Hydrologic Effects of Climate Change in the Sierra-Nevada

Knowles, Noah (1); Dettinger, Michael (2); and Cayan, Daniel (2)
(1) USGS, Menlo Park, CA
(2) USGS; Scripps Institution of Oceanography, La Jolla, CA

1. Observed hydrologic changes
   a. Snowpack
   b. Runoff timing
   c. Snowfall versus Rain

2. Projected hydrologic changes
   a. Snowpack, snow-covered area
   b. Runoff timing, flow peaks
   c. Interannual variability
   d. Soil moisture

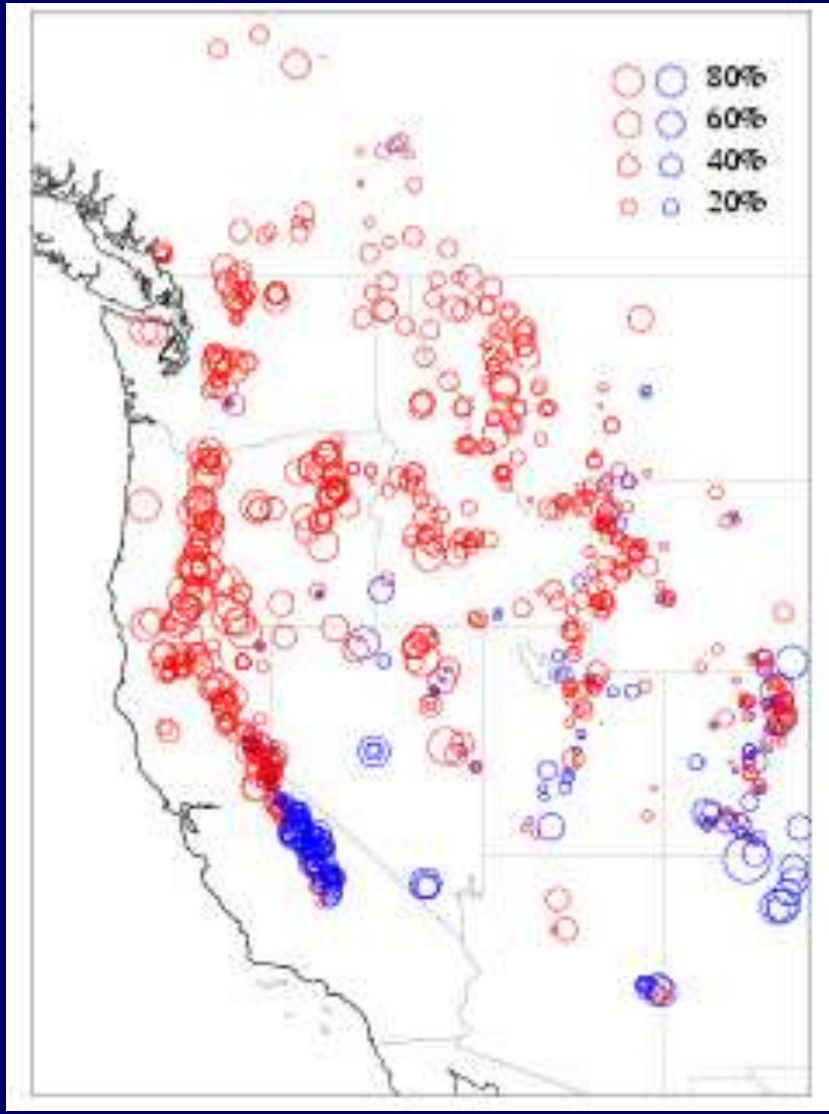
Funded by the USGS NRC and Hydroclimatology Programs, NOAA OGP, DOE, the California Energy Commission's Public Interest Energy Research Program (PIER) through the California Climate Change Center at Scripps Institution of Oceanography, and by the CALFED Science Program through the USGS CASCaDE Project.

USGS science for a changing world

1. Observed Hydrologic Changes

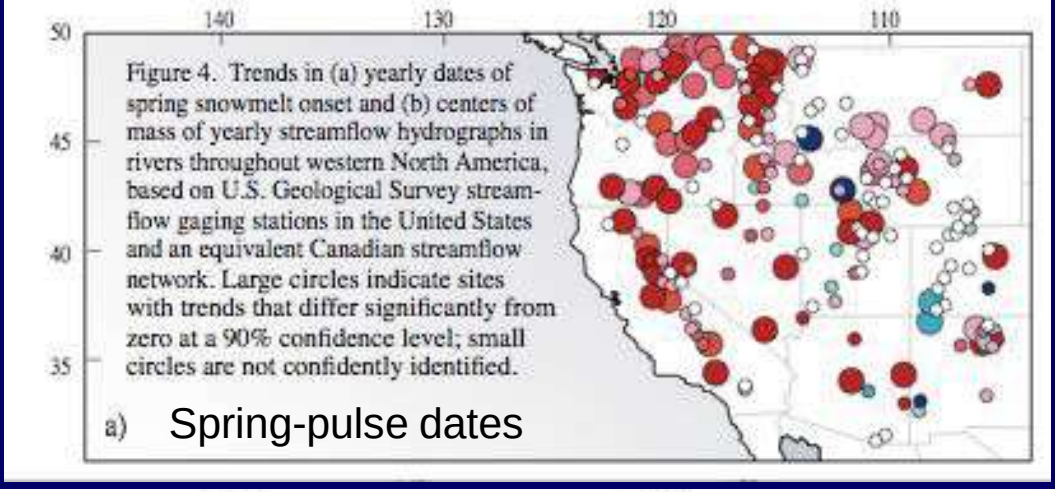
Snowpacks across the western U.S. and Canada have been declining.

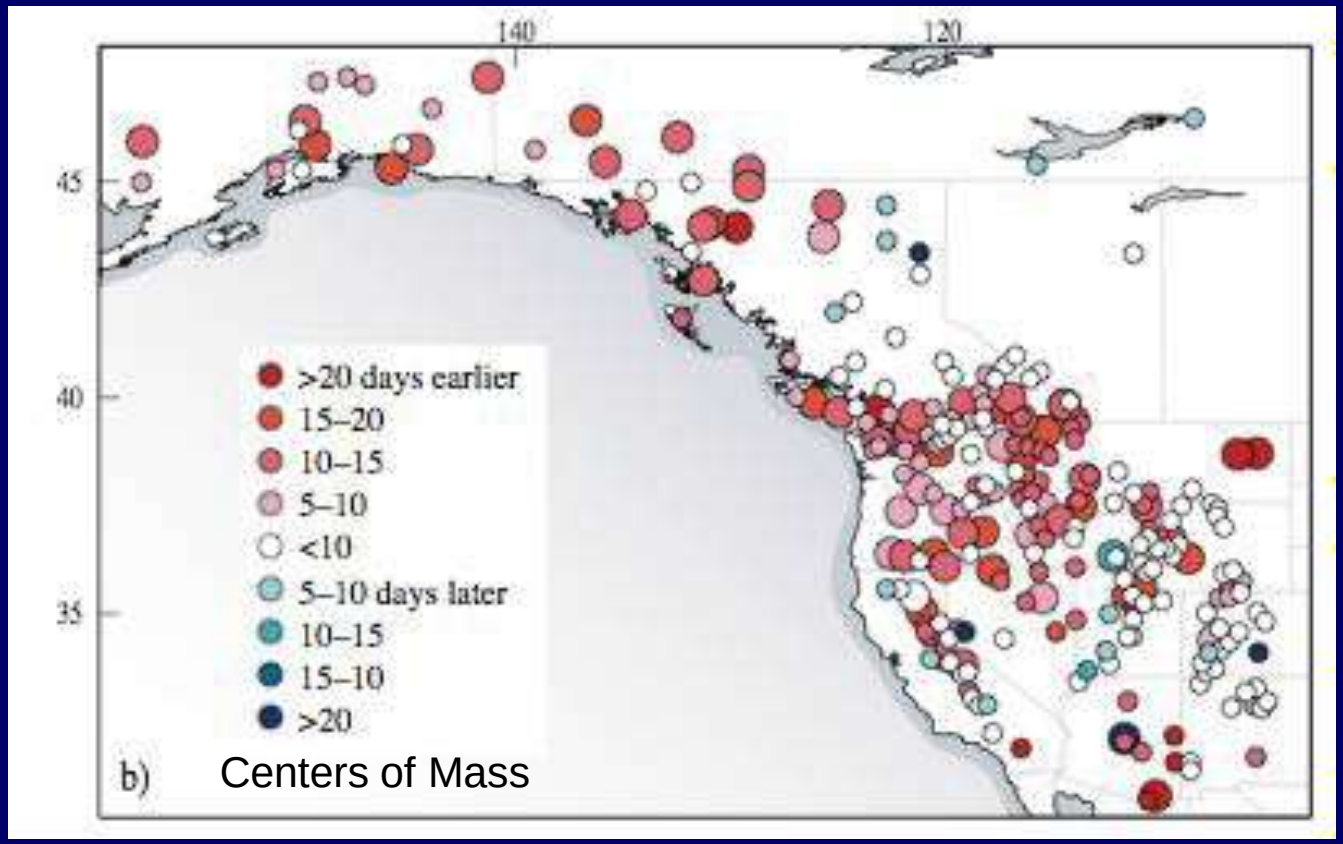
TRENDS (1950-97) in
April 1 snow water content at
western snow measurement sites



Mote et al., BAMS 2005

Also, western streamflow has been arriving earlier in the year in recent decades.





Stewart et al., 2005

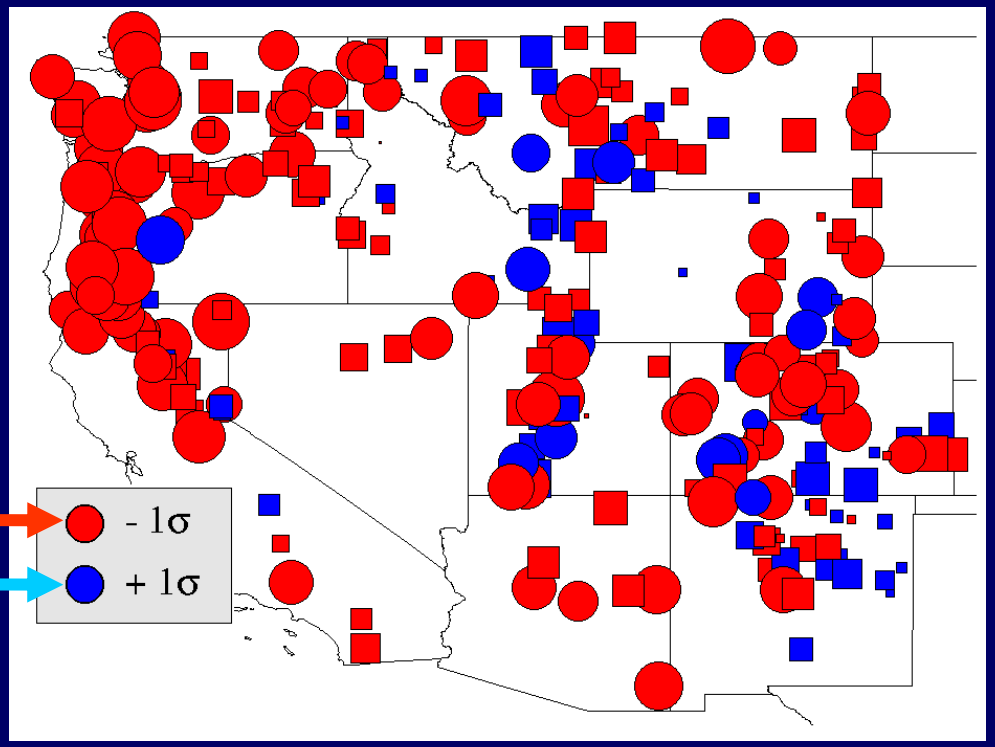
Also: Dettinger and Cayan, 1995; Cayan et al., 2001

A west-wide shift from snowfall to rainfall has taken place

Trends in Precipitation Form (1949-2004)

MORE RAIN, LESS SNOW

LESS RAIN, MORE SNOW

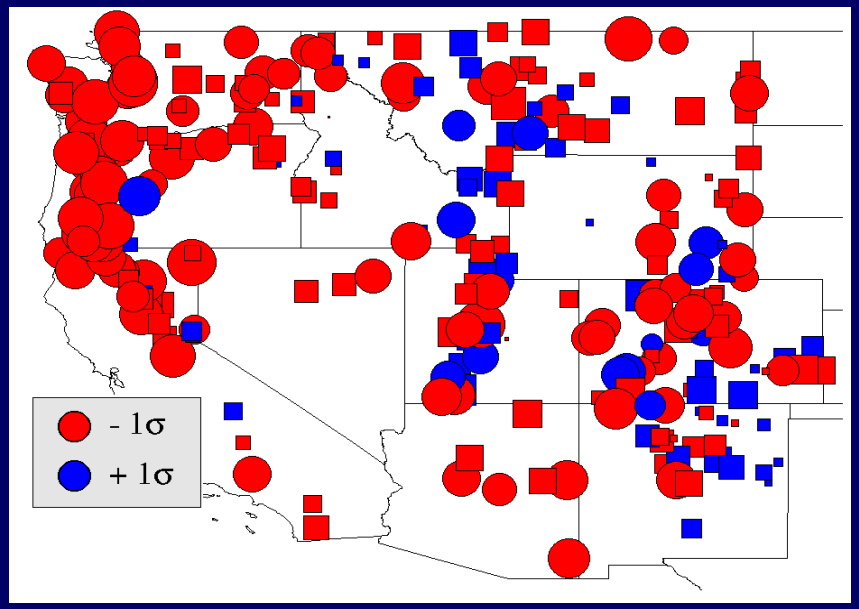


Trends in ratio of winter (Nov-Mar) snowfall water equivalent (SFE) to total winter precipitation (rain *plus* snow) for the period WY1949-2004. Circles represent significant ($p<0.05$) trends, squares represent less significant trends.

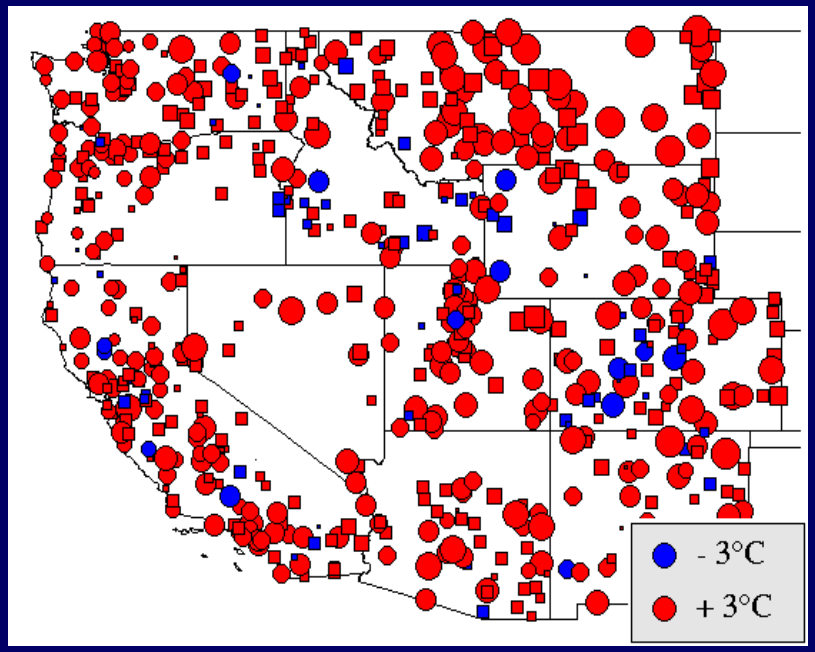
Knowles, N., M.D. Dettinger, and D.R. Cayan 2006. Trends in Snowfall versus Rainfall in the Western United States. Journal of Climate, 19(18), 4545–4559.

Temperature changes have driven these trends

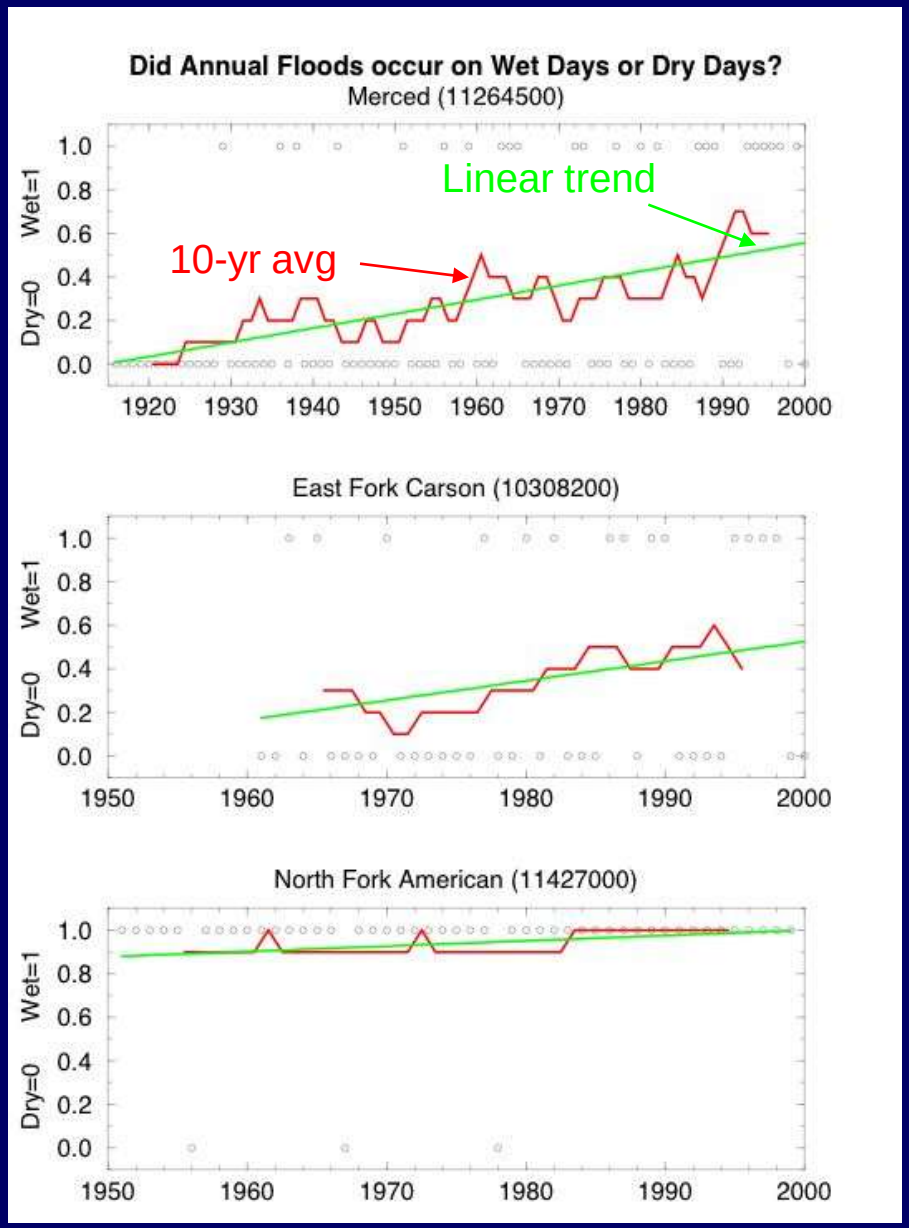
Trends in Precipitation Form

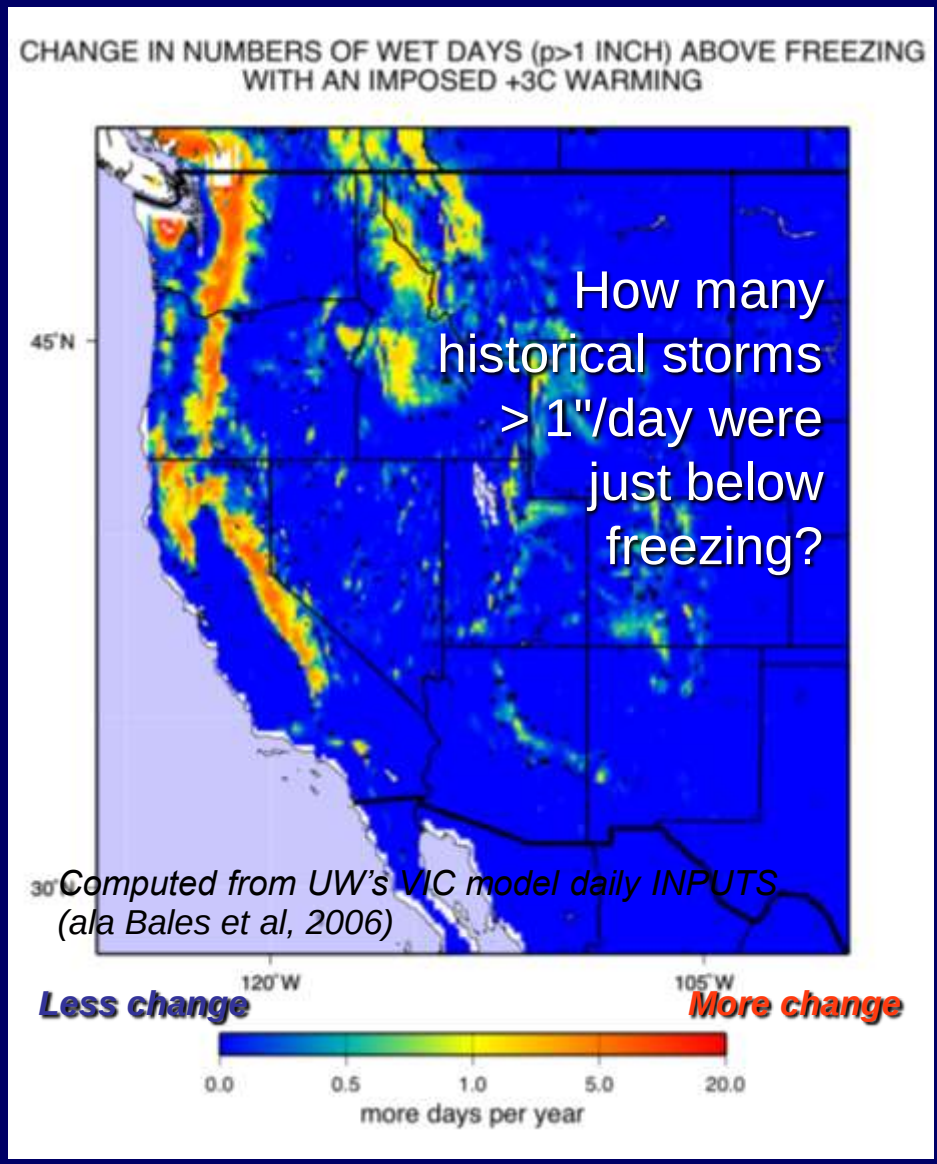


Temperature Trends



If the warming continues, where should we expect the largest changes in warm-storm flooding to be manifested?





Computed from UW's VIC model daily INPUTS (ala Bales et al, 2006)

"Warm-storm flooding"

More than half of the regional trend is anthropogenic.

By comparing Western U.S. temperature, snowpack, and streamflow timing from observations and from “naturally” and “anthropogenically” forced GCMs, Barnett et al (*Science*, 2008) showed:

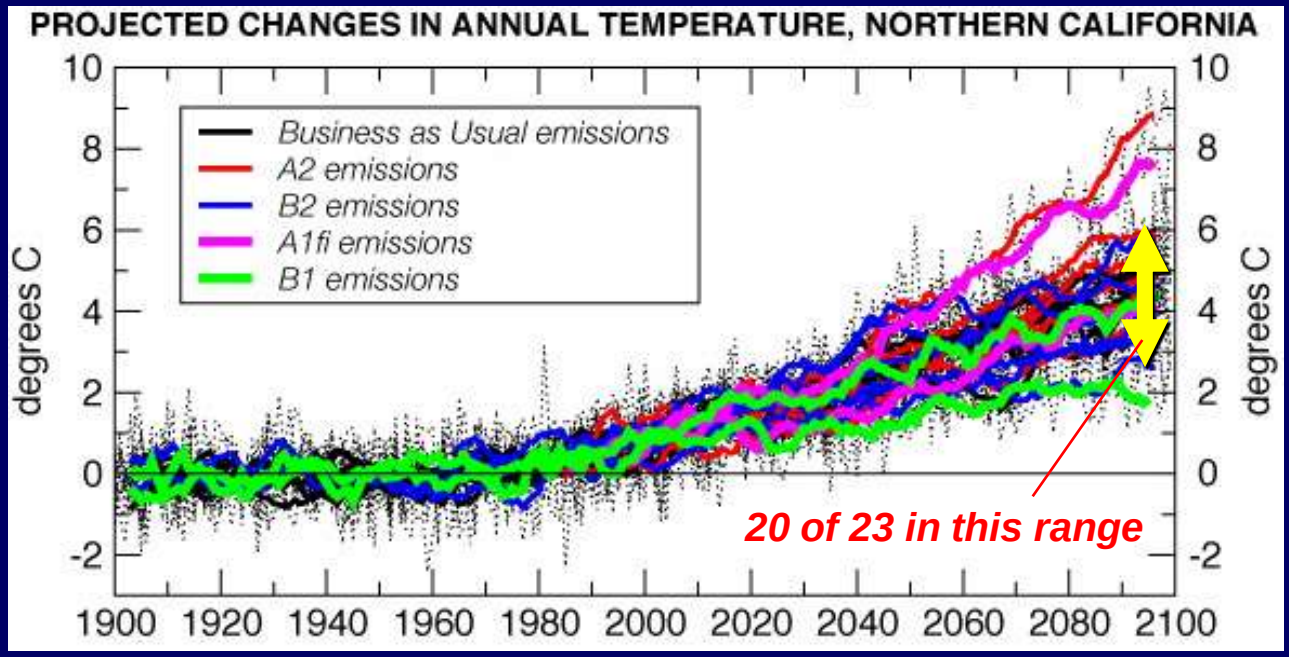
• Trends in all quantities are detectable (beyond natural variability).

• ~60% of 1949-1999 “trends” in these quantities are attributable to anthropogenic forcings (greenhouse gases, ozone, sulfate aerosols).

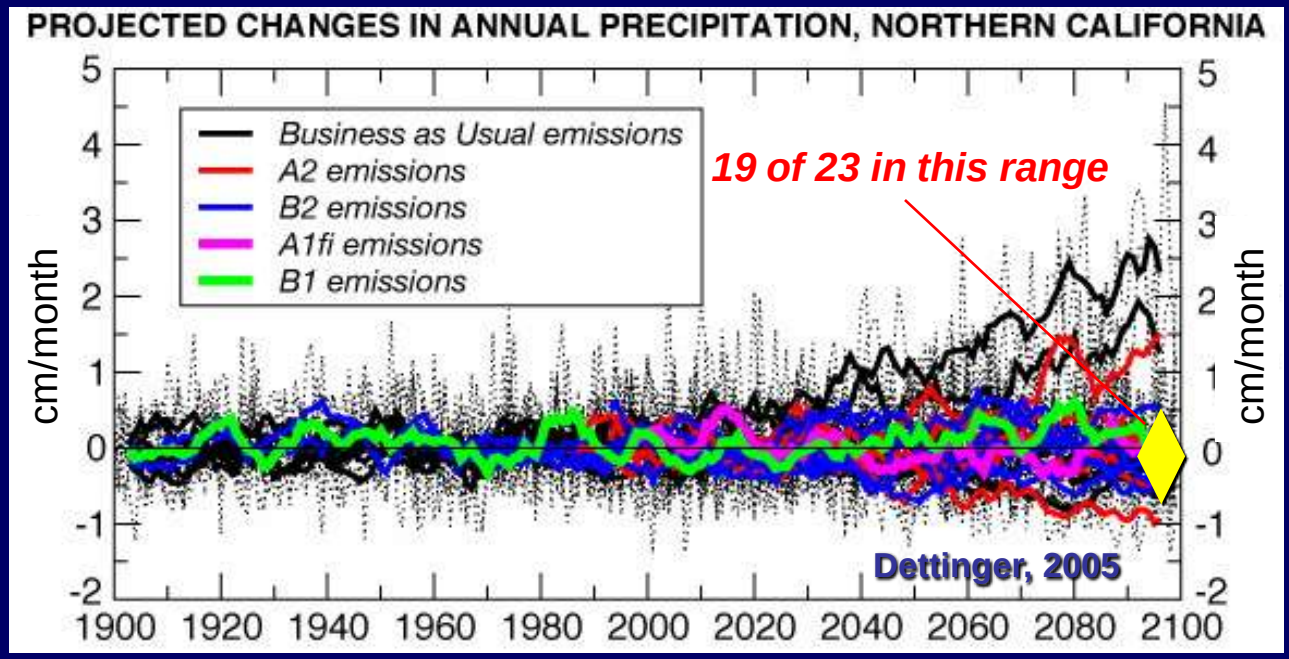
Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan, and M. D. Dettinger, 2008: Human-induced changes in the hydrology of the western United States. *Science*, 319, 1080-1083.

2. Projected Hydrologic Changes

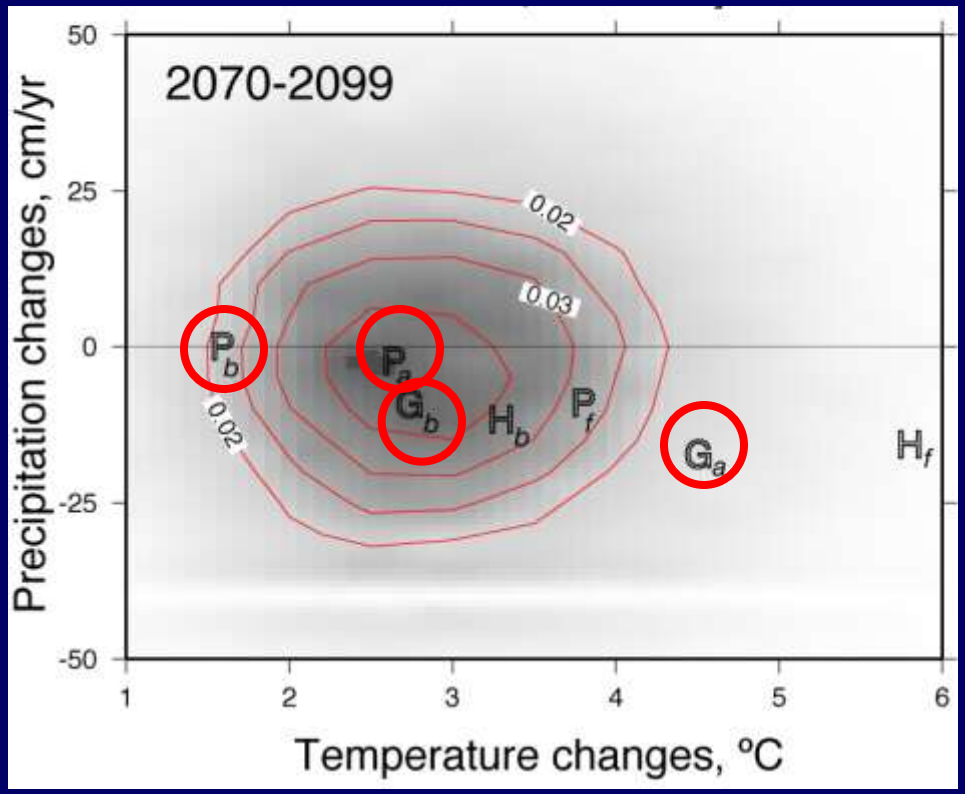
Under projected greenhouse forcings, all climate models yield warmer futures for California…



…and most climate models yield a fairly narrow range of precipitation changes in California.



From amongst the most recent ensemble of climate-change projections, we have chosen four scenarios to consider:



Pb: Not so much warmer
No ppt change

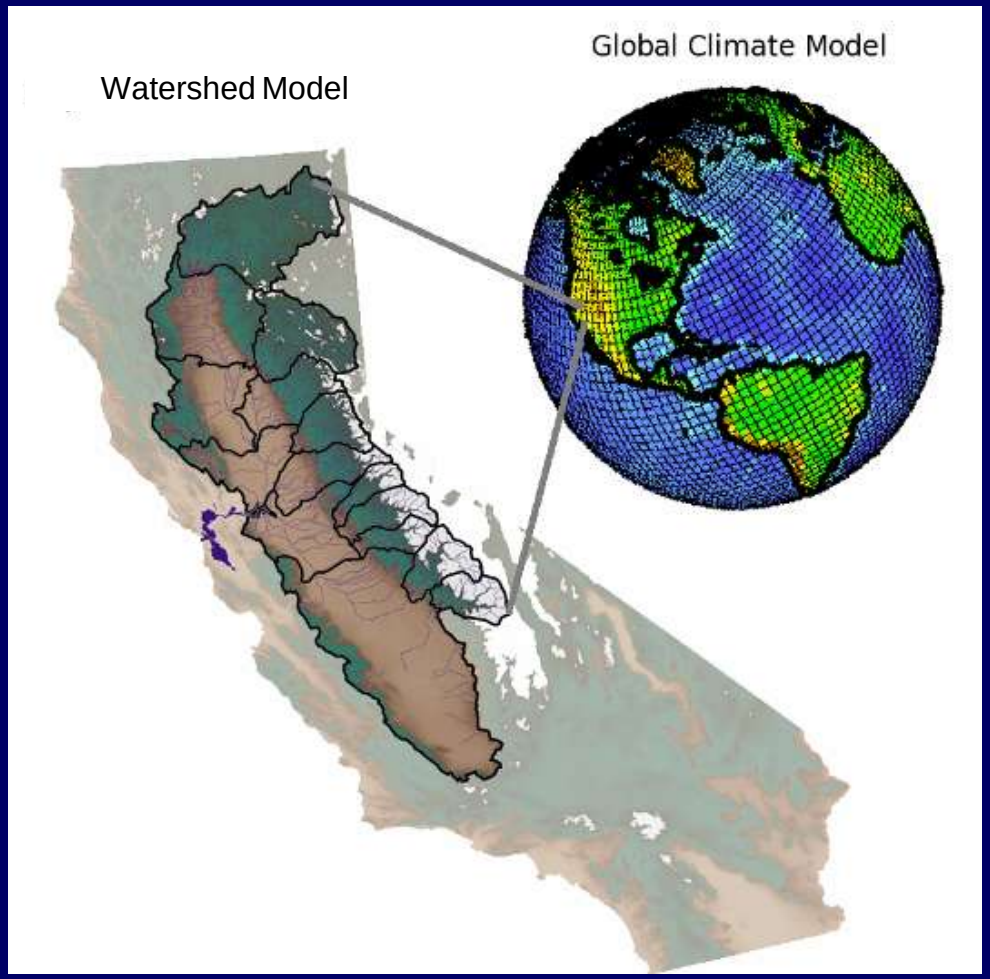
Pa: Medium warmer
Small ppt decrease

Gb: Medium warmer
Drier

Ga: Much warmer
Drier

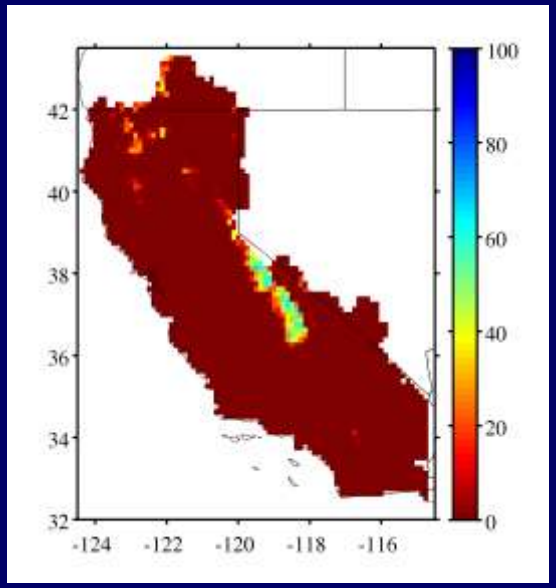
Cayan et al., 2006, Report to Governor

Modeling Sequence

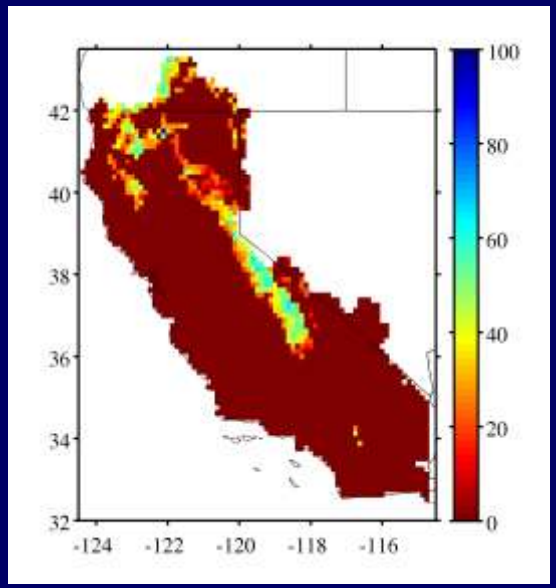


Avg 2070-2099 Snow Water Equivalent as percentage of 2001-2030 avg

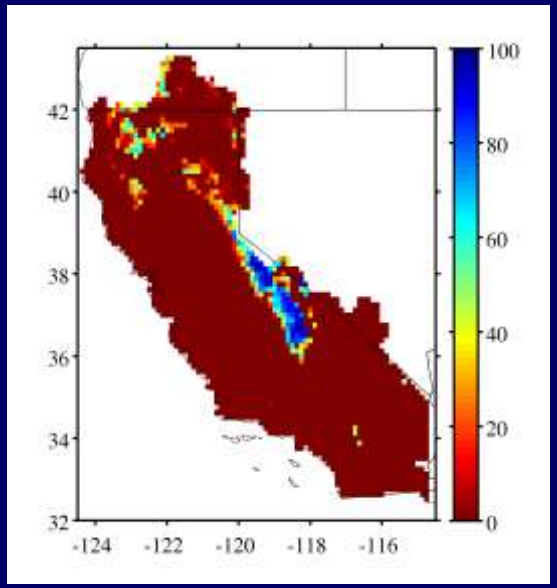
GFDL-A2



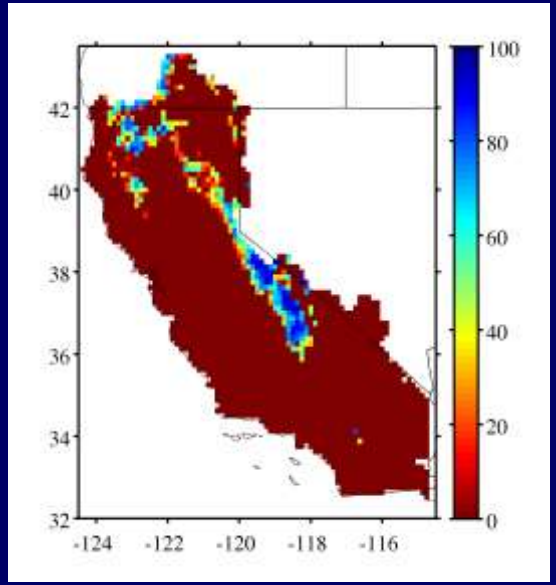
GFDL-B1



PCM-A2

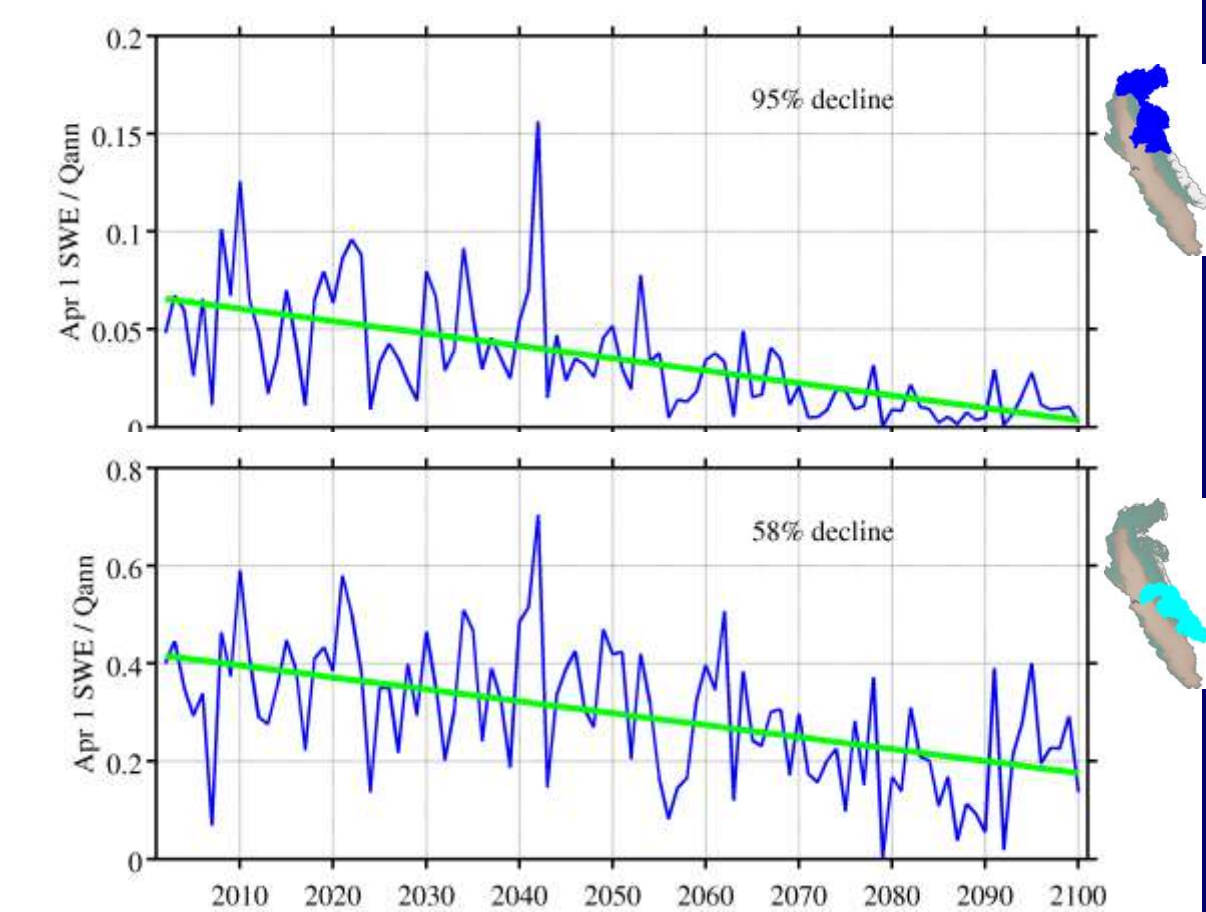


PCM-B1



Peak Snowpack as a Fraction of Total Annual Runoff

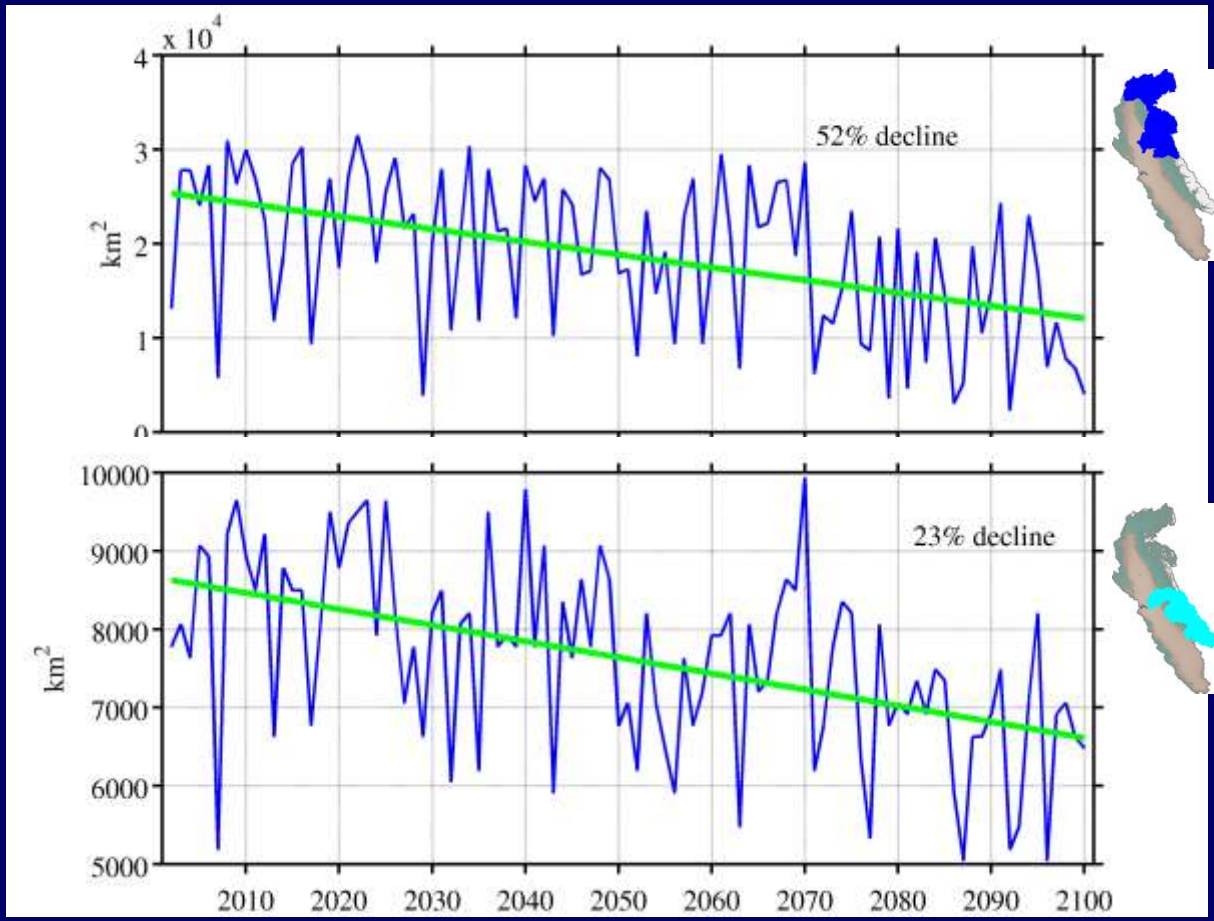
GFDL-A2



	Northern	Southern
GFDL-A2	-95%	-58%
GFDL-B1	-80%	-50%
PCM-A2	-74%	-31%
PCM-B1	-61%	-33%

Annual Maximum Snow-Covered Area

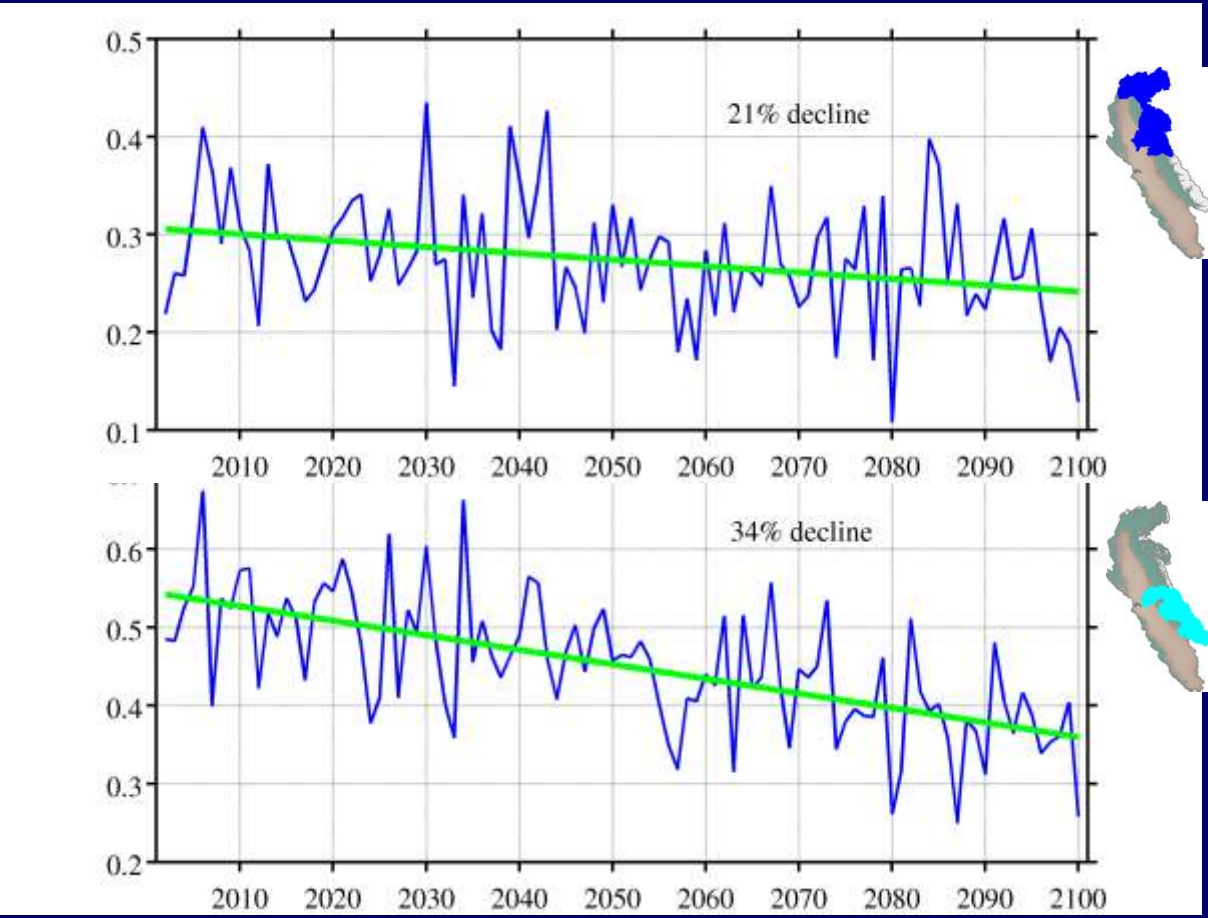
GFDL-A2



	Northern	Southern
GFDL-A2	-52%	-23%
GFDL-B1	-46%	-19%
PCM-A2	-37%	-12%
PCM-B1	-26%	-11%

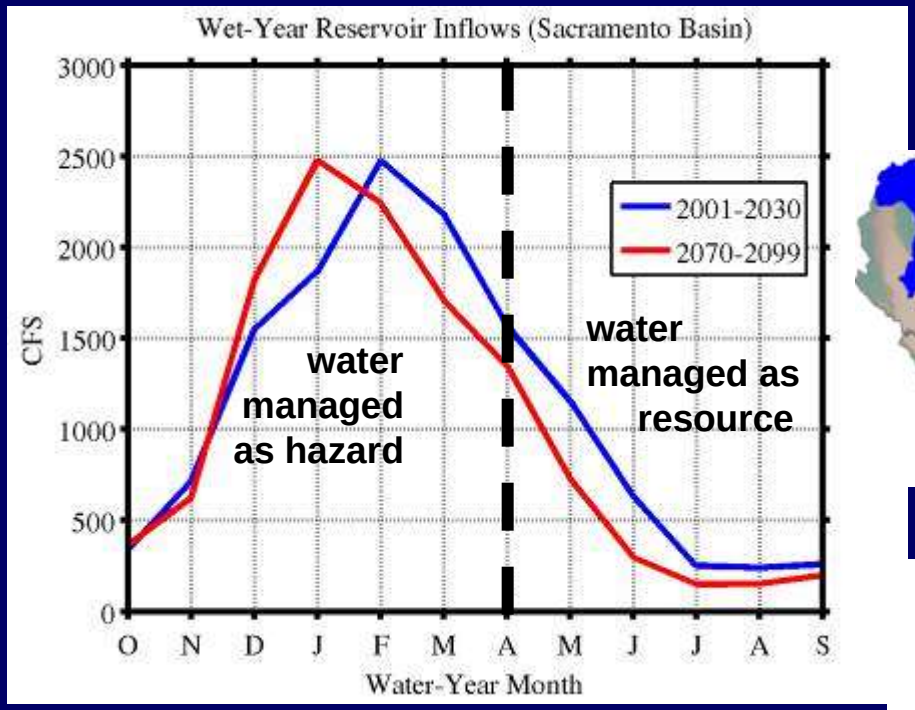
post-April fraction of annual runoff

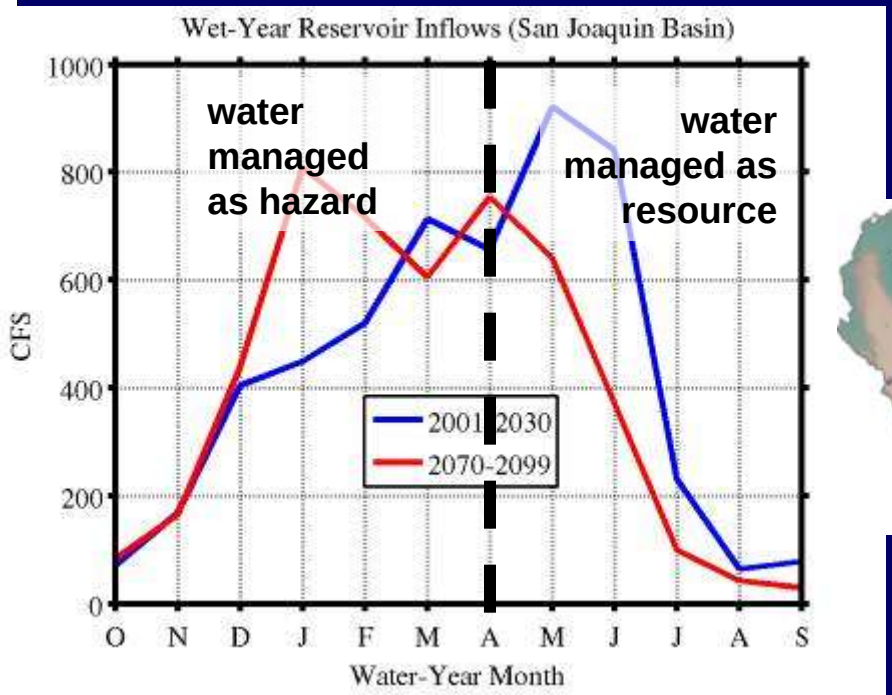
GFDL-A2



	Northern	Southern
GFDL-A2	-21%	-34%
GFDL-B1	-08%	-19%
PCM-A2	-23%	-18%
PCM-B1	-10%	-14%

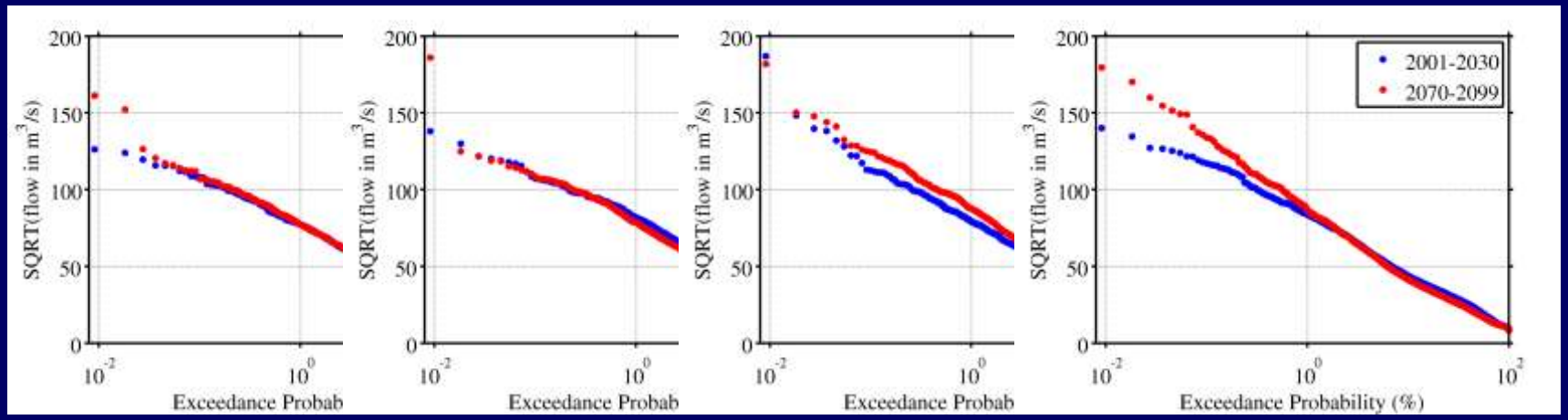
Reduces snowpack leads to earlier runoff, resulting in more water being managed as a hazard.

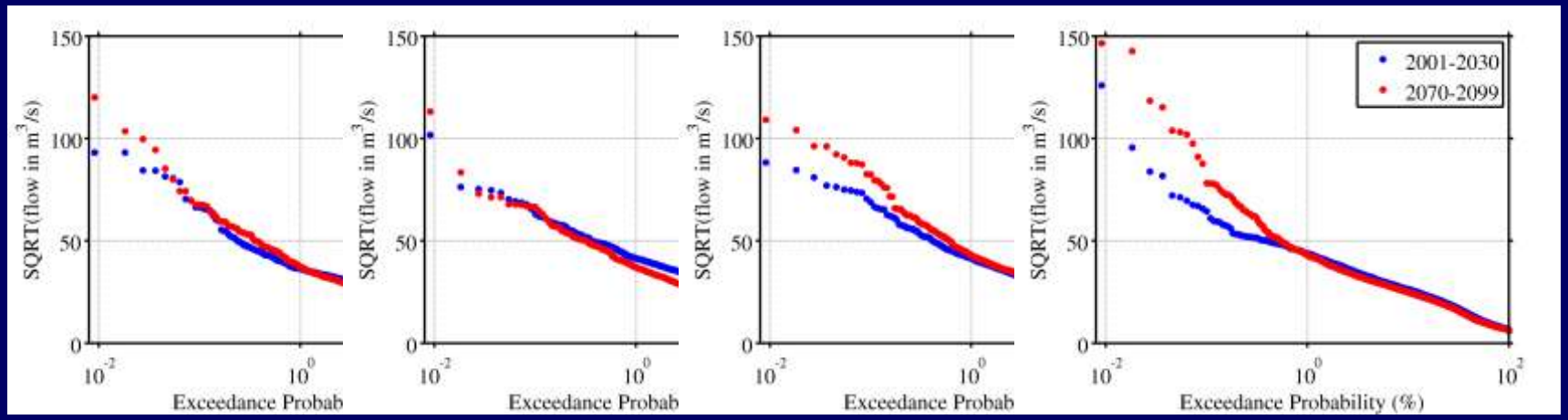




Changes in peak flows driven by…?

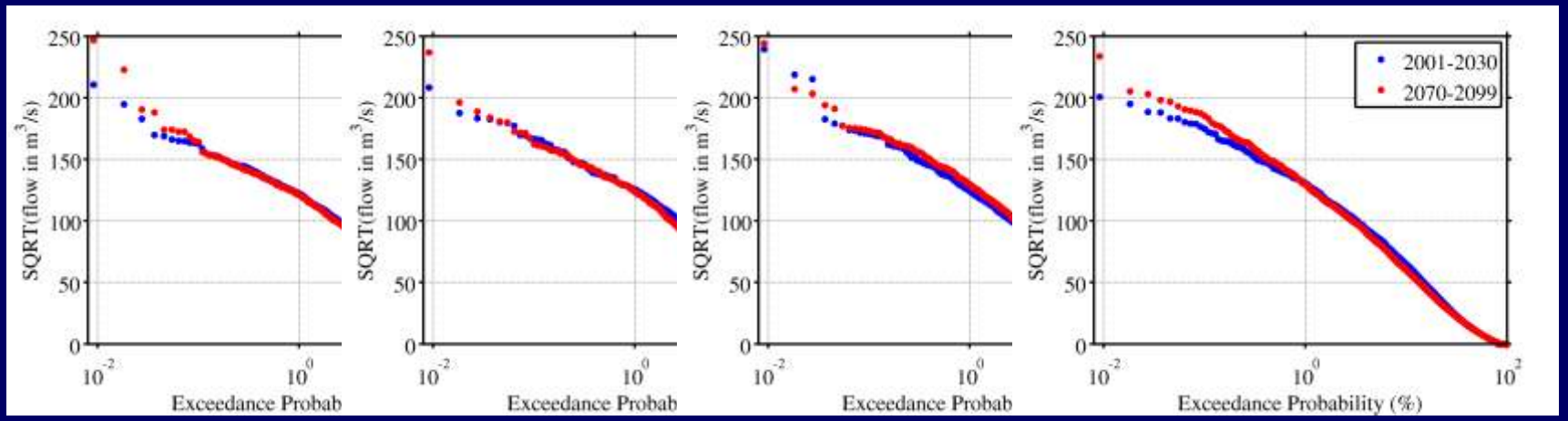
GFDL-A2 GFDL-B1 PCM-A2 PCM-B1

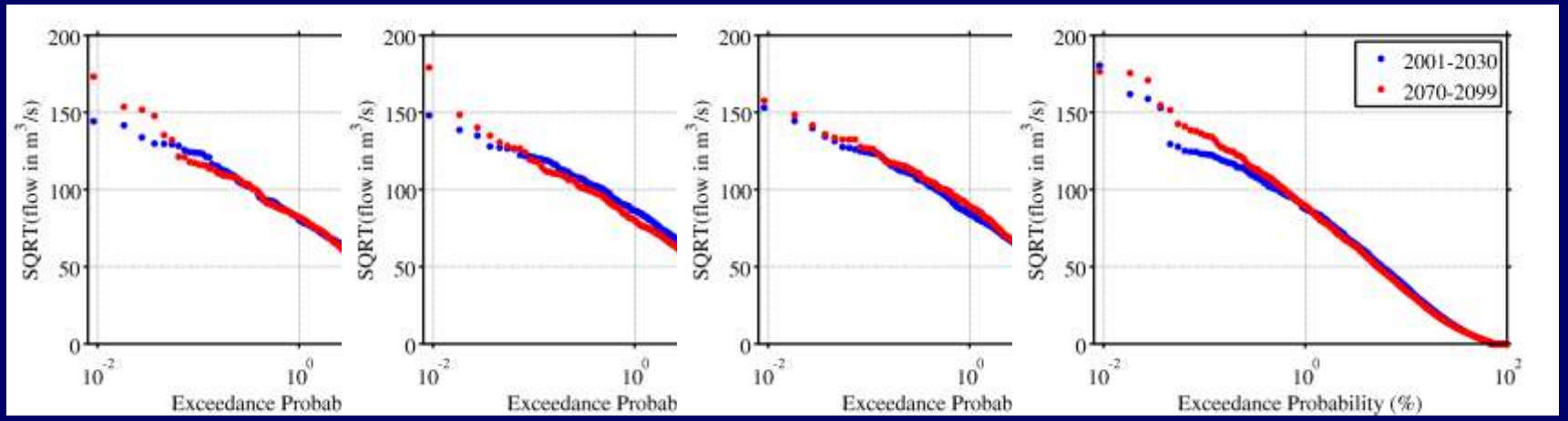


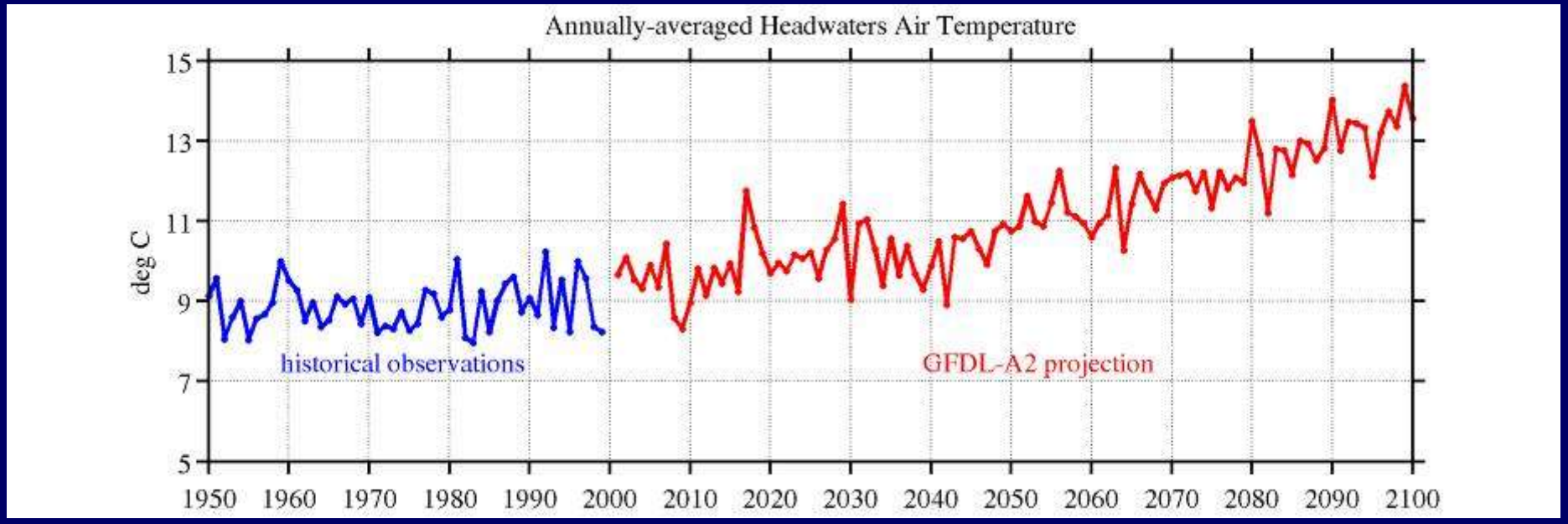


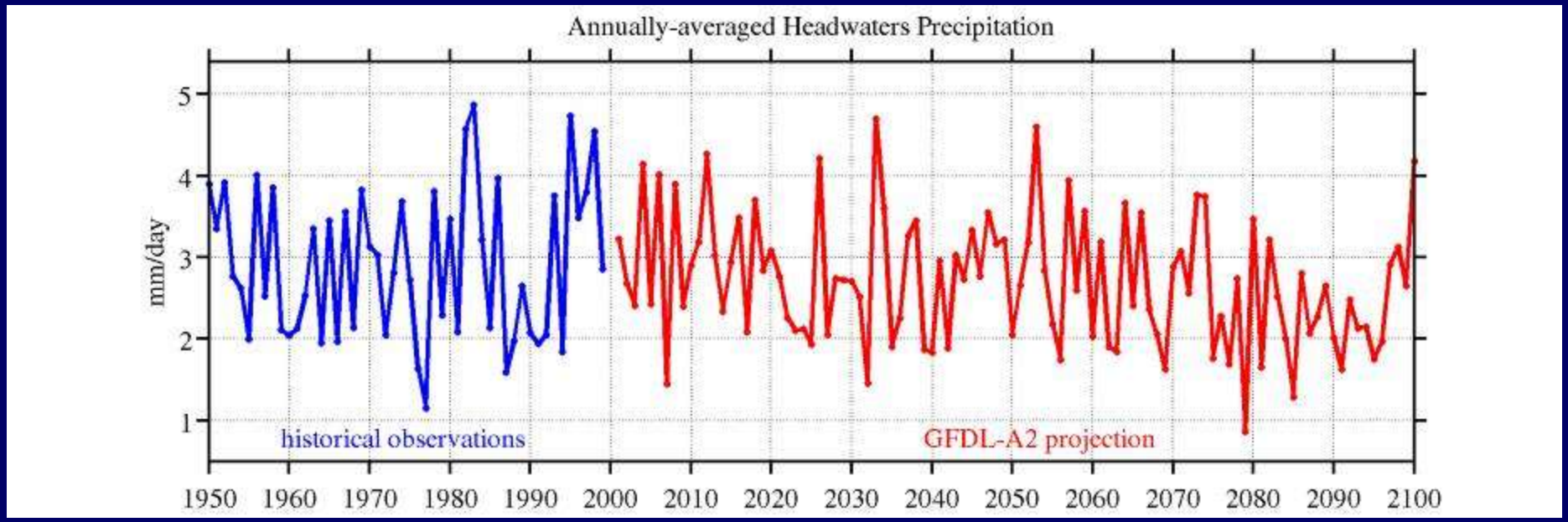
Changes in peak precipitation events

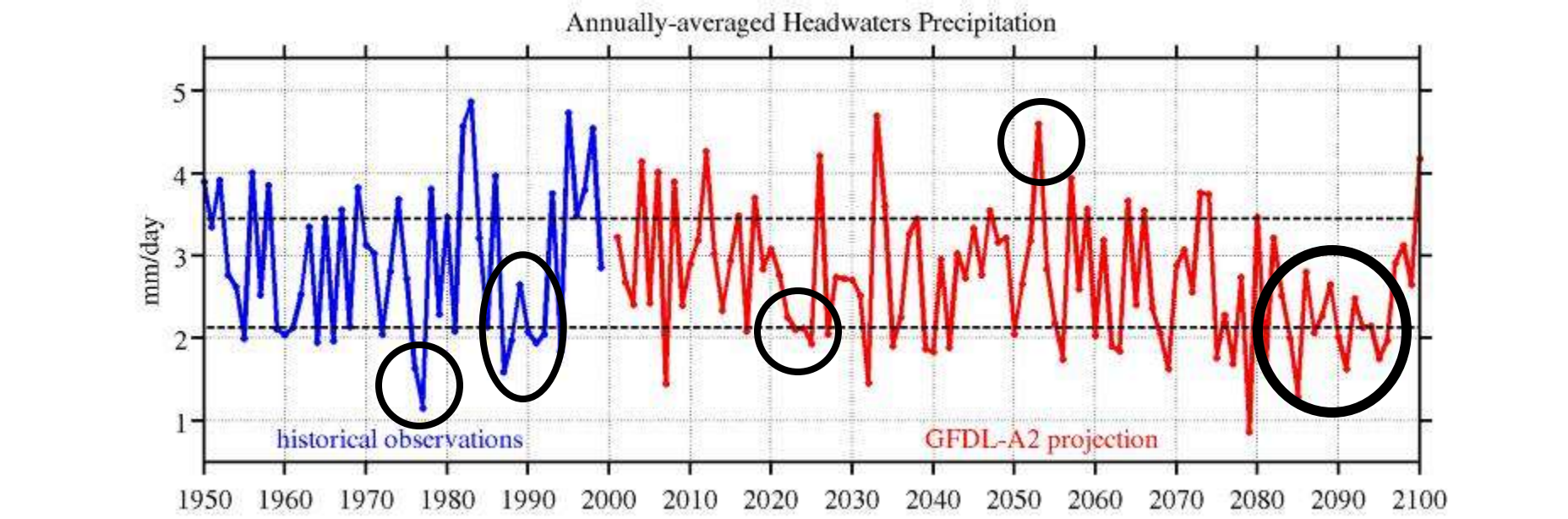
GFDL-A2 GFDL-B1 PCM-A2 PCM-B1





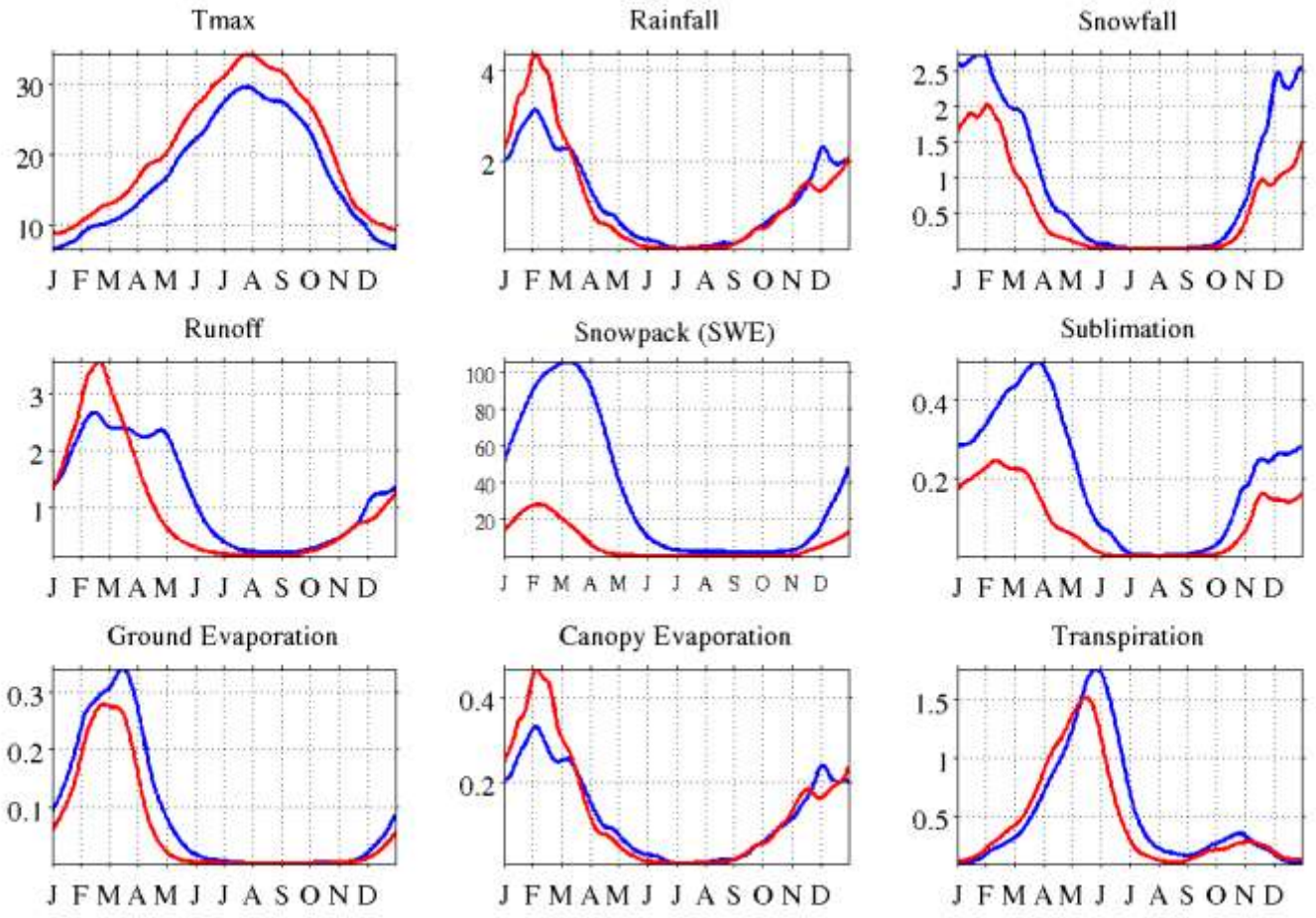

Annually-averaged Headwaters Air Temperature
deg C
15
13
11
9
7
5
historical observations
GFDL-A2 projection
1950 1960 1970 1980 1990 2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100


Annually-averaged Headwaters Precipitation
mm/day
5
4
3
2
1
historical observations
GFDL-A2 projection
1950 1960 1970 1980 1990 2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100

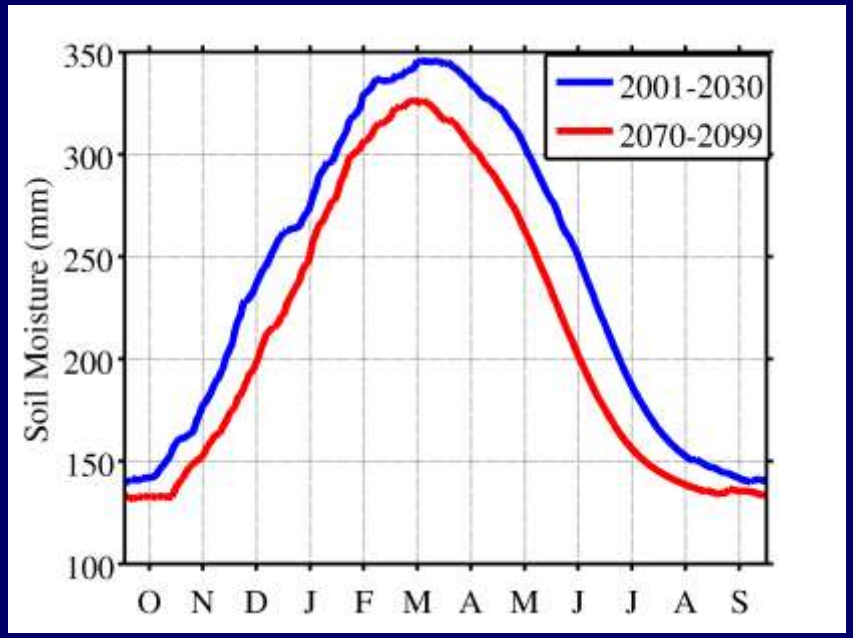


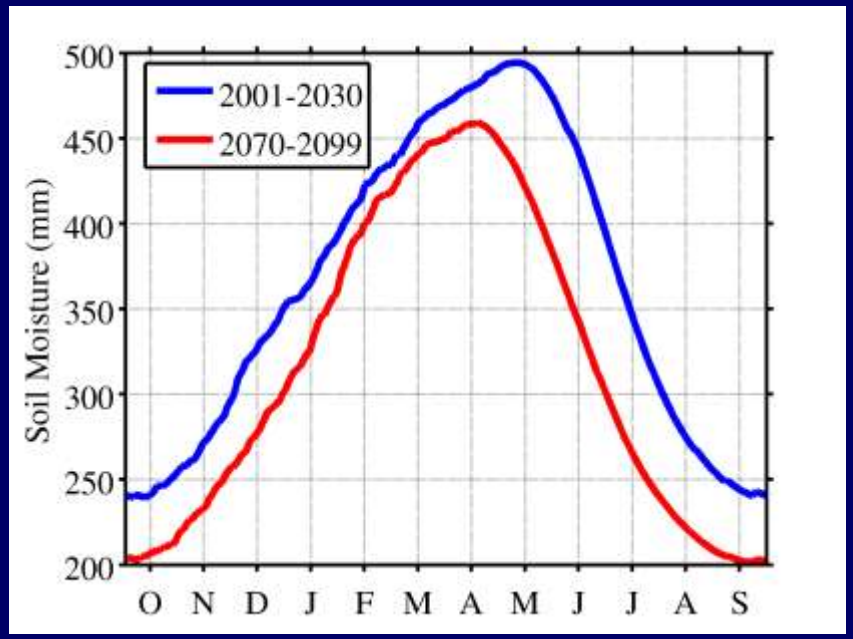
NOT A PREDICTION

Changes in mean annual cycles for GFDL-A2: 2070-2099 (red) vs. 2001-2030 (blue)

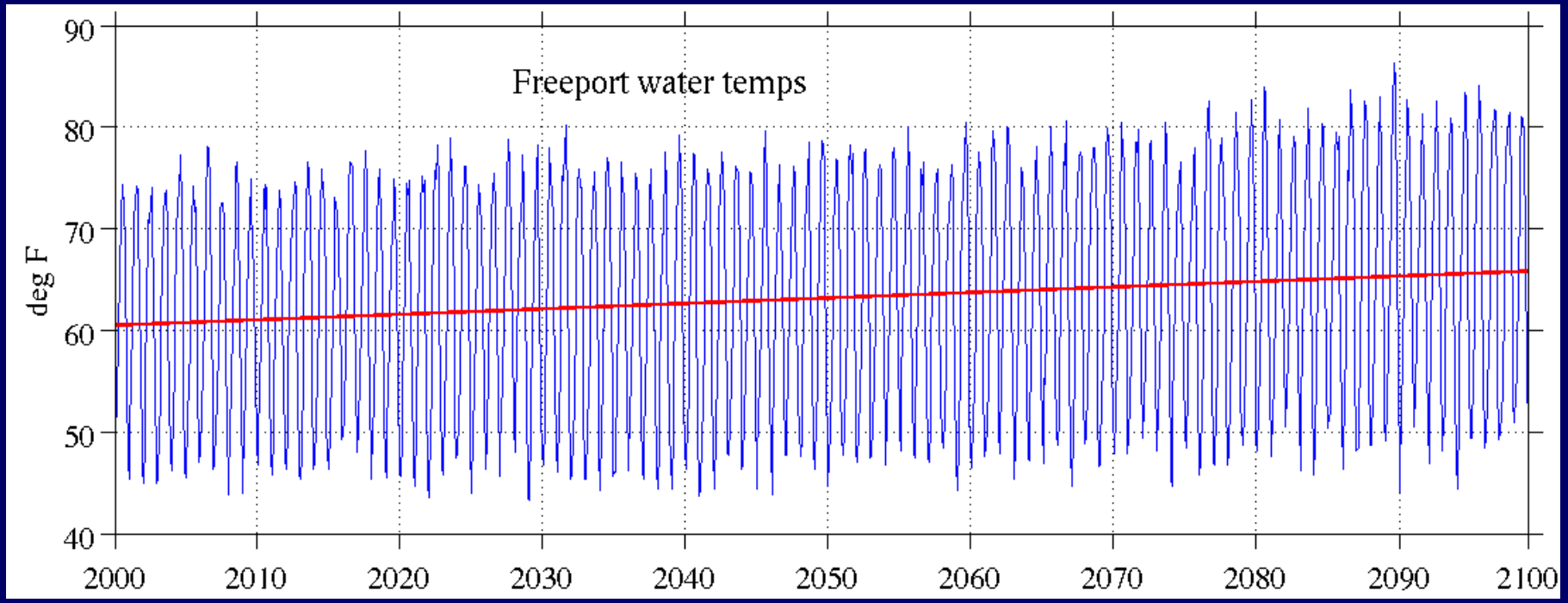


Reduced Soil Moisture, esp in Spring-Summer in S. Sierra





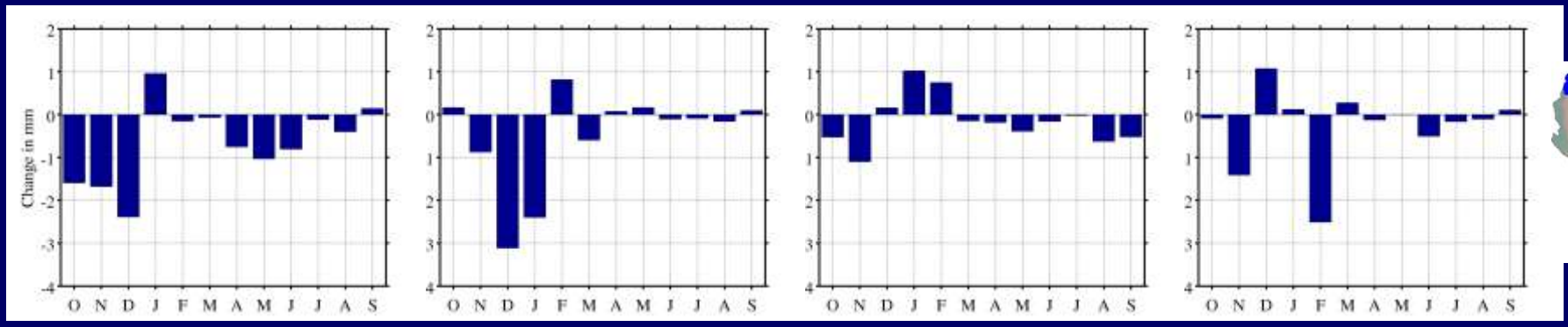
Due to reduced snowmelt and warmer air temps, stream temps also rise.

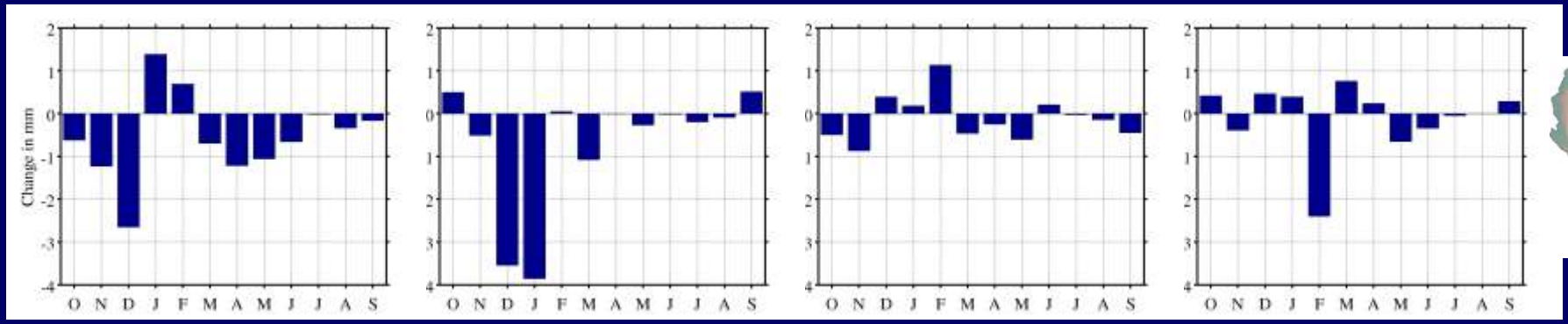


See http://cascade.wr.usgs.gov for more.

Precipitation Trends

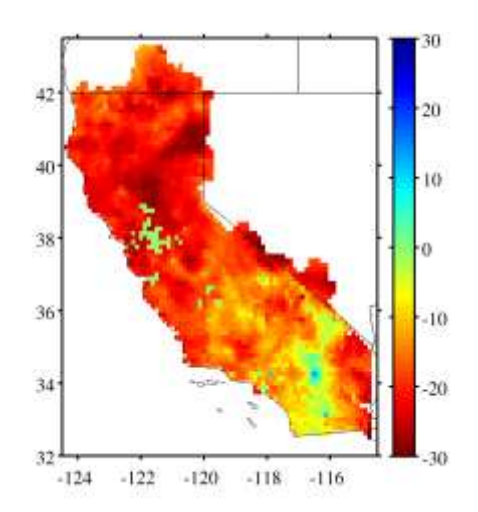
GFDL-A2 GFDL-B1 PCM-A2 PCM-B1



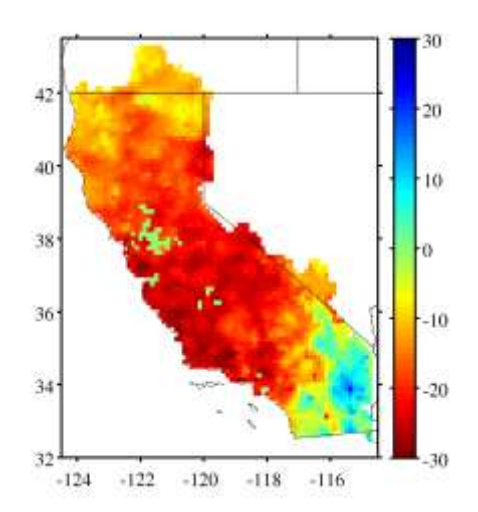


Precipitation Trends

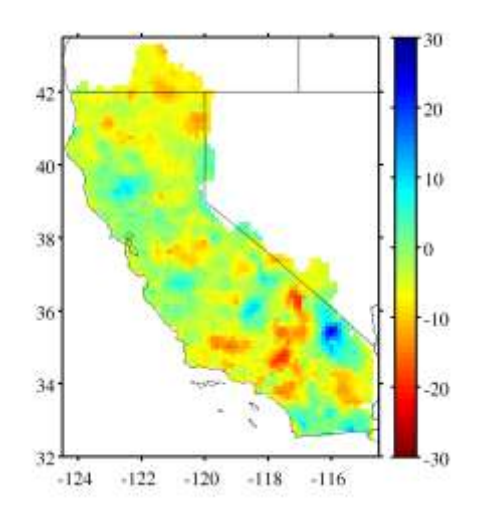
GFDL-A2



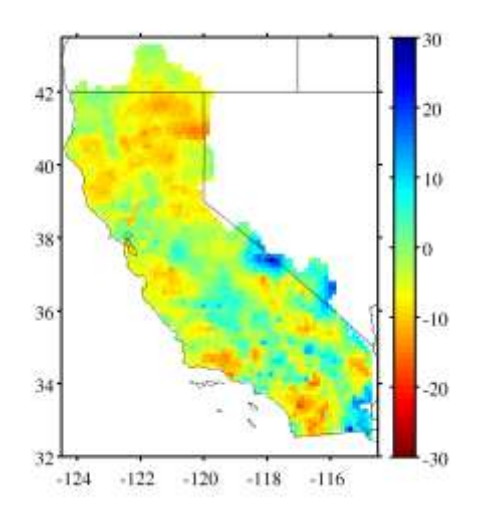
GFDL-B1



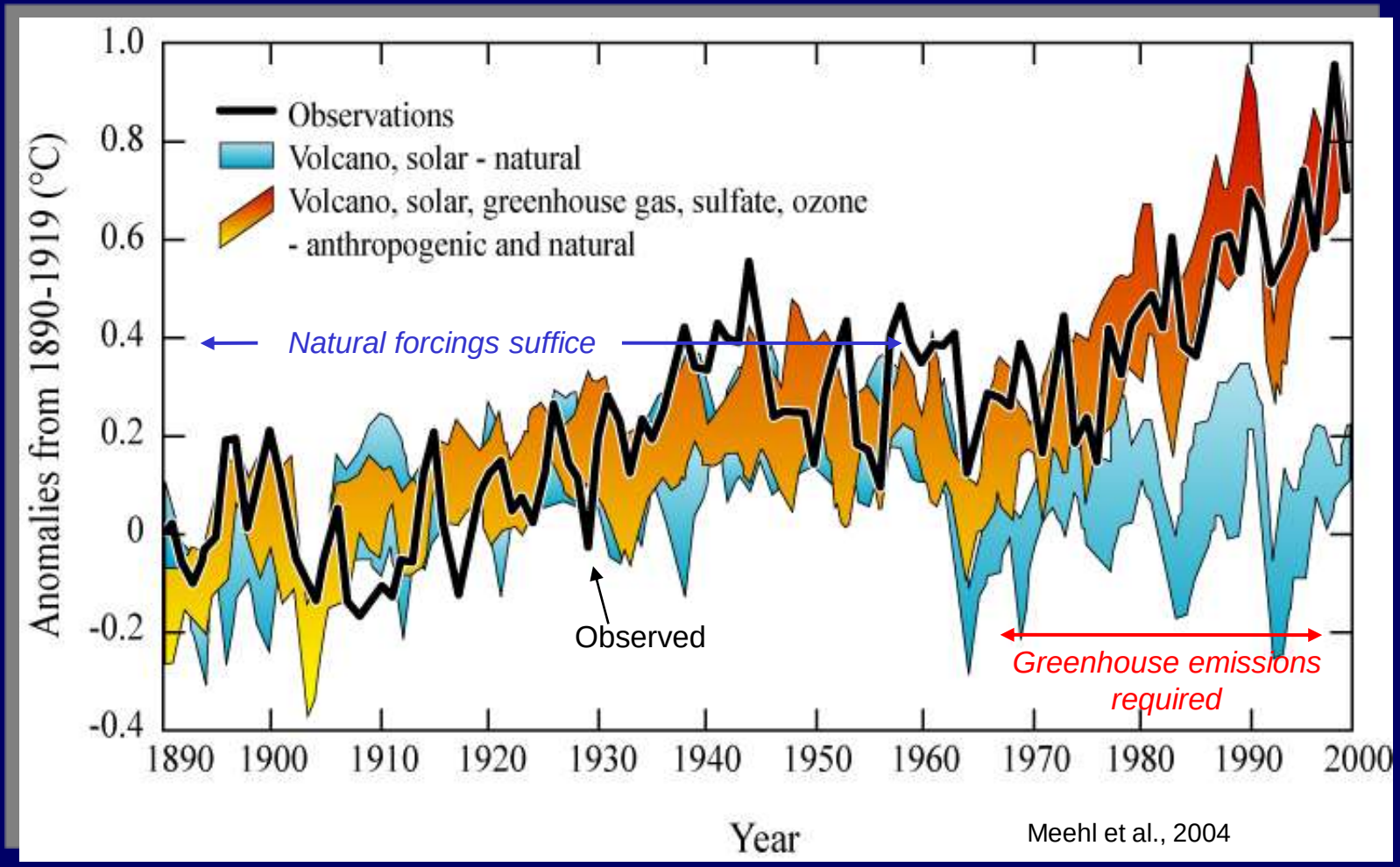
PCM-A2



PCM-B1

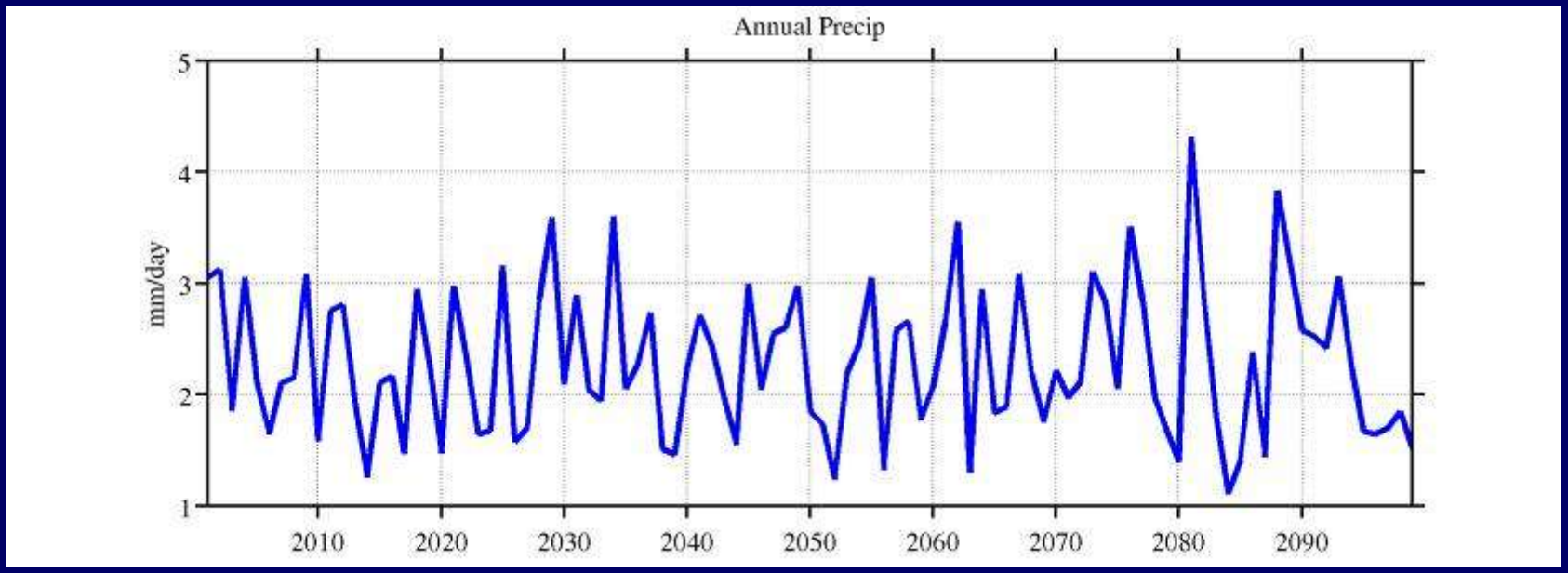


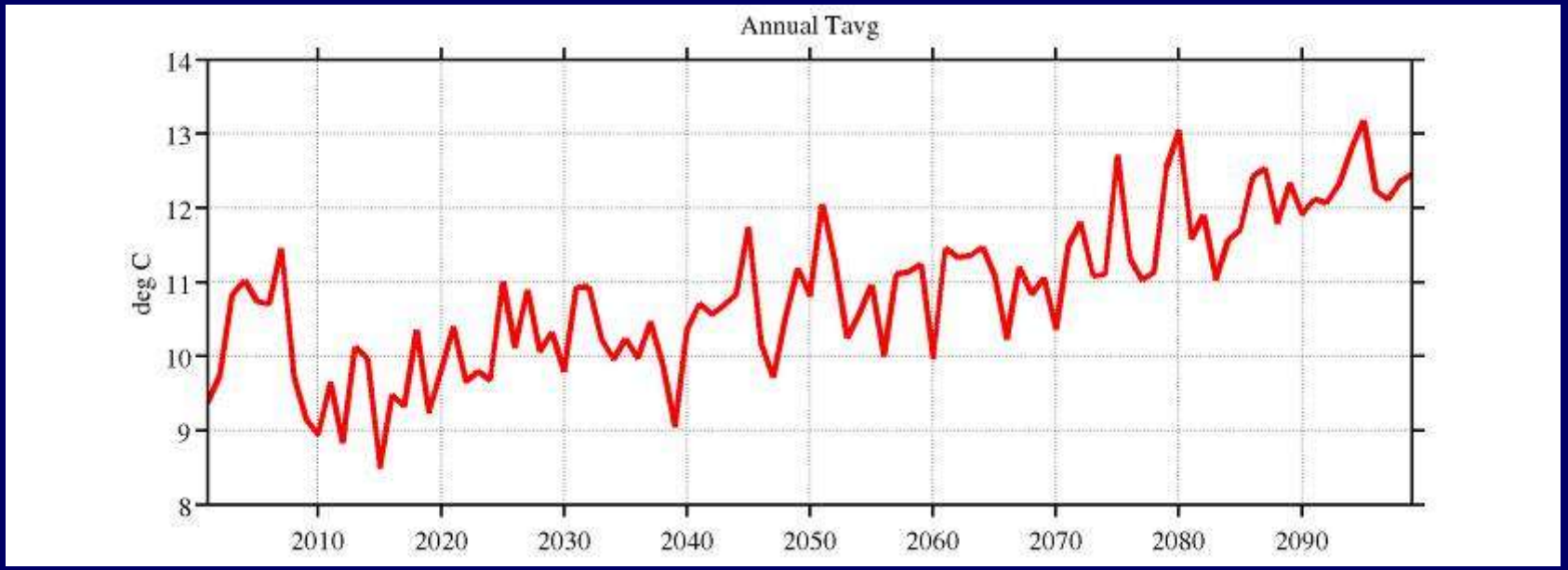
Globally, since ~1970, natural climate variability has been *augmented* by warming trends associated with increases in the global greenhouse effect…



Climate-model simulations of global-average temperature

PCM-A2


Annual Precip
mm/day
5
4
3
2
1
2010
2020
2030
2040
2050
2060
2070
2080
2090


Annual Tavg
deg C
14
13
12
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10
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2010
2020
2030
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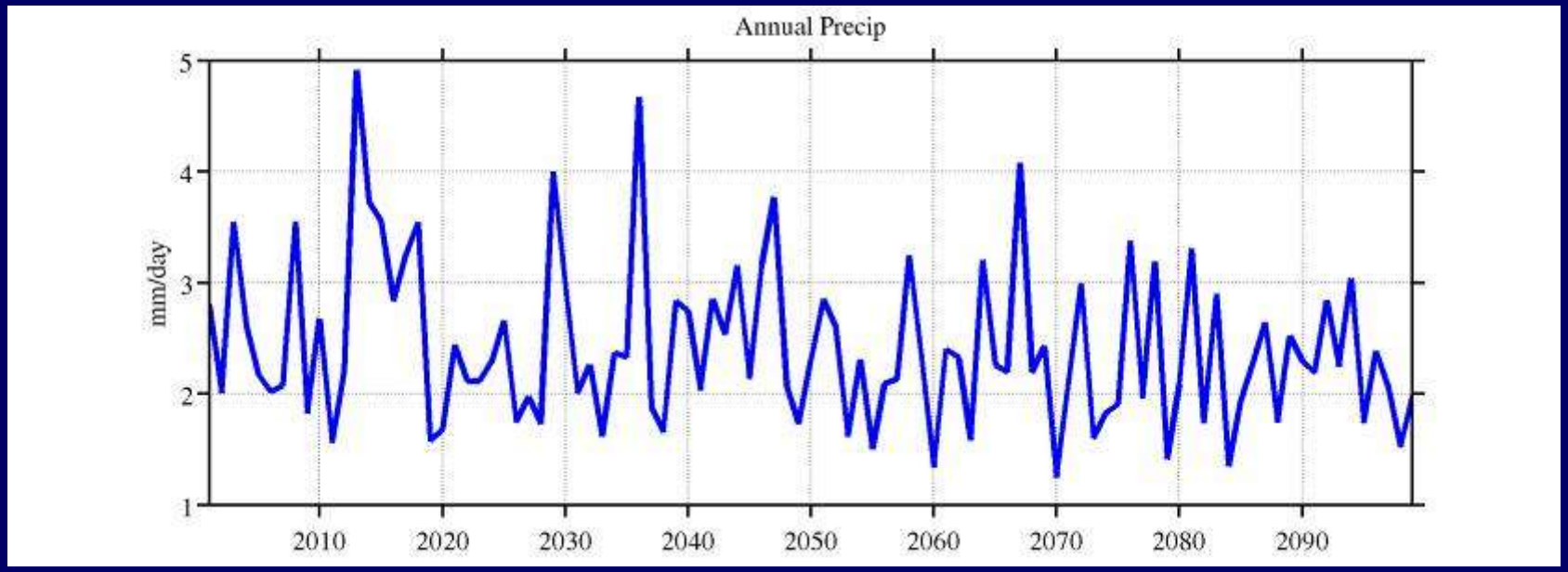
2080
2090

GFDL-B1


Annual Precip
mm/day
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4
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2010
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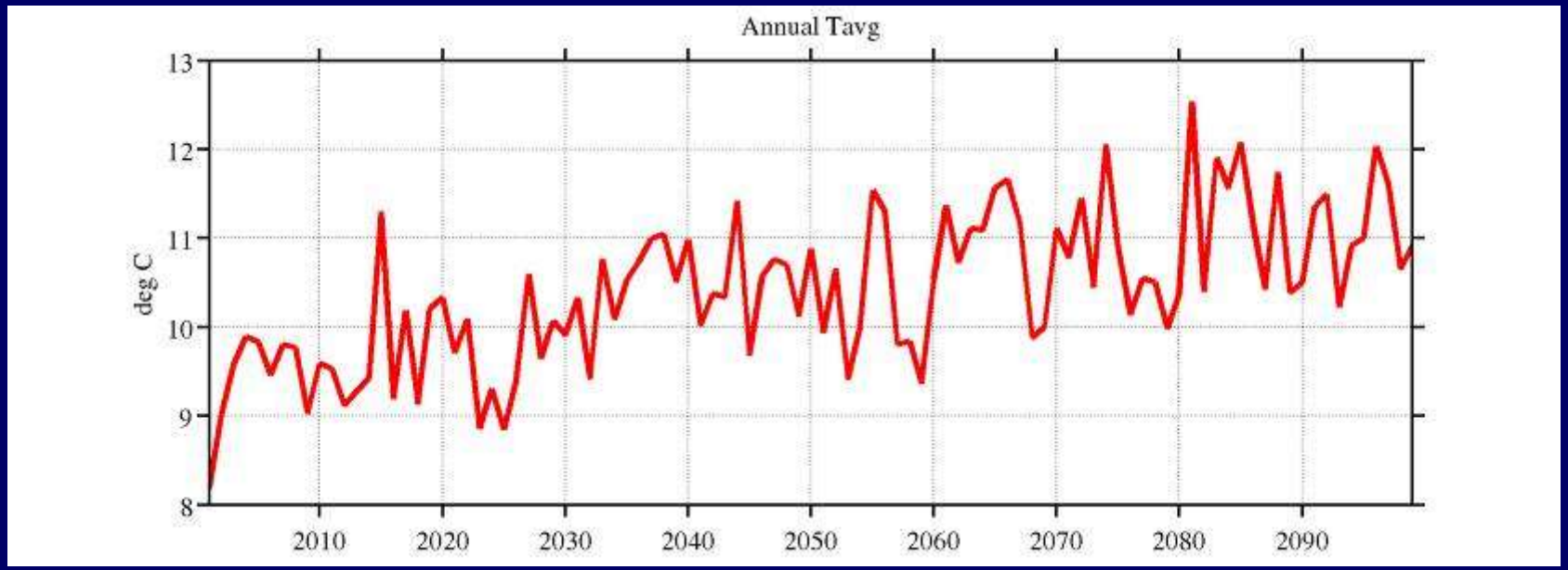
Annual Tavg
deg C
13
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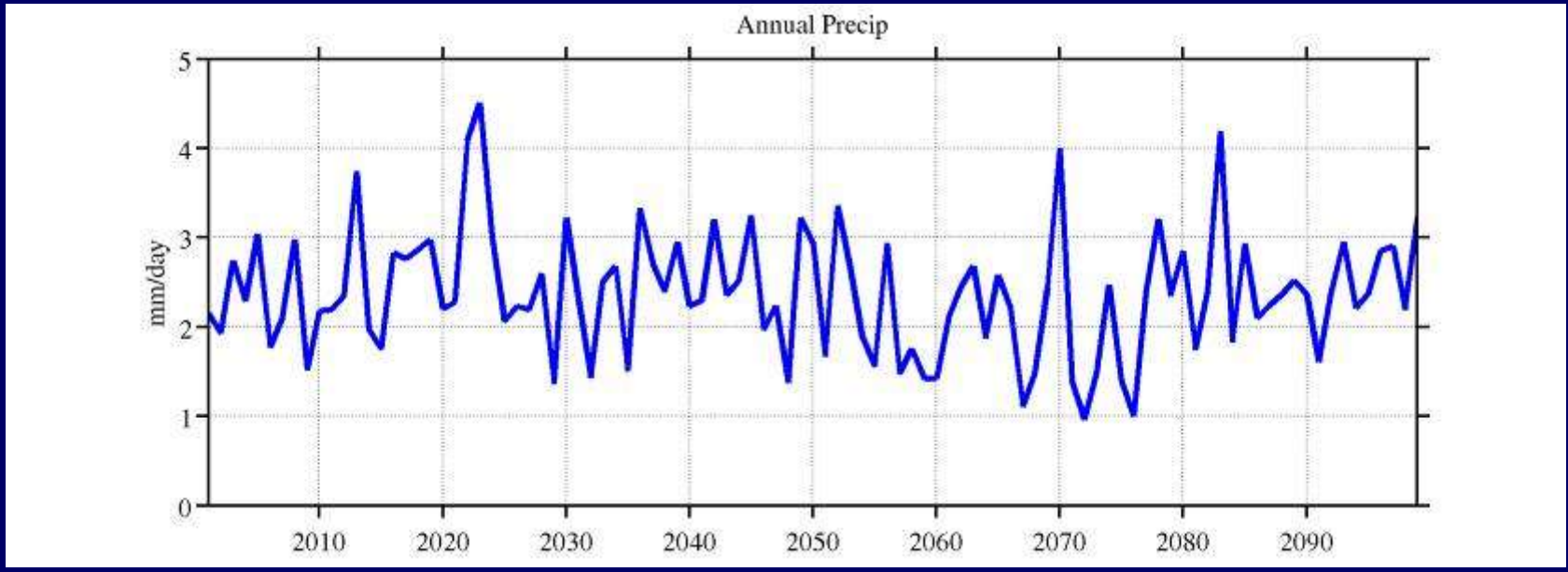
PCM-B1


Annual Precip
mm/day
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2010
2020
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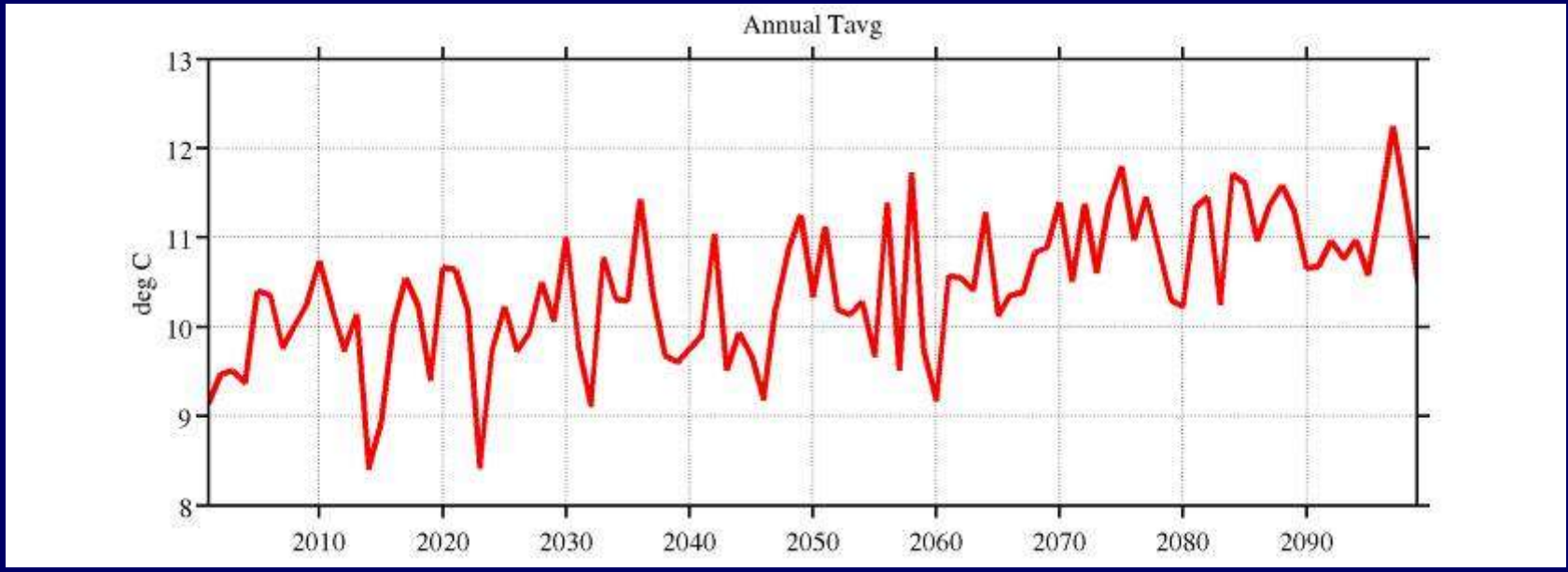
2080
2090


Annual Tavg
deg C
8
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2010
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2040
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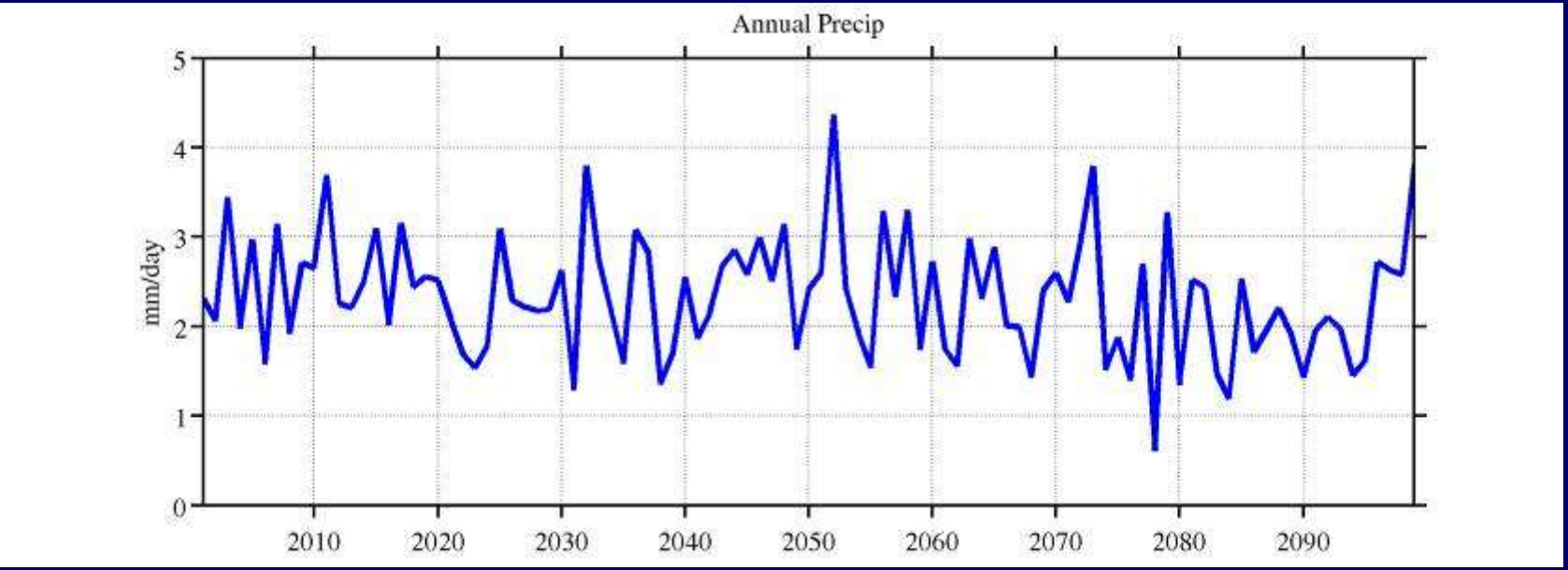
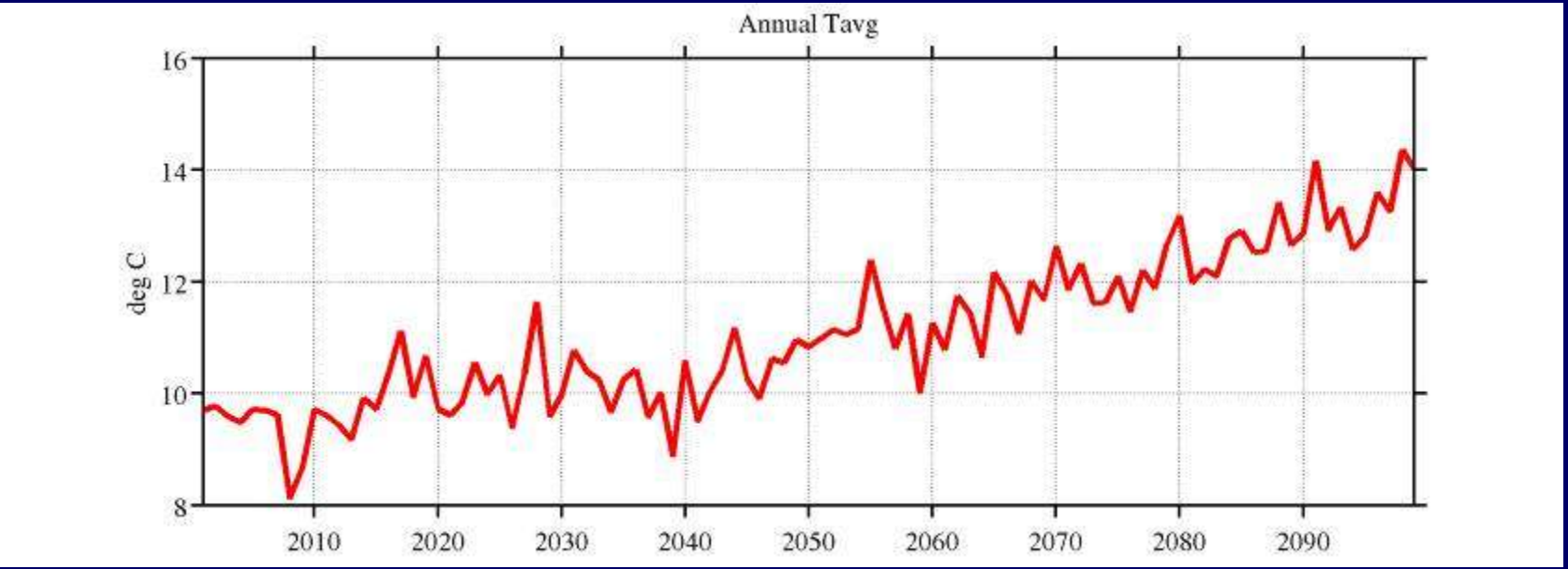
2080
2090

GFDL-A2


Annual Precip
mm/day
0
1
2
3
4
5
2010
2020
2030
2040
2050
2060
2070
2080
2090


Annual Tavg
deg C
8
10
12
14
16
2010
2020
2030
2040
2050
2060
2070
2080
2090

GFDL-A2 Reservoir Storage