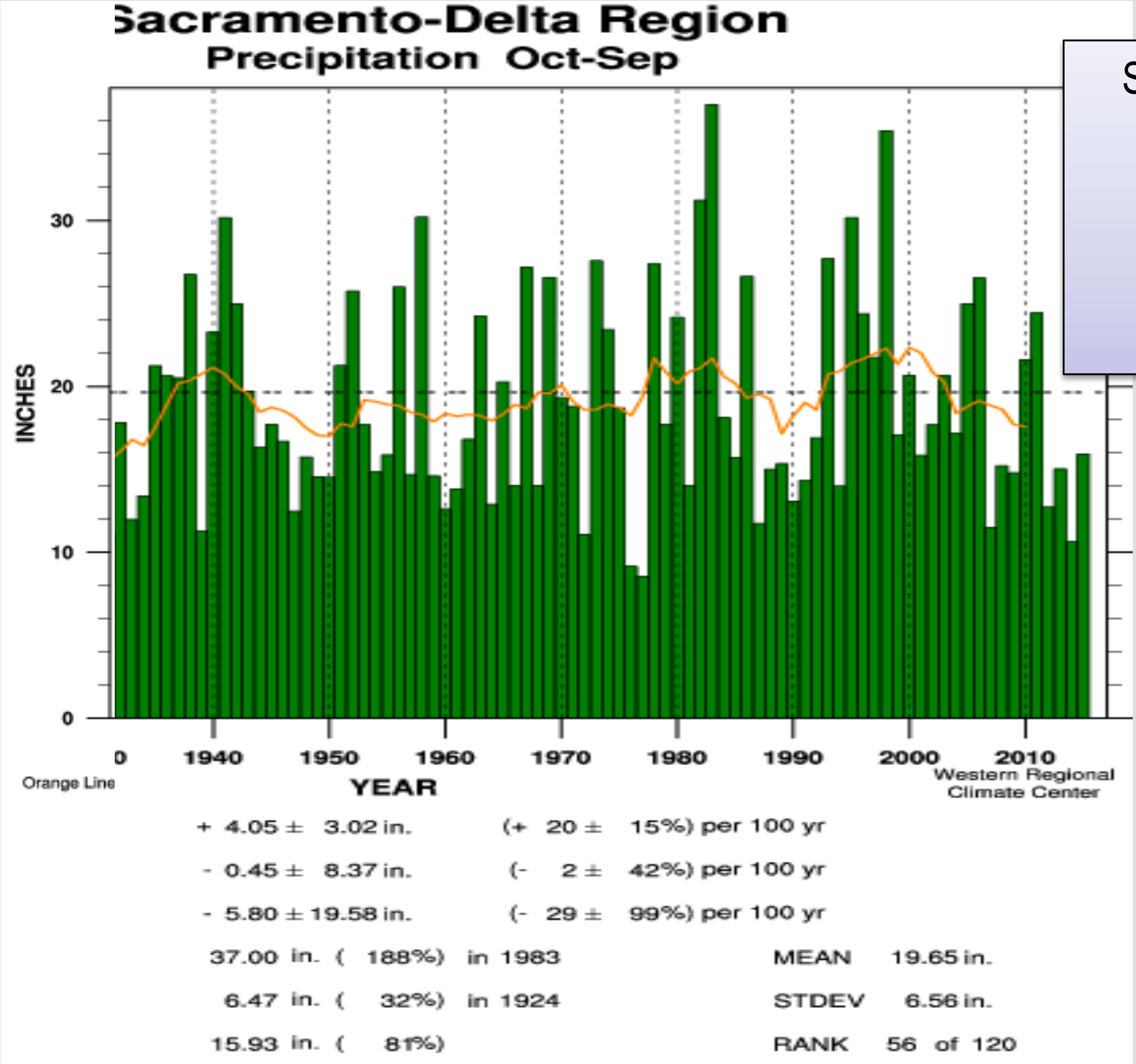
extraordinarily low snowpack in 2014 and 2015

Figure 1 Monthly totals of water stored in (dark blue) 12 major reservoirs and (light blue) 148 other, mostly smaller reservoirs, stacked on top of each other, and (green bars) estimated statewide-total of water stored in April 1 snowpacks each year, January 1970 through April 2015

Mike Dettinger, Mike Anderson

Dettinger, Michael D.; & Anderson, Michael L.(2015). Storage in California's Reservoirs and Snowpack in this Time of Drought. San Francisco Estuary and Watershed Science, 13(2). jmie_sfews_27912.

2012-2015 dry spell is characteristic of California's volatile precipitation climate



Sacramento-Delta Region
Precipitation Oct-Sep

+ 4.05 ± 3.02 in. (+ 20 ± 15%) per 100 yr

- 0.45 ± 8.37 in. (- 2 ± 42%) per 100 yr

- 5.80 ± 19.58 in. (- 29 ± 99%) per 100 yr

37.00 in. (188%) in 1983		MEAN	19.65 in.
6.47 in. (32%) in 1924		STDEV	6.56 in.
15.93 in. (81%)		RANK	56 of 120

Sacramento Delta Drainage
Annual Precipitation

coef of Variation 33%

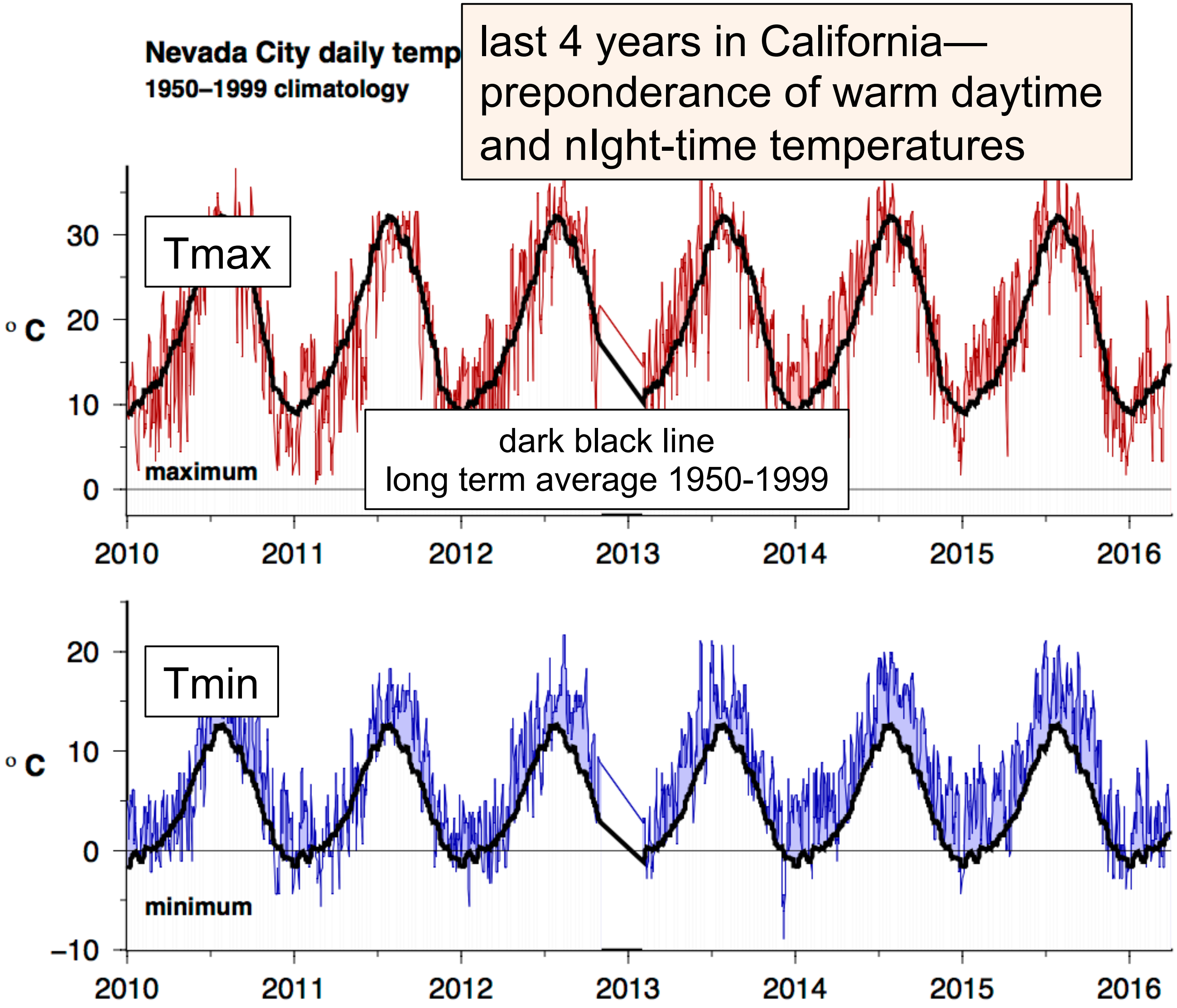
mean 19.7 inches
std dev 6.6 inches

California has a narrow seasonal window to generate its annual water supply.

If atmospheric conditions are unfavorable during that period, a dry year results

2014 ~50% of long term average

California Climate Tracker
Western Regional Climate Center



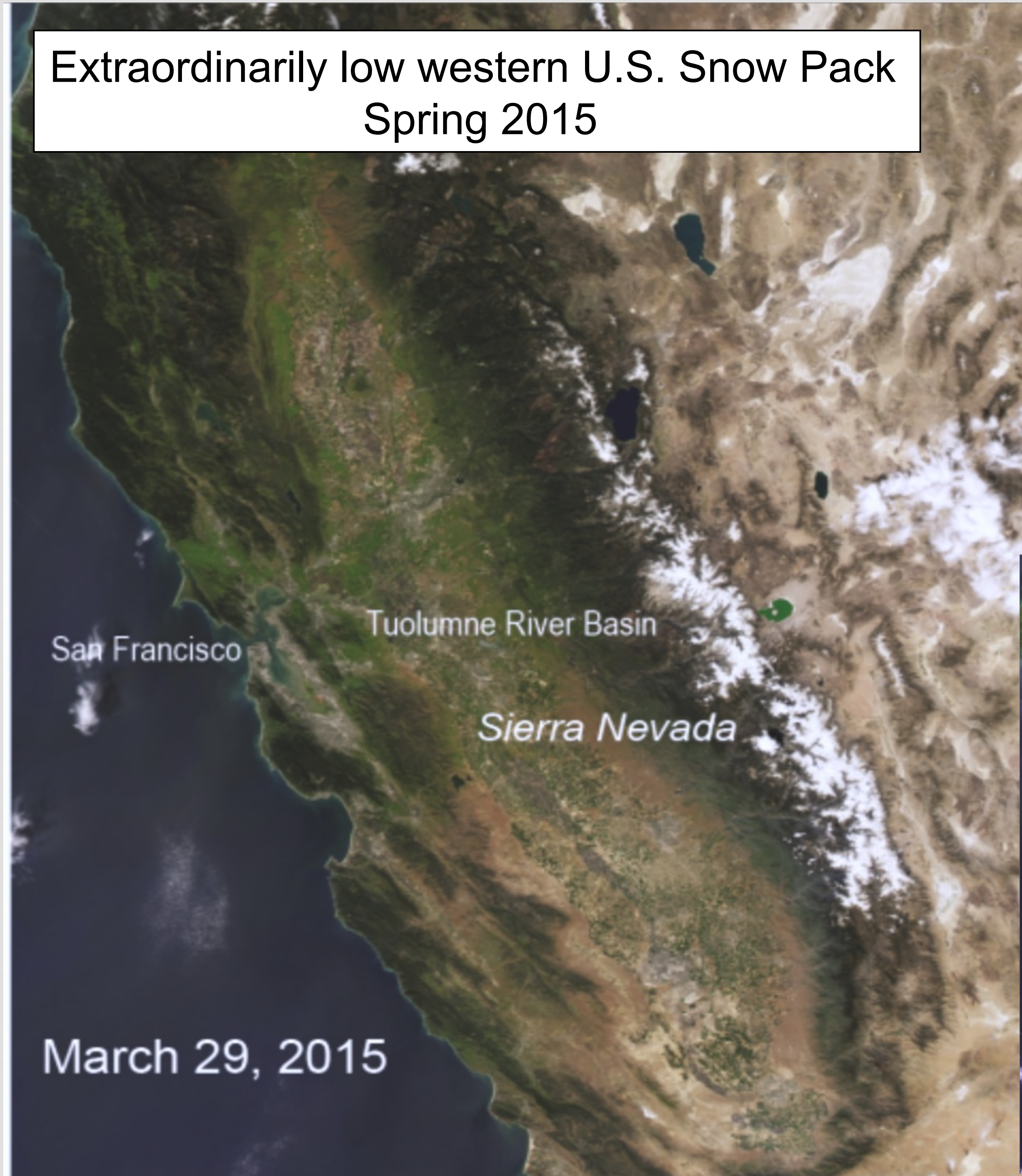
last 4 years in California—
preponderance of warm daytime
and nIght-time temperatures

Tmax

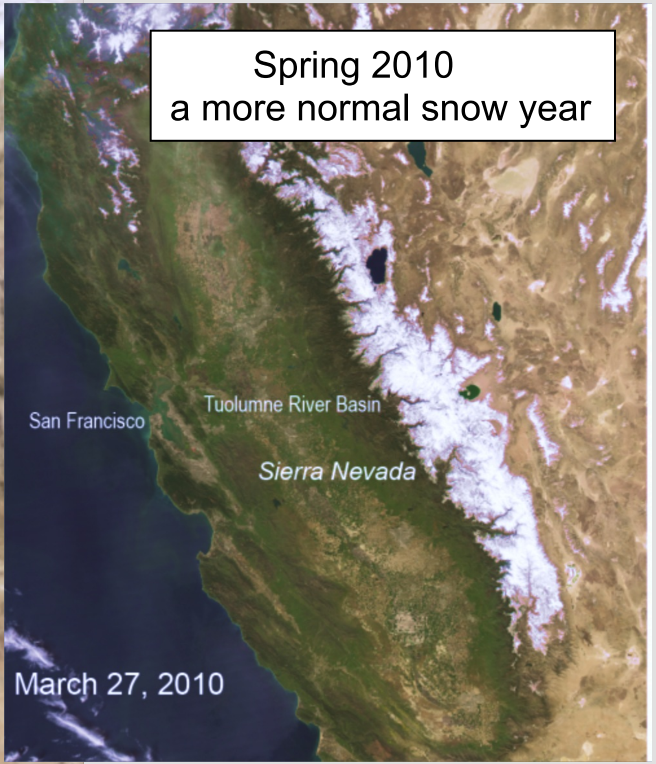
dark black line
long term average 1950-1999

Tmin

Extraordinarily low western U.S. Snow Pack
Spring 2015

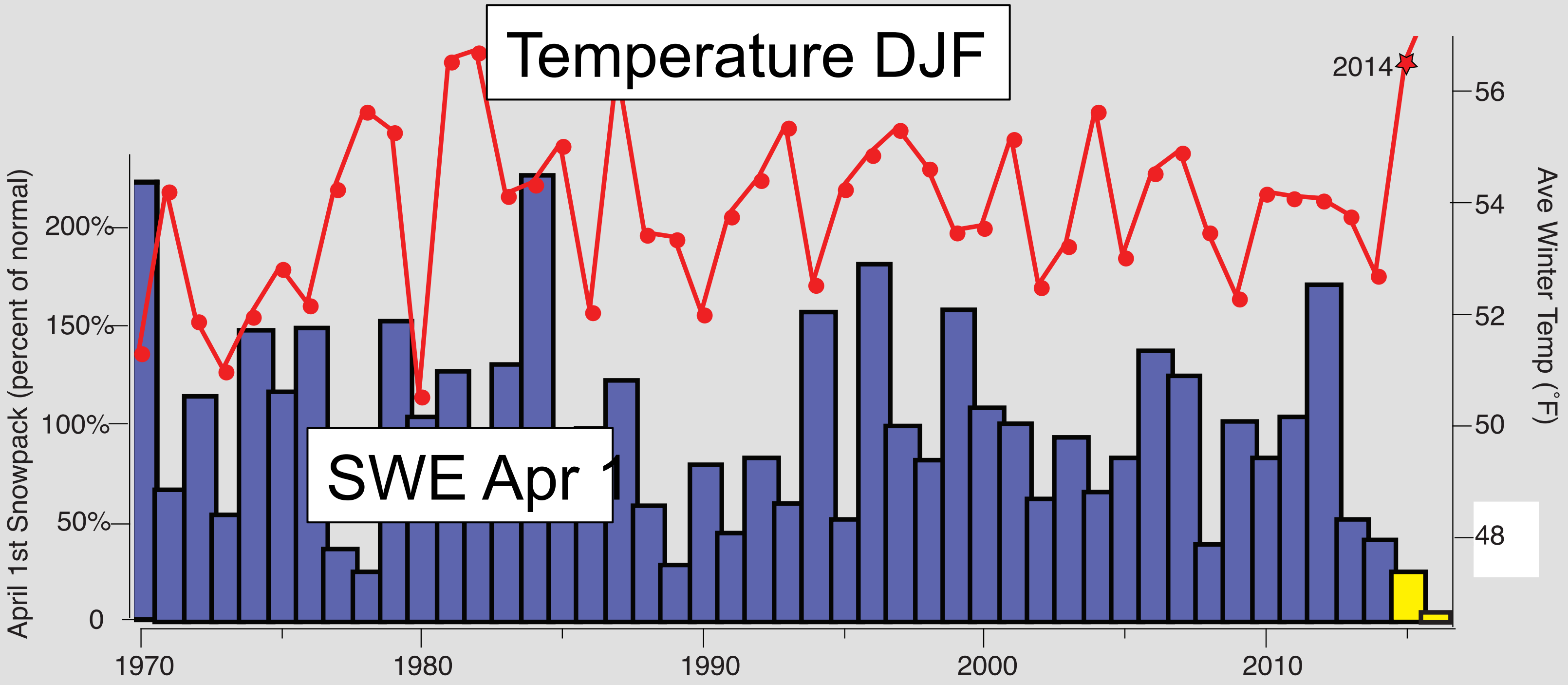


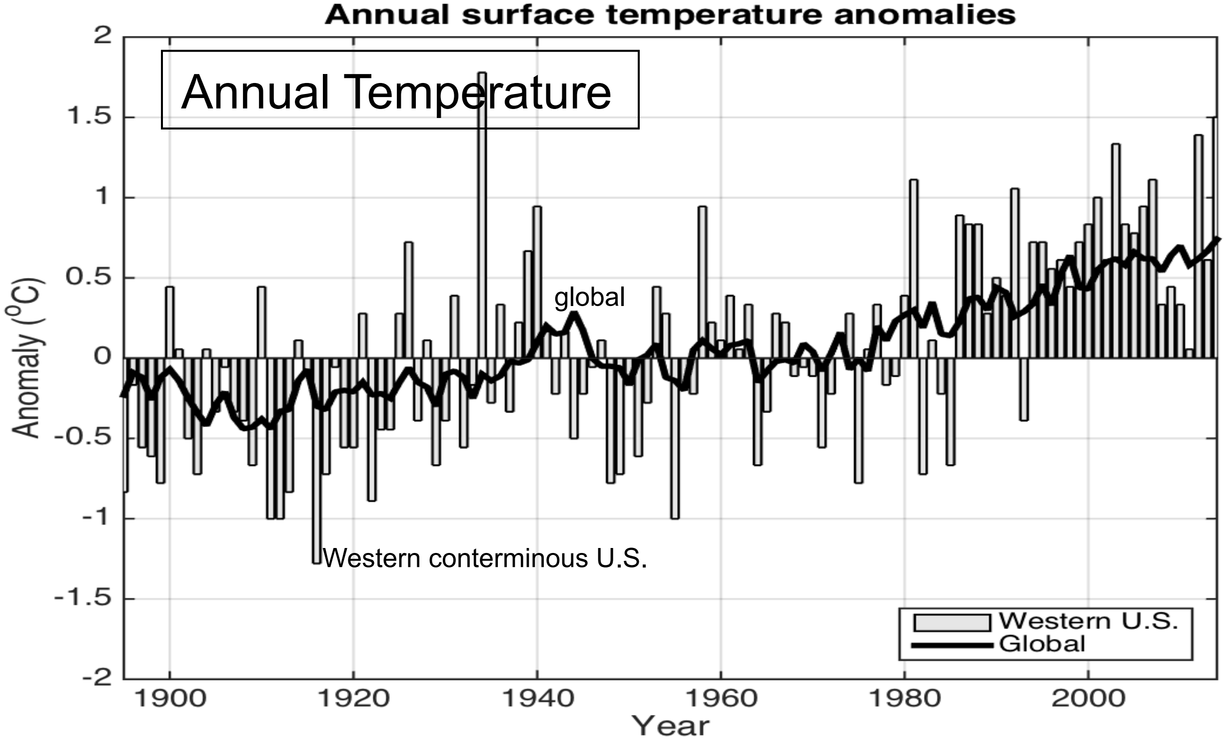
Spring 2010
a more normal snow year



Temperature is only moderately correlated with California Snowpack

but lowest snow years tend to be quite warm



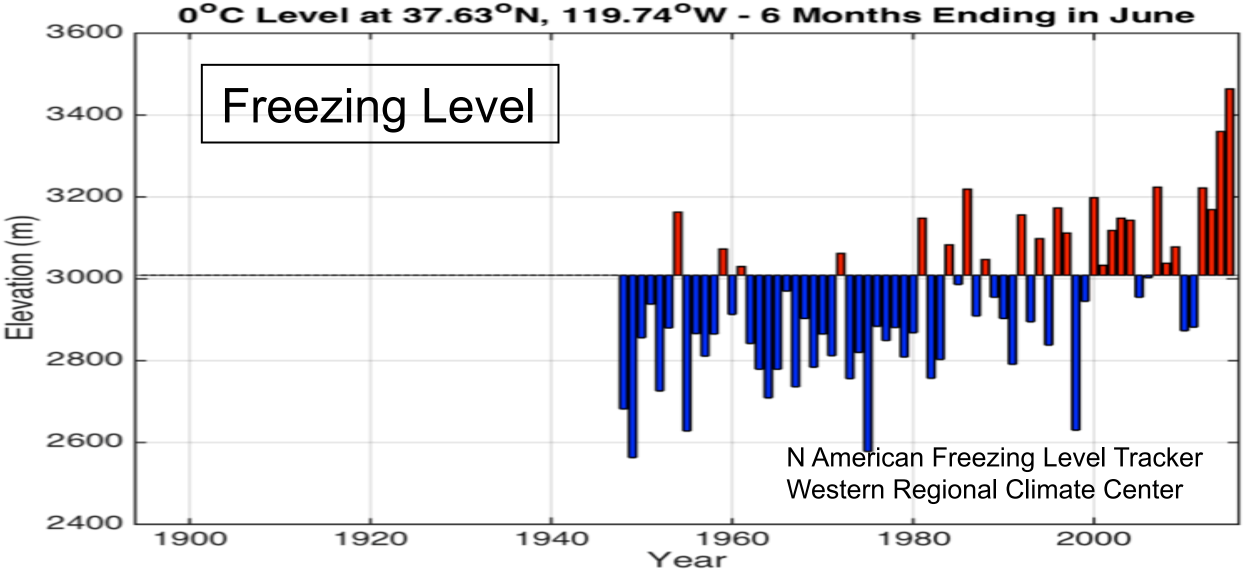


Annual surface temperature anomalies

Annual Temperature

global

Western conterminous U.S.

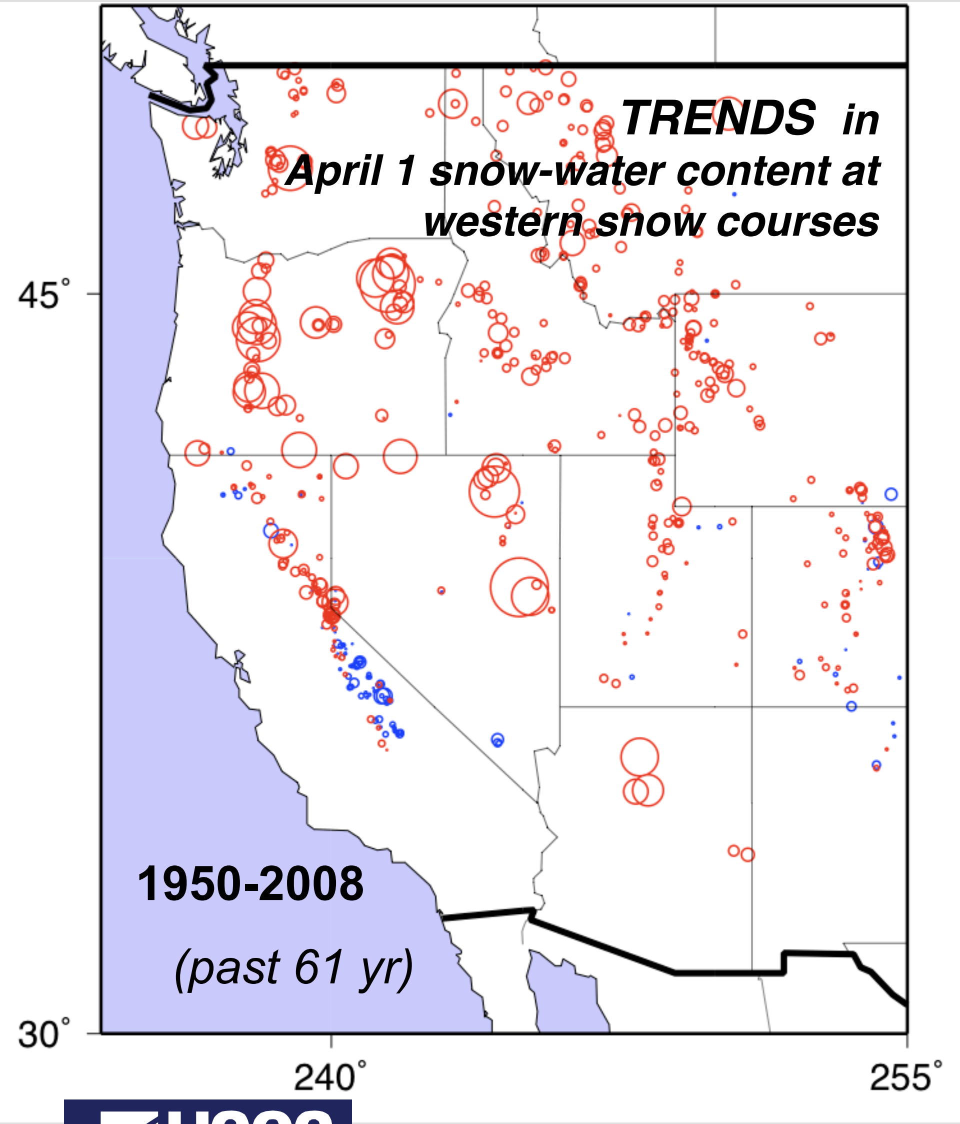


0°C Level at 37.63°N, 119.74°W - 6 Months Ending in June

Freezing Level

N American Freezing Level Tracker
Western Regional Climate Center

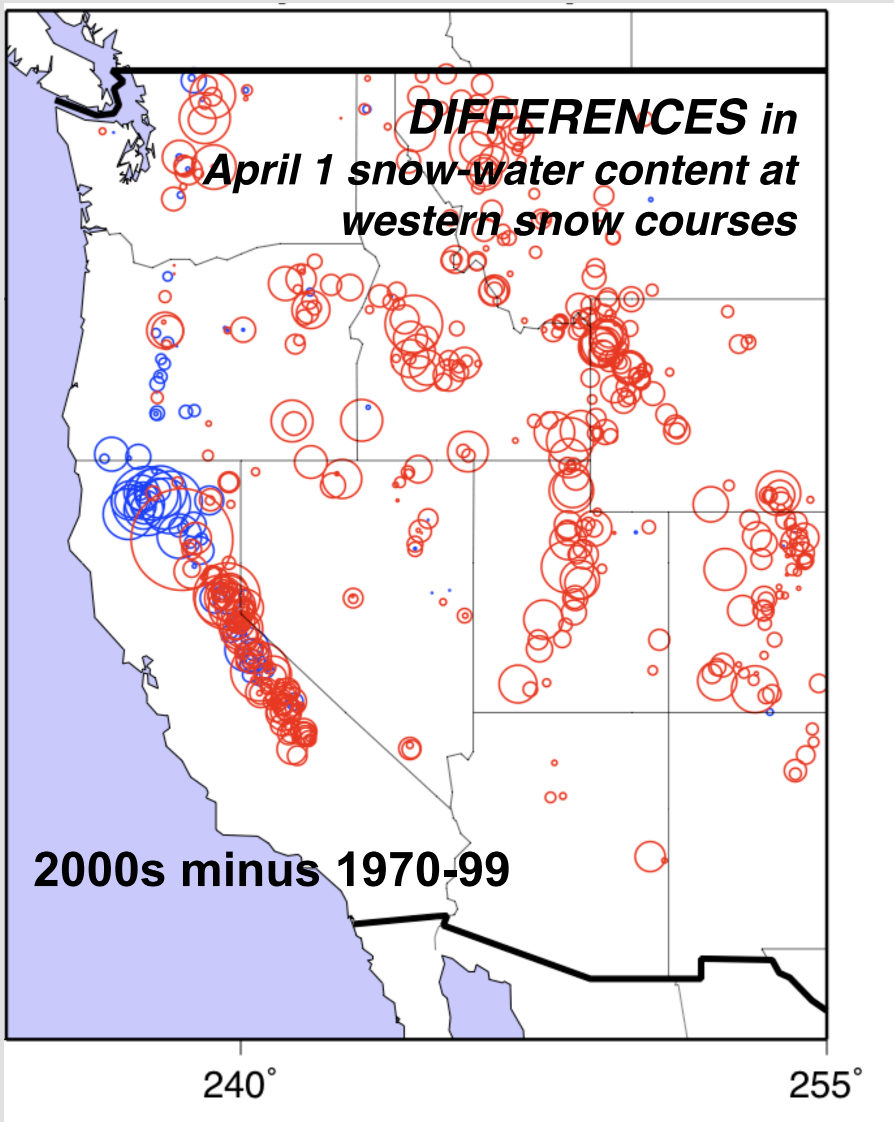
Western Snowpack declines continue



TRENDS in April 1 snow-water content at western snow courses

1950-2008

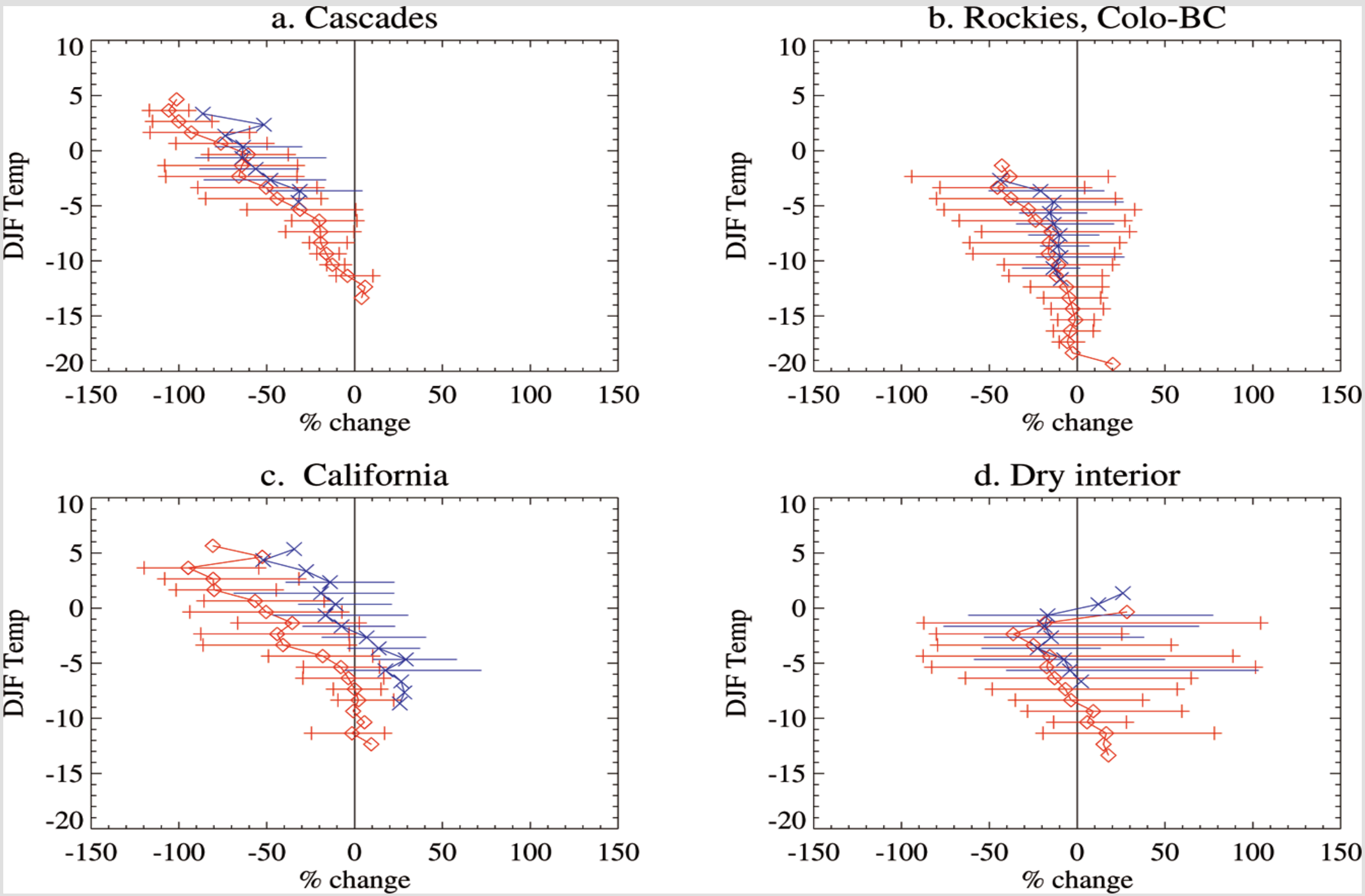
(past 61 yr)



DIFFERENCES in April 1 snow-water content at western snow courses

2000s minus 1970-99

Mike Dettinger, after Phil Mote et al



Snow losses (Apr 1) have occurred in lower (warmer) elevations as shown directly from snow course observations (blue) and VIC model reanalysis (red)

Phil Mote and colleagues (2005)

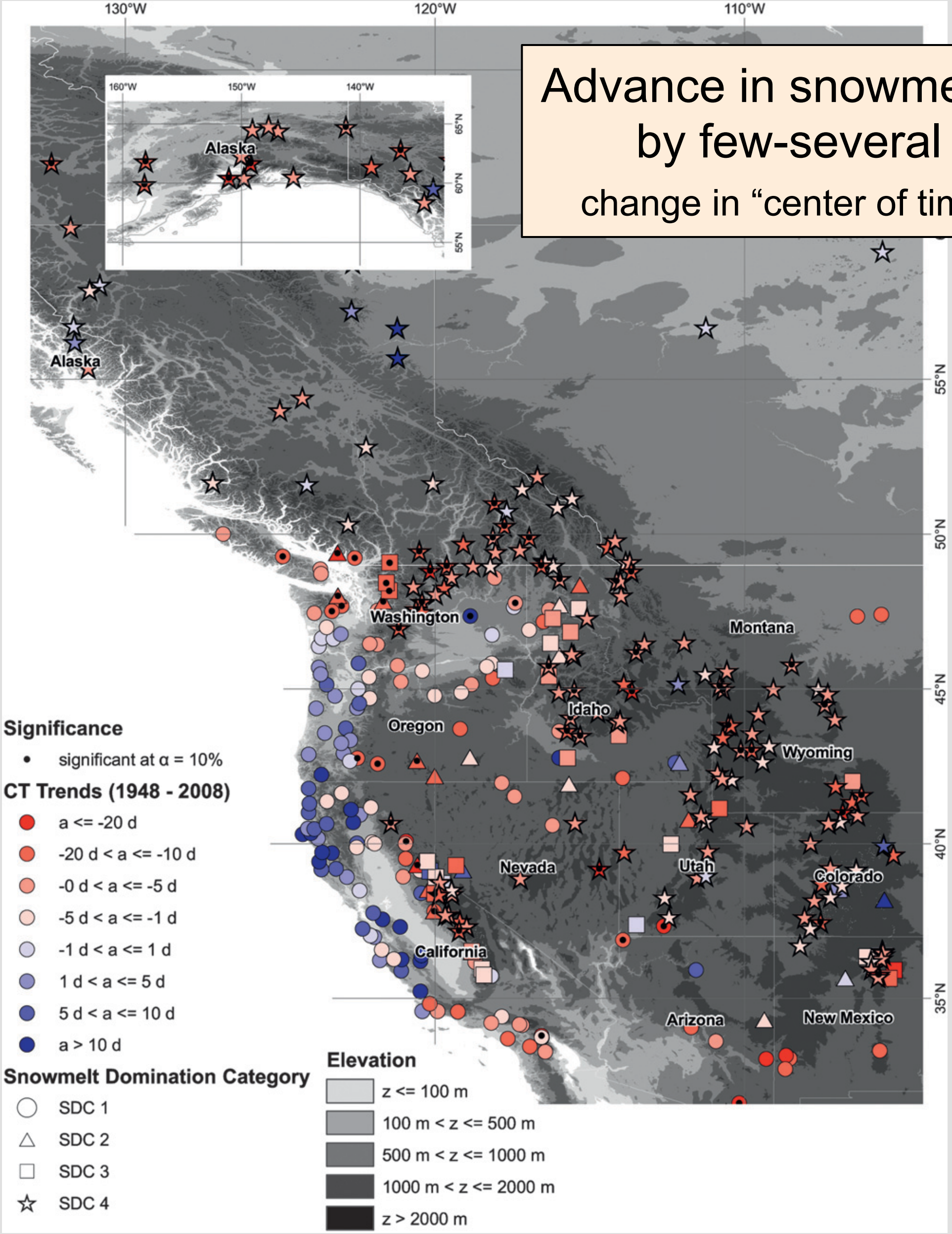


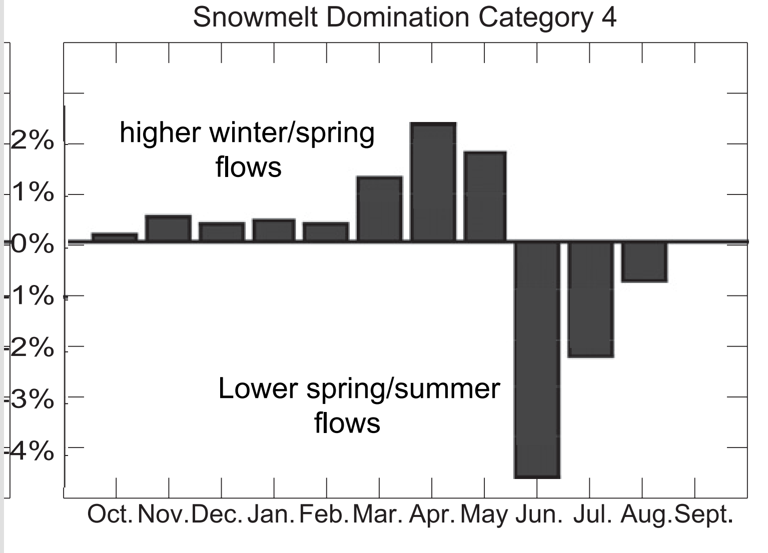
FIG. 3. Trends in CT for each SDC. Trend values are given in days over the 61-yr period.

Advance in snowmelt streamflow by few-several days

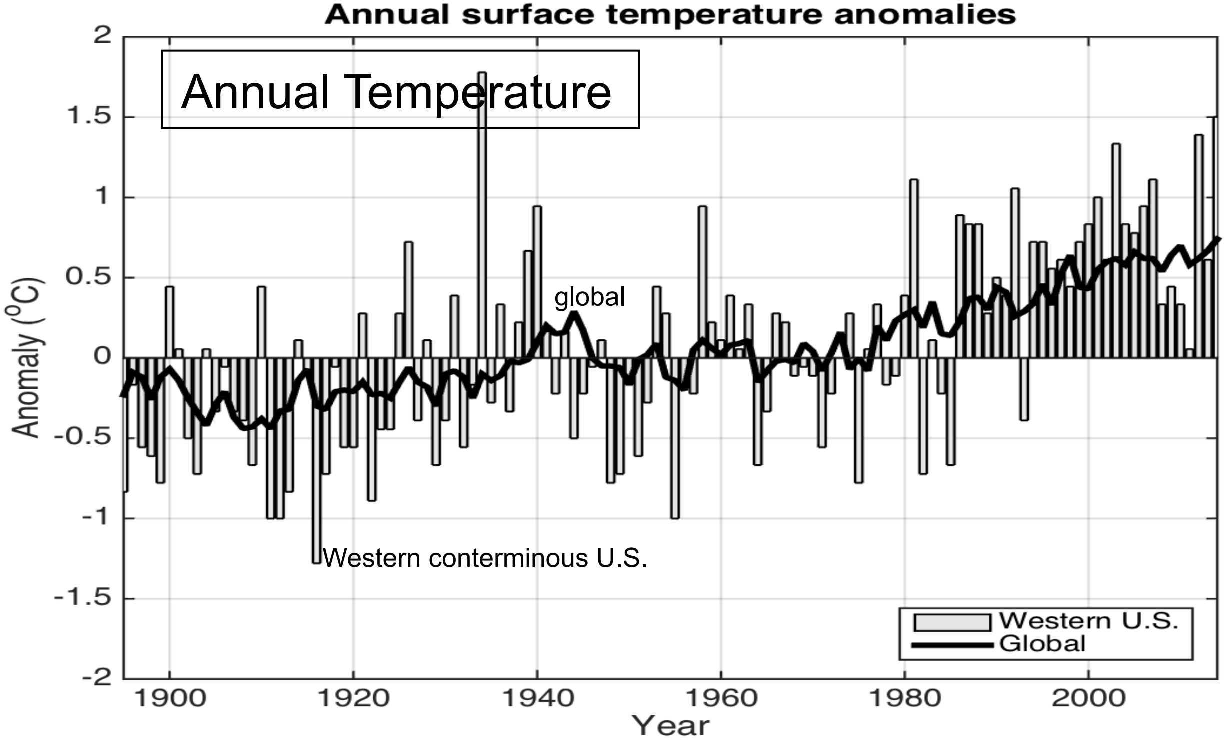
change in "center of timing" 1948-2008

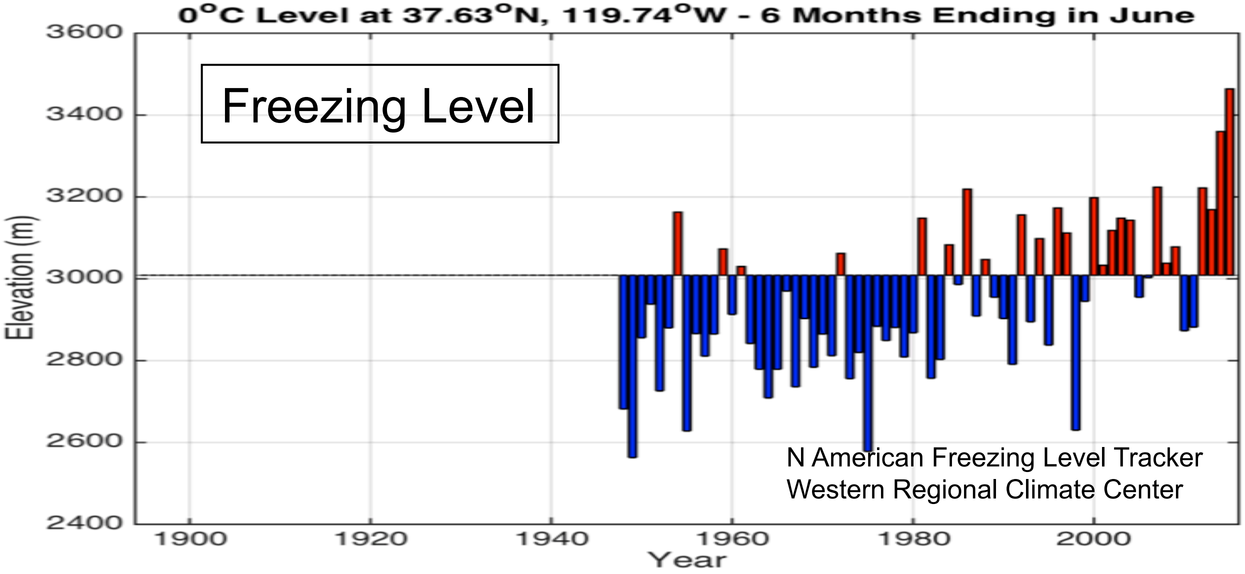
shift toward earlier flows in snow-dominated streams

shown by changes in
monthly fraction of annual flow



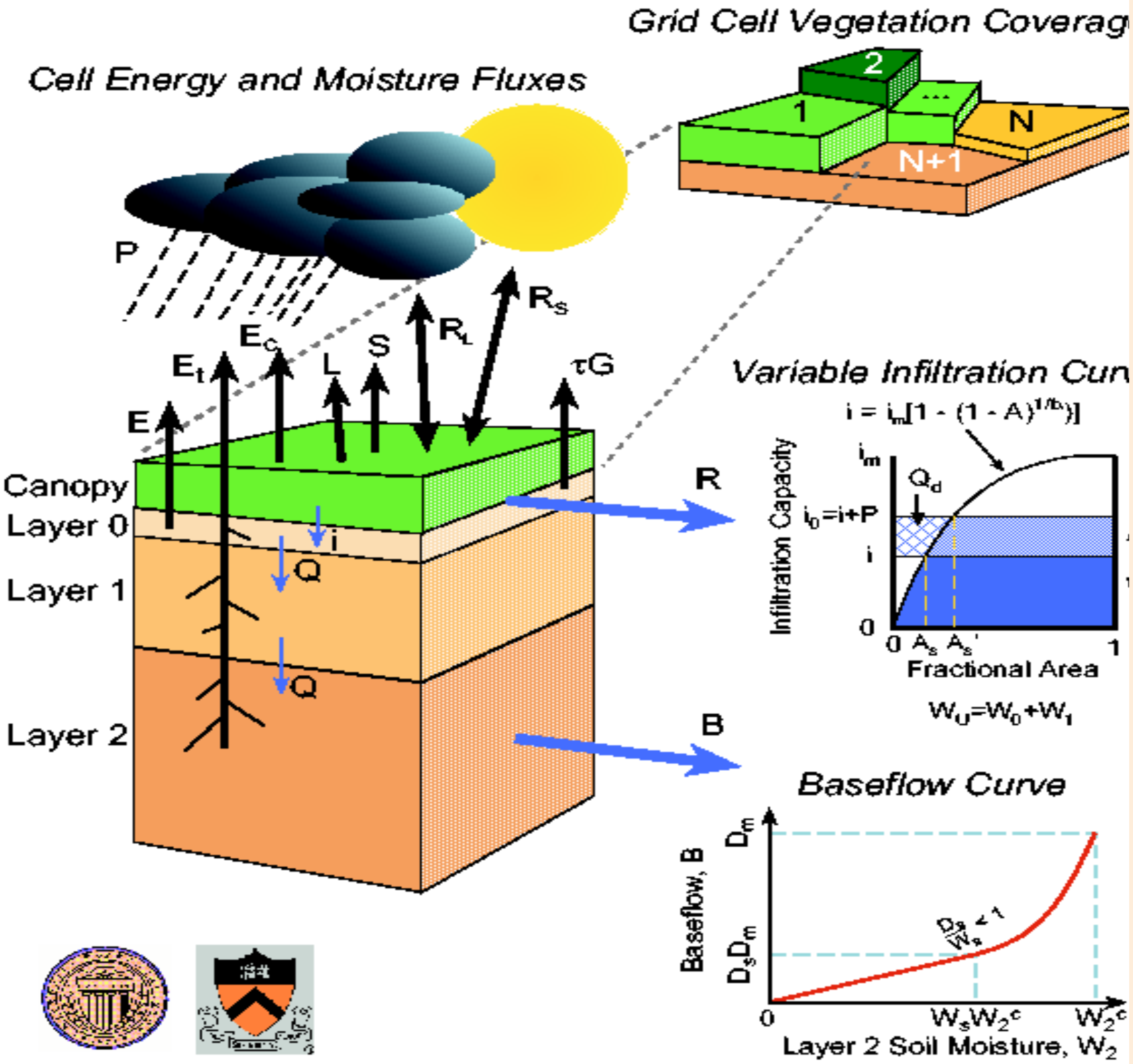
Holger Fritze, Iris T. Stewart, and Edzer Pebesma, 2011:
Shifts in Western North American Snowmelt Runoff….
J. Hydrometeor, 12, 989–1006.





N American Freezing Level Tracker
Western Regional Climate Center

Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model



To estimate water balance, Including snow water we use the Variable Infiltration Capacity (VIC) model,a land surface hydrologic water/energy accounting model.

VIC is run offline from GCMs or RCMs, using downscaled precipitation,temperature and winds as input variables.

Most of the results here are from VIC calculations run at 1/8° (12km), although more recently we are using a finer (1/16°) downscaling and attendant VIC hydrology.

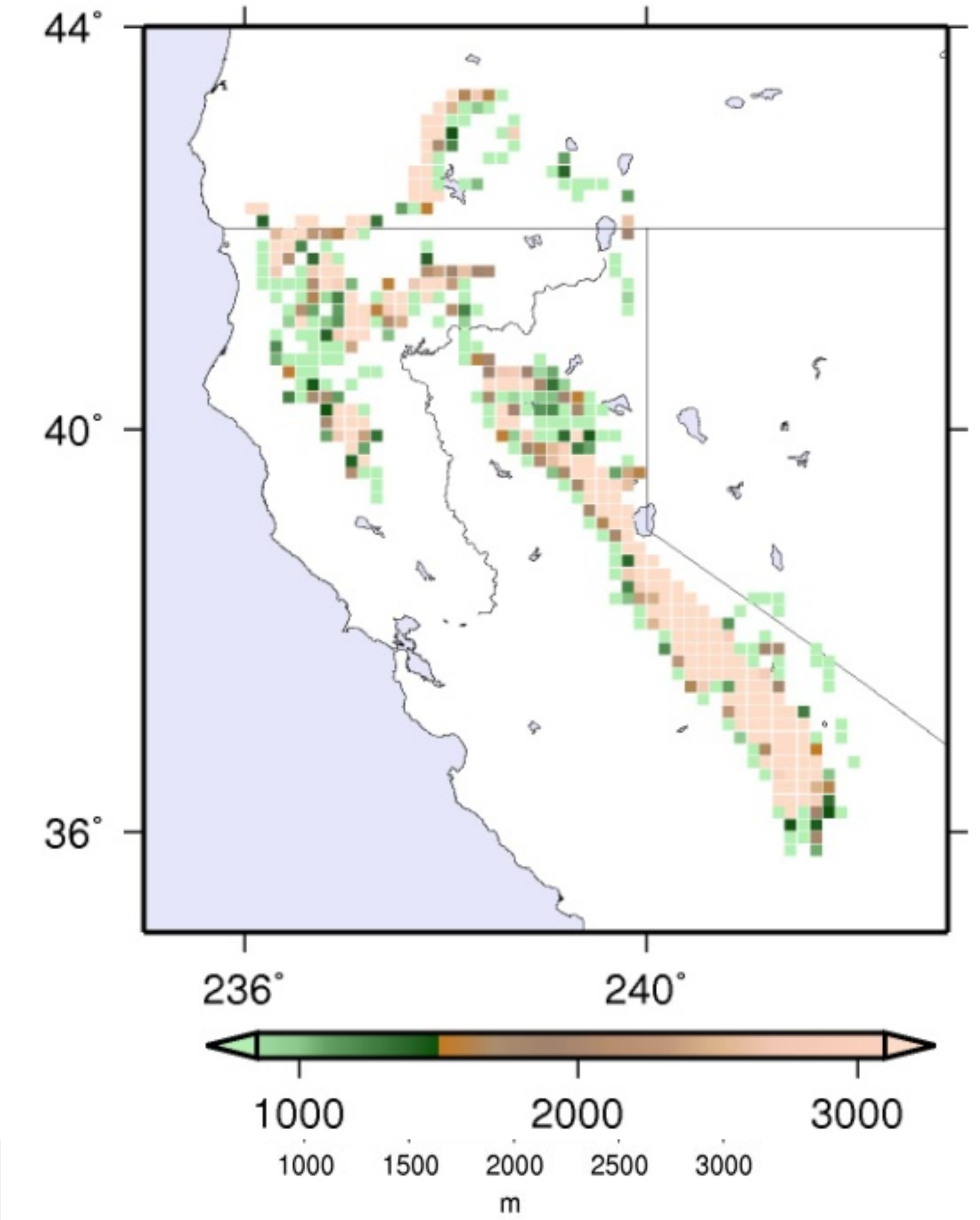
The GCMs, downscaling and VIC simulations cover 1950-2100. They have been run using 2 scenarios of future GHG concentration, SRES B1 and A2 or RCP 4.5 and 8.5.

Liang, X., Lettenmaier, D.P., Wood, E.P., Burges, S.J., 1994. A simple hydrologically based model of land surface water and energy fluxes for GSMs. J. Geophys. Res 99 (D7), 14415–14428.

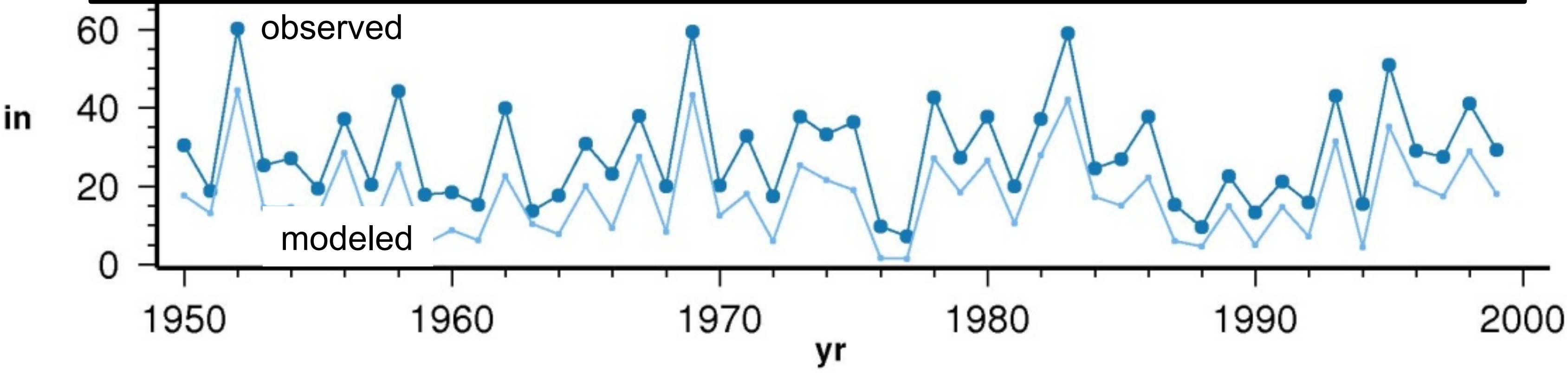
We considered 32 simulations
16 AR4 GCM's 16 A2 and 16B1
BCSD downscaled to 12 km

Map depicts elevation >800m
Sierra Nevada+ high terrain

Hydrology translated using
VIC (Variable Infiltration Capacity)
driven by downscaled
precipitation and temperature



VIC modeled vs snow course (35 sites) observed April 1 SWE
correlation=0.97



VIC snow accumulation agrees closely with observed snow course observations

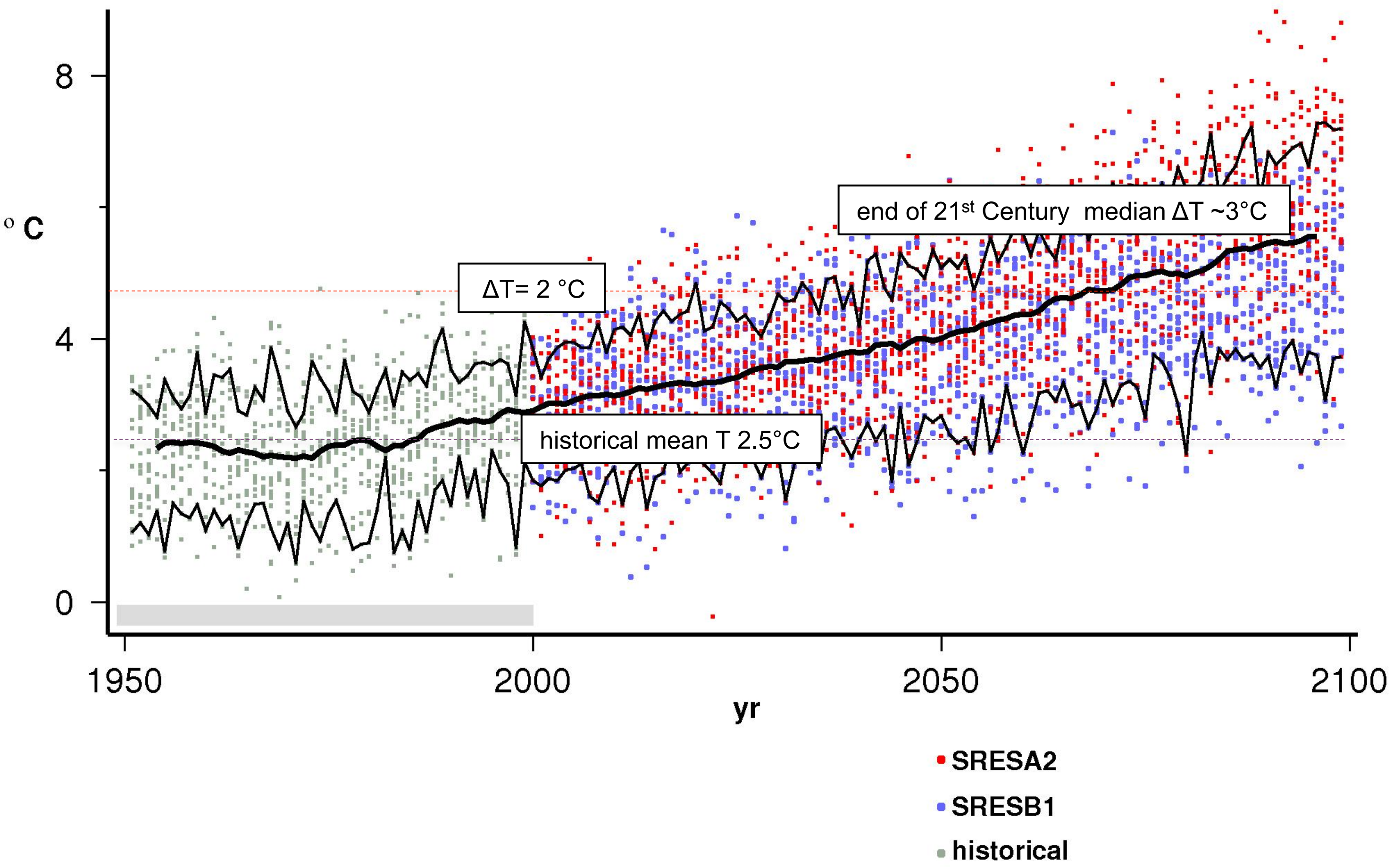
variability of Apr 1 Snow Water Equivalent (SWE), VIC modeled vs. observations avg of 35 snow courses

California October–March Sierra temperature from climate simulations

32 BCSD (16 SRESA2 and 16 SRESB1)

7–year smoothed median: heavy black line

90th and 10th percentiles: light black lines



change in snow water projected for Sierra Nevada+ is substantial

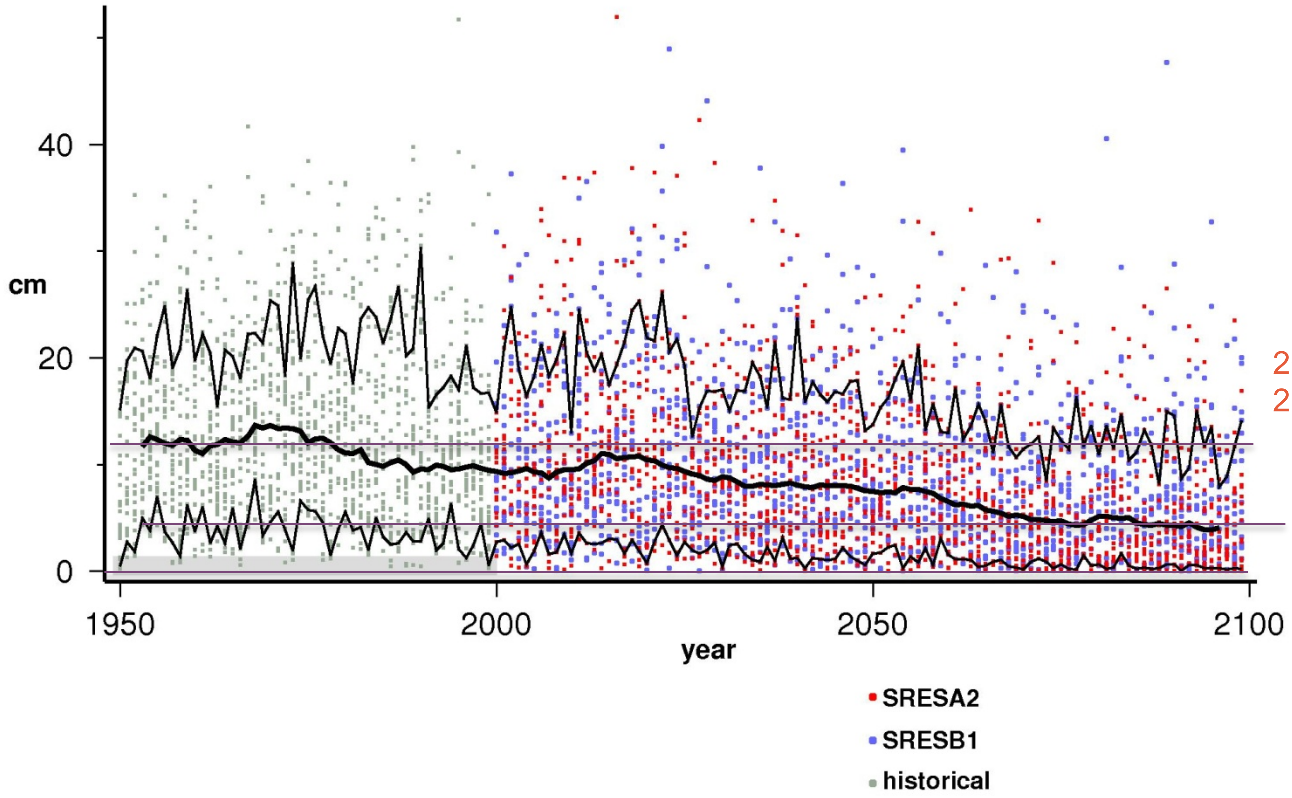
16 GCMs, A2 and B1 emissions scenarios

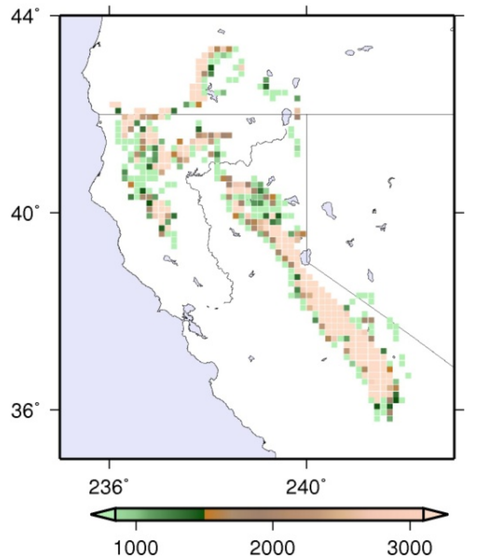
California April 1 SWE from climate simulations

32 BCSD (16 SRESA2 and 16 SRESB1)

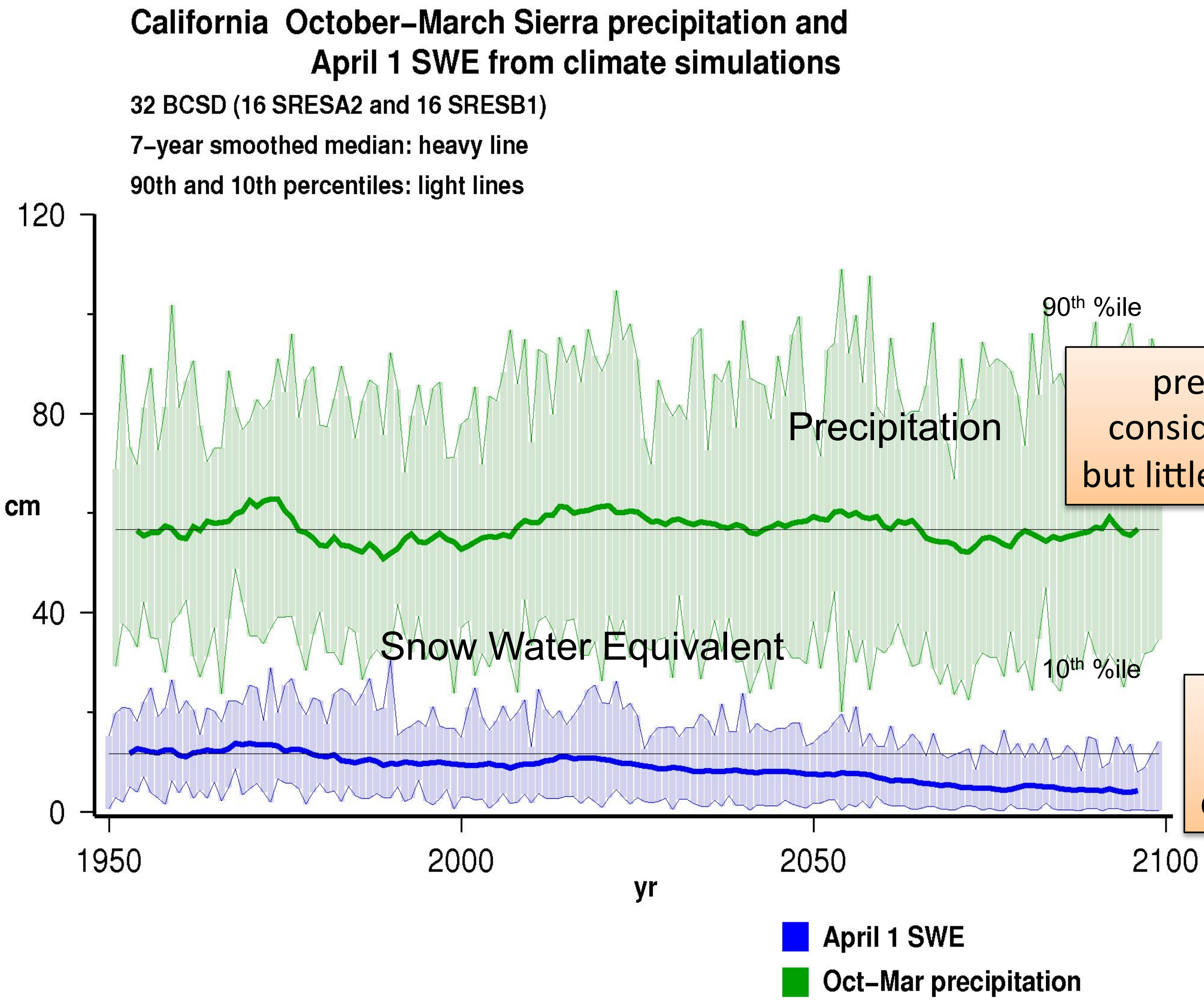
7–year smoothed median: heavy black line

90th and 10th percentiles: light black lines





declining Apr 1 SWE:
2050 median SWE ~ 2/3 historical median
2100 median SWE ~ 1/3 historical median

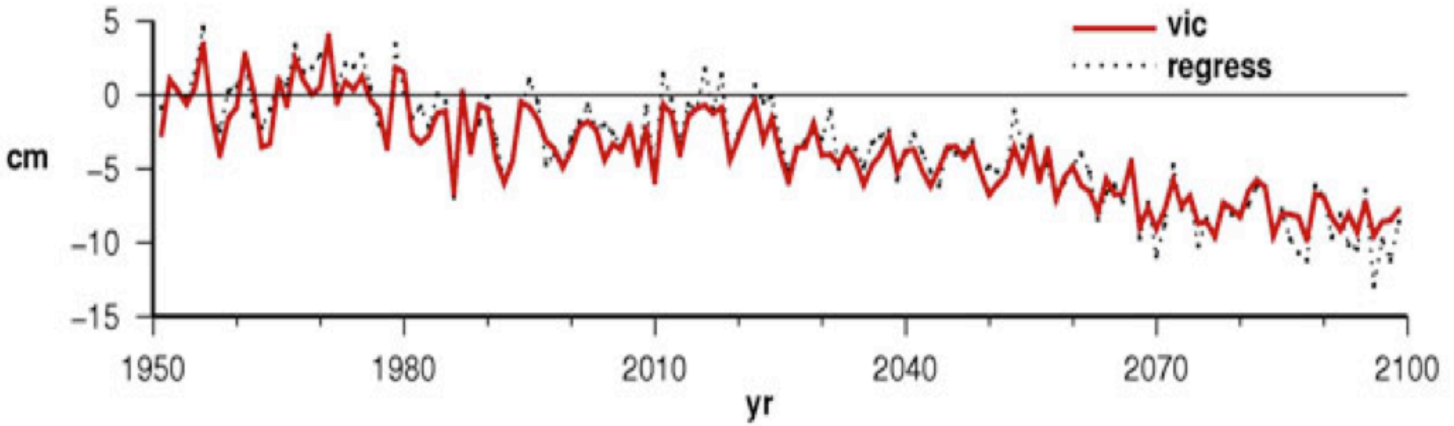


precipitation
considerable variability
but little overall change

but
spring snow
declines steadily

Linear regression—a good approximation for Calif spring SWE

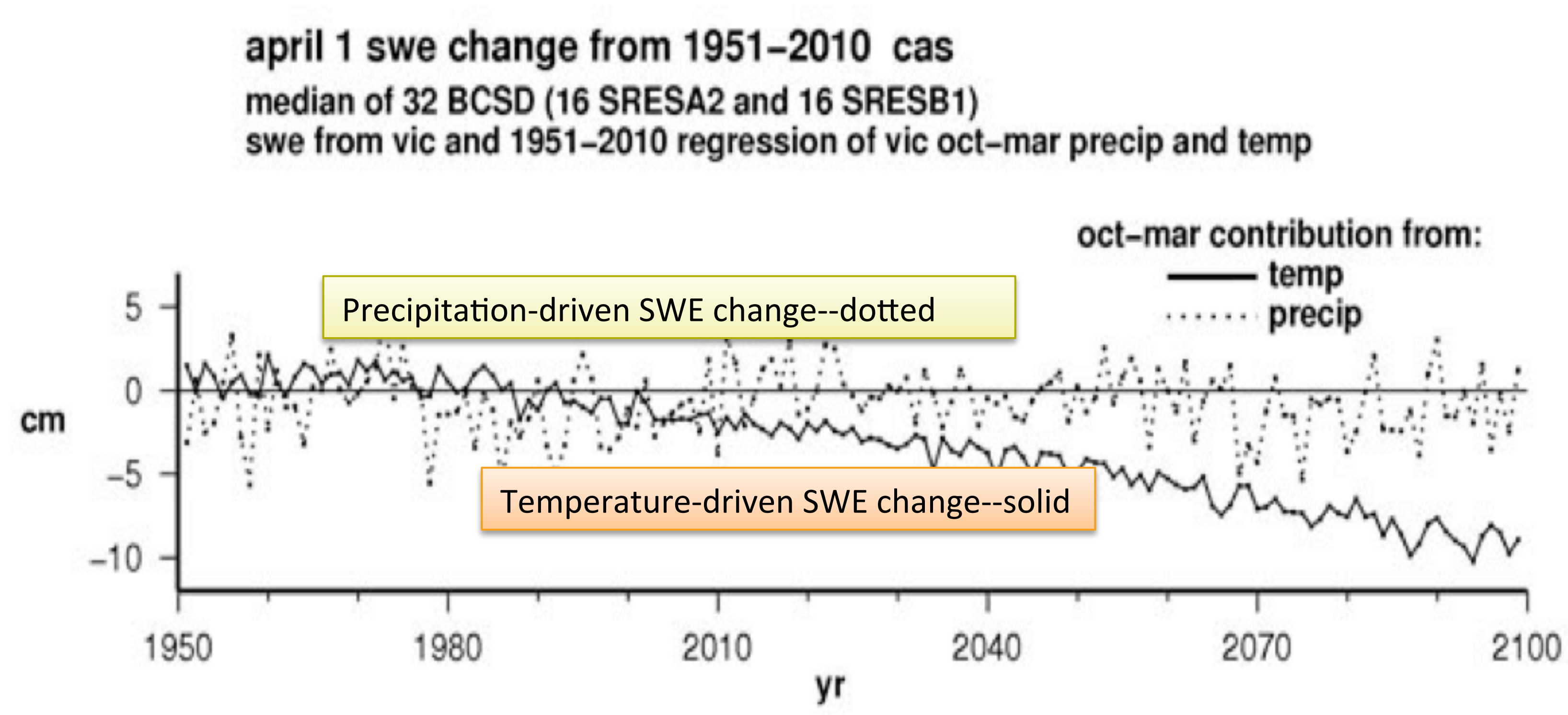
Linear Regr Modeled Apr 1 SWE dashed, VIC modeled SWE dashed black



Steady warming diminishes California spring SWE

Precipitation (ONDJFM) fluctuations: ±10% Δprecip ➔ ±16% ΔSWE
but precip fluctuations are not trending

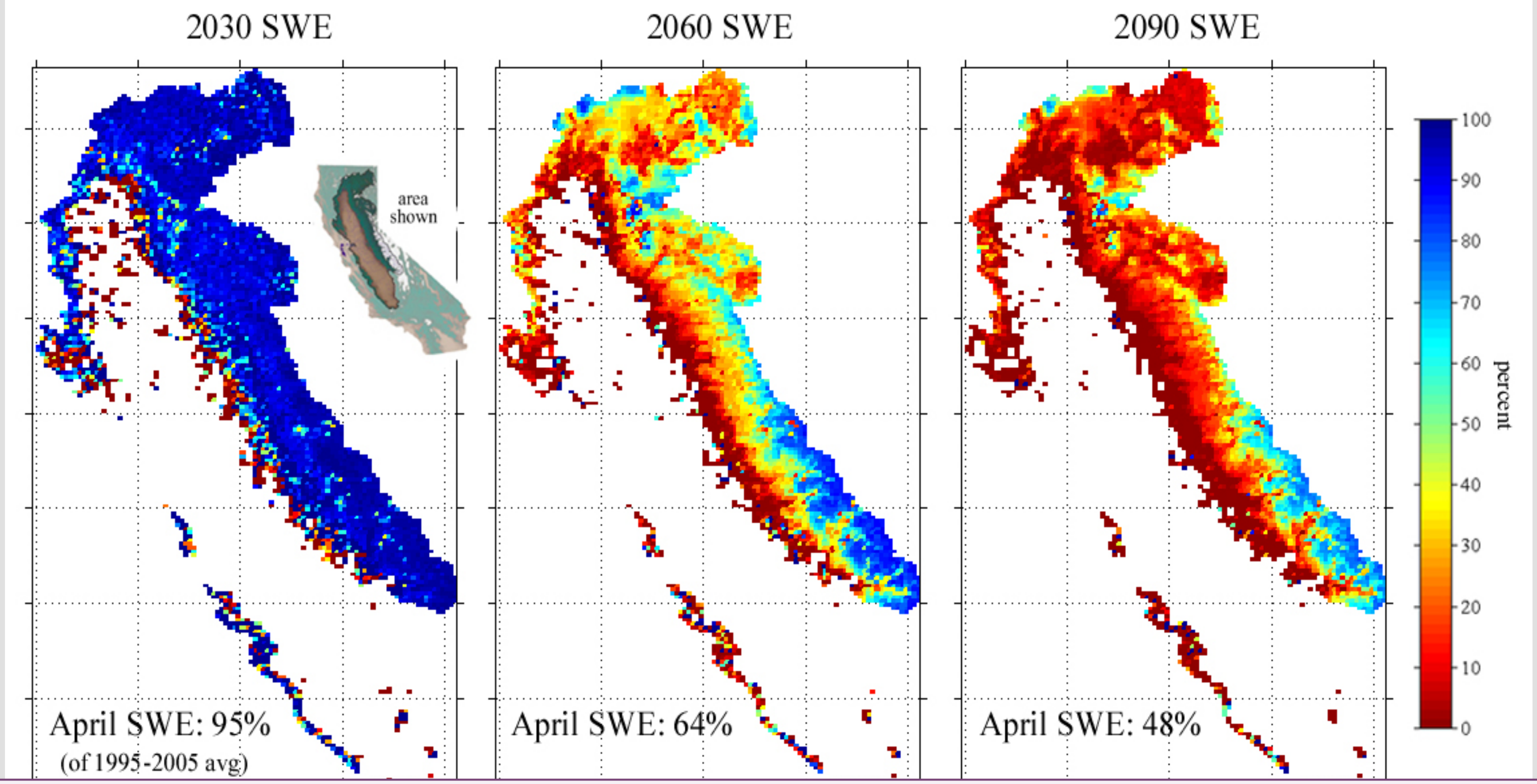
Temperature (ONDJFM) fluctuations: +1°C ΔT ➔ -23% ΔSWE
temperature change is trending strongly



Precipitation-driven SWE change--dotted

Temperature-driven SWE change--solid

Loss of California Spring Snowpack from 21st Century warming

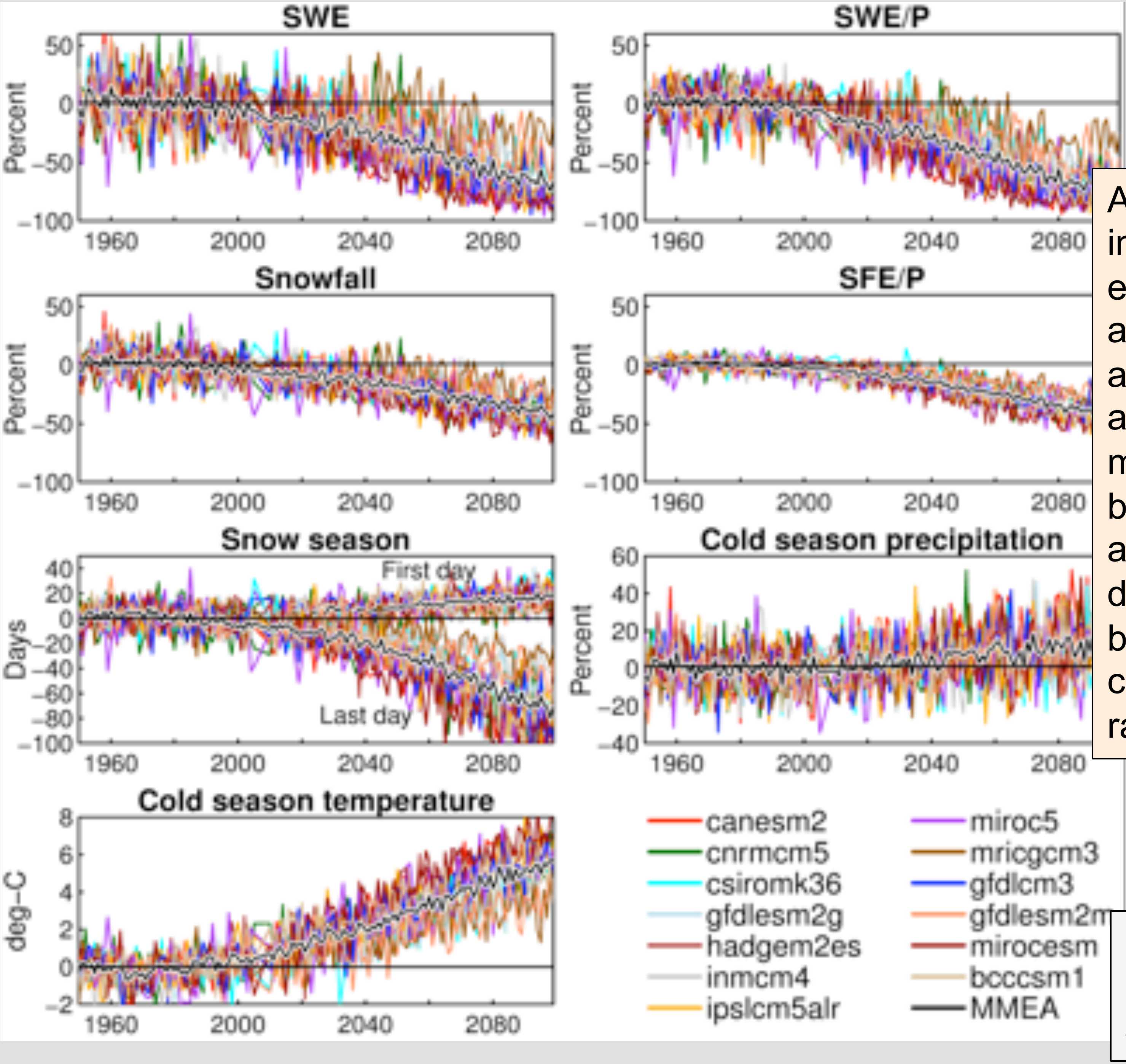


•Under this scenario, California loses half of its spring (April 1) snow pack due to climate warming. Less snow, more rain, particularly at lower elevations. The result is earlier run-off, more floods, Less stored water. This simulation by Noah Knowles is guided by temperature changes from PCM's Business-as-usual coupled climate simulation. (this is a low-middle of the road emissions and warming scenario)

Knowles, N., and D.R. Cayan, 2002: Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary. *Geophysical Research Letters*, **29**(18), 1891.

regional snow and hydrology—
a sensitive index of climate variation and change

Douglas Alden
Scripps Institution
of Oceanography
Installing met station
Lee Vining, CA



As climate warms in this RCP 8.5 ensemble averaged over all all eight regions, all snow related measures change, but those that are most strongly dominated by temperature change more rapidly.

David Pierce, D. Cayan 2013 2013: The uneven response of different snow measures to human-induced climate warming. *Journal of Climate*

climate change signal/noise in 2025

western U.S. snow and snow-related variables

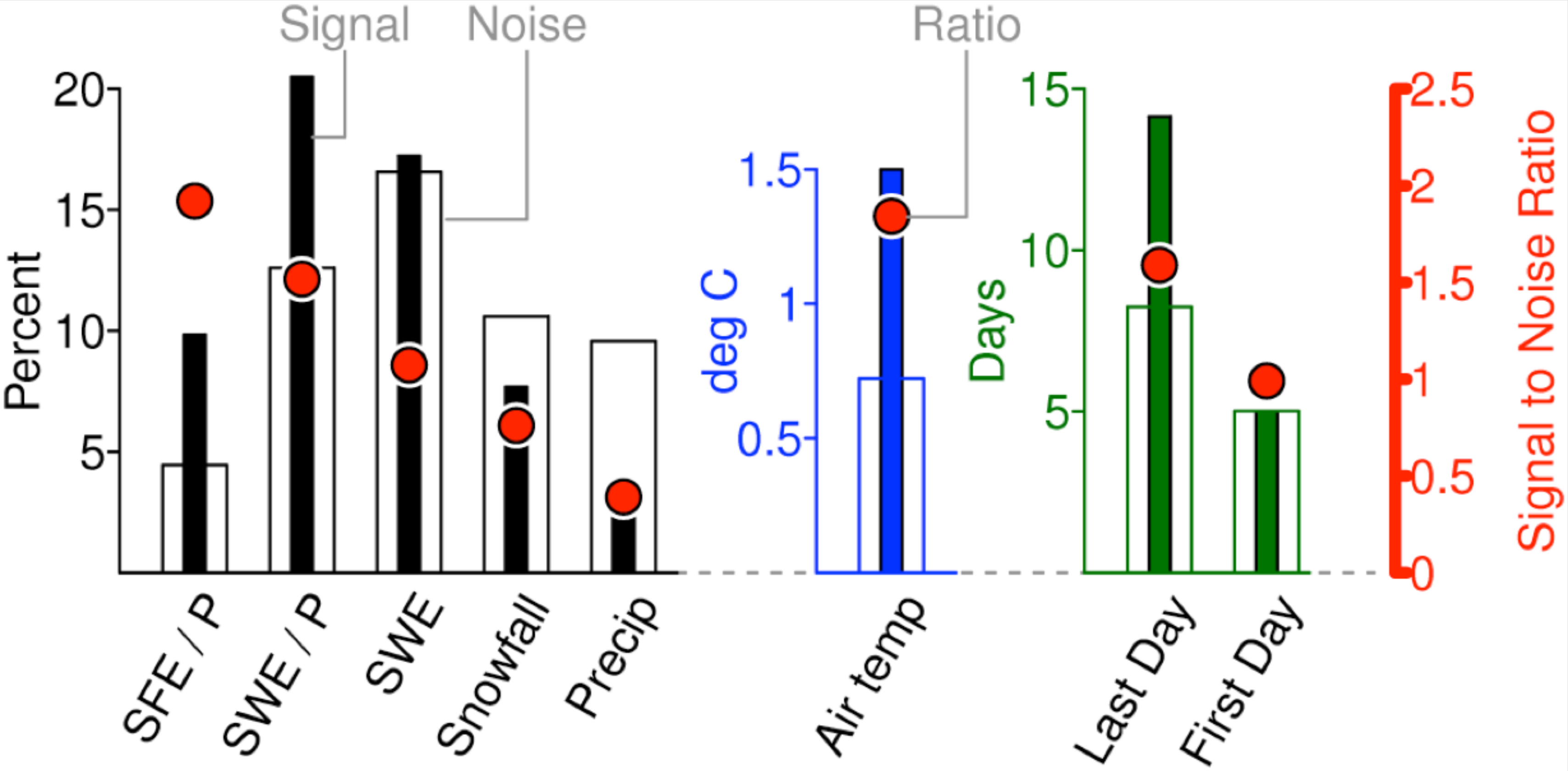
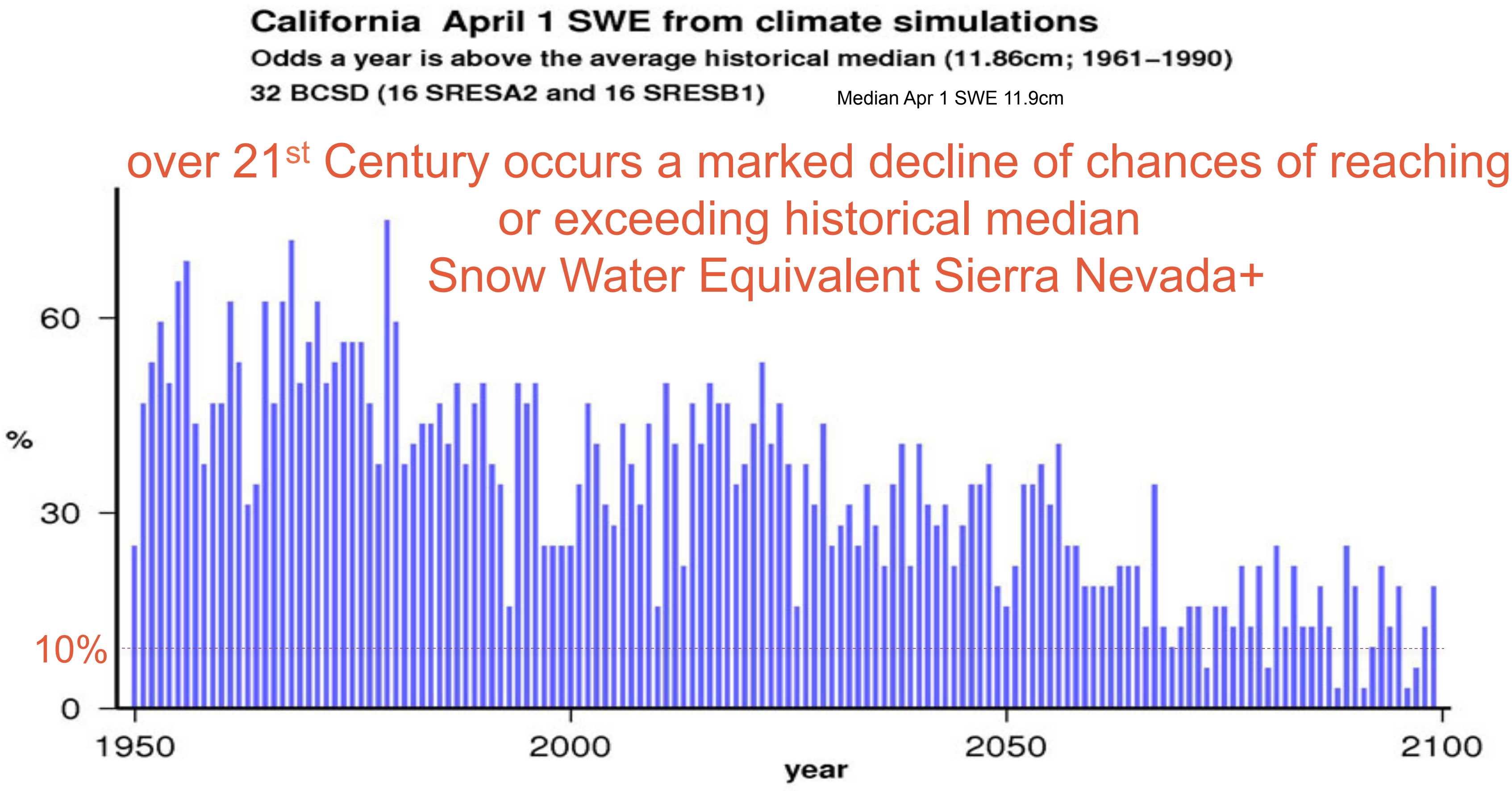


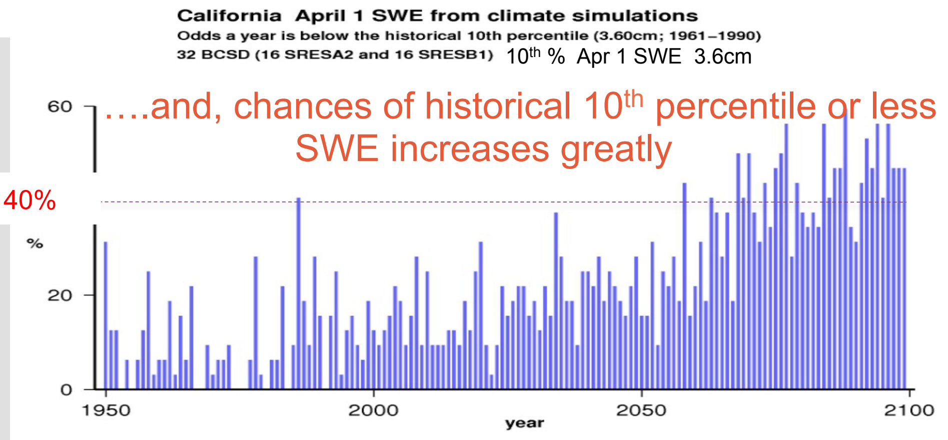
FIG. 15. Comparison of the climate change signal in 2025 (the change estimated by the least squares linear trend in the indicated variable from 1950 to 2025; solid bars), noise (twice the autocorrelation-adjusted standard error in the uncertainty in the trend; hollow bars), and SNR (red dots), averaged across snow locations in the western United States for the RCP 4.5 scenario. Colors indicate the units of the variable being considered: black (%), blue (8C), and green (days). The SNR (red dots; rightmost y axis) is dimensionless, and so can be directly compared across all variables.   Pierce and Cayan 2013

over 21st Century occurs a marked decline of chances of reaching or exceeding historical median Snow Water Equivalent Sierra Nevada+



10%

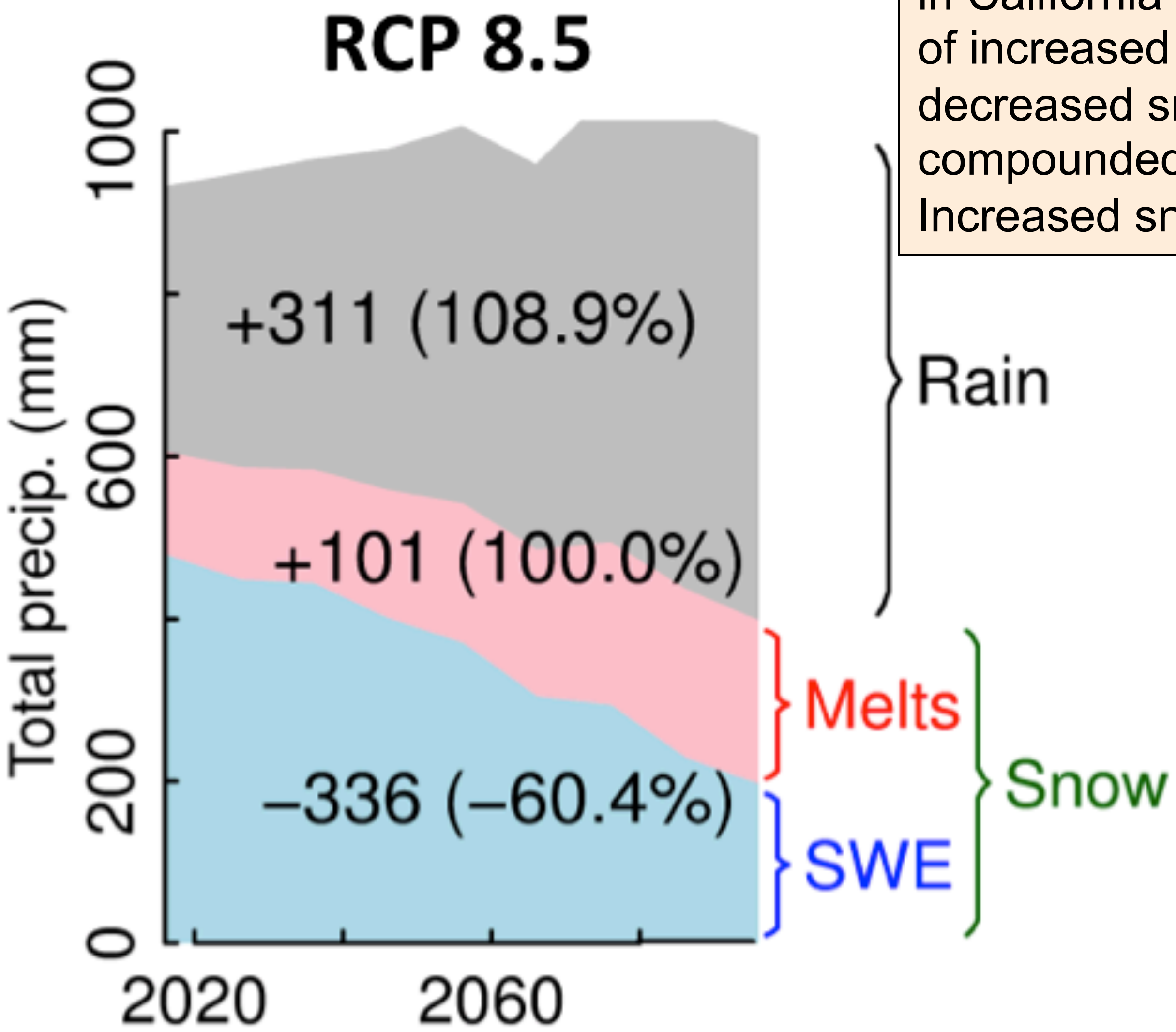
....and, chances of historical 10th percentile or less SWE increases greatly



40%

According to VIC---

end-of-century April 1 SWE losses in California occur mostly because of increased rainfall (and decreased snowfall), but are compounded by
Increased snowmelt

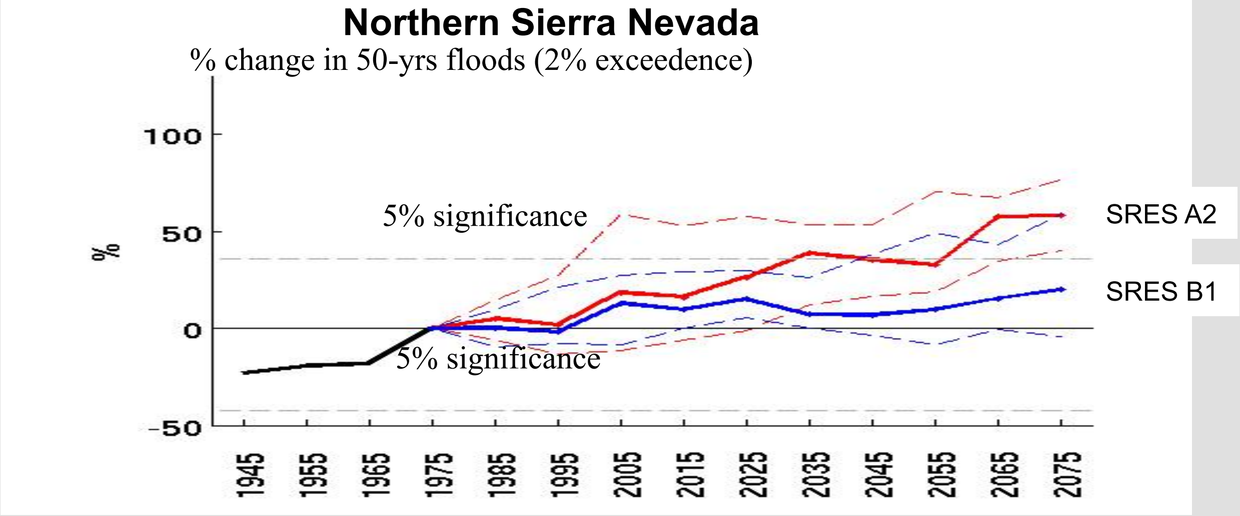


David Pierce, D. Cayan 2013
2013: The uneven response of different snow measures to human-induced climate warming. *Journal of Climate*

Projections indicate Increasing Flood Flows

50 year return period annual maximum 3-day floods

for both Northern (shown below) and Southern Sierra Nevada from VIC simulations



some, not all, of flood flow increase can be attributed to change in rain/snow and snowmelt

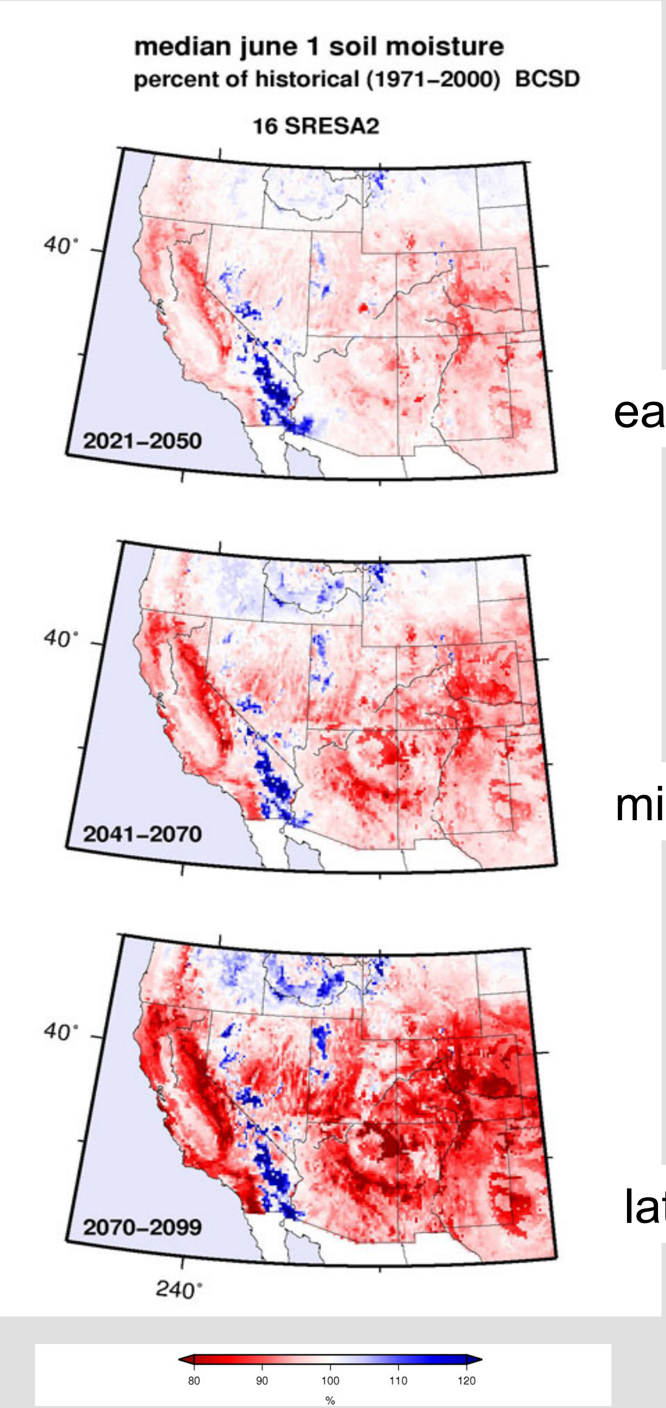
Percentage change in 50-yrs (2% exceedence) flood discharge. The % change is computed with respect to the 50-yrs flood computed over the period 1951-1999. The second, third and next on points are computed for the period with 10-yrs sliding period (e.g., the second point represents change of the flood magnitude computed for the 1961-2009 period with respect to flood discharge computed in the period 1951-1999). The plot shows 25th, 50th and 75th percentiles from sixteen climate models from SRESA2 (red color curves) and SRESB1 (blue color curves) simulations for Northern Sierra Nevada (left) and Southern Sierra Nevada (right). In the plot, black color curves show the % change in 50-yrs flood with respect to historical flood (1951-1999) from VIC simulation as simulated by historical observed meteorologies (Hamlet and Lettenmaier, 2005). 5% significant level computed using a long control simulation (750-yrs) from PCM1 is shown as dotted gray lines. Numbers in the x-axis indicate the middle year of each 49-yrs time window used to compute the flood.

Das, T., M.D. Dettinger, D.R. Cayan and H.G. Hidalgo, 2011: Potential increase in floods in California's Sierra Nevada under future climate projections. *Climatic Change*

Drier Summer Landscapes

increased warming and diminished snow causes successively greater soil drying throughout 21st Century

(*this picture could change somewhat under more recent CMIP5 simulations*)



median june 1 soil moisture
percent of historical (1971–2000) BCSD

16 SRESA2

early 21st

middle 21st

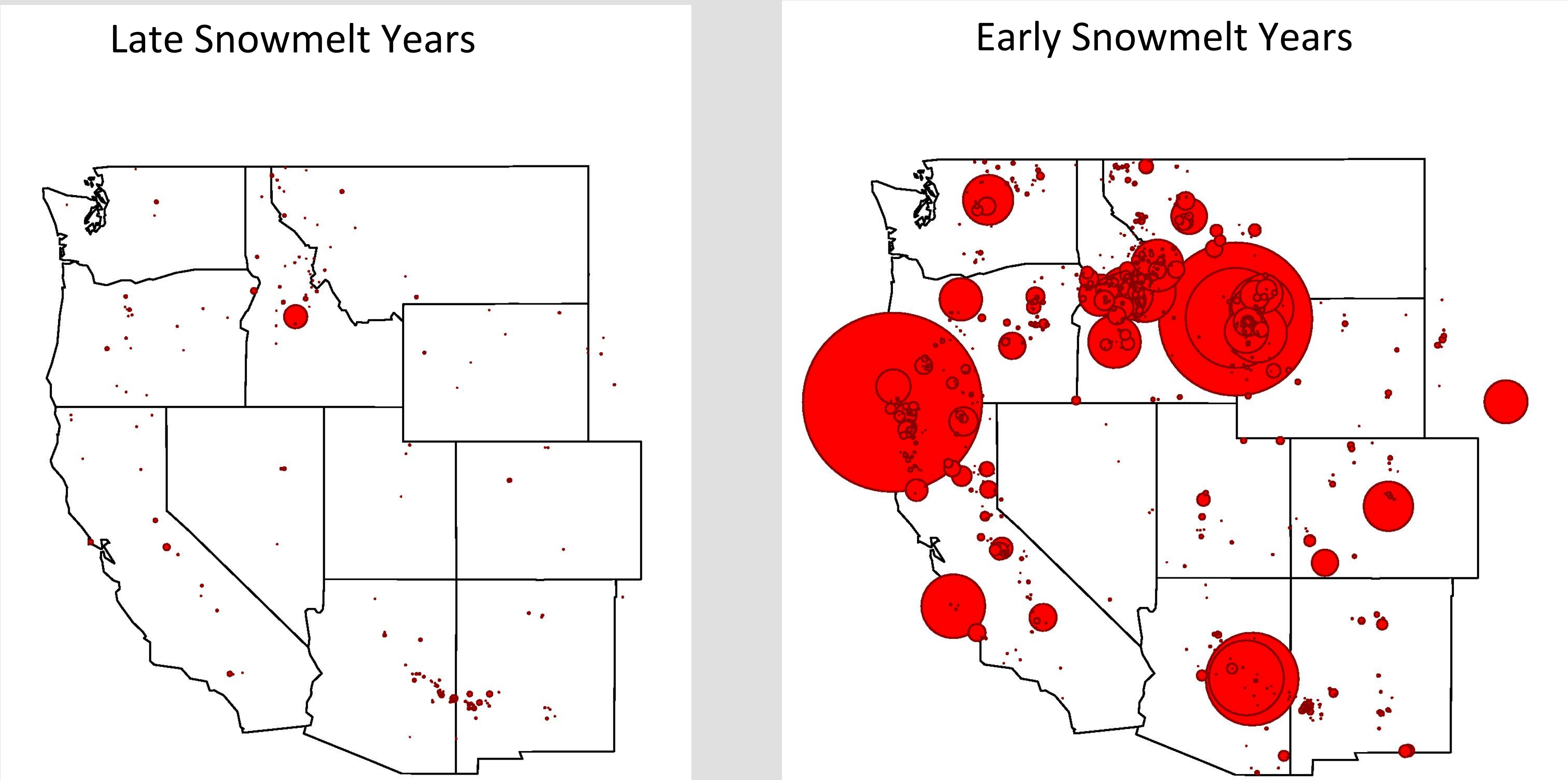
late 21st

Cayan et al. Ch 6 Southwest Climate Assessment

since 1985 the number of large wildfires in western U.S. increased four-fold
relative to previous 15 years,   mostly forest fires, not shrubland fires

Anthony Westerling et al.   *Science*   August 2006

large summer wildfires occur more often in years with early/warm springs



Late Snowmelt Years

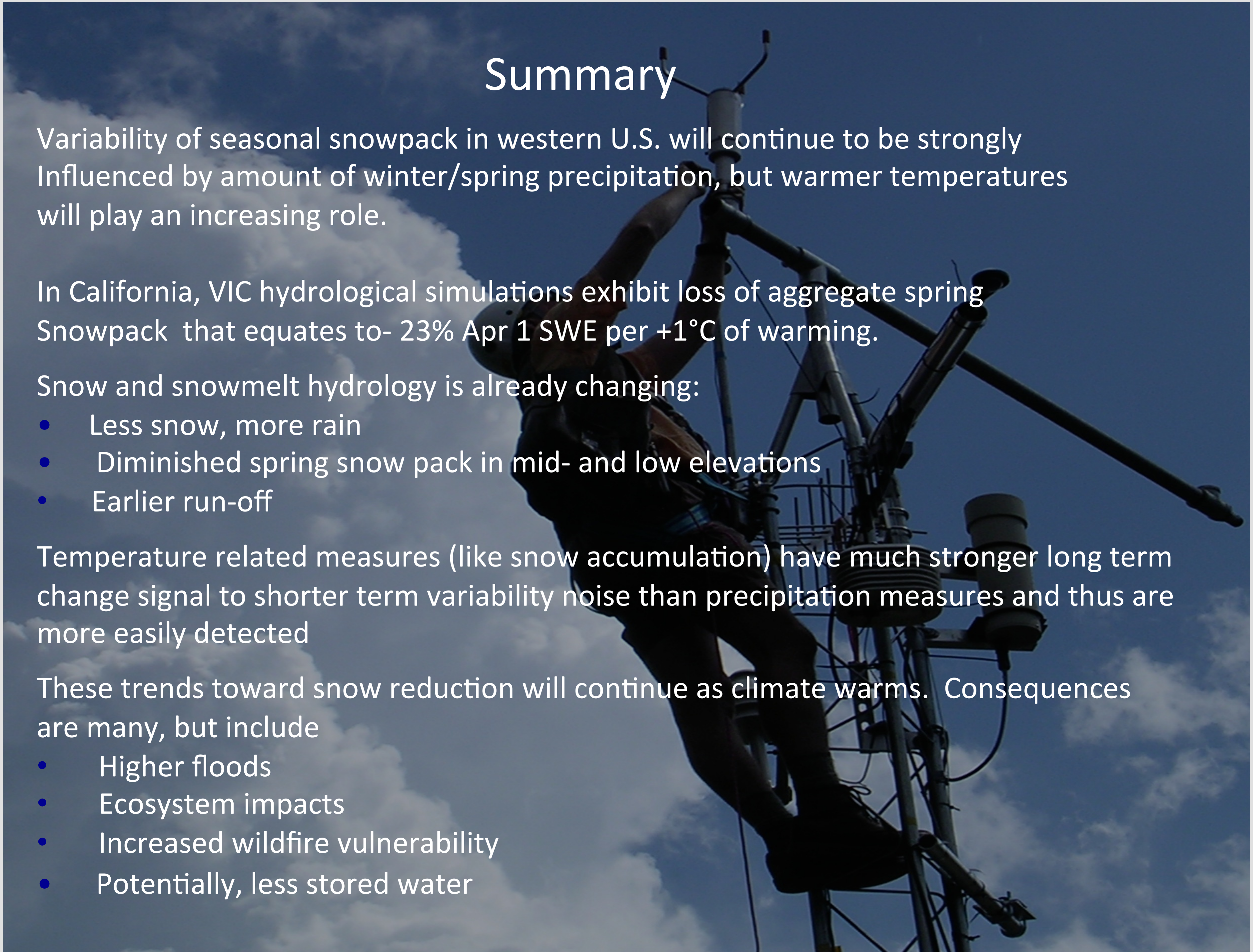
Early Snowmelt Years

1972 - 2003, NPS, USFS & BIA Fires over 1000 acres

Area burned is proportional to size of red dots

The warming and earlier springs during last few decades have extended and intensified the fire season in mid-elevation forests

Tony Westerling et al *Science* 2006



Summary

Variability of seasonal snowpack in western U.S. will continue to be strongly Influenced by amount of winter/spring precipitation, but warmer temperatures will play an increasing role.

In California, VIC hydrological simulations exhibit loss of aggregate spring Snowpack that equates to- 23% Apr 1 SWE per +1˚C of warming.

Snow and snowmelt hydrology is already changing:

- Less snow, more rain
- Diminished spring snow pack in mid- and low elevations
- Earlier run-off

Temperature related measures (like snow accumulation) have much stronger long term change signal to shorter term variability noise than precipitation measures and thus are more easily detected

These trends toward snow reduction will continue as climate warms. Consequences are many, but include

- Higher floods
- Ecosystem impacts
- Increased wildfire vulnerability
- Potentially, less stored water