Human-induced changes in the hydrological cycle of the western United States and their impacts

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[2]*Lawrence Livermore National Lab*

[3]*National Inst. Environmental Sciences (Japan)*

[4]*Univ. Washington*

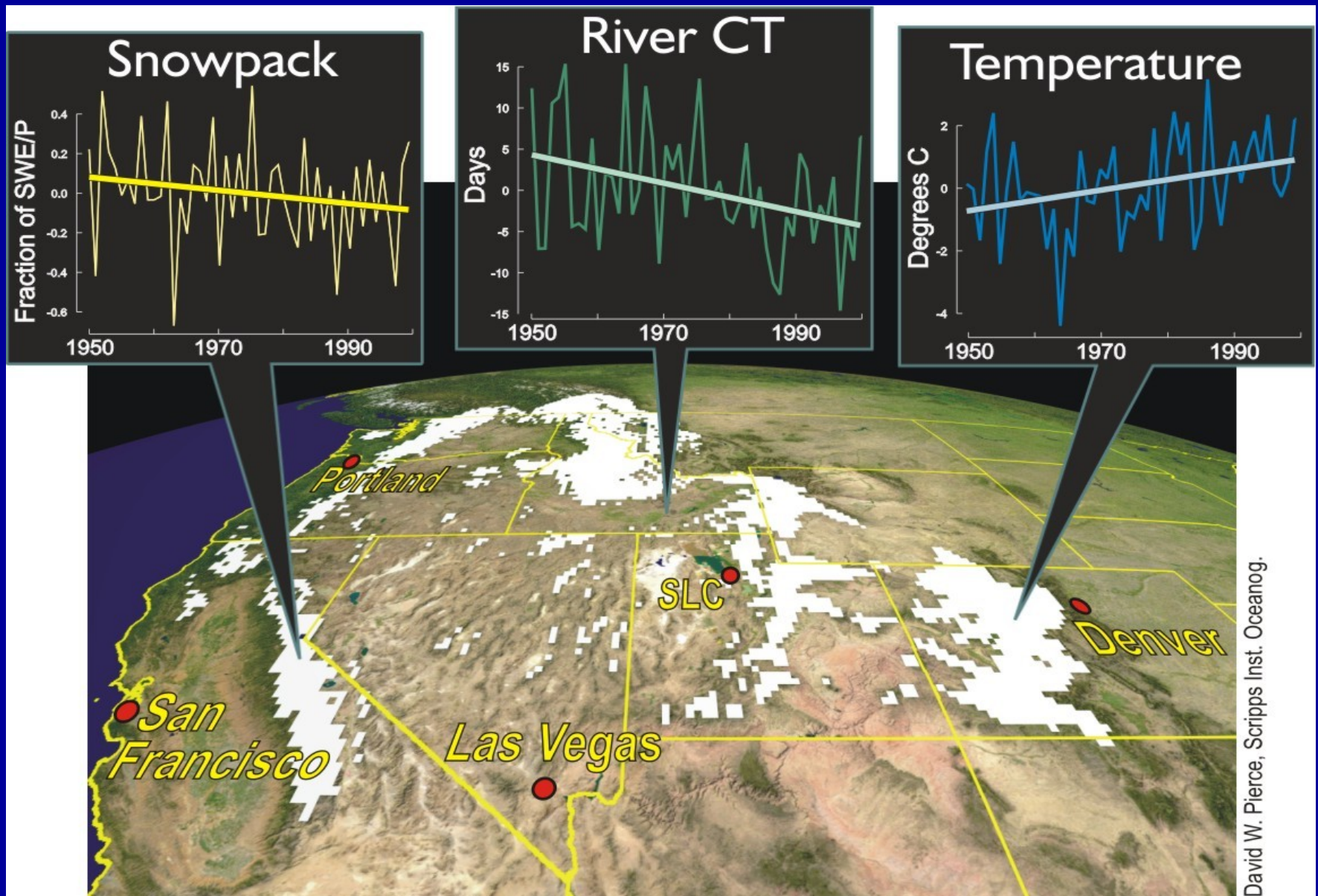
The Problem

The hydrological cycle is changing over the western United States

WHY?

Natural variability or man made?

Typical western climate changes

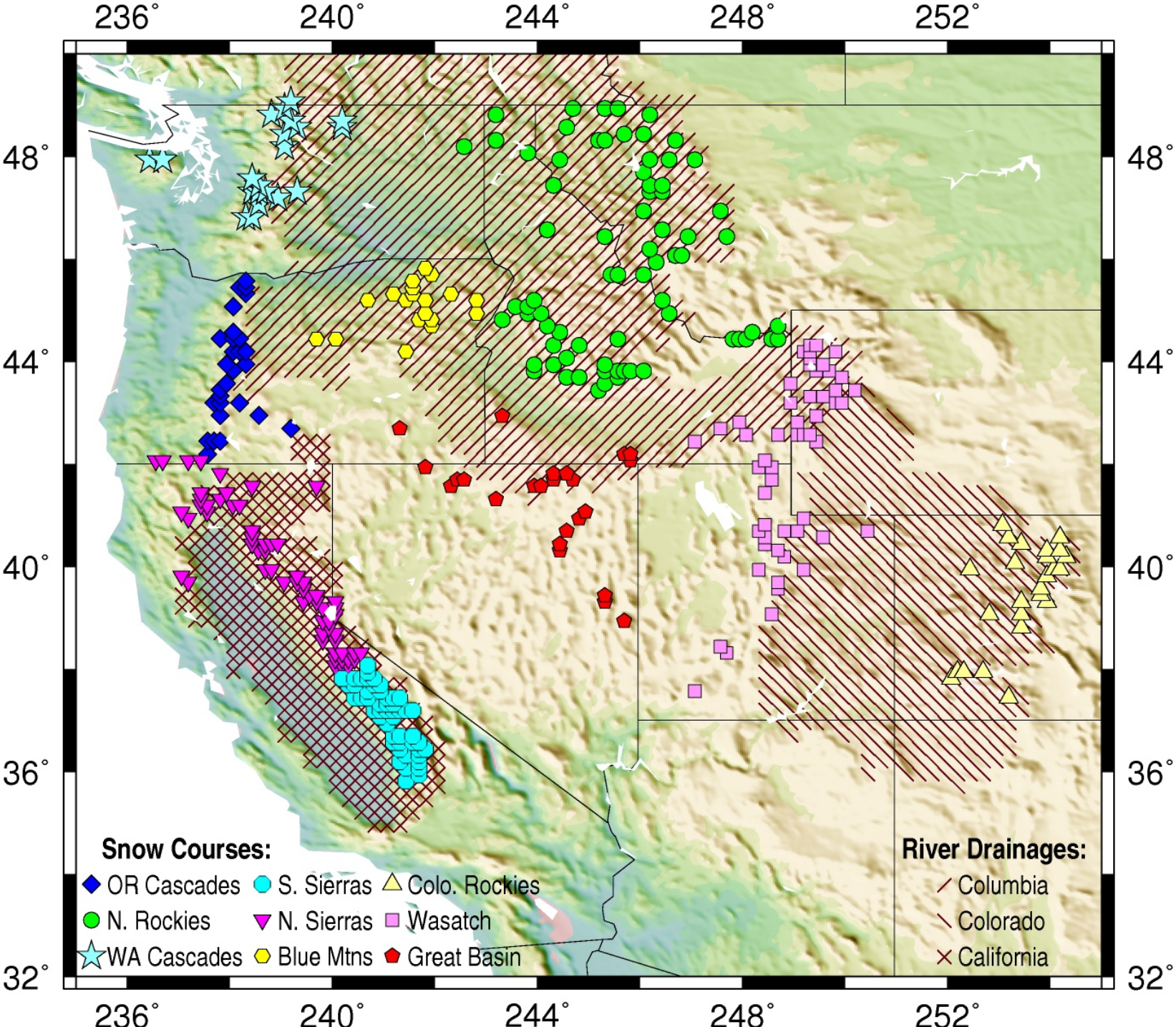


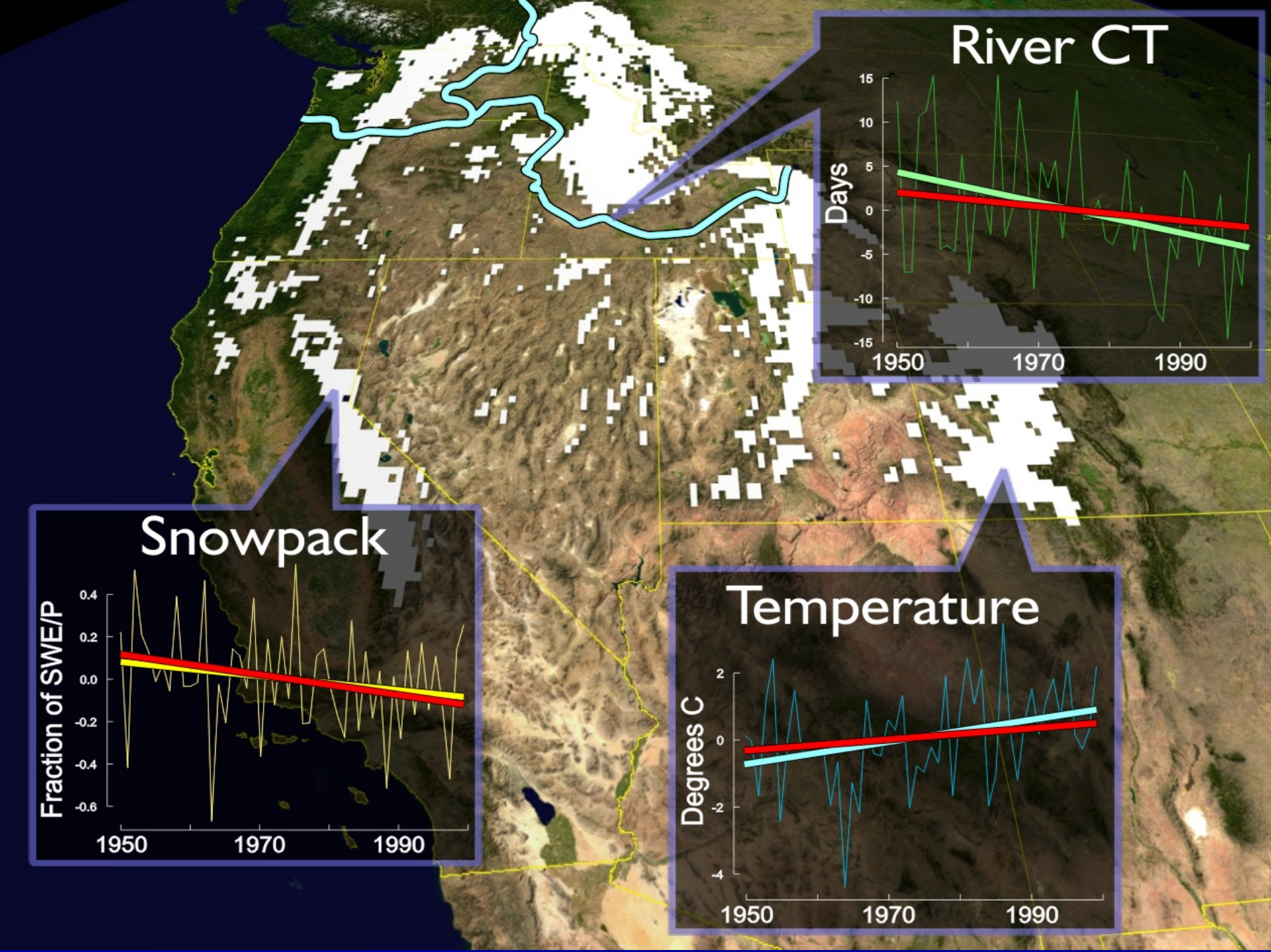
Detection & Attribution: Overall scheme

1. Start with global GCMs: control and anthropogenically forced runs
2. Downscale to region of interest (Wood, et al, 2004;Hidalgo, et al, 2007)
3. Run VIC hydrological model w/ downscaled data
4. D&A on 3 variables:
   - SWE/P (1 April Snow Water Equv. / Oct-Mar precip)
   - Temperature (examined JFM daily minimum temperature)
   - River flow (examined JFM fraction and CT, center of timing)

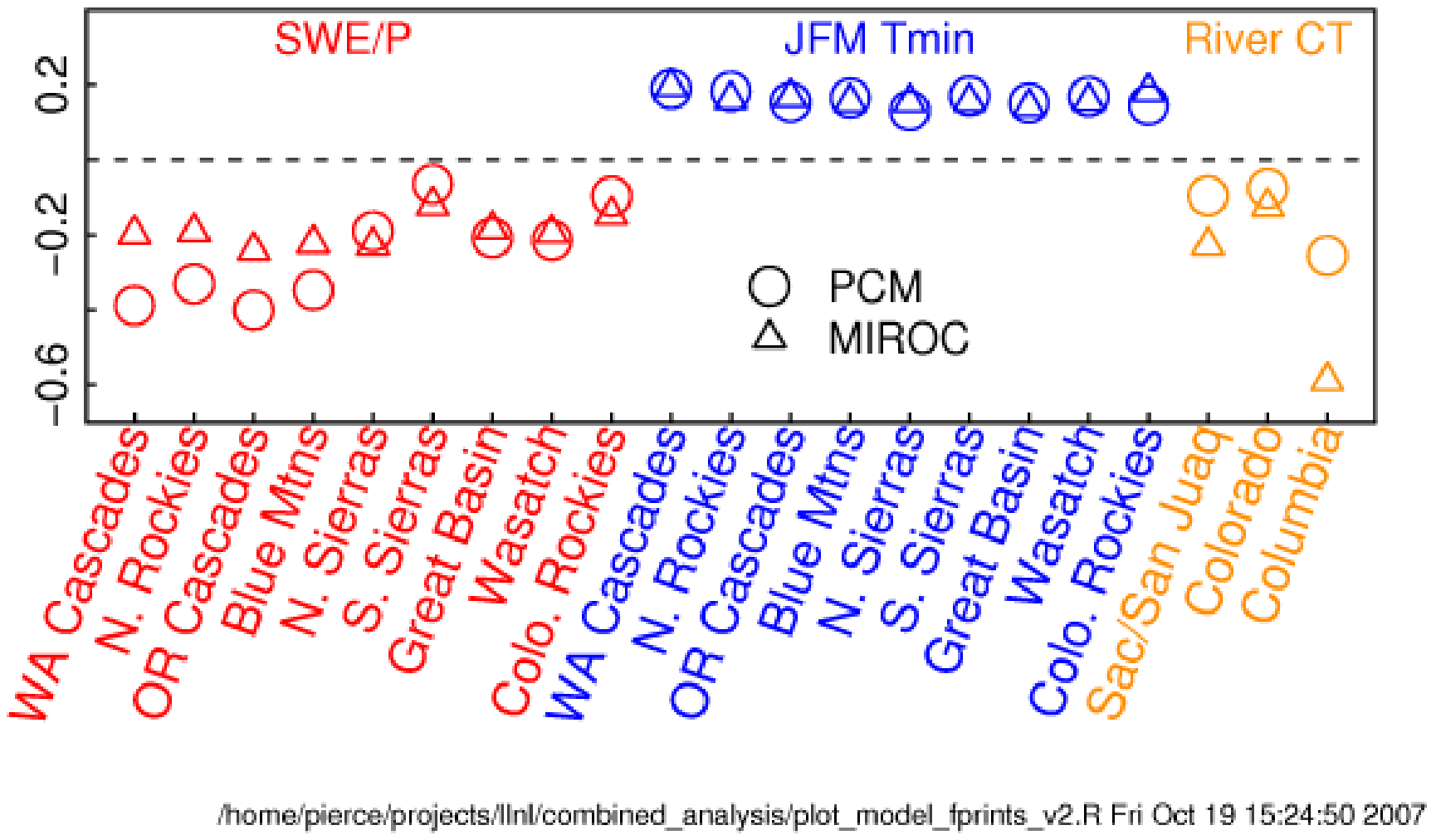
Models and data ….20 Tb

- Control model GCM runs
  - 850 yrs CCSM3-FV (1.25^{O}x1^{O}; finer resolution than T85)
  - 750 yrs PCM (T42)
- Anthropogenically forced GCM runs, 1900-1999
  - PCM (4 members)
  - MIROC (10 members)
- Regional statistical downscaling of GCM forcing
  - 2 methods, 12 km resolution
- VIC hydrological model (1/8 deg resolution)
- Observations, 1950-1999
  - Snow courses for SWE
  - UW, Maurer, PRISM for T and P
  - Naturalized flow from Colorado R. (Lee's Ferry), Columbia R. (Dalles), Sacramento and San Joaquin river


236°
240°
244°
248°
252°
48°
44°
40°
36°
32°
Snow Courses:
OR Cascades
S. Sierras
Colo. Rockies
N. Rockies
N. Sierras
Wasatch
WA Cascades
Blue Mtns
Great Basin
River Drainages:
Columbia
Colorado
California


River CT
Days
15
10
5
0
-5
-10
-15
1950
1970
1990
Snowpack
Fraction of SWE/P
0.4
0.2
0.0
-0.2
-0.4
-0.6
1950
1970
1990
Temperature
Degrees C
2
0
-2
-4
1950
1970
1990

Multivariate fingerprint: PCM vs. MIROC

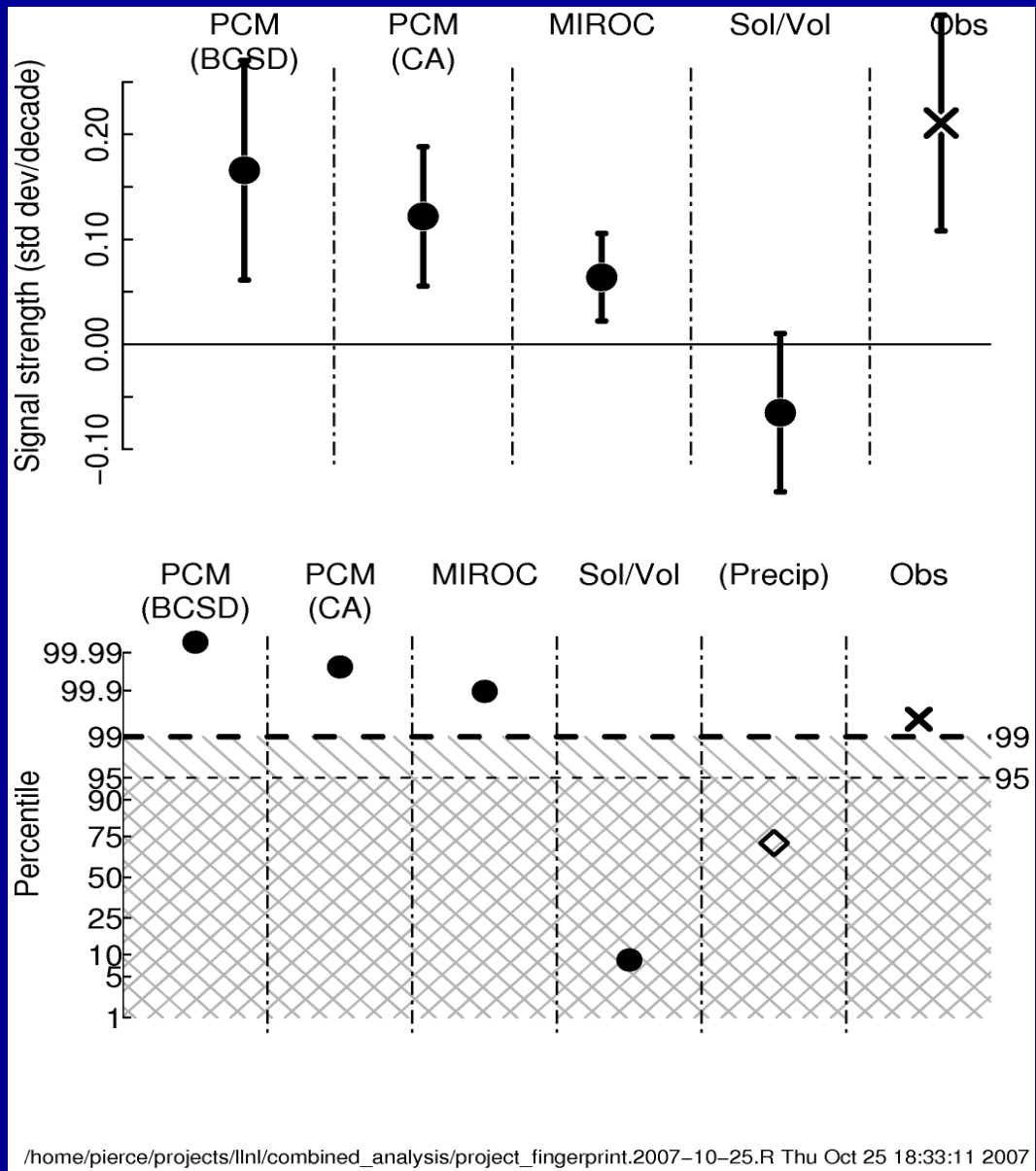


Ensemble signal strength & significance

Fingerprint

Signal Strength

Significance



D&A summary

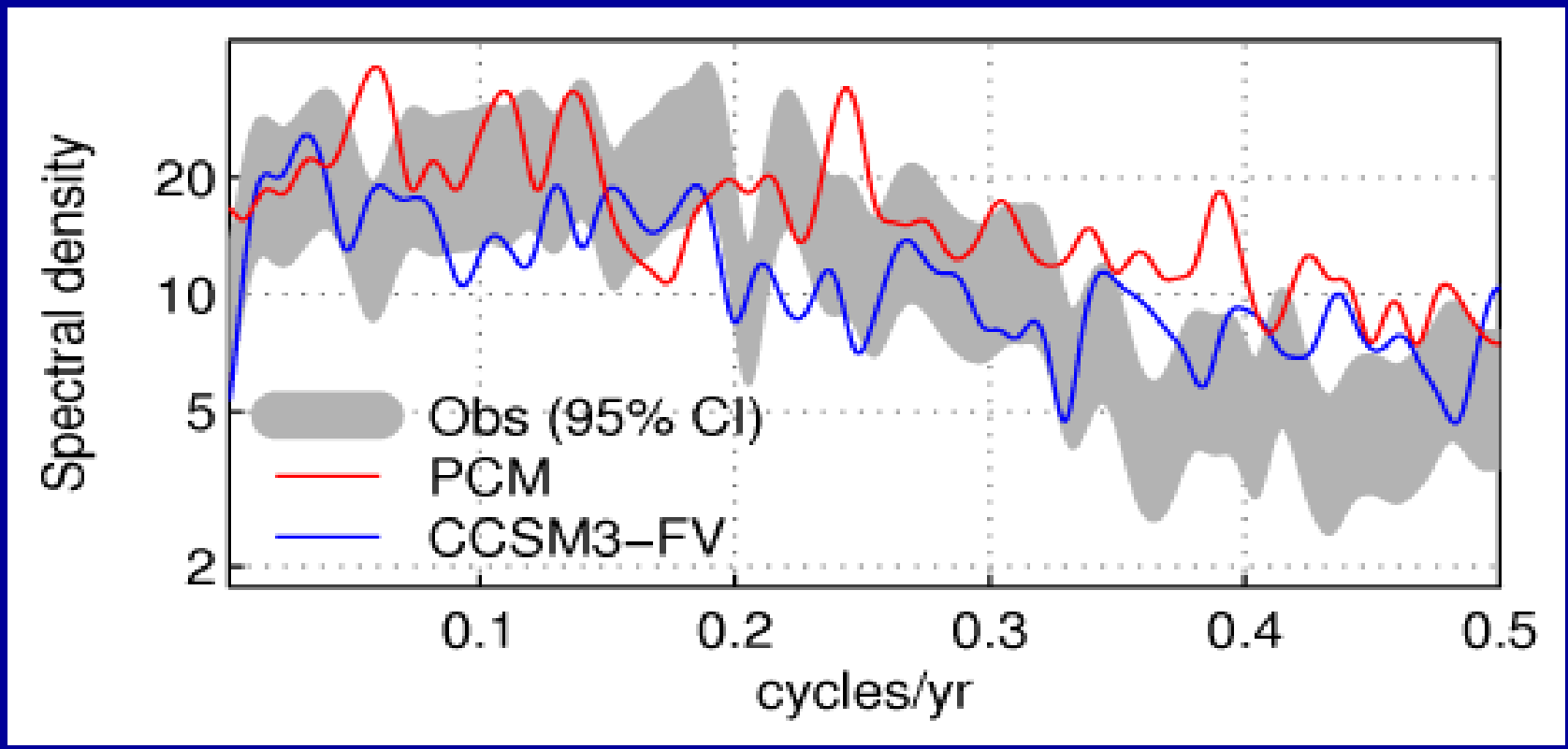
- Natural variability cannot explain obs.
- Solar/volcanic forcing cannot explain obs
- Changes in precipitation cannot explain obs

- ANTHROPOGENIC warming CAN explain obs. changes very well

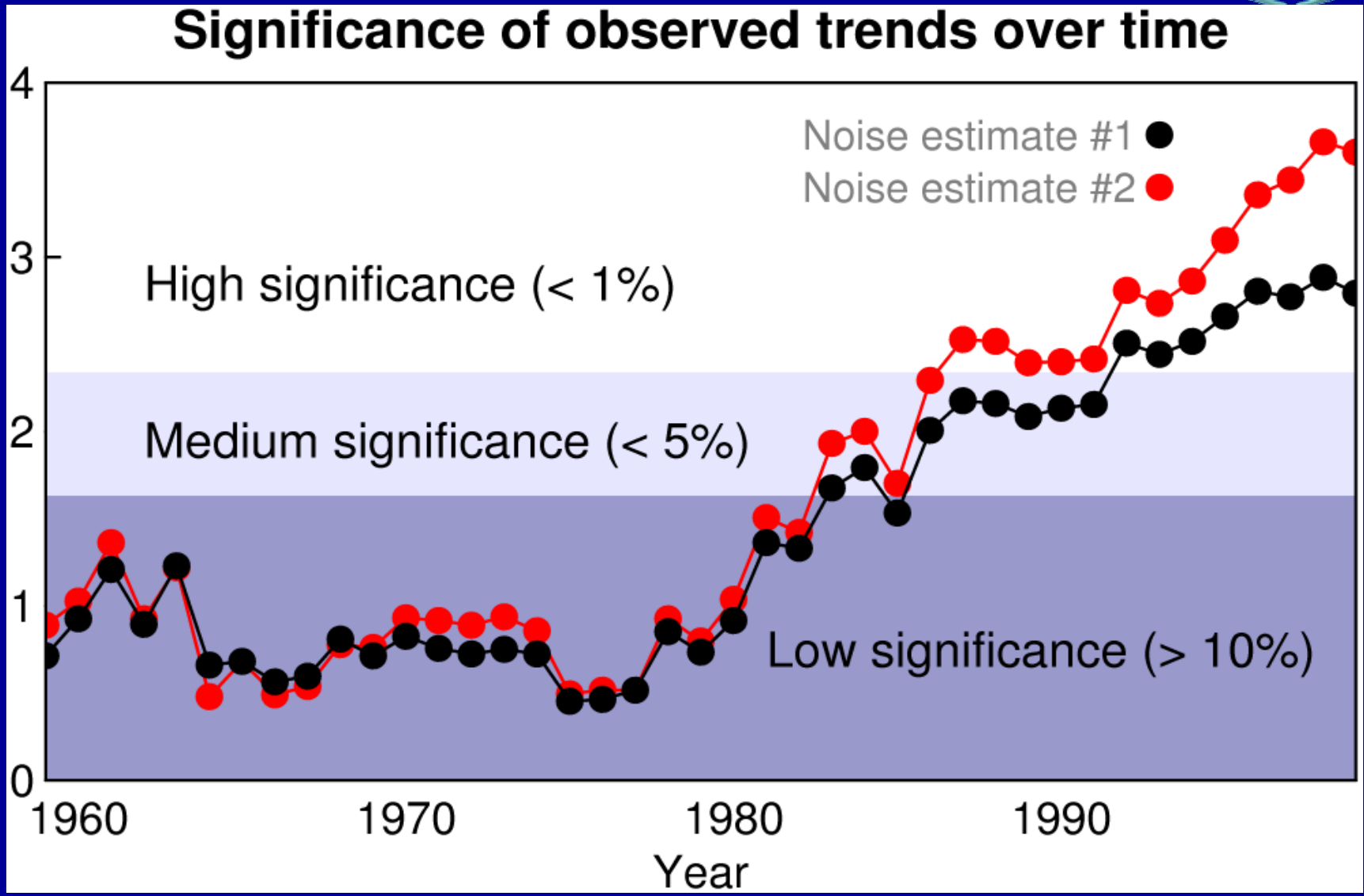
Q: WHY? ANS: It is ‘US’!

How good are estimates of Natural Variability?

Spectra reconstructed Colorado River flow last 1000+ years



Time dependent D&A



Barnett, et al, SCIENCE,2008

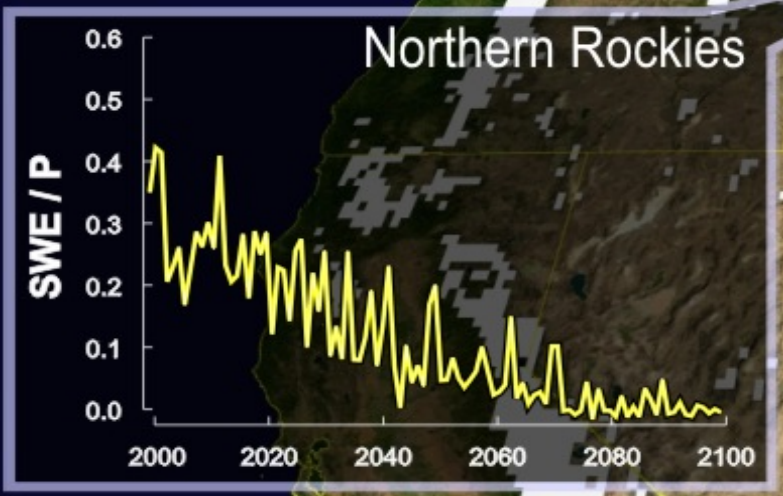
Conclusions

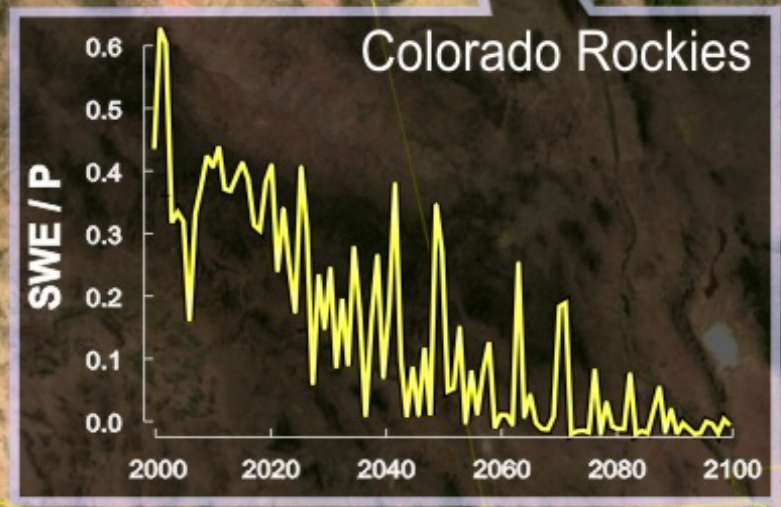
- The changes in western hydrology over 1950-99 are largely due to human-induced warming; PCM captures 60% of low frequency signal
- The PCM, run in forecast mode, shows a grim view of western U.S. water supplies within the next 30 years (ACPI). If PCM worked so well over the last 50 years, we have good reason to believe these predictions

Western United States Water Supply:

A glimpse of the future

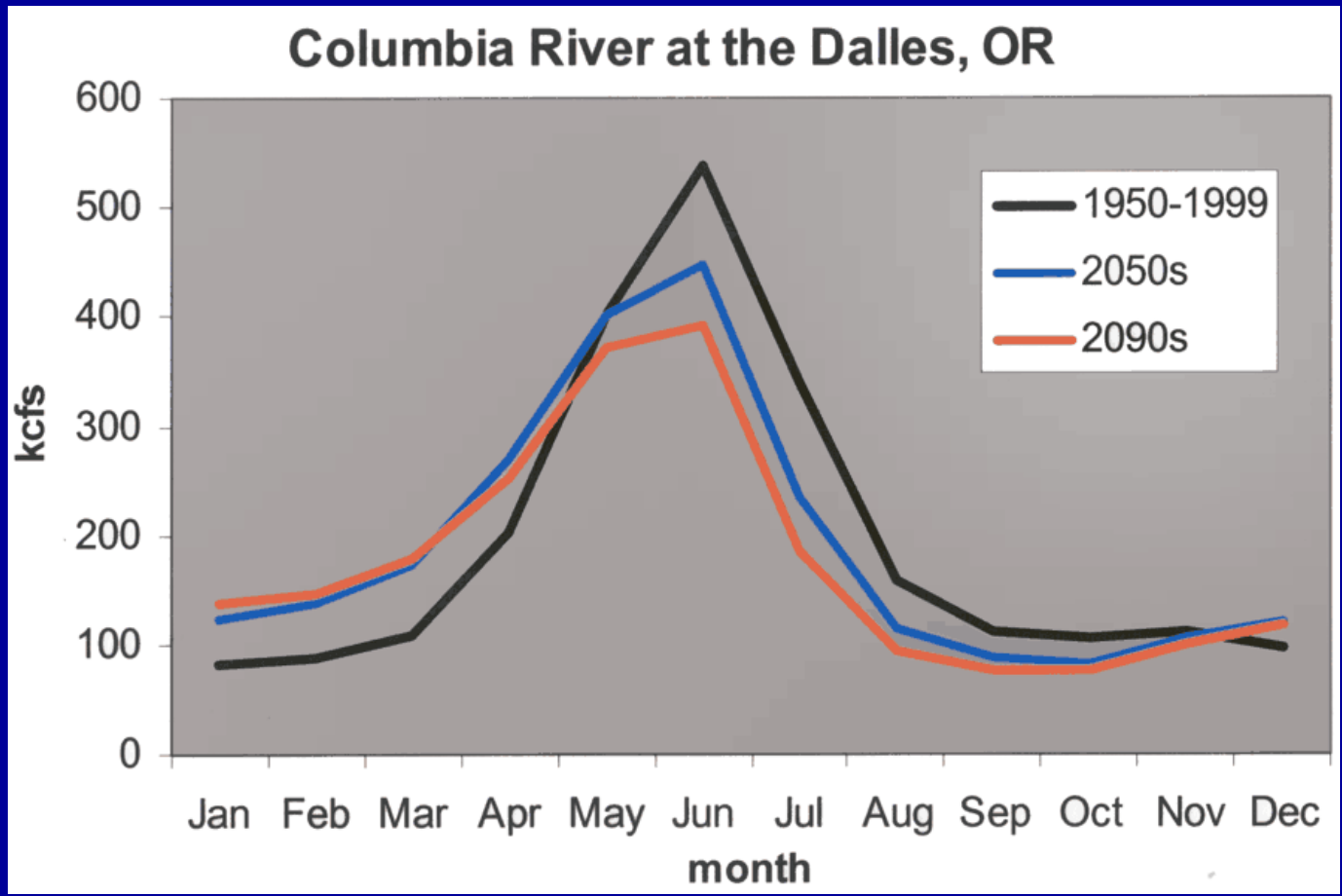
April 1st snowpack





Columbia River basin

Such Changes Would Clearly Affect Water Resources



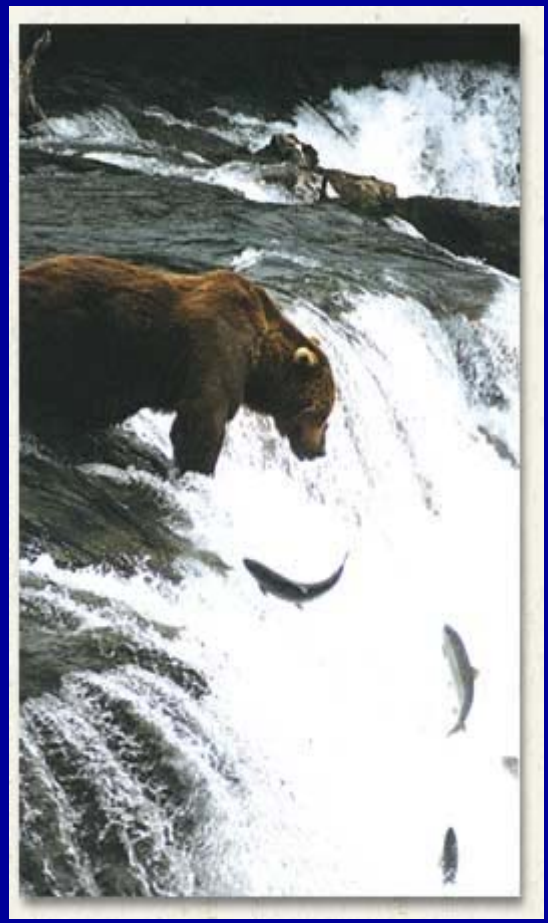
Andrew Wood, Univ. of Washington

Columbia Basin Options

Hydropower

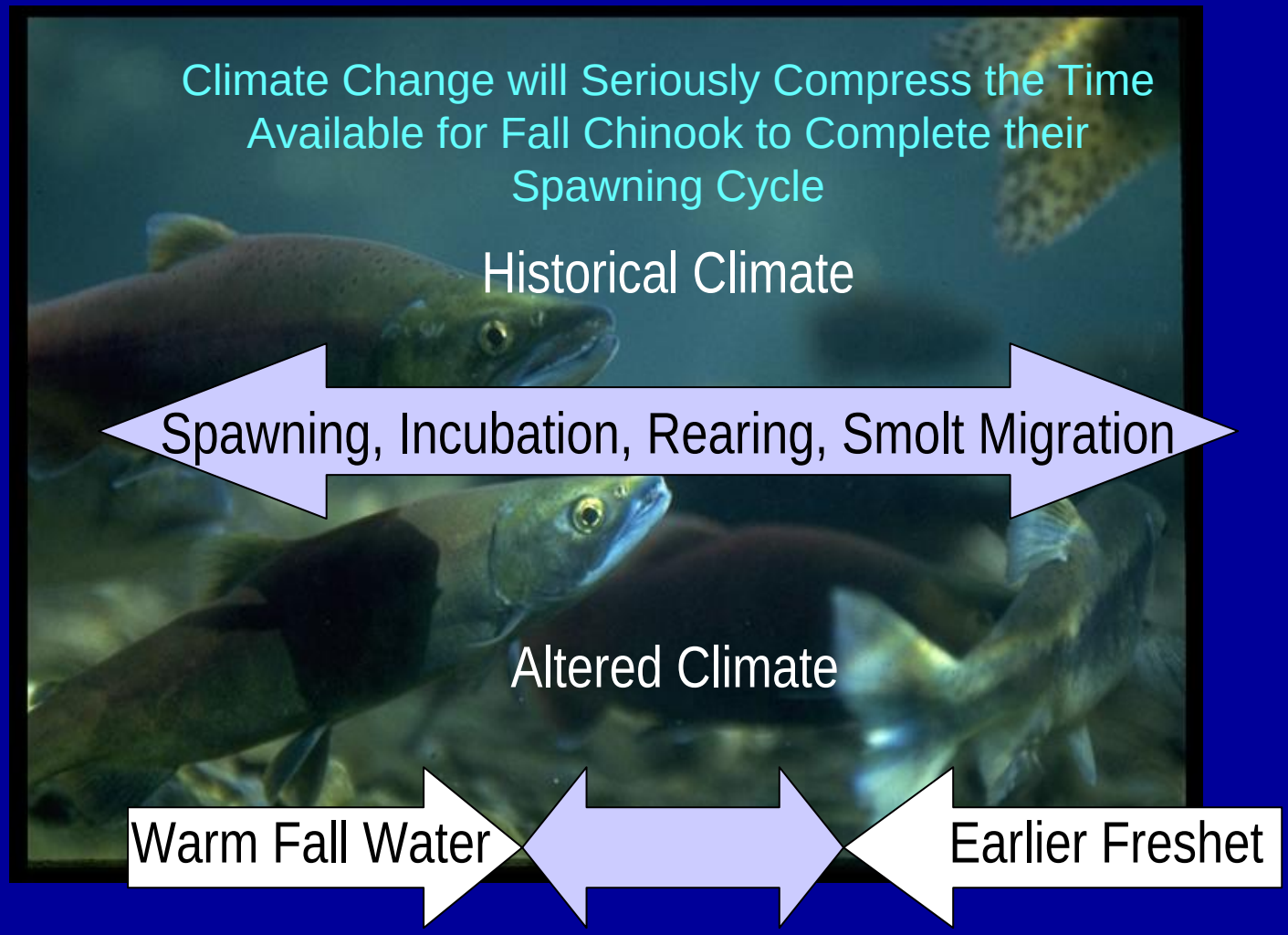
Or

Salmon



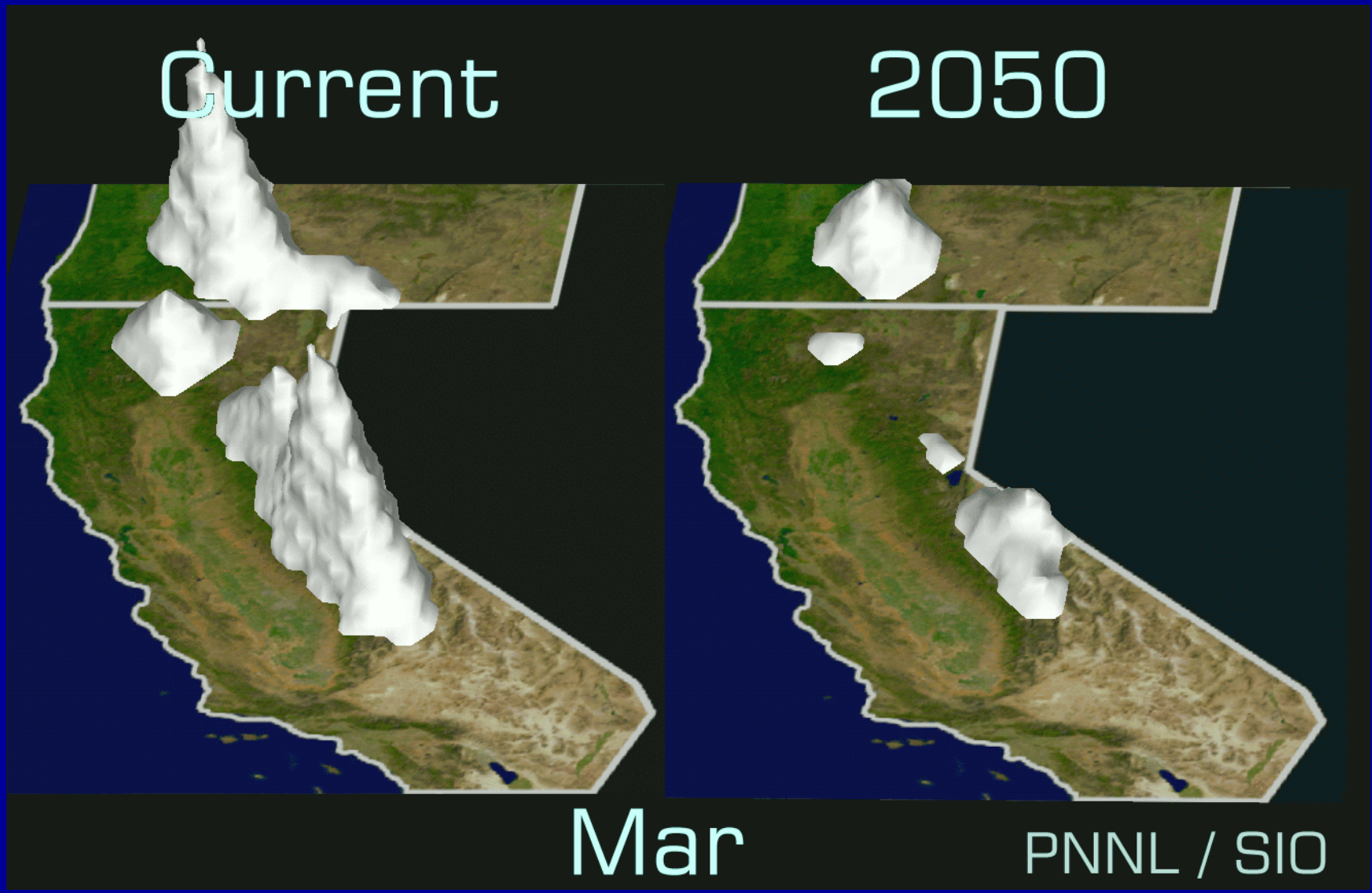
Klamath low flow salmon kill (circa 2002)

Can salmon survive in the PNW?

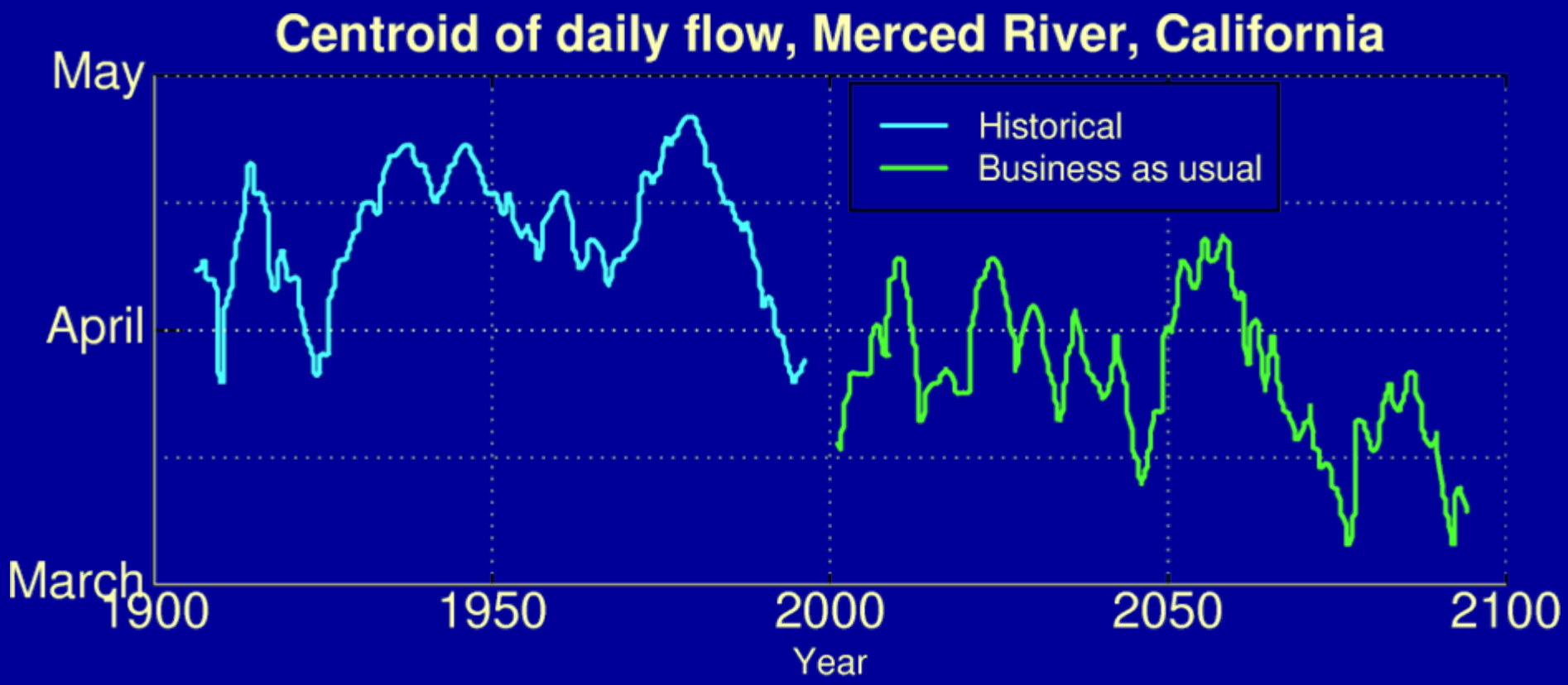


Sacramento/San Joaquin River basin

Projected change in California snowfall...

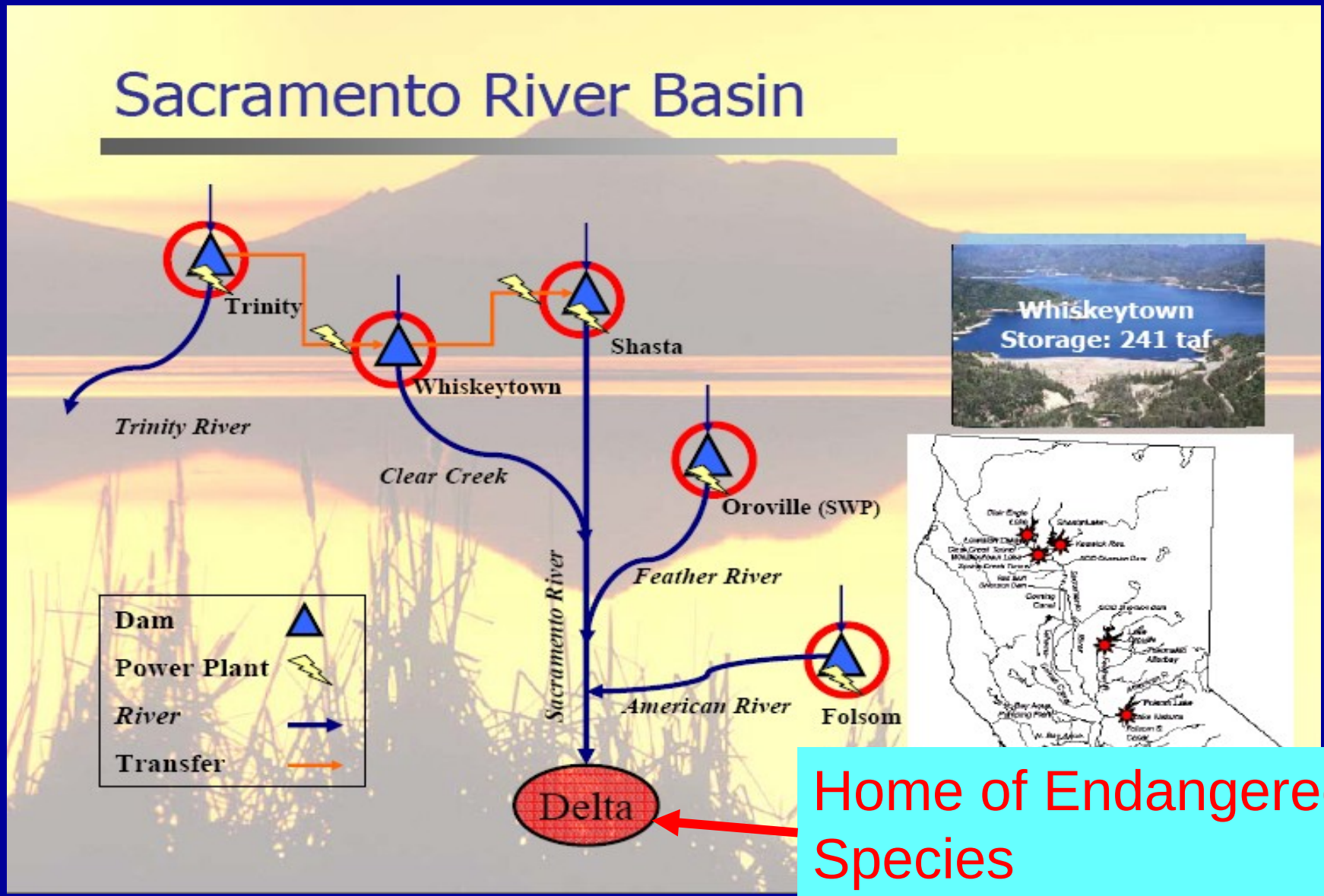


River flow earlier in the year



Source: Michael Dettinger, SIO/USGS

Most of So. Cal water supply flows thro the Delta: Problem 1

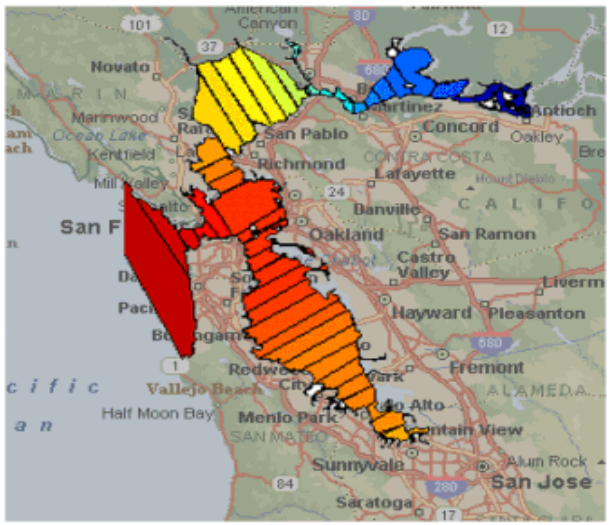


Home of Endangered Species

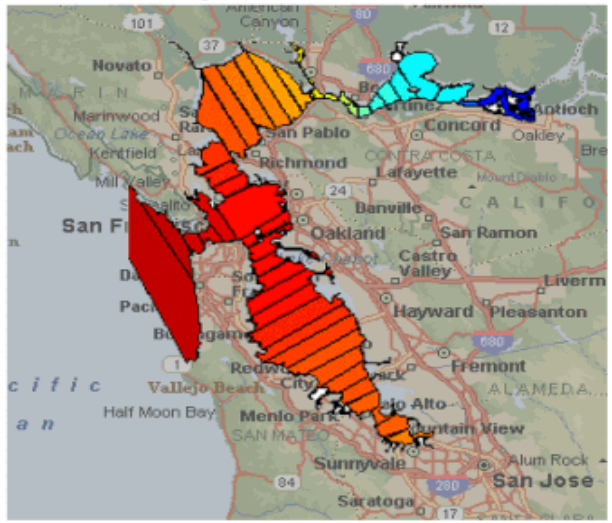
Sacramento Delta Salinity: Now & 2060

Impacts of PCM-Projected Warming on San Francisco Bay Summer Salinities

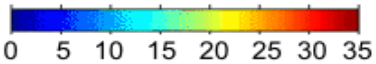
Current summer conditions



Projected 2060



Salinity



Dr. Noah Knowles
noah@ucsd.edu

The dreaded Delta Smelt

Lake Hodges during a wet year

PROBLEM 2: Calif does not have enough water storage

Calif. has storage capacity for only 21% of its annual precipitation

Shasta spilling

California: Mandated water releases cannot be met

Colorado River basin

Colorado River drainage

Water supply for:

- 27 million people
- 3.5 million acres of farmland

Users in:

- 7 states
- 2 countries

The Three Keys to the Colorado System's future

- Mother Nature

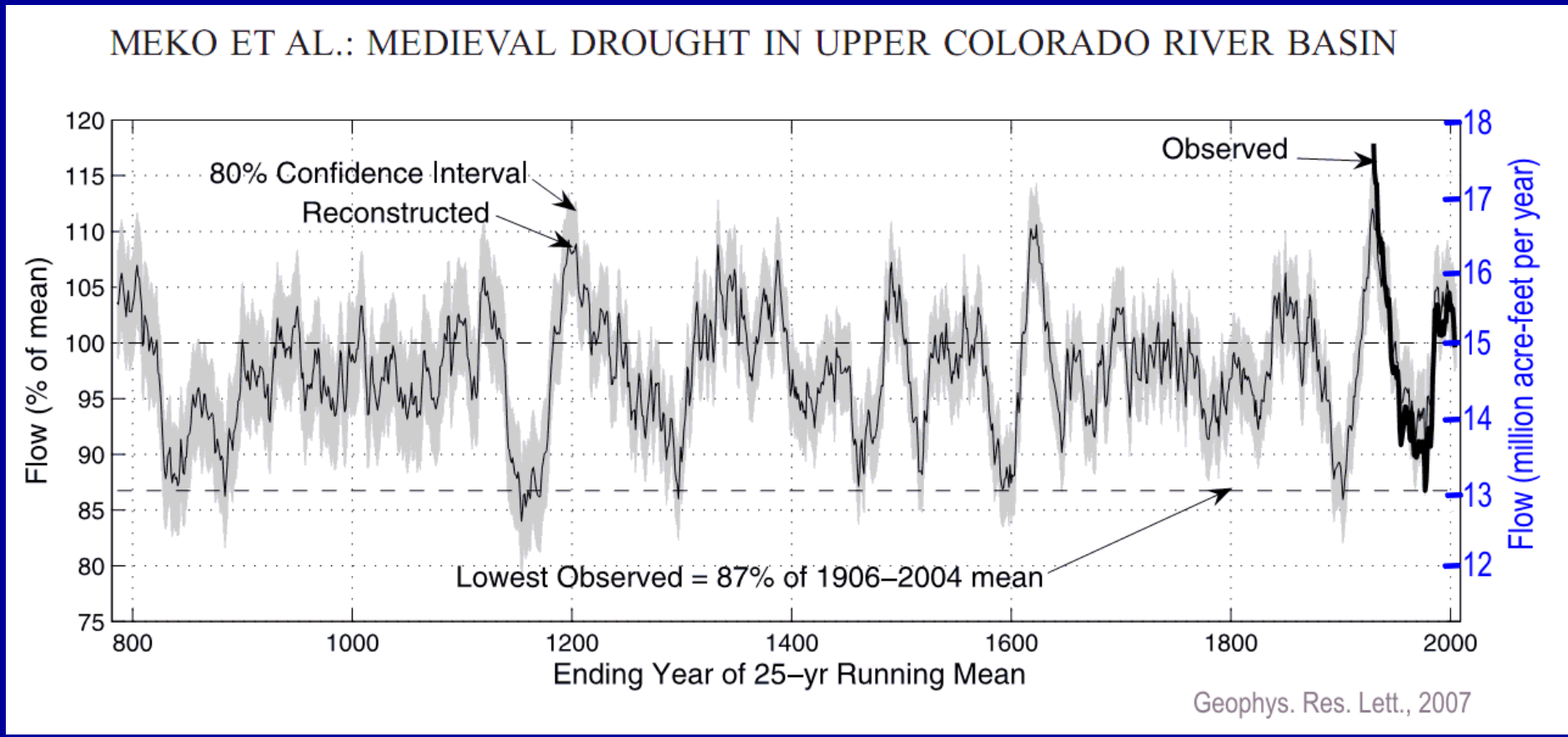
- Our stewart-ship of existing resources

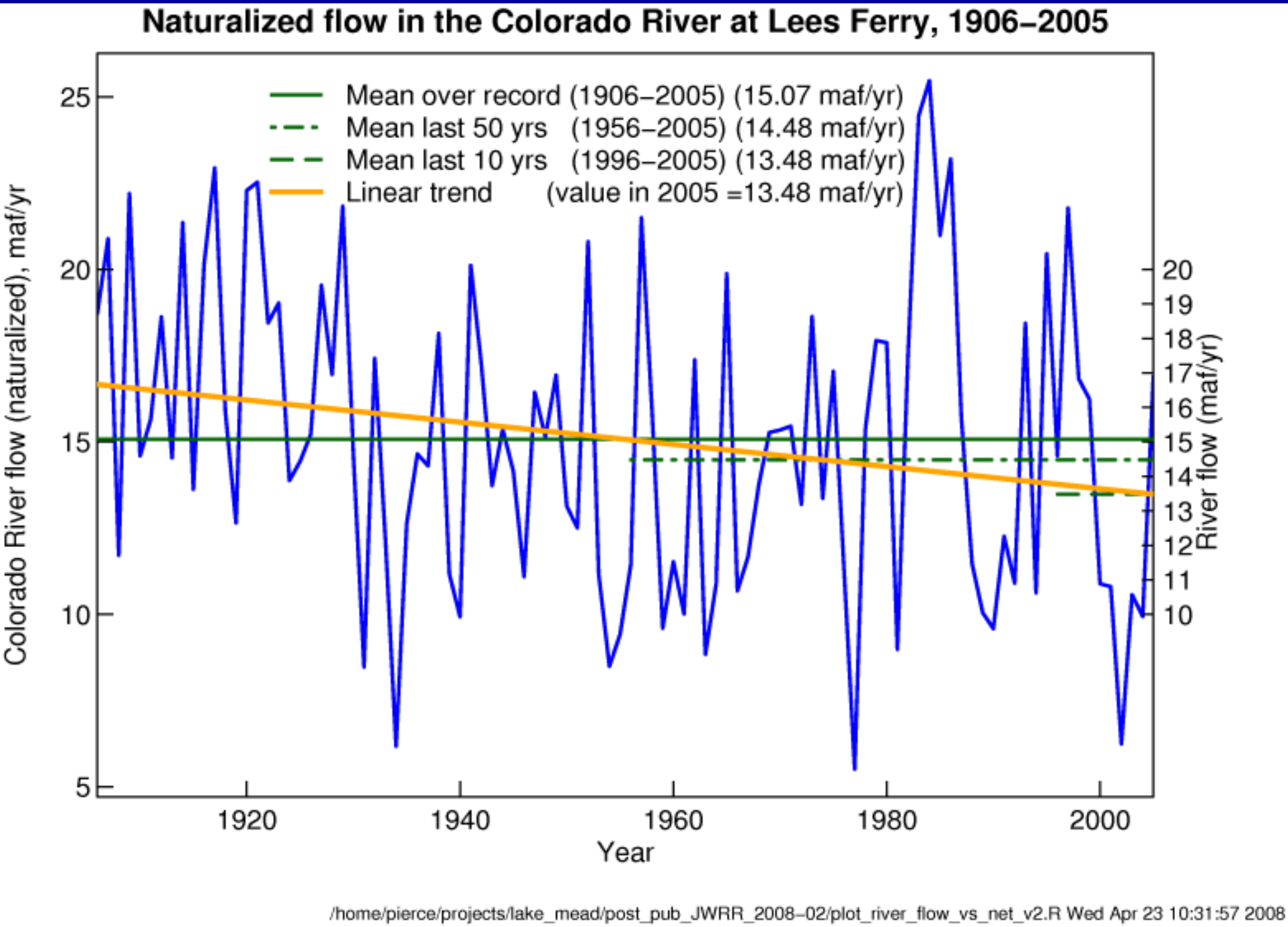
- Human-induced climate change

from "When will Lake Mead go dry?"

Water Resources Research, 2008

Colorado River flow from tree rings




Naturalized flow in the Colorado River at Lees Ferry, 1906–2005
Mean over record (1906–2005) (15.07 maf/yr)
Mean last 50 yrs (1956–2005) (14.48 maf/yr)
Mean last 10 yrs (1996–2005) (13.48 maf/yr)
Linear trend (value in 2005 =13.48 maf/yr)
Colorado River flow (naturalized), maf/yr
River flow (maf/yr)
Year
25
20
15
10
5
20
19
18
17
16
15
14
13
12
11
10
1920
1940
1960
1980
2000
/home/pierce/projects/lake_mead/post_pub_JWRR_2008-02/plot_river_flow_vs_net_v2.R Wed Apr 23 10:31:57 2008

The Problem Today

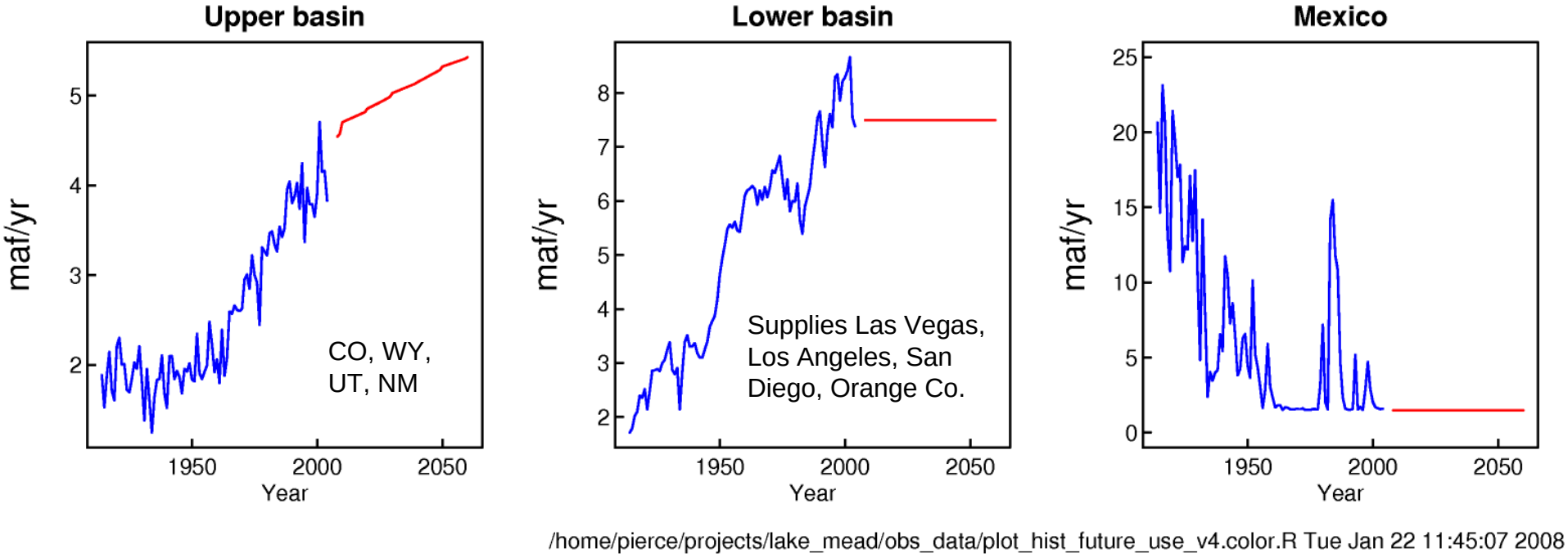
Continuing deliveries of 8.23 million acre-feet per year (MAFY) will result in Lake Mead continuing to drop:

- With average side (tributary) inflows and normal deliveries to CA, AZ and NV, Lake Mead storage will continue to decline between 0.75 to 1.0 MAFY.
- Side inflow about balances evaporative losses at Lake Mead on an average annual basis.
- The Lower Basin cannot sustain 7.5 MAFY of use ("normal" deliveries") if releases from Lake Powell continue to be 8.23 MAFY for a prolonged period.

Annual LCRB Water Balance:

Inflow:	+ 8.23 MAF
	+ 0.77 MAF
	+ 9.00 MAF
(Powell release + side inflows)	
Outflow:	- 7.5 MAF
	- 1.5 MAF
	- 0.3 MAF
	- 9.30 MAF
(LB & Mexico apportionments + downstream regulation, gains and losses)	
Evaporation:	**- 0.70 MAF**
(Lake Mead annual evaporation loss)	
Balance:	**- 1.0 MAFY**

Historic and scheduled water deliveries



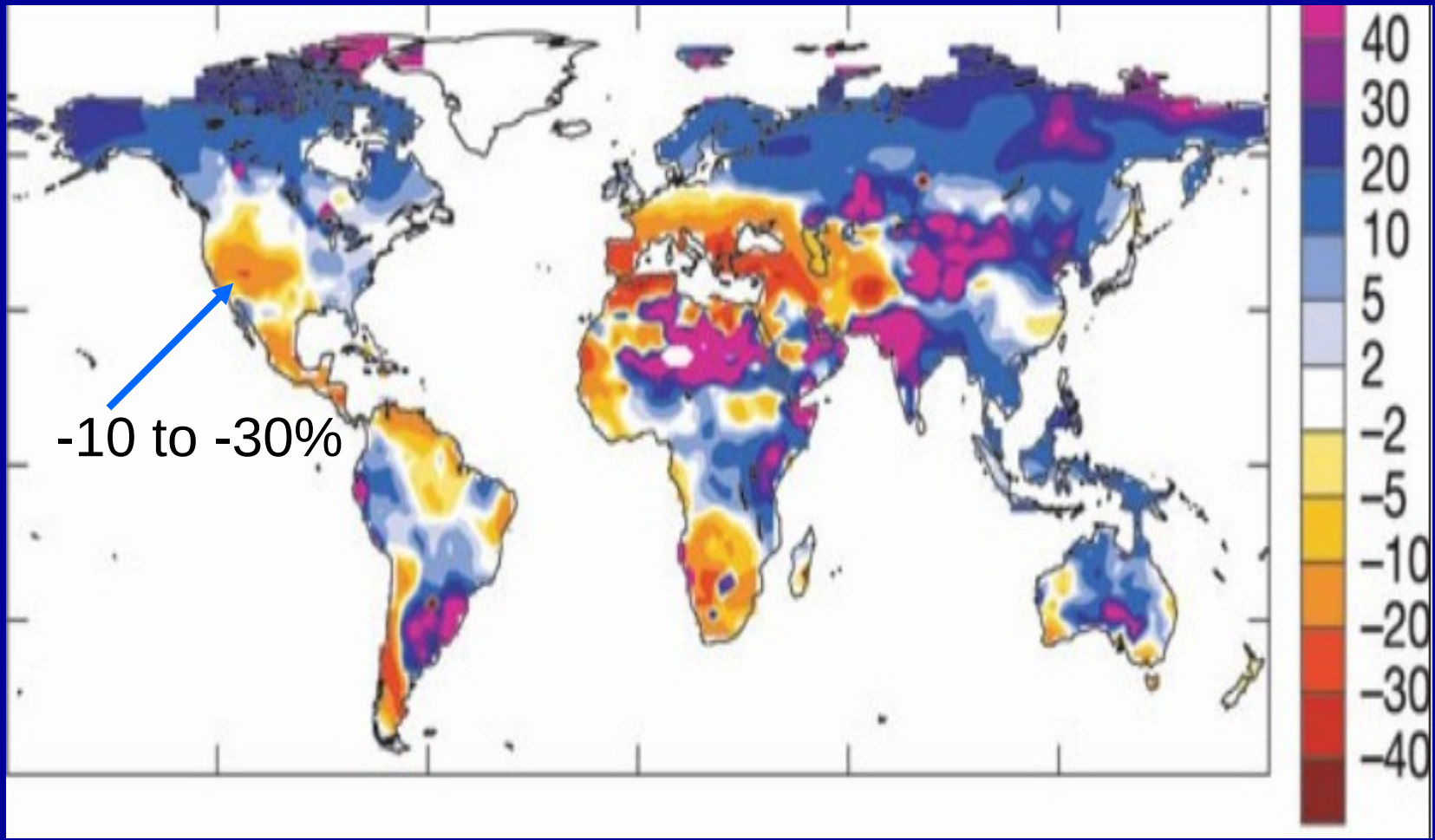
Scheduled deliveries are from
the U.S. Bureau of Reclamation, 2007

Lake Mead, Oct 2007

Lake Mead's elevation is 15 feet lower than last year at this time!
Lake Mead is 118 feet below maximum elevation!
Lake Mead has fallen to 46% of capacity!

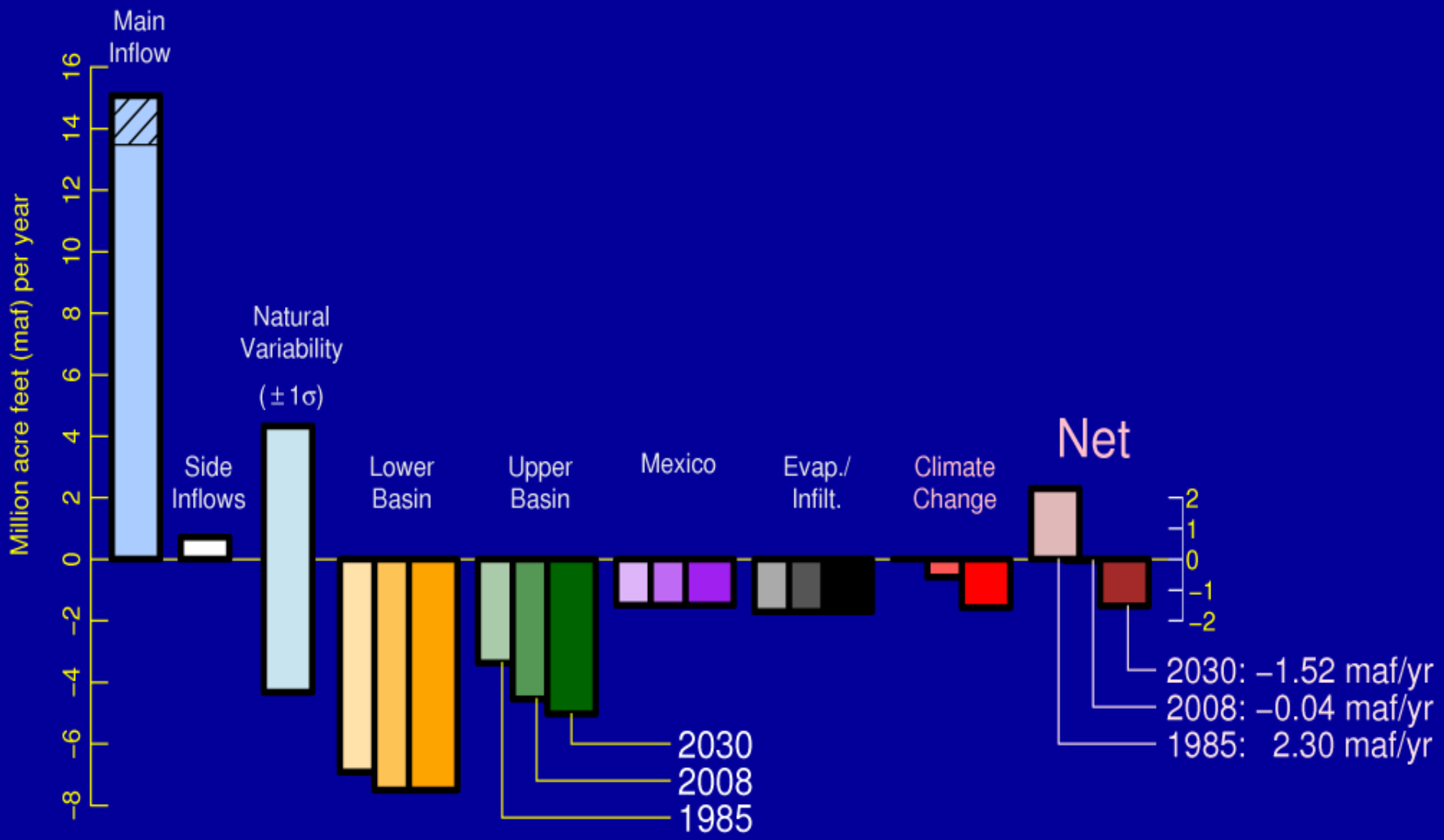
From K. Dewey, HPRCC

Human-Induced Runoff Reduction by 2050 (%)



After Milly et al 2005

Colorado River water budget

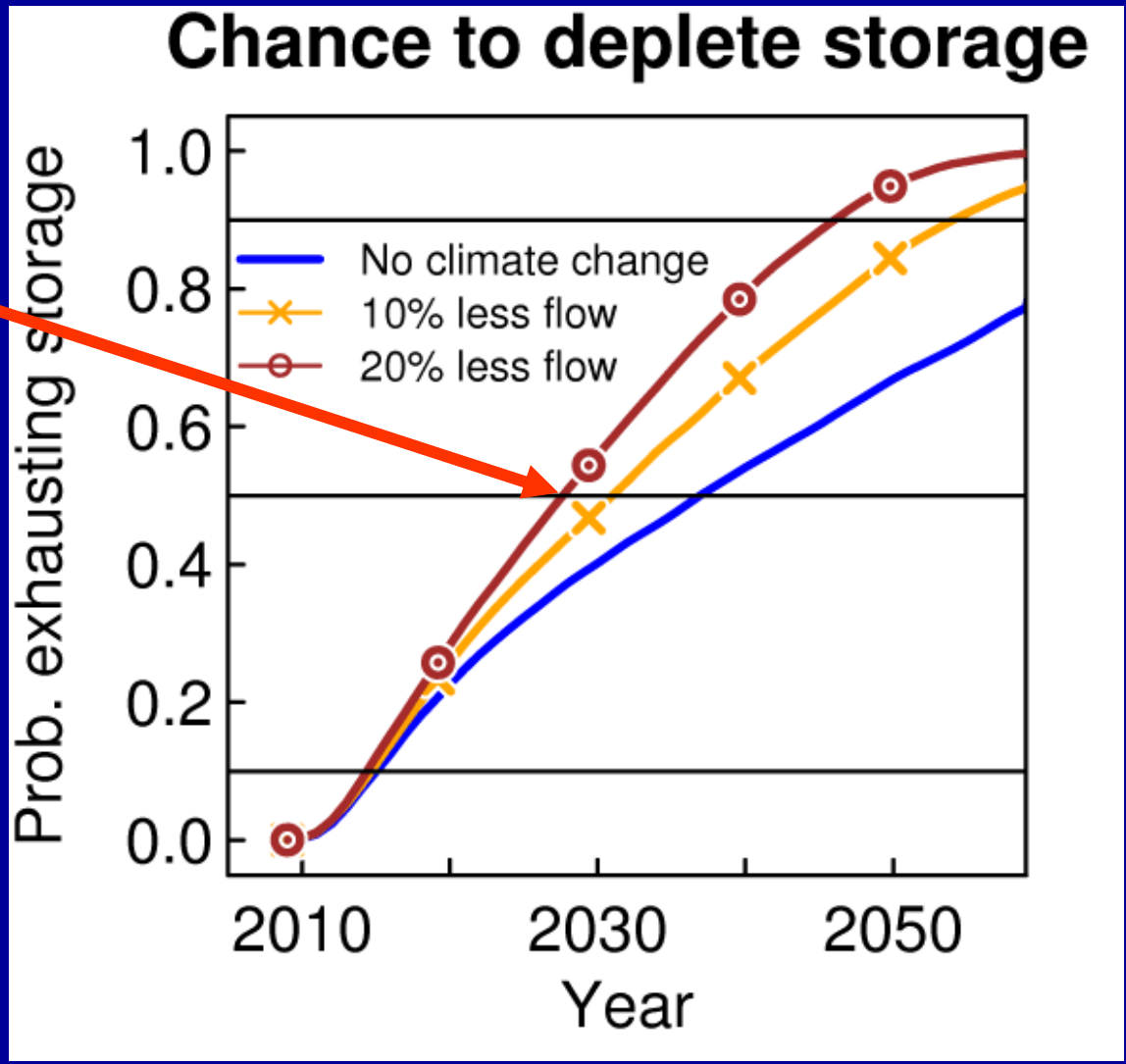


NOTE: Full climate change impacts not realized in 2050

/home/pierce/projects/lake_mead/budget_bar_graph/budget_bar_graph_v5.R Wed Apr 23 12:54:29 2008

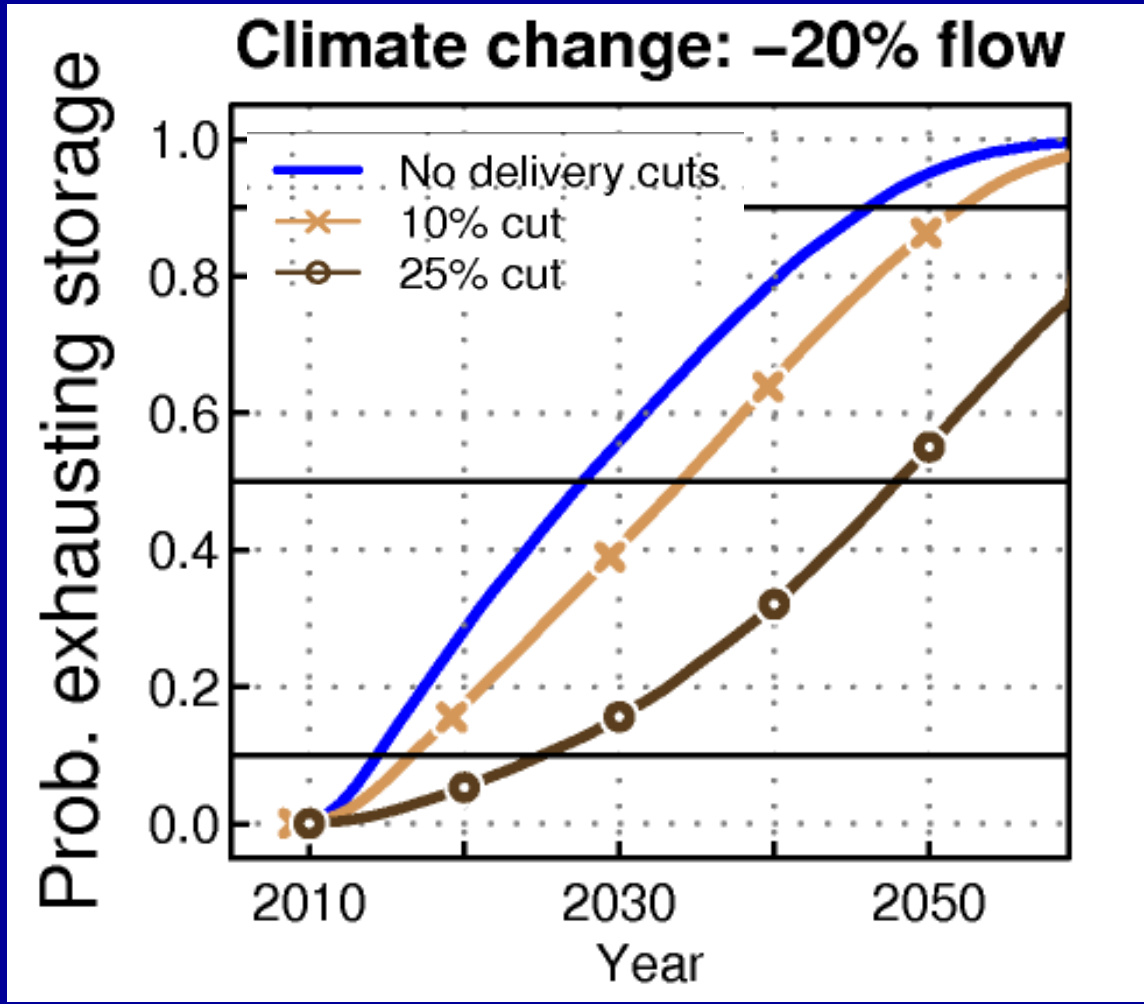
MEAD TOMORROW: Human-induced runoff reduction impacts

50% chance
Mead goes
Dry by 2028



Can we sustain Lake Mead?

Consumption cuts vs. Human-induced Runoff reduction



10%=1.5maf/yr $USBR_{max}$=0.5maf/yr

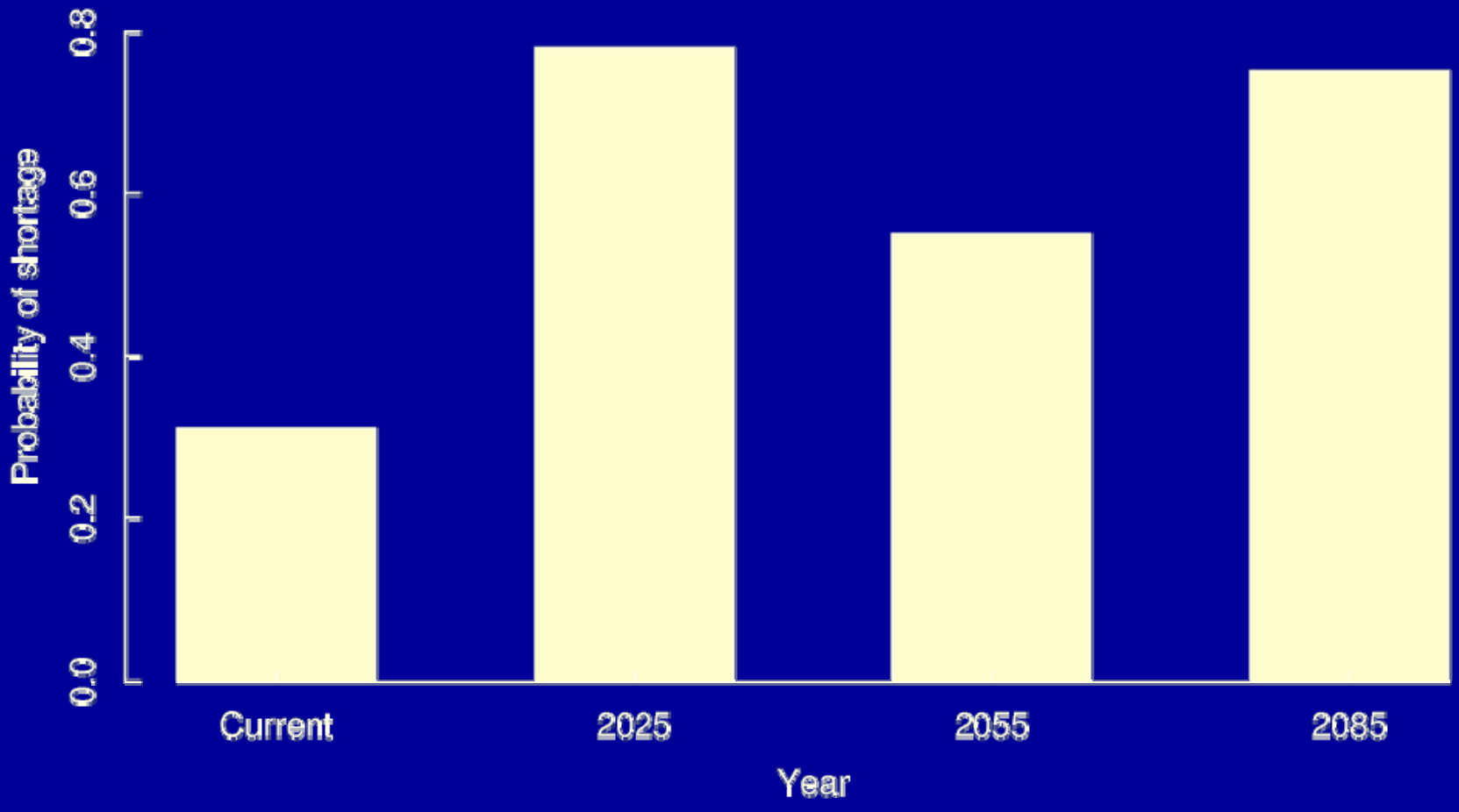
Effects of climate change on Lake Mead

Scenario	50% chance of running dry
Reservoirs drop to dead pool	2021-2028
Deliveries cut 10% (1.5 maf); Reservoirs drop to dead pool	2034-2040
Deliveries cut 25% (3.75 maf); Reservoirs drop to dead pool	2048-2065
Reservoirs drop to power pool	2017-2023

10 million people in Los Angeles

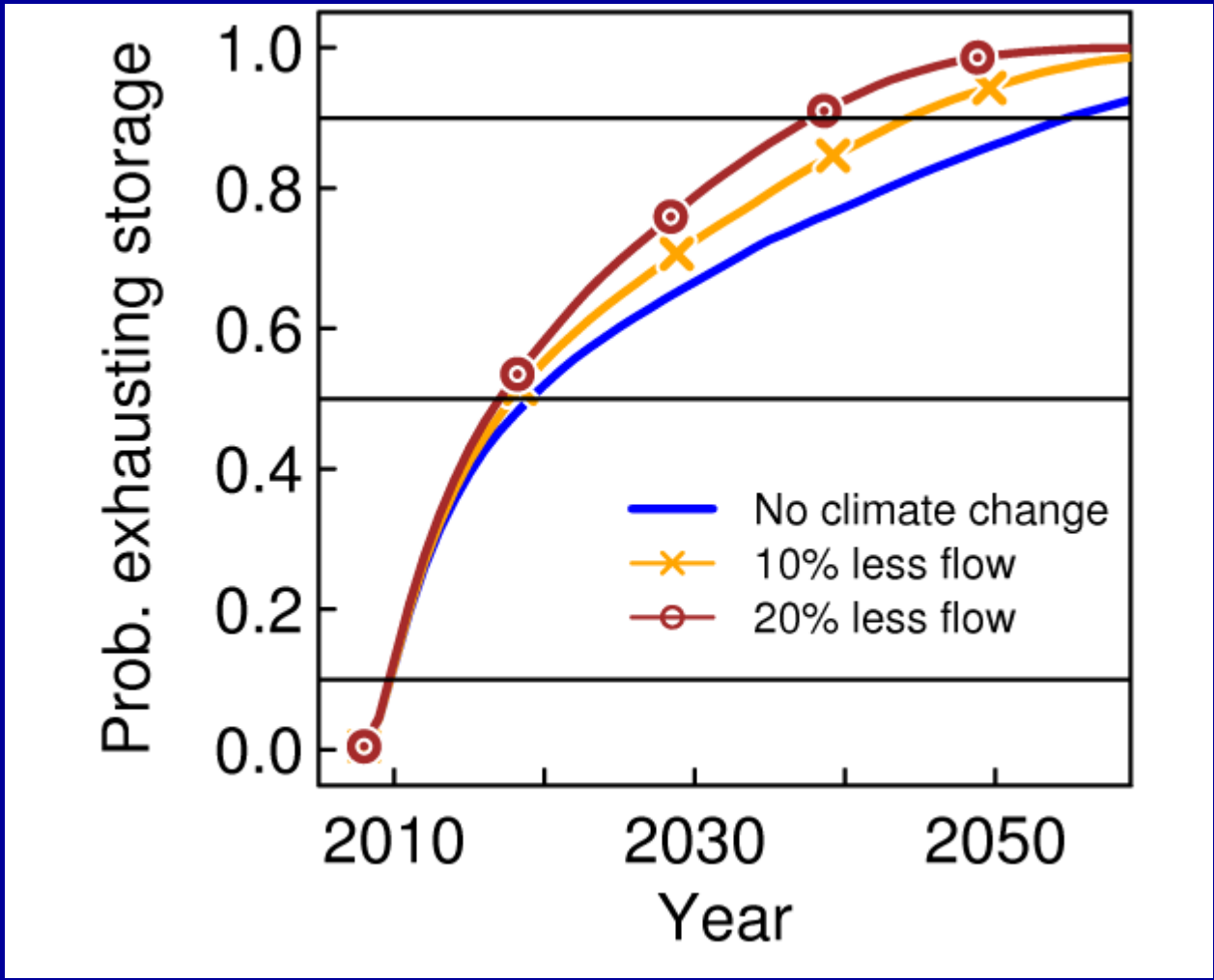
Western U.S. Water Crisis

Probability of Los Angeles water shortage



Christensen et al., *Climatic Change*, 2004

Chance to deplete to power pool level



Hydropower Reductions in a warmer world (from ACPI)

REGION	2010-39	2040-69	2070-98
Columbia	9%	14%	14%
CA Central Valley	10%	6%	12%
Colorado*	56%	45%	53%

* Lakes Mead and Powell drop below min pool elevation

Source: Climatic Change, Vol 62, 2004

Do we have time to change directions??

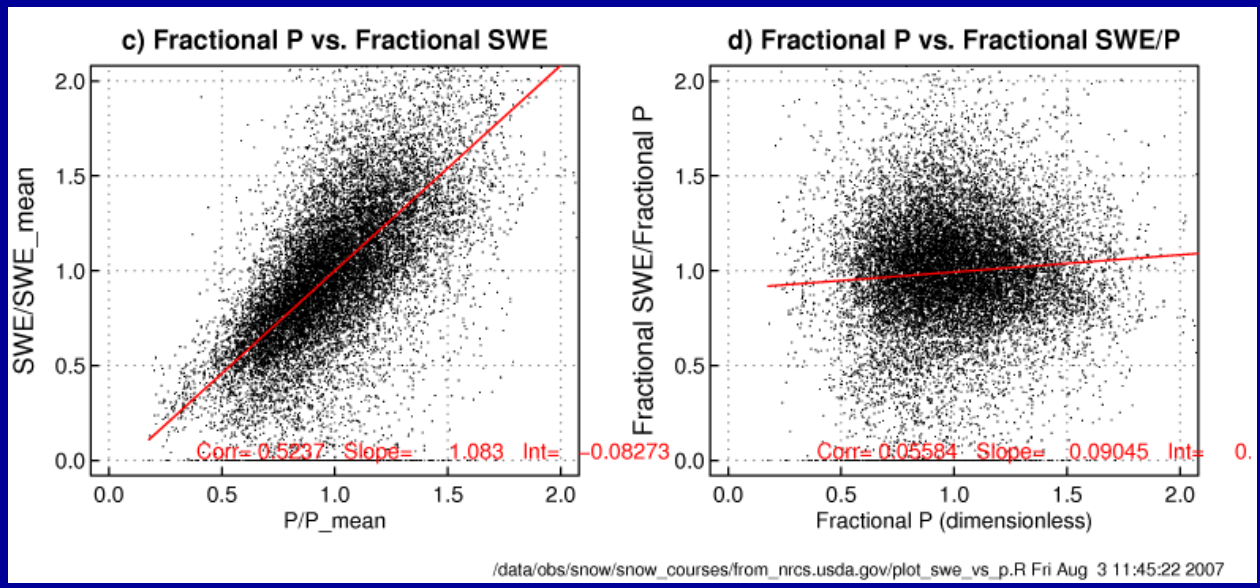
So we have a pretty good idea what the future holds

What do we do about it?

We have lots of options!

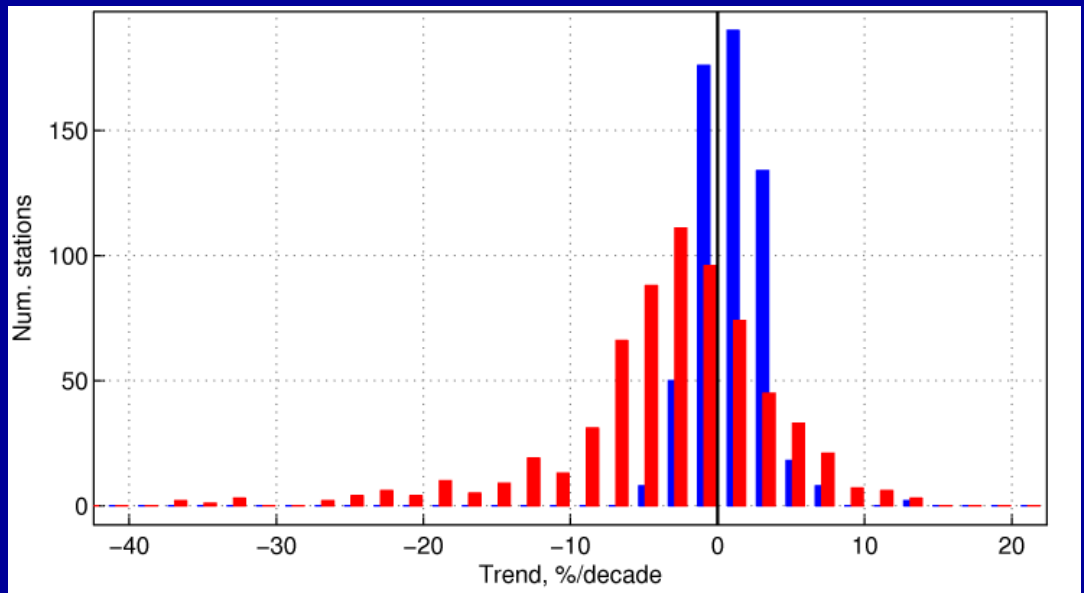
P affecting SWE/P?

Dividing by P removes majority of correlation between SWE and P

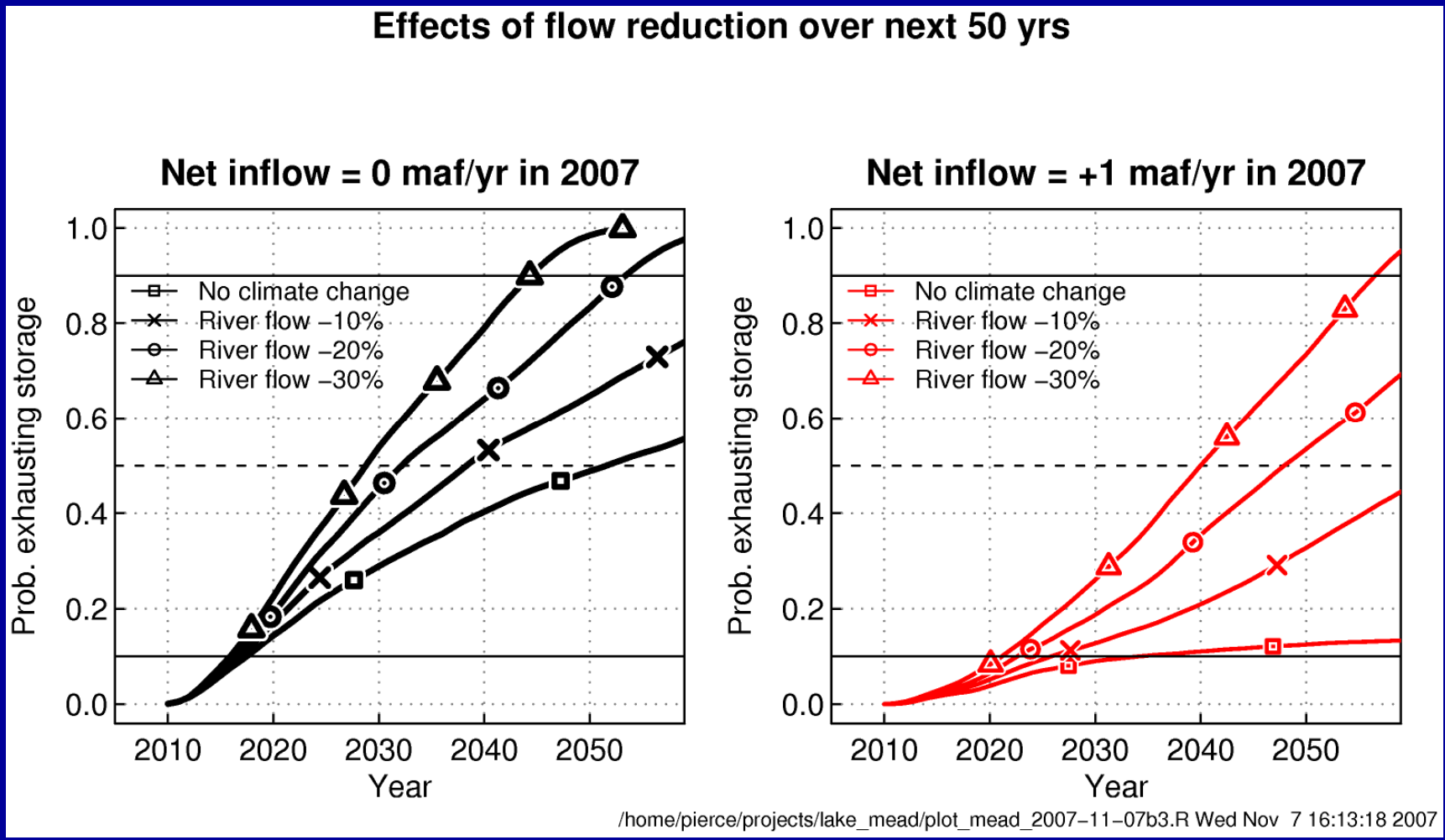


Trend in P (blue) vs. SWE (red), 1950-1999

60% of stations show increasing P, but 71% show decreasing SWE



Effect of river flow reduction



Probability of exhausting Powell/Mead storage given net flow into system and various levels of climate change

Net inflow = river flow – (consumption + evaporation)

Colorado River: Not enough water to meet *current* demands

Conclusions

- Much previous work noting changes in snow cover, temperature, and river flow over the western U.S., but no formal D&A, nor multivatiate
- We have performed a formal multivariate detection and attribution analysis of SWE/P, JFM temperatures, and river flow
- The changes in western hydrology over 1950-99 are largely human-induced; PCM captures 74% of low frequency signal
- The PCM, run in forecast mode, shows a grim view of western U.S. water supplies within the next 30 years. If it worked so well over the last 50 years, we have good reason to believe these predictions

The hydrological cycle is changing

- Examples of such changes are well documented:
  - Changes in snowfall & snow pack
    - e.g., Mote 2003; Mote et al. 2005; Knowles et al. 2006
  - Changes in streamflow
    - e.g., Cayan et al. 2001; Stewart et al. 2005; Maurer et al. 2007
  - Warmer air temperatures
    - e.g., Dettinger et al. 1995; Easterling 2002

Can we say with confidence that these changes are due to human effects?

Questions

1. Are the changes due to *warming* or different amount of *precipitation*?

2. What do other models say?

WHY? Detection and Attribution (D&A)

- Detection: are the changes *inconsistent* with natural variability?
- Attribution: are the changes *consistent* with anthropogenic (or other) forcing?
- Generate a *"fingerprint"* that encapsulates changes expected (from model runs)
- Match fingerprint in obs and forced models

Novel aspects

- *Multivariate* Detection and Attribution (D&A)

  Analyze snowpack, river flow and air temperature simultaneously

- *Regional*
  - Have to address problems of large amplitude natural variability
- *Related to the hydrological cycle*
  - Rare in formal D&A work
  - People can immediately relate to it

The Future

We are headed for a water 'crisis' in the Western U.S.

(and it has already started)

The hydrological cycle is changing over the western United States

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  - Changes in streamflow
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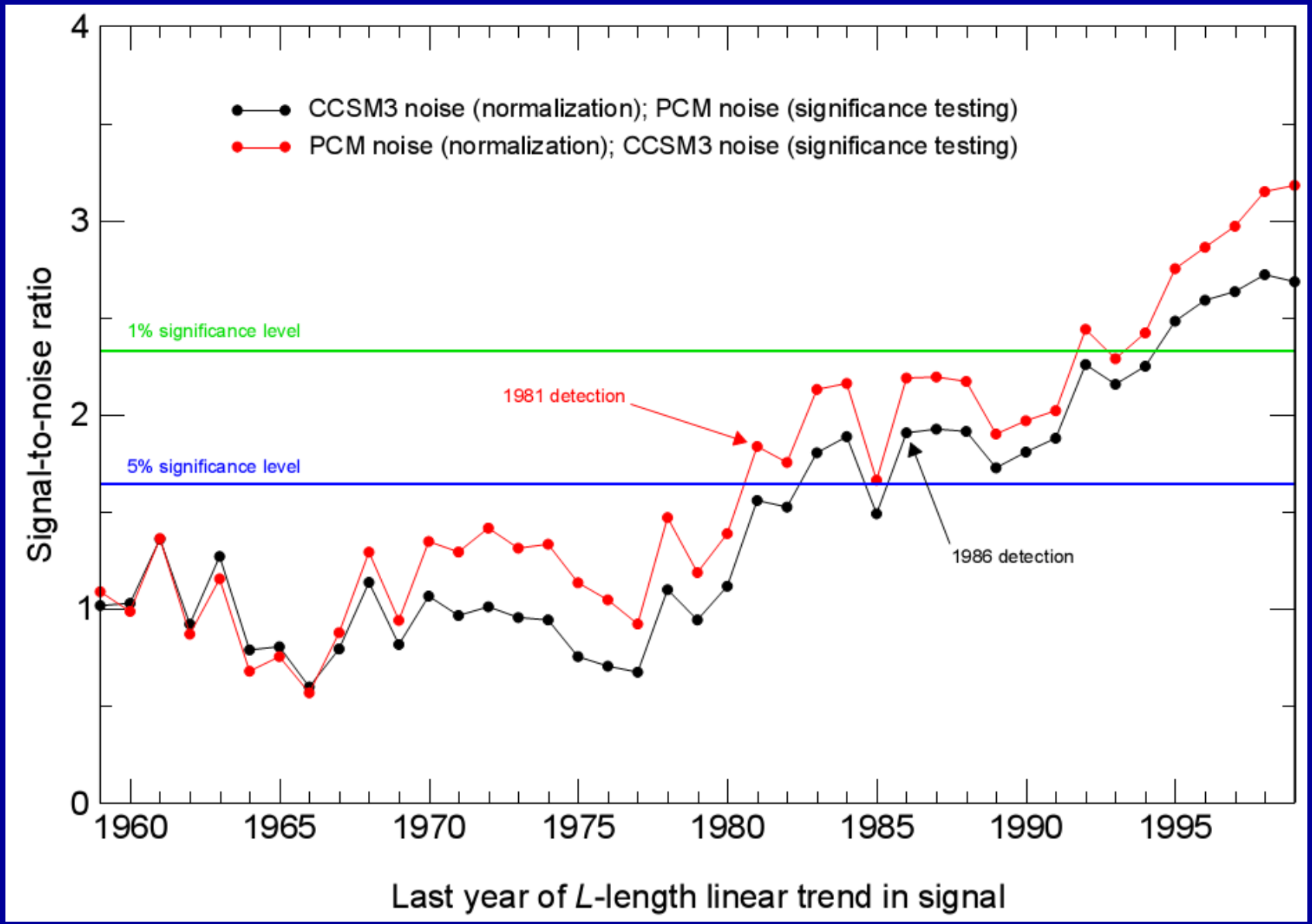
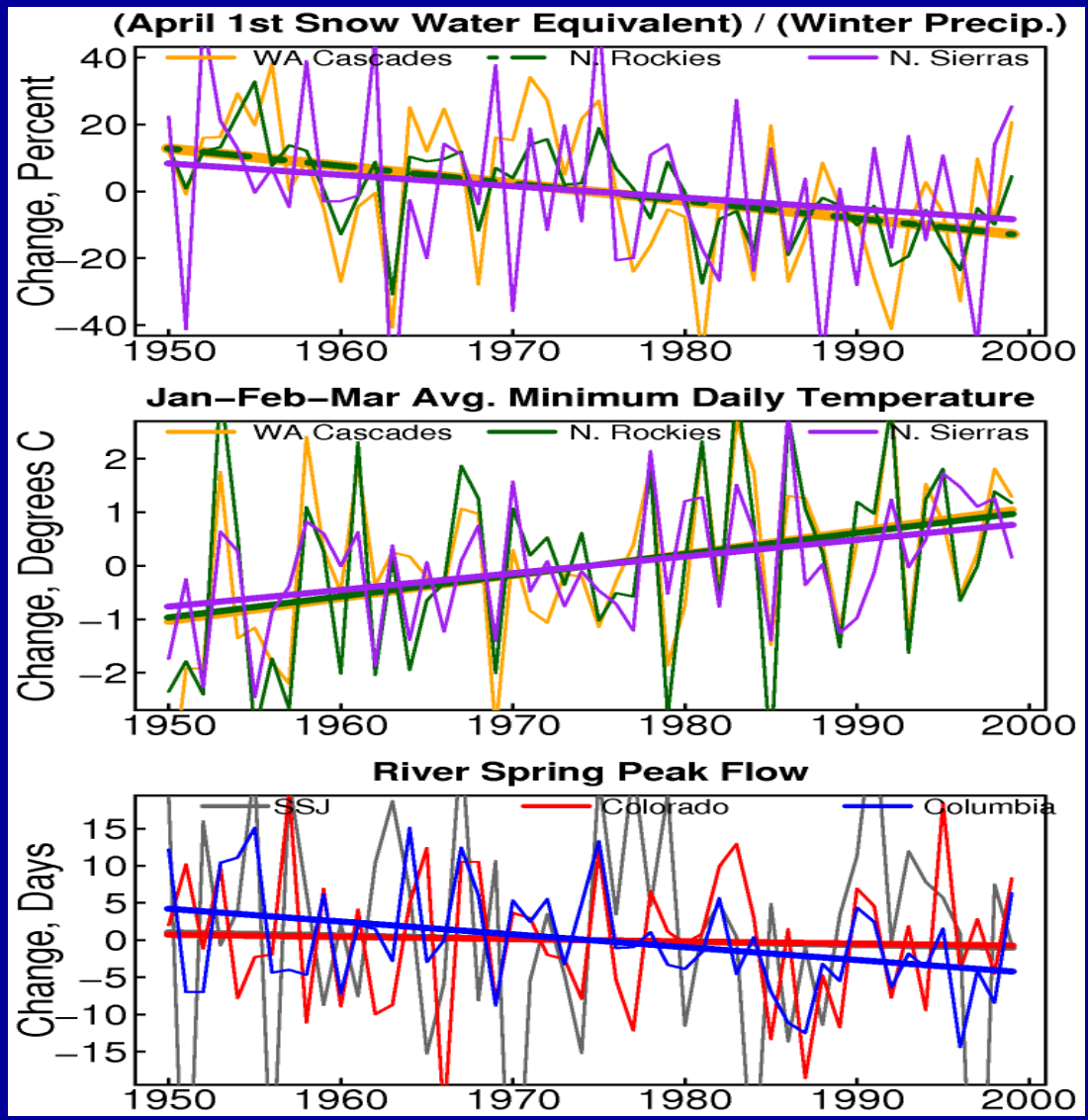
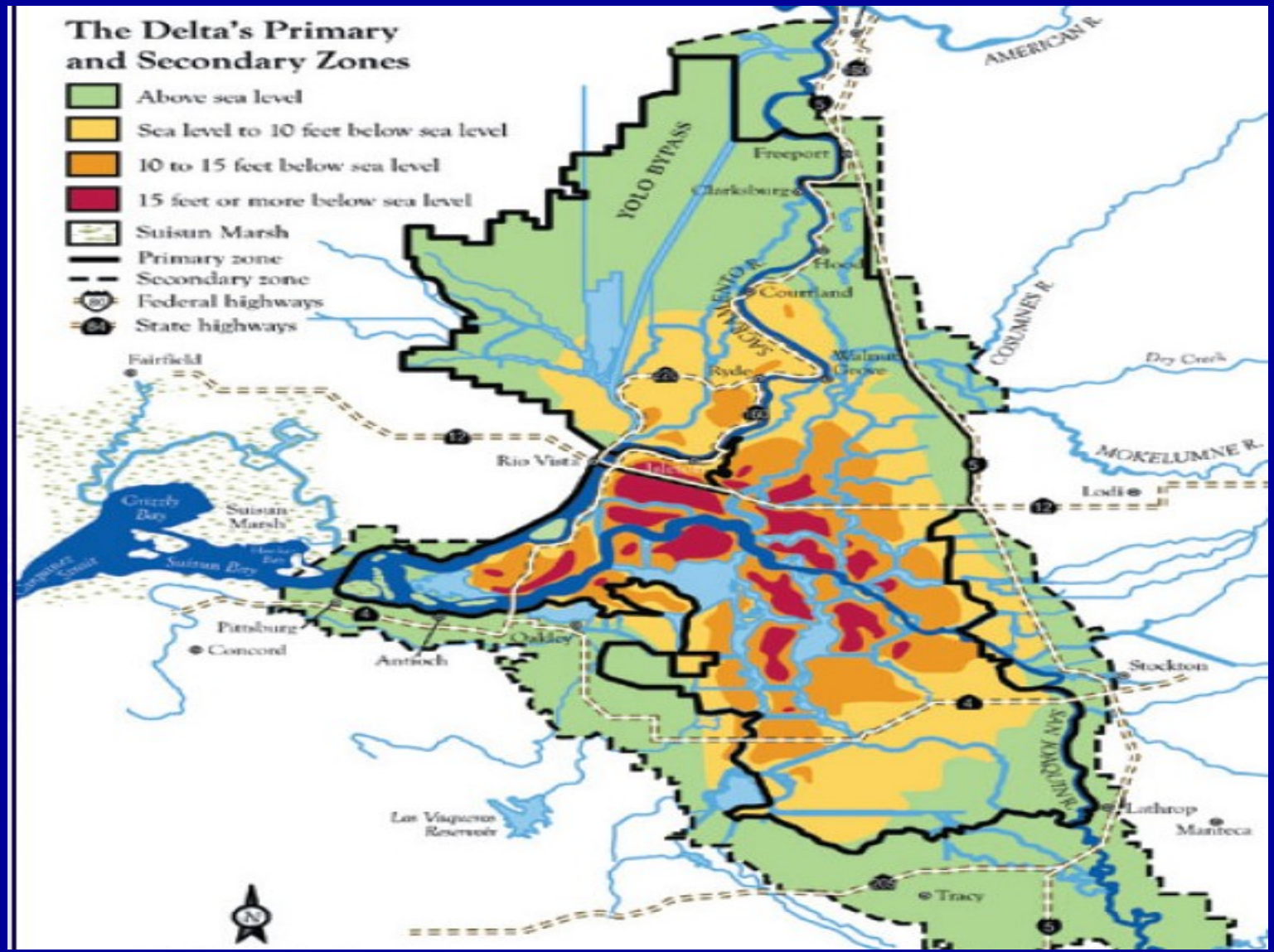
WHY?

Time to detection




(April 1st Snow Water Equivalent) / (Winter Precip.)
WA Cascades
N. Rockies
N. Sierras
Change, Percent
40
20
0
−20
−40
1950
1960
1970
1980
1990
2000
Jan−Feb−Mar Avg. Minimum Daily Temperature
WA Cascades
N. Rockies
N. Sierras
Change, Degrees C
2
1
0
−1
−2
1950
1960
1970
1980
1990
2000
River Spring Peak Flow
SSJ
Colorado
Columbia
Change, Days
15
10
5
0
−5
−10
−15
1950
1960
1970
1980
1990
2000

The Sacramento Delta



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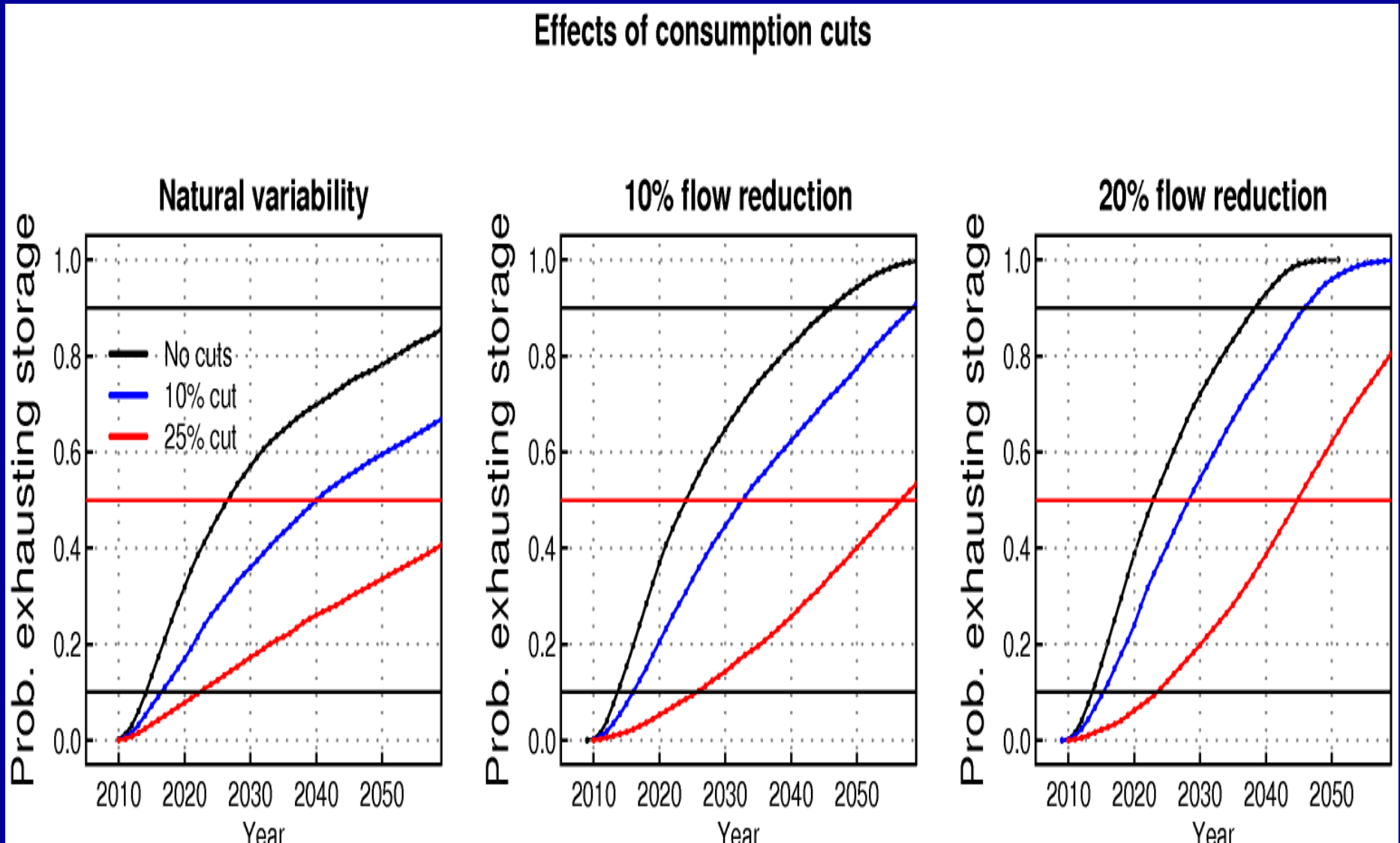
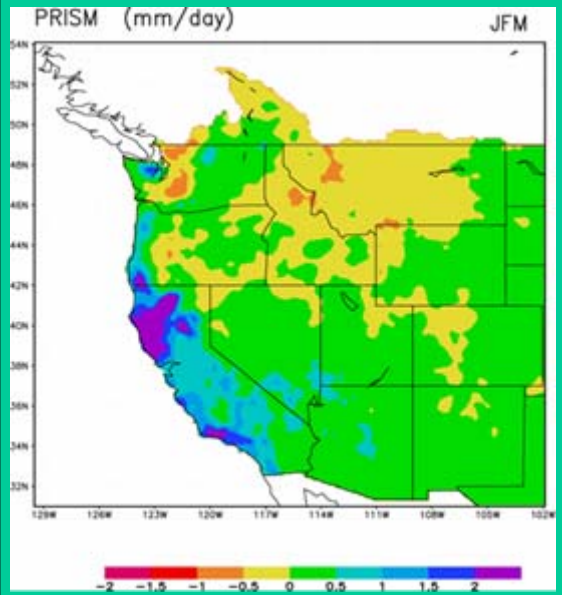


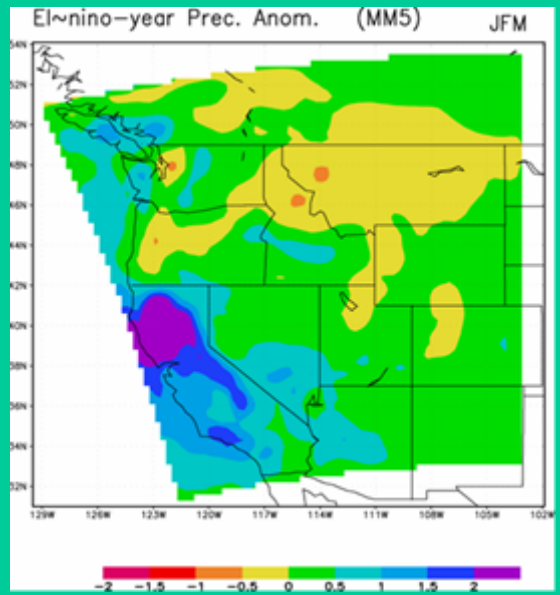
It works

El Nino rainfall simulation

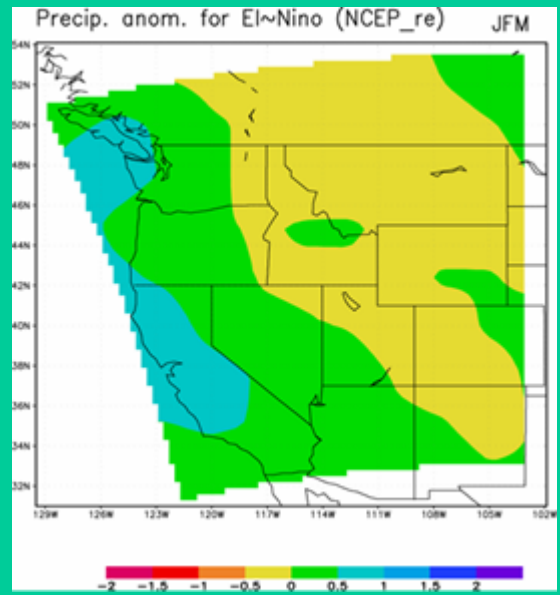
Observations



Downscaled model

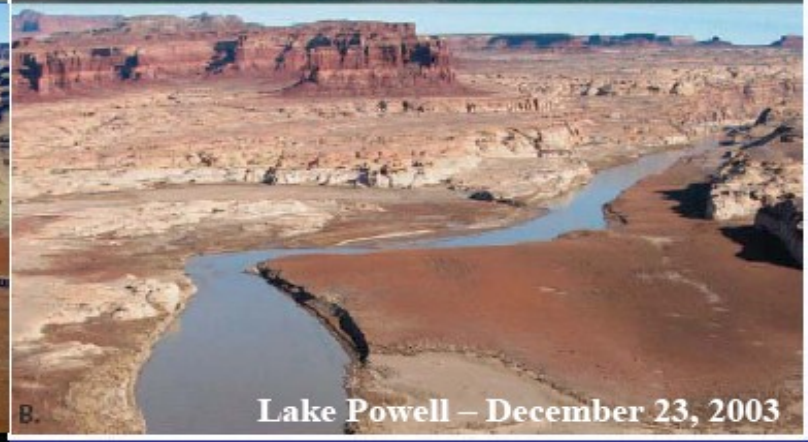


Standard reanalysis

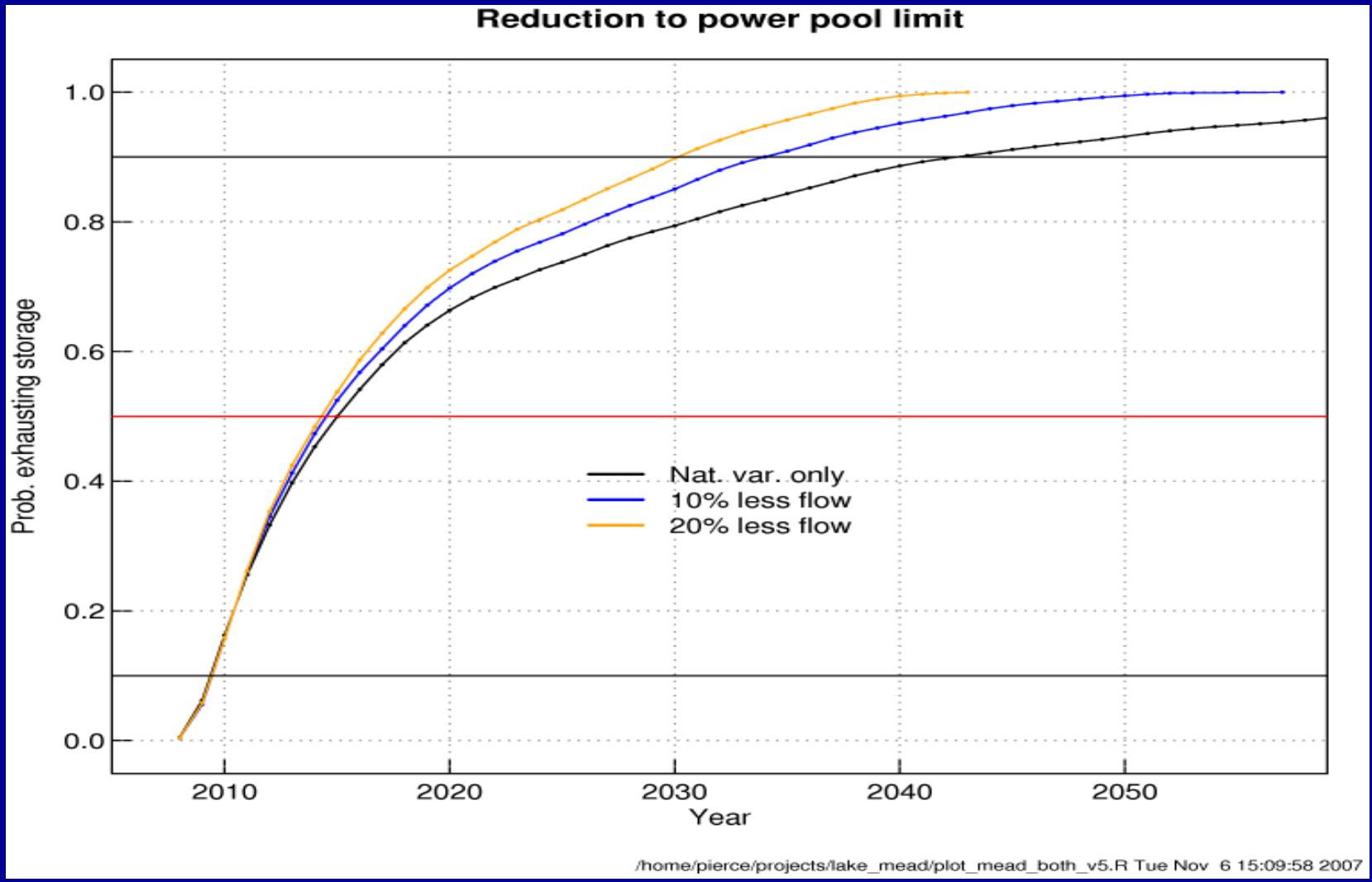


Ruby Leung, PNNL

Colorado Reservoirs: Then vs. Now



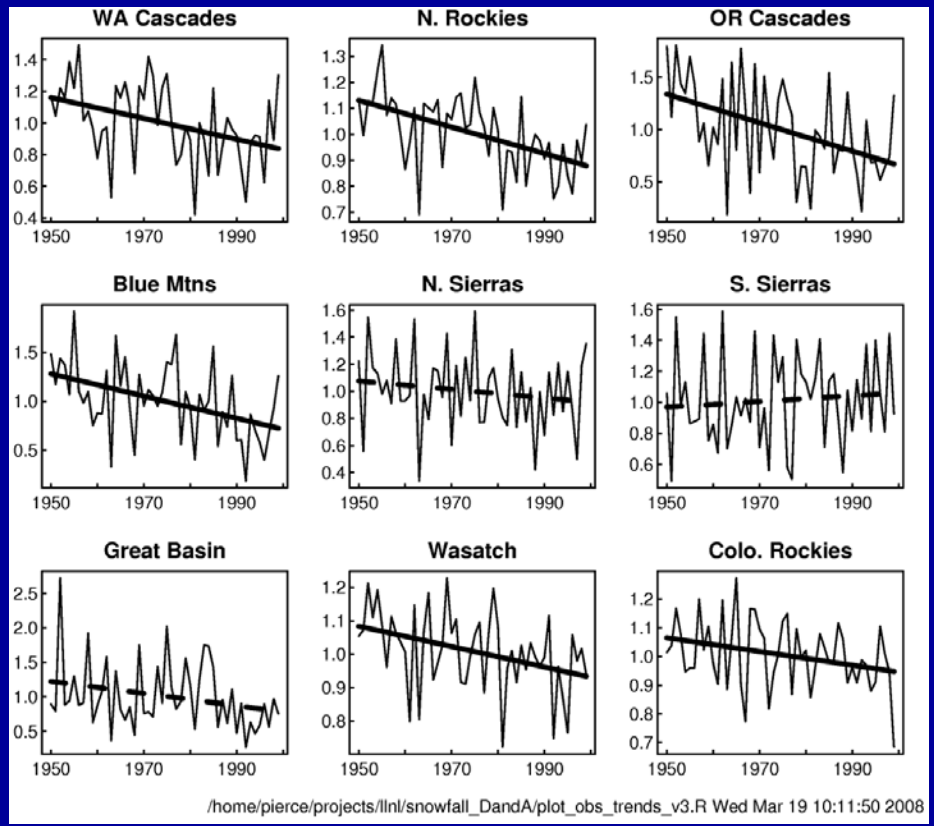
Minimum power pool elevation breached



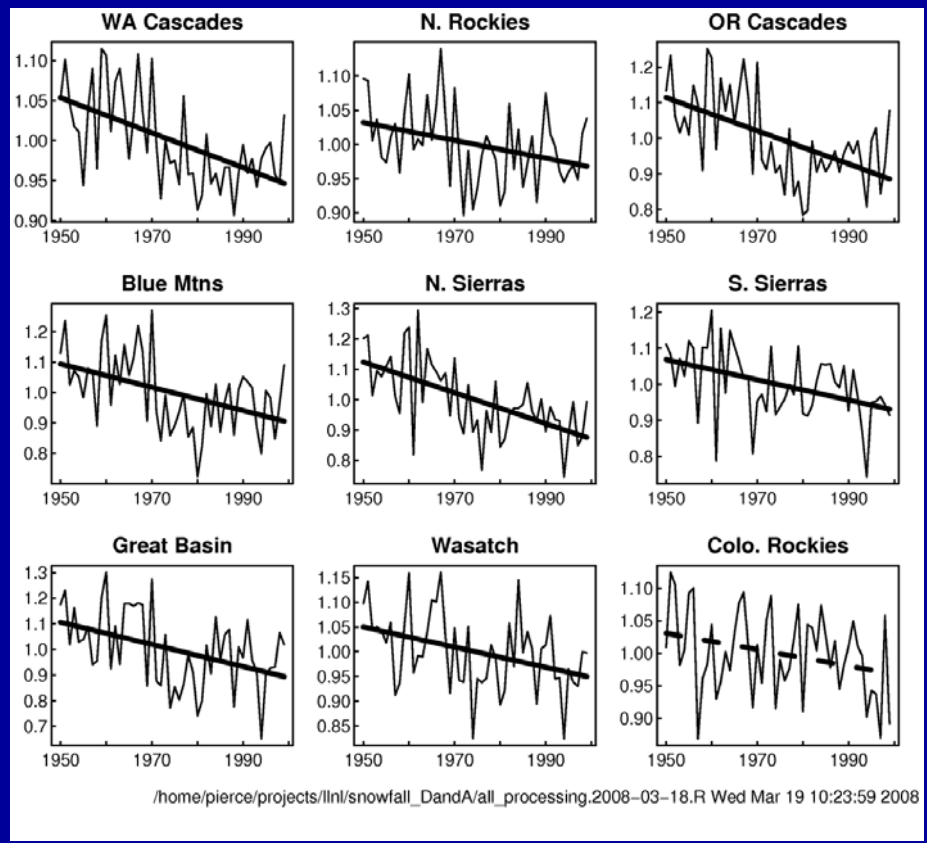
SWE/P TREND COMPONENT

These time series are the basis for the fingerprint

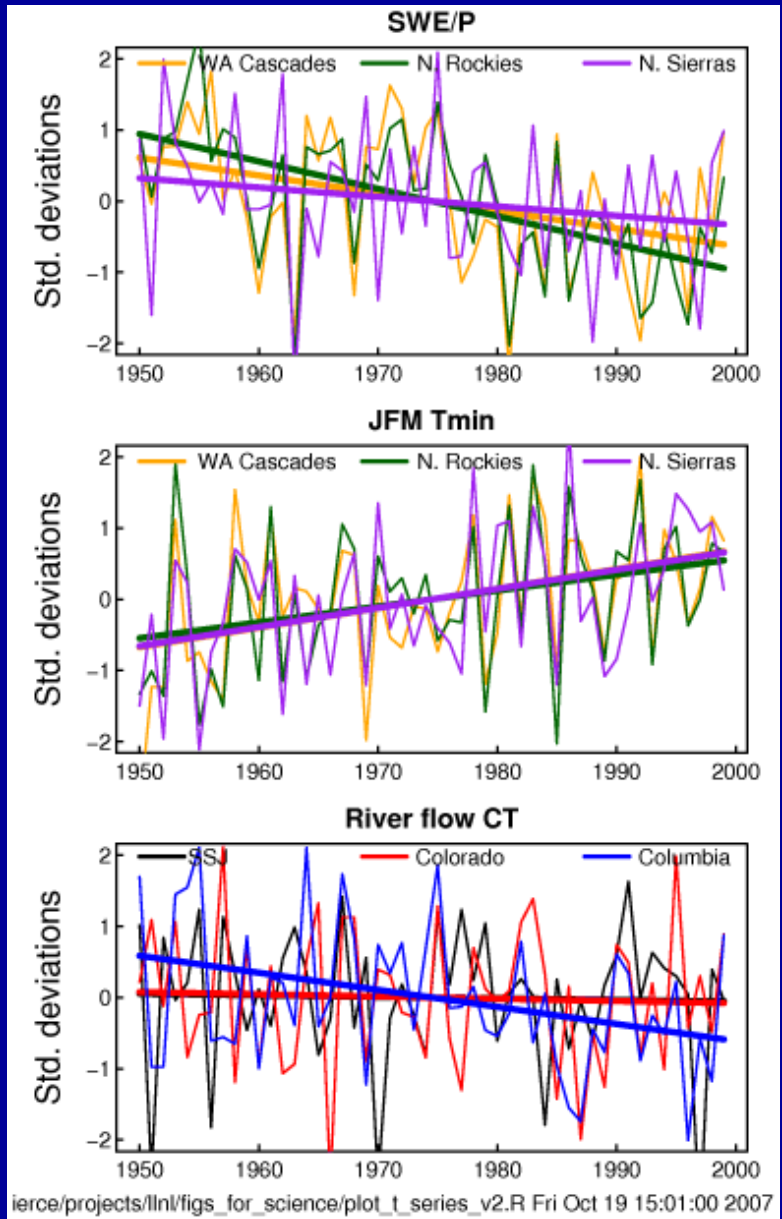
Obs snow course



Model based



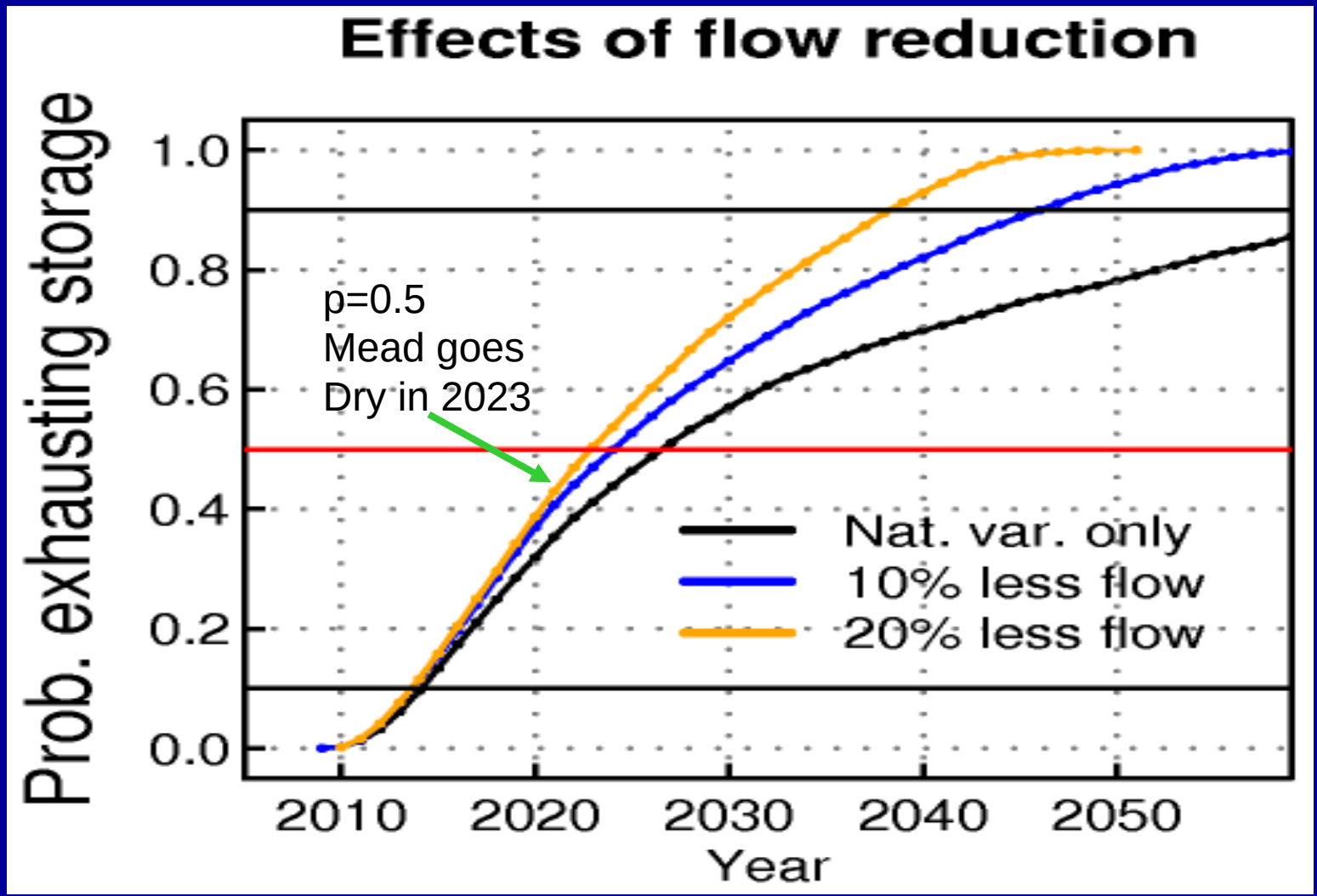
Time series of key variables (obs.)



All variables have been normalized (fractionalized) by dividing by the CCSM3-FV control run mean over first 300 yrs.

Necessary for the multivariate detection and attribution (D&A), so have same variance in each variable (the “units problem”).

MEAD TOMORROW: Human-induced runoff reduction



Assumes 1 MAF/yr overdraft continues