The 21st Century Colorado River Hot Drought and Implications for the Future

Glen Canyon Dam Adaptive Management Program
Technical Workgoup Meeting
April 24, 2018

The twenty-first century Colorado River hot drought and implications for the future

Bradley Udall[1,2] and Jonathan Overpeck[2,3]

[1]Colorado Water Institute, Colorado State University, Fort Collins, Colorado, USA, [2]Colorado River Research Group, Boulder, Colorado, USA, [3]Department of Geosciences and Department of Hydrology and Atmospheric Sciences, Institute for the Environment, University of Arizona, Tucson, Arizona, USA

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Water Resources Research

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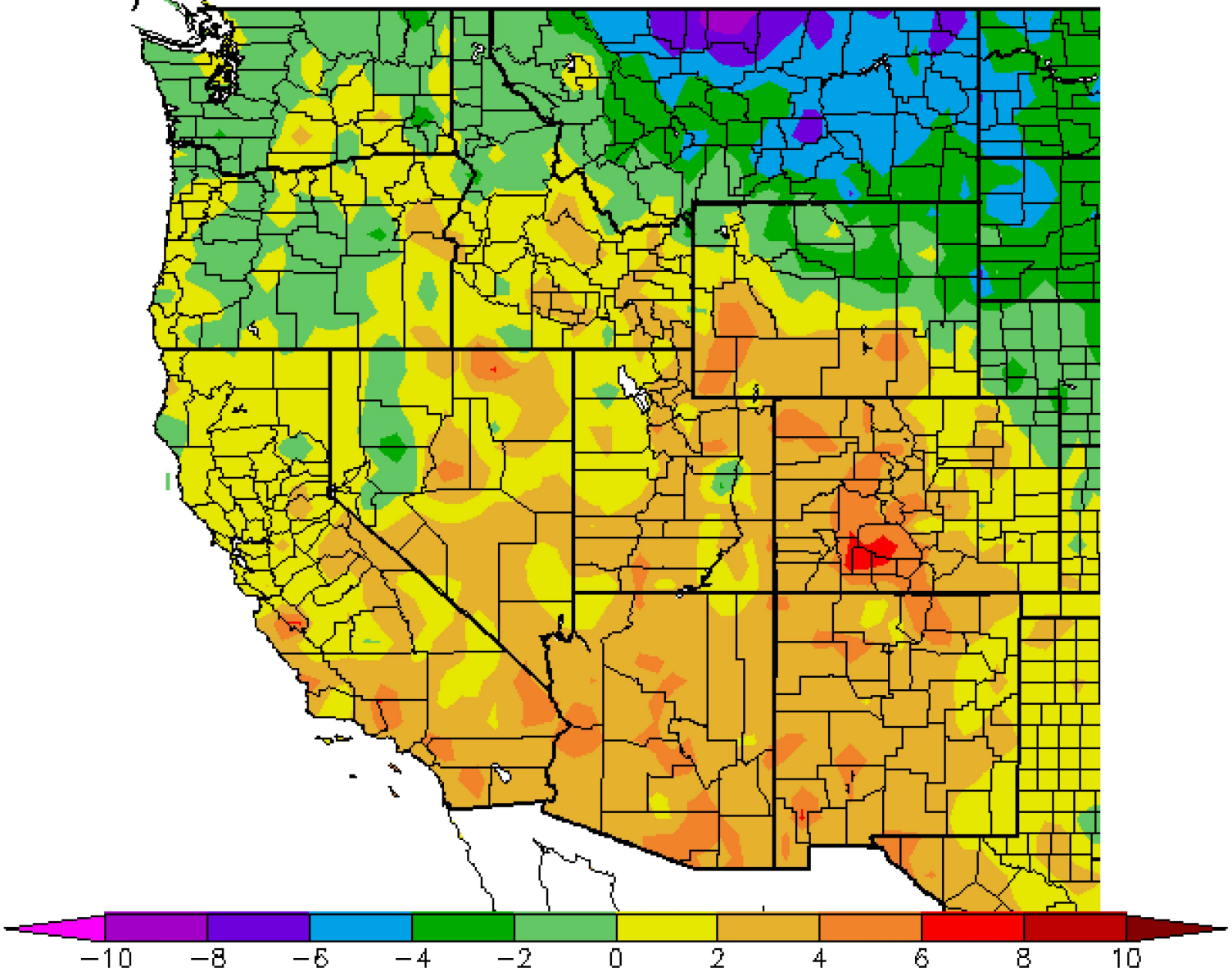
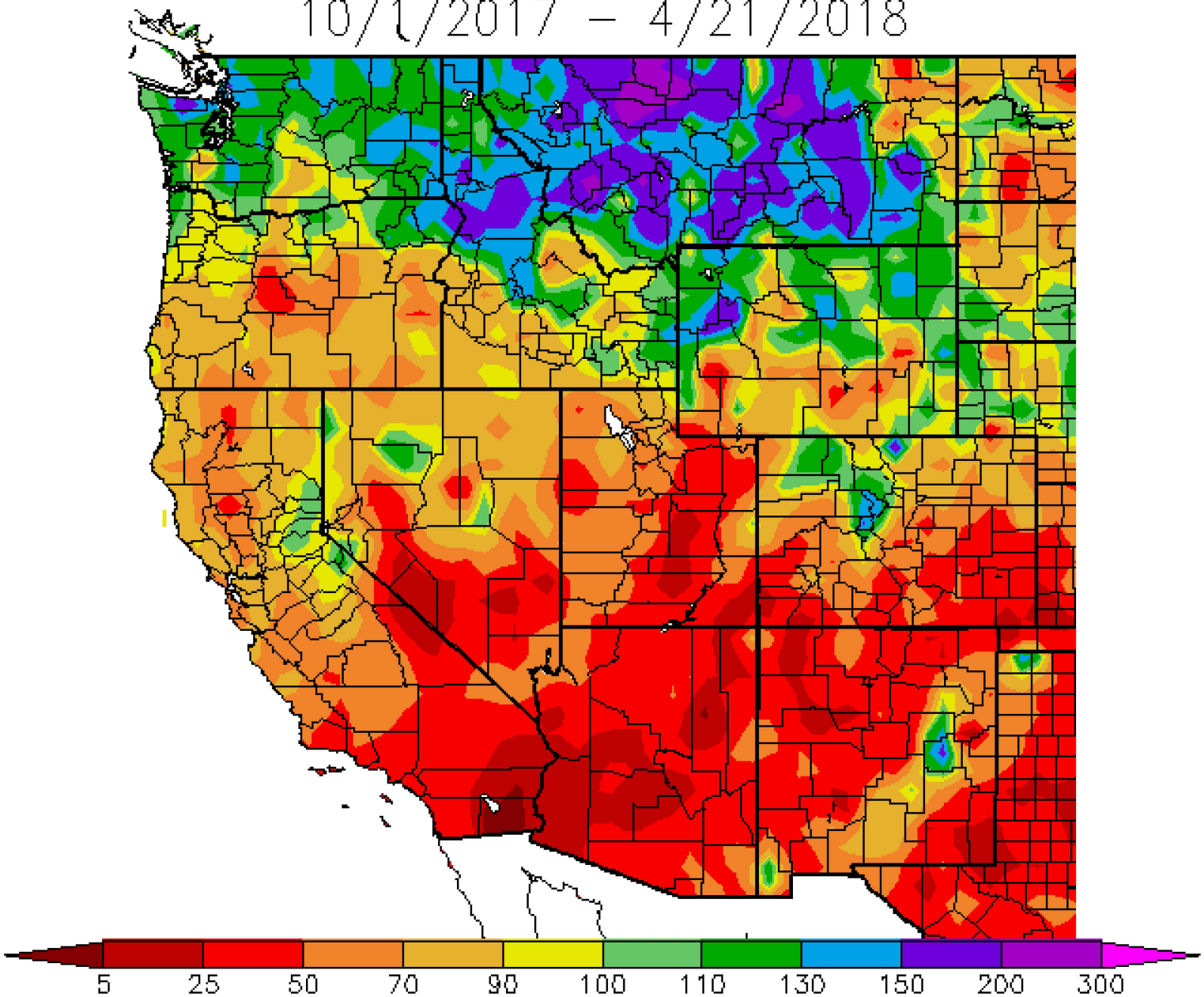
Ave. Temperature dep from Ave (deg F)
10/1/2017 – 4/21/2018



Generated 4/22/2018 at WRCC using provisional data.
NOAA Regional Climate Centers

Percent of Average Precipitation (%)
10/1/2017 – 4/21/2018

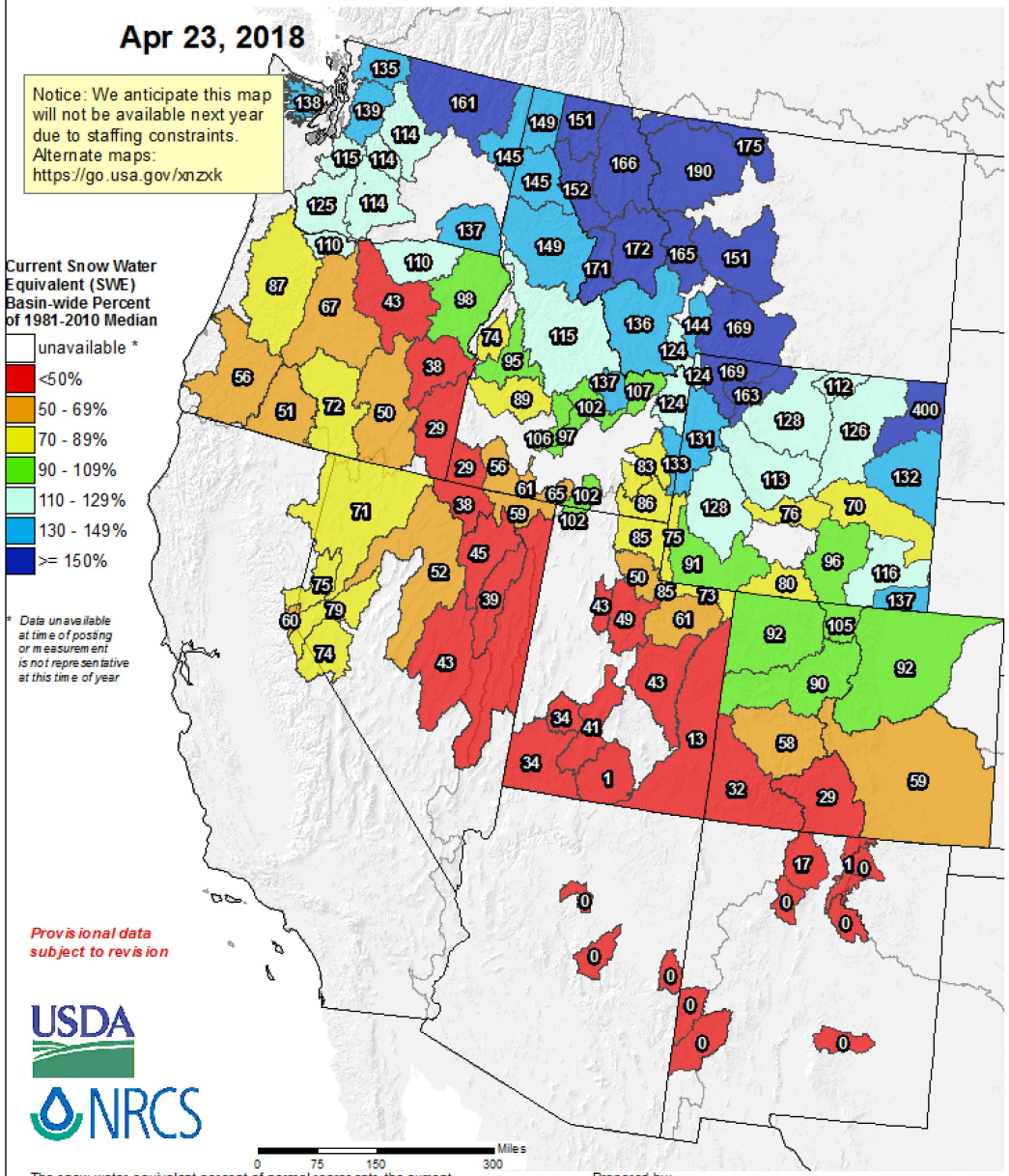


Generated 4/22/2018 at WRCC using provisional data.
NOAA Regional Climate Centers

Westwide SNOTEL Current Snow Water Equivalent (SWE) % of Normal

Apr 23, 2018

Notice: We anticipate this map will not be available next year due to staffing constraints. Alternate maps: https://go.usa.gov/xnzxk



The snow water equivalent percent of normal represents the current snow water equivalent found at selected SNOTEL sites in or near the basin compared to the average value for those sites on this day. Data based on the first reading of the day (typically 00:00).

Prepared by:
USDA/NRCS National Water and Climate Center
Portland, Oregon
http://www.wcc.nrcs.usda.gov

```
ZCZC SLCESPSTR CSW
TTAA00 KSTR DDHHMM
:National Weather Service, Colorado Basin River Forecast Center, SLC, Utah

:April mid-month Forecast      April 16, 2018

"product_issuance=mid-month"
.B SLC 180801 M DH24/DC1804161800/DVM04/QCVFEZ5
:FLOOD CONTROL RESERVOIR UNREGULATED INFLOW FORECASTS
:1 April through 31 July 2018 (units:: 1000's Acre-Feet)
:Reservoir            Most
:ID   Name            Probable
LKSA3:Lake Mead      :    3453
GLDA3:Lake Powell    :    3300
NVRN5:Navajo         :     220
BMDC2:Blue Mesa Res  :     360
GRNU1:Flaming Gorge  :    1070
.END
:
:Other Reservoir Unregulated Inflow Forecasts
:
.B SLC 180430 M DH24/DC1804161800/QCMFEZ5/DRE+1/QCMFEZ5/DRE+2/QCMFEZ5
.B1 DY180801/DVM04/QCVFEZ5
:                                Obs        mar    Forecast       Outlook
:                      dec  jan  feb  mar  %Avg   apr   may   jun apr-jul %Avg
GLDA3:Lake Powell      299  262  269  332   50%:  450/  850/ 1450/ 3300/:  46%
GBRW4:Fontenelle        46   42   38   58  110%:   90/  180/  420/  970/: 134%
GRNU1:Flaming Gorge     52   52   57   86   84%:  115/  215/  450/ 1070/: 109%
BMDC2:Blue Mesa         25   20   23   28   78%:   46/  121/  143/  360/:  53%
MPSC2:Morrow Point      26   22   24   29   72%:   52/  130/  153/  390/:  53%
CLSC2:Crystal           29   25   27   33   71%:   60/  144/  165/  430/:  51%
TPIC2:Taylor Park      4.1  4.2  3.8  4.6  104%:    8/   21/   28/   66/:  67%
VCRC2:Vallecito        3.2  2.7  2.9  3.9   45%:    9/   27/   17/   60/:  64%
NVRN5:Navajo          10.3 12.2 14.6   24   26%:   58/   90/   50/  220/:  30%
LEMC2:Lemon           0.50 0.40 0.38 0.61   38%:  1.5/    5/    3/   11/:  20%
MPHC2:McPhee          0.71 1.68  2.1  2.9   14%:   10/   37/   21/   74/:  25%
RBSC2:Ridgway          3.7  3.4  3.1  3.4   59%:    5/   14/   19/   47/:  47%
```

Arizona Department of Water Resources

"Protecting & enhancing Arizona's water supplies for current and future generations."

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Lowest January-March
Verde-Salt Runoff
since at least 1913

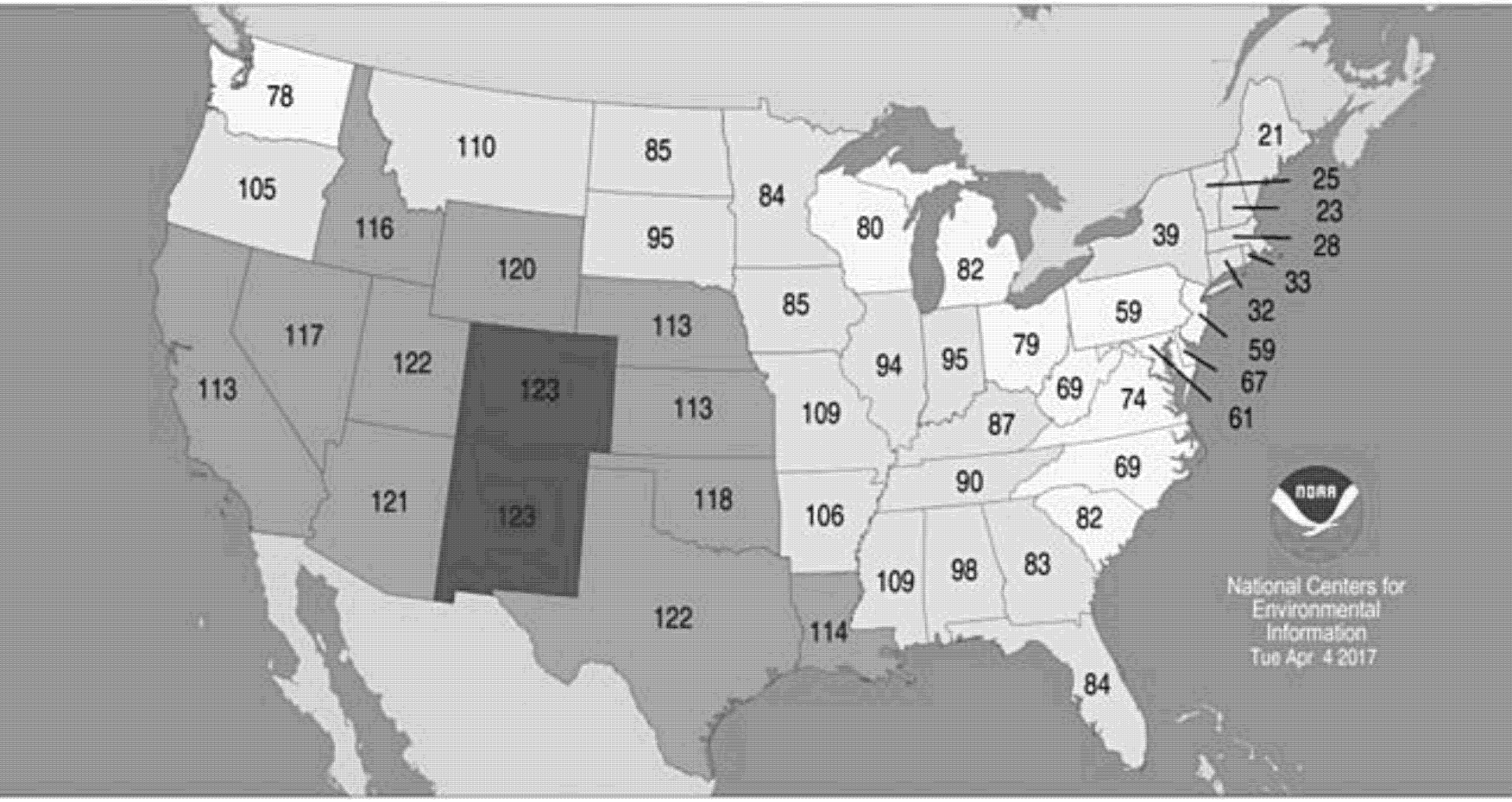
It's official: 2018 has been the driest winter ever for Arizona's mountain watersheds

Published: April 6, 2018

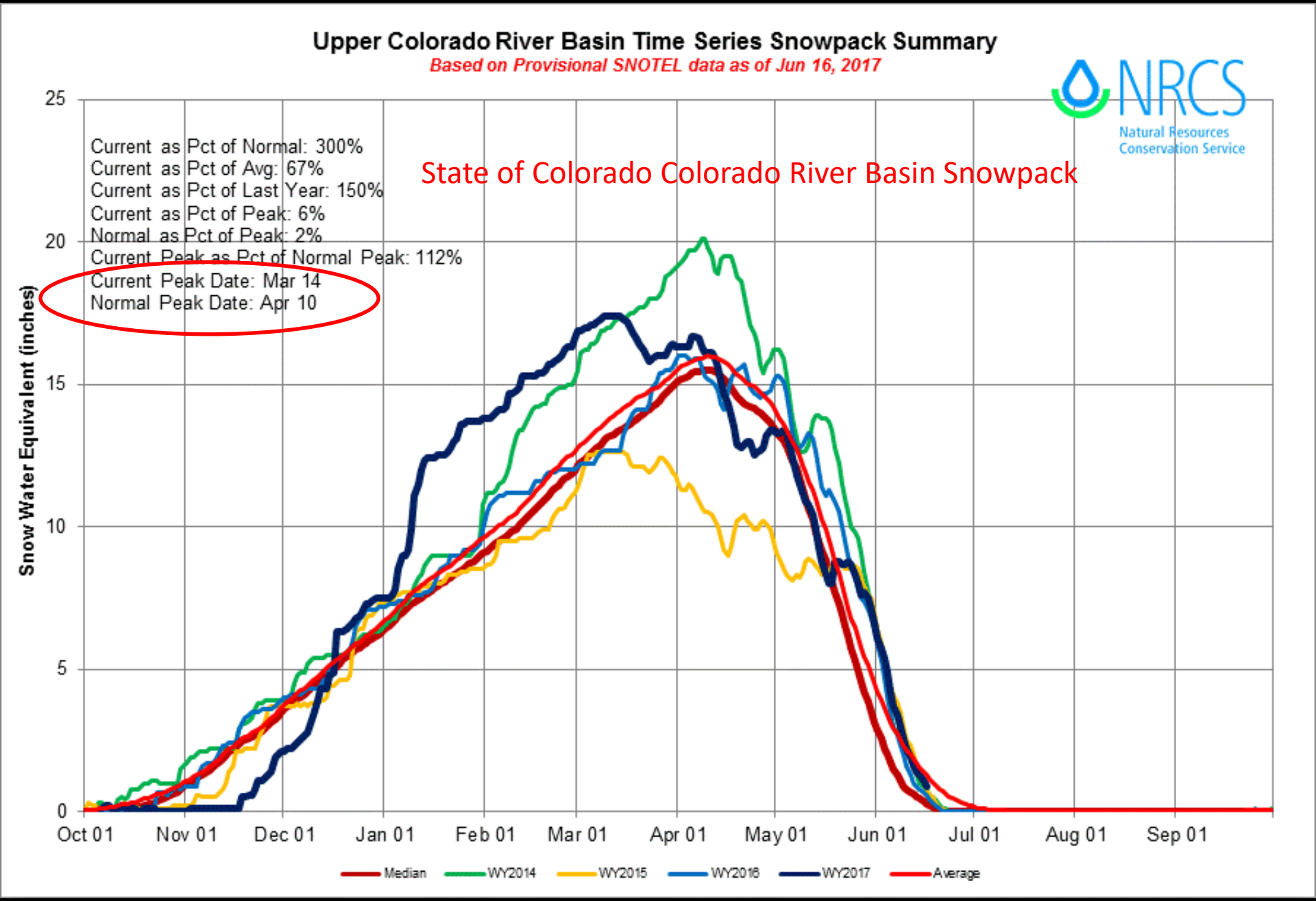
Statewide Average Temperature Ranks

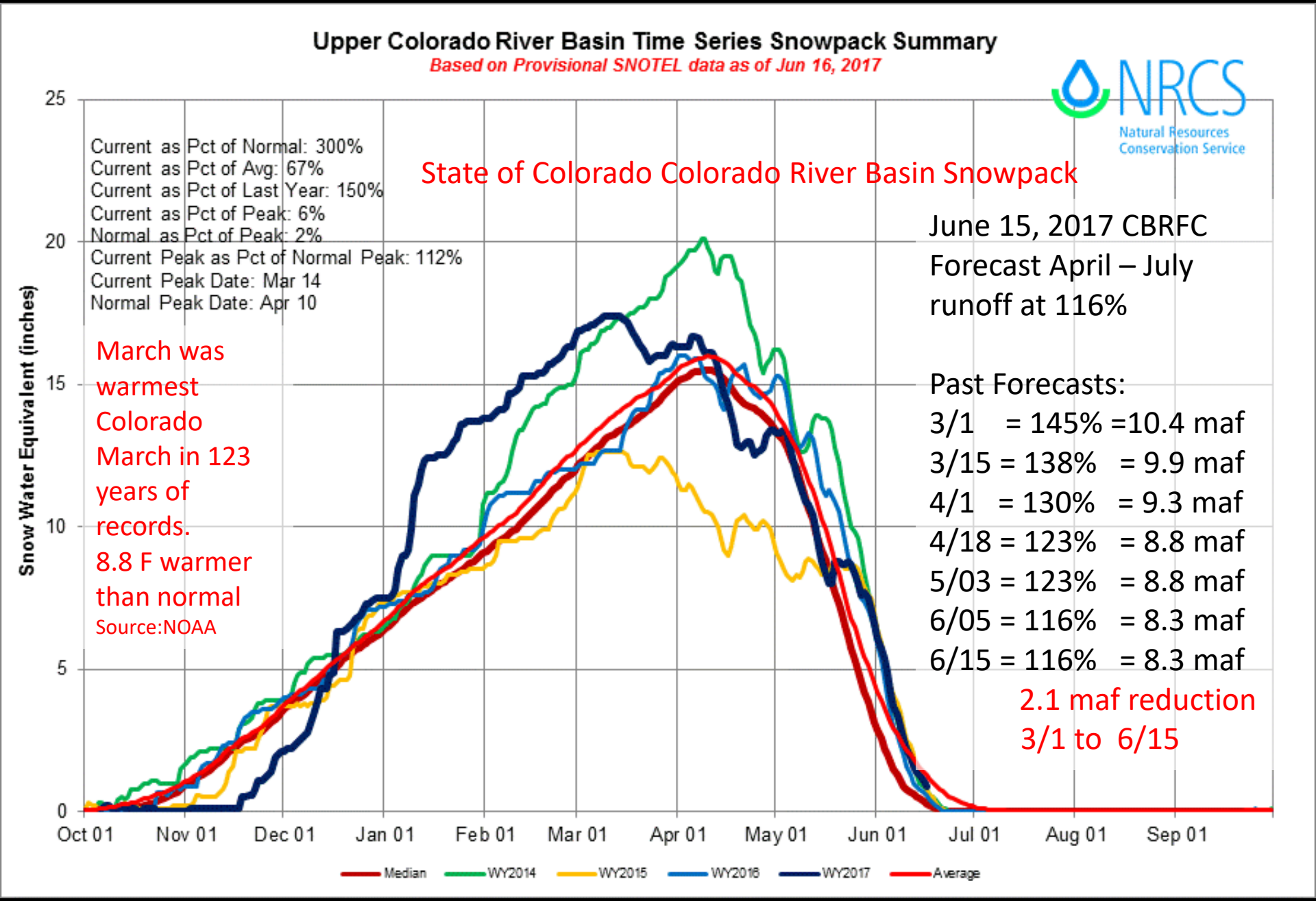
March 2017

Period: 1895–2017



Record Coldest (1) | Much Below Average | Below Average | Near Average | Above Average | Much Above Average | Record Warmest (123)


Upper Colorado River Basin Time Series Snowpack Summary
Based on Provisional SNOTEL data as of Jun 16, 2017
NRCS
Natural Resources Conservation Service
State of Colorado Colorado River Basin Snowpack
Current as Pct of Normal: 300%
Current as Pct of Avg: 67%
Current as Pct of Last Year: 150%
Current as Pct of Peak: 6%
Normal as Pct of Peak: 2%
Current Peak as Pct of Normal Peak: 112%
Current Peak Date: Mar 14
Normal Peak Date: Apr 10
Snow Water Equivalent (inches)
25
20
15
10
5
0
Oct 01
Nov 01
Dec 01
Jan 01
Feb 01
Mar 01
Apr 01
May 01
Jun 01
Jul 01
Aug 01
Sep 01
Median
WY2014
WY2015
WY2016
WY2017
Average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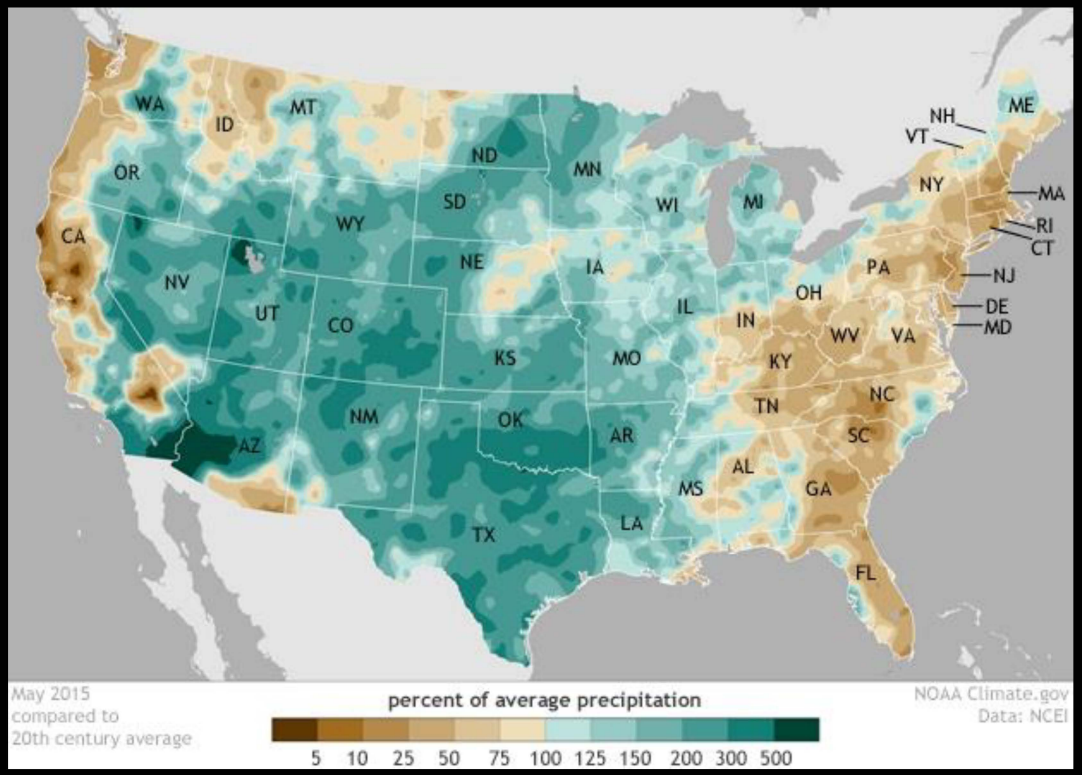
Normal as Pct of Peak: 2%
Current Peak as Pct of Normal Peak: 112%
Current Peak Date: Mar 14
Normal Peak Date: Apr 10
State of Colorado Colorado River Basin Snowpack
March was warmest Colorado March in 123 years of records.
8.8 F warmer than normal
Source:NOAA
June 15, 2017 CBRFC Forecast April – July runoff at 116%
Past Forecasts:
3/1 = 145% =10.4 maf
3/15 = 138% = 9.9 maf
4/1 = 130% = 9.3 maf
4/18 = 123% = 8.8 maf
5/03 = 123% = 8.8 maf
6/05 = 116% = 8.3 maf
6/15 = 116% = 8.3 maf
2.1 maf reduction 3/1 to 6/15
Snow Water Equivalent (inches)
25
20
15
10
5
0
Oct 01
Nov 01
Dec 01
Jan 01
Feb 01
Mar 01
Apr 01
May 01
Jun 01
Jul 01
Aug 01
Sep 01
Median
WY2014
WY2015
WY2016
WY2017
Average

May 2015 was wettest month ever recorded in U.S.

Friday, June 12, 2015

May 2015 was the country's wettest May since records began 121 years ago.

In fact, it was the wettest month ever recorded!

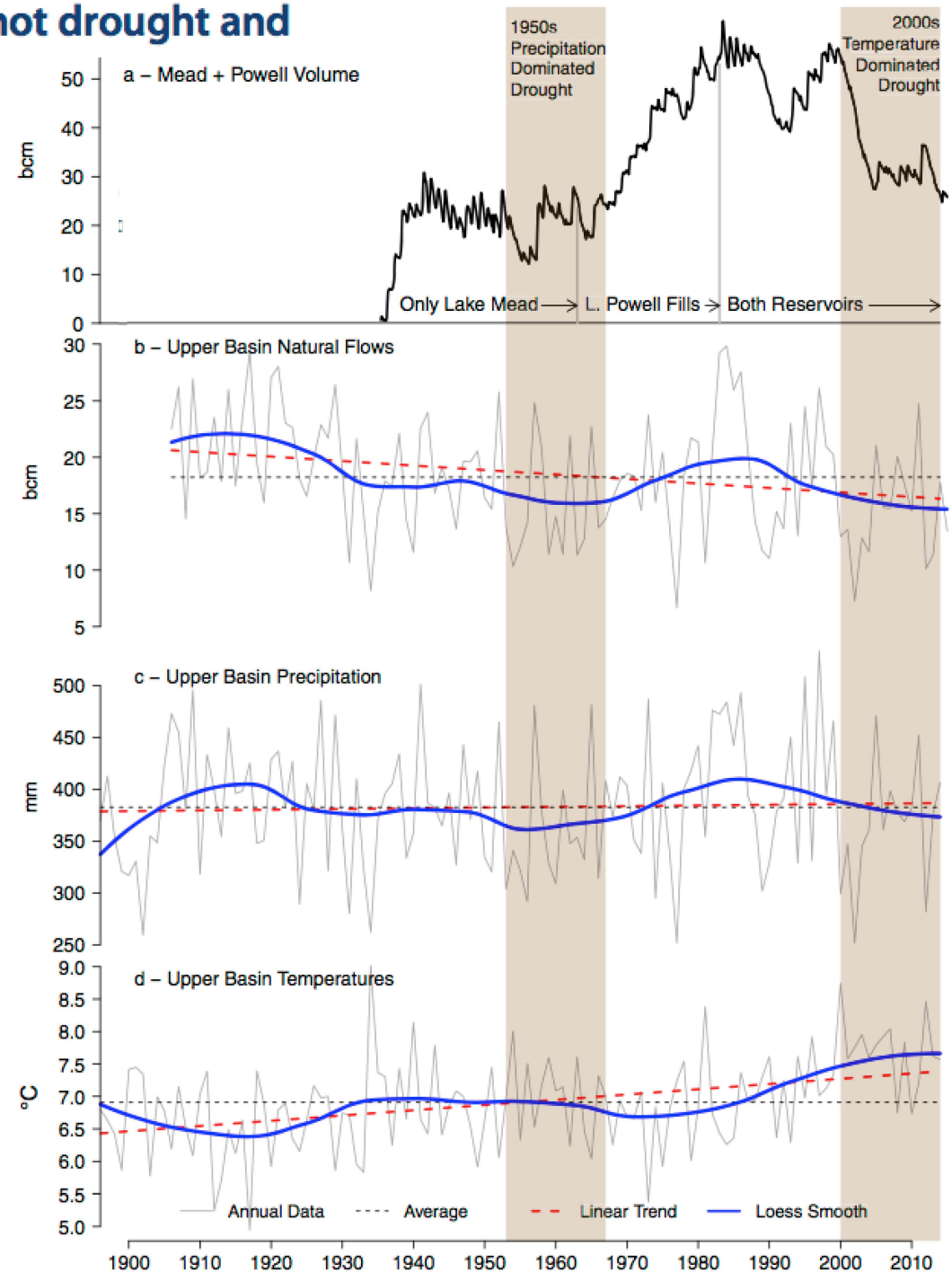


https://www.climate.gov/news-features/featured-images/may-2015-was-wettest-month-ever-recorded-us

The twenty-first century Colorado River hot drought and implications for the future

Bradley Udall[1,2] and Jonathan Overpeck[2,3]

AGU Water Resources Research

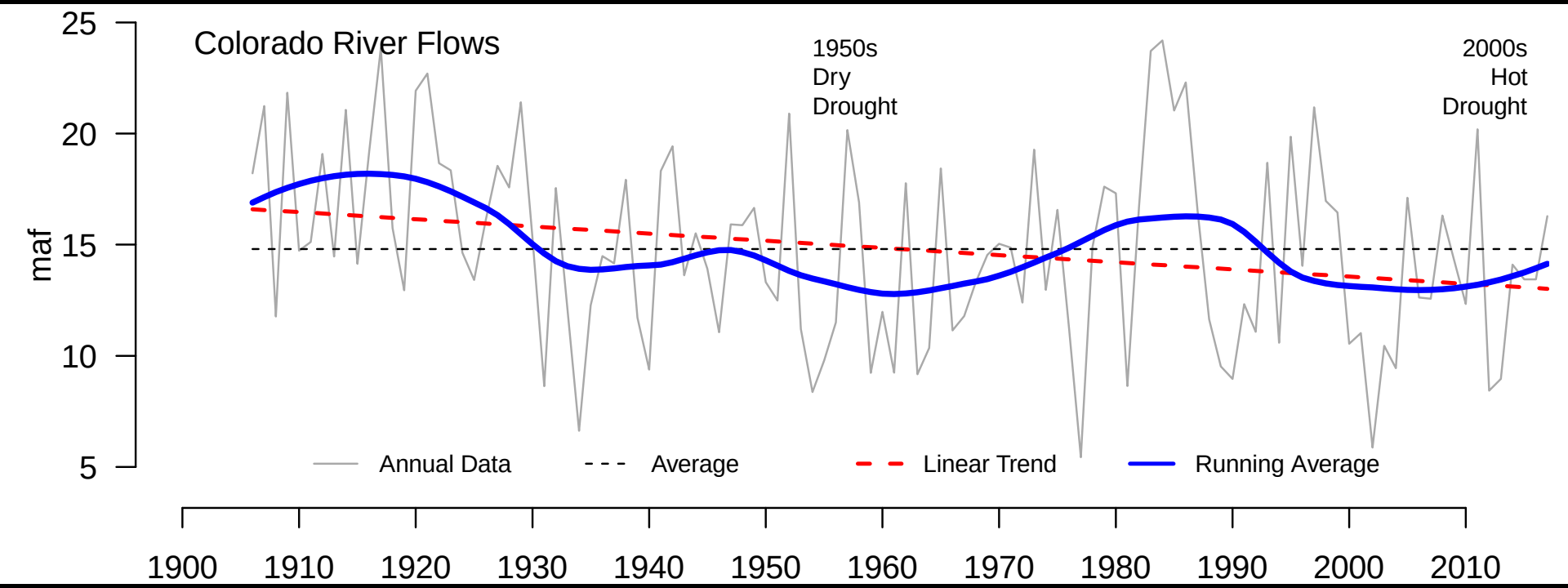


Key Points:

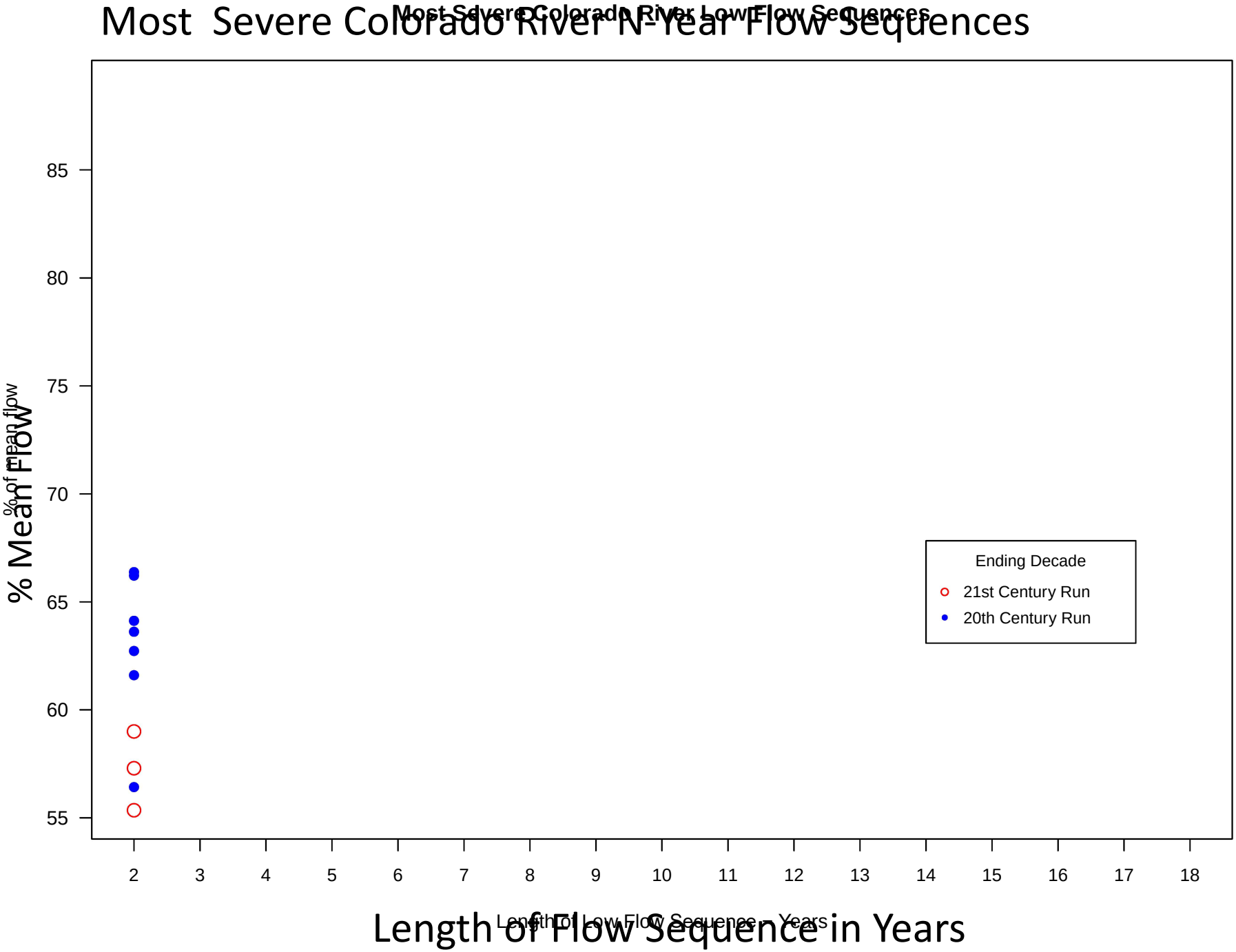
- Record Colorado River flow reductions averaged 19.3% per year during 2000–2014. One-third or more of the decline was likely due to warming
- Unabated greenhouse gas emissions will lead to continued substantial warming, translating to twenty-first century flow reductions of 35% or more
- More precipitation can reduce the flow loss, but lack of increase to date and large megadrought threat, reinforce risk of large flow loss

The Unusual 21st Century Colorado River Hydrology

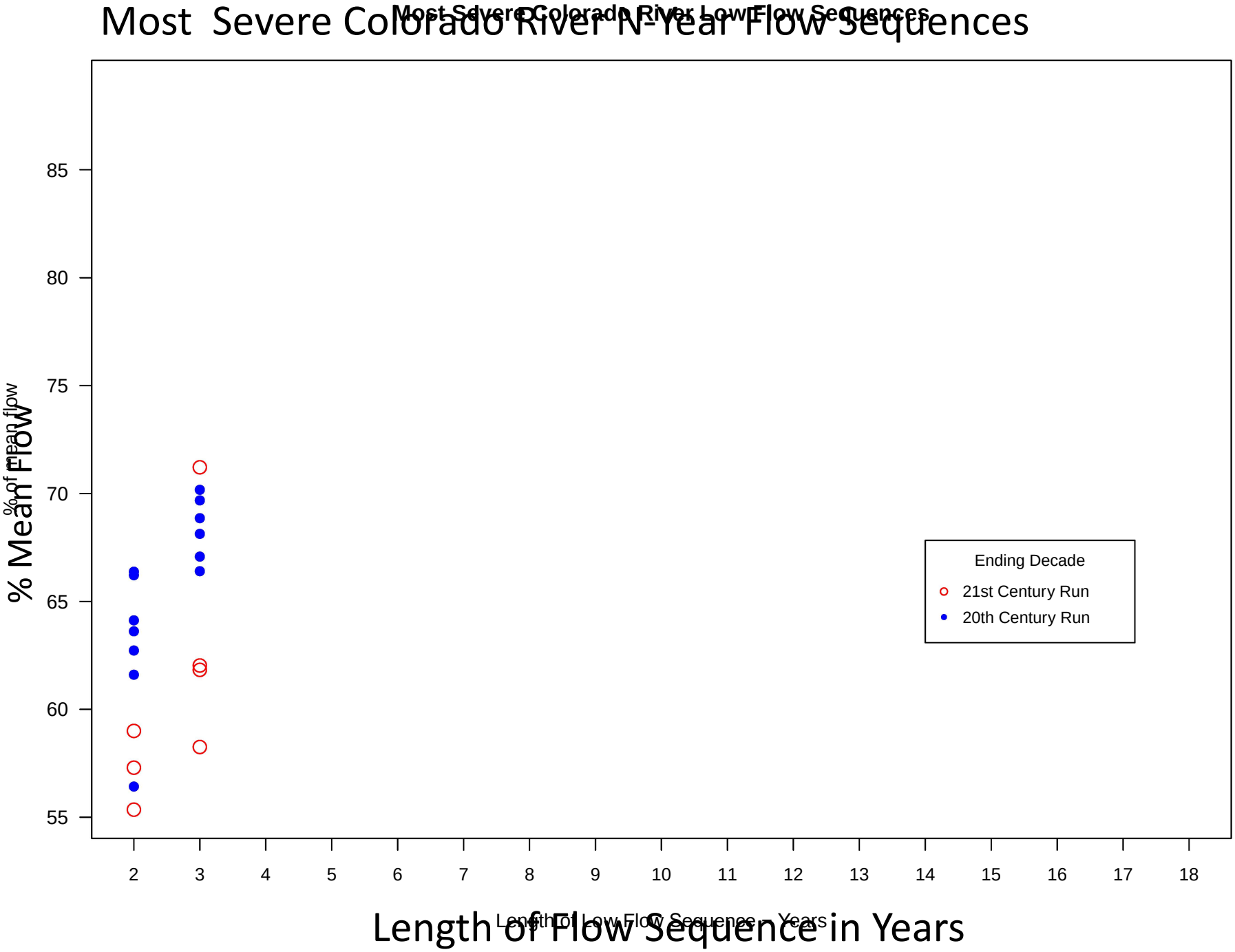
- 2 5–Year Periods below average flow
- Only 4 Years with above average flow
- ~ 19% Flow Loss Relative to 20th Century



Most Severe Colorado River N-Year Flow Sequences

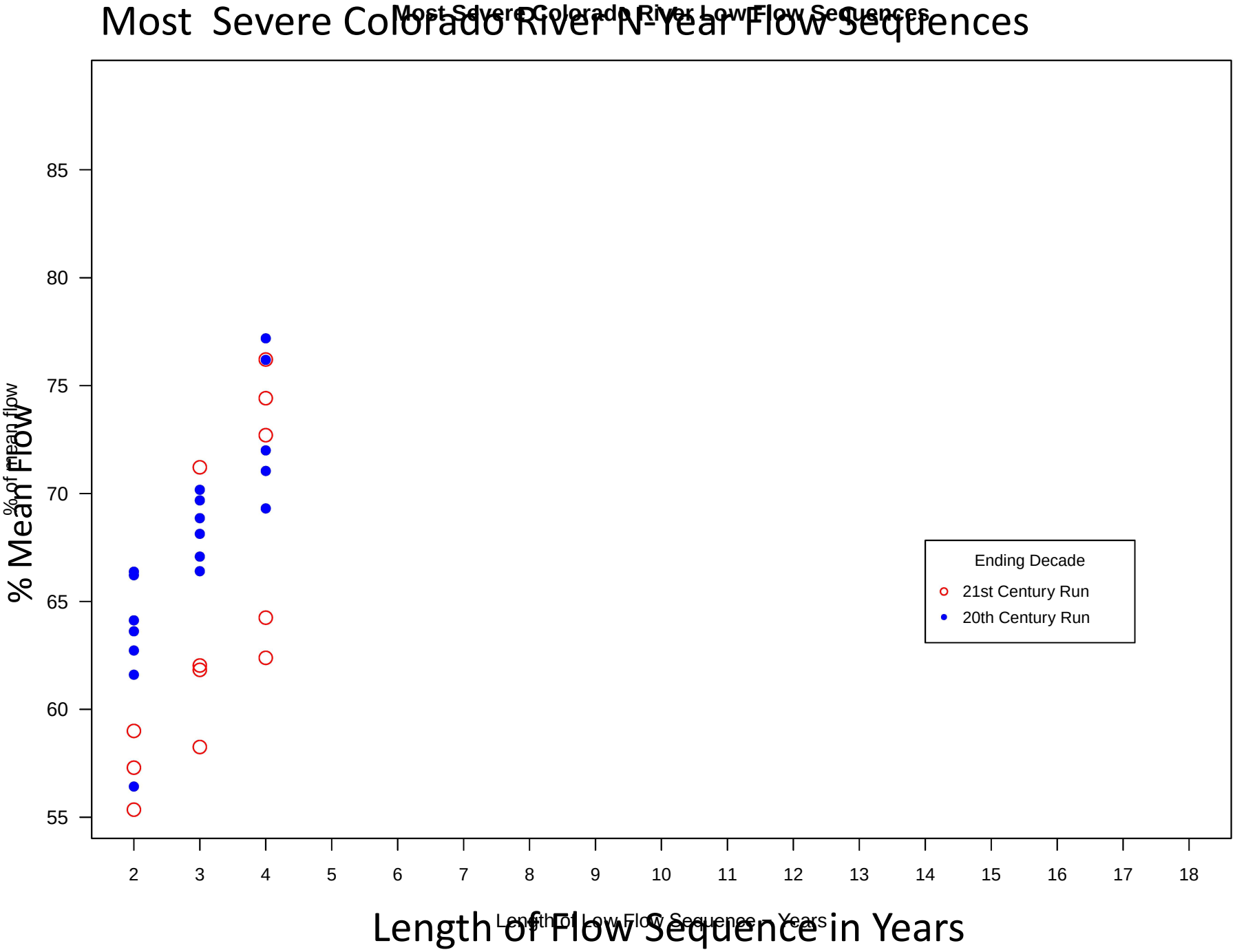


Most Severe Colorado River N-Year Flow Sequences



Length of Flow Sequence in Years

Most Severe Colorado River N-Year Flow Sequences



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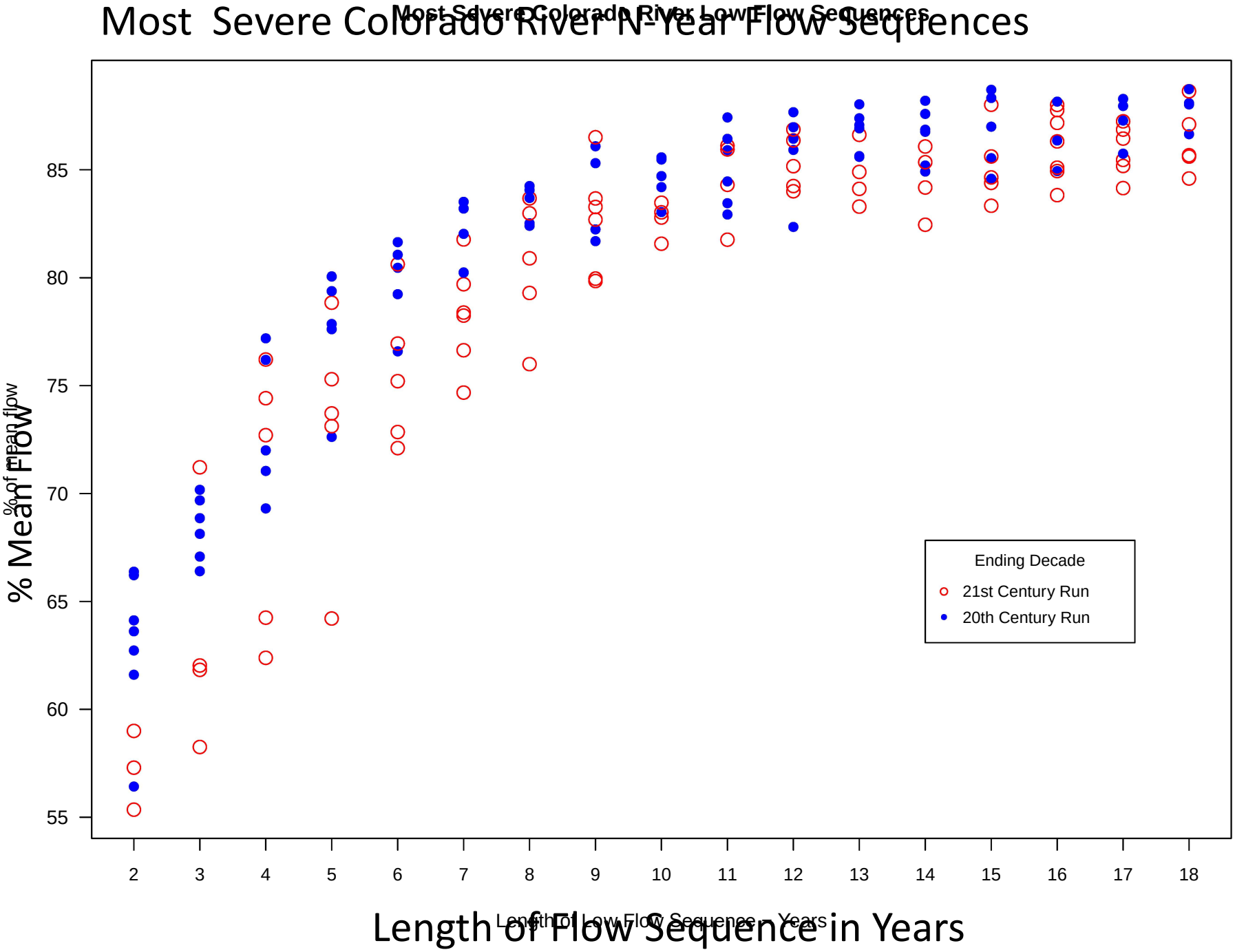
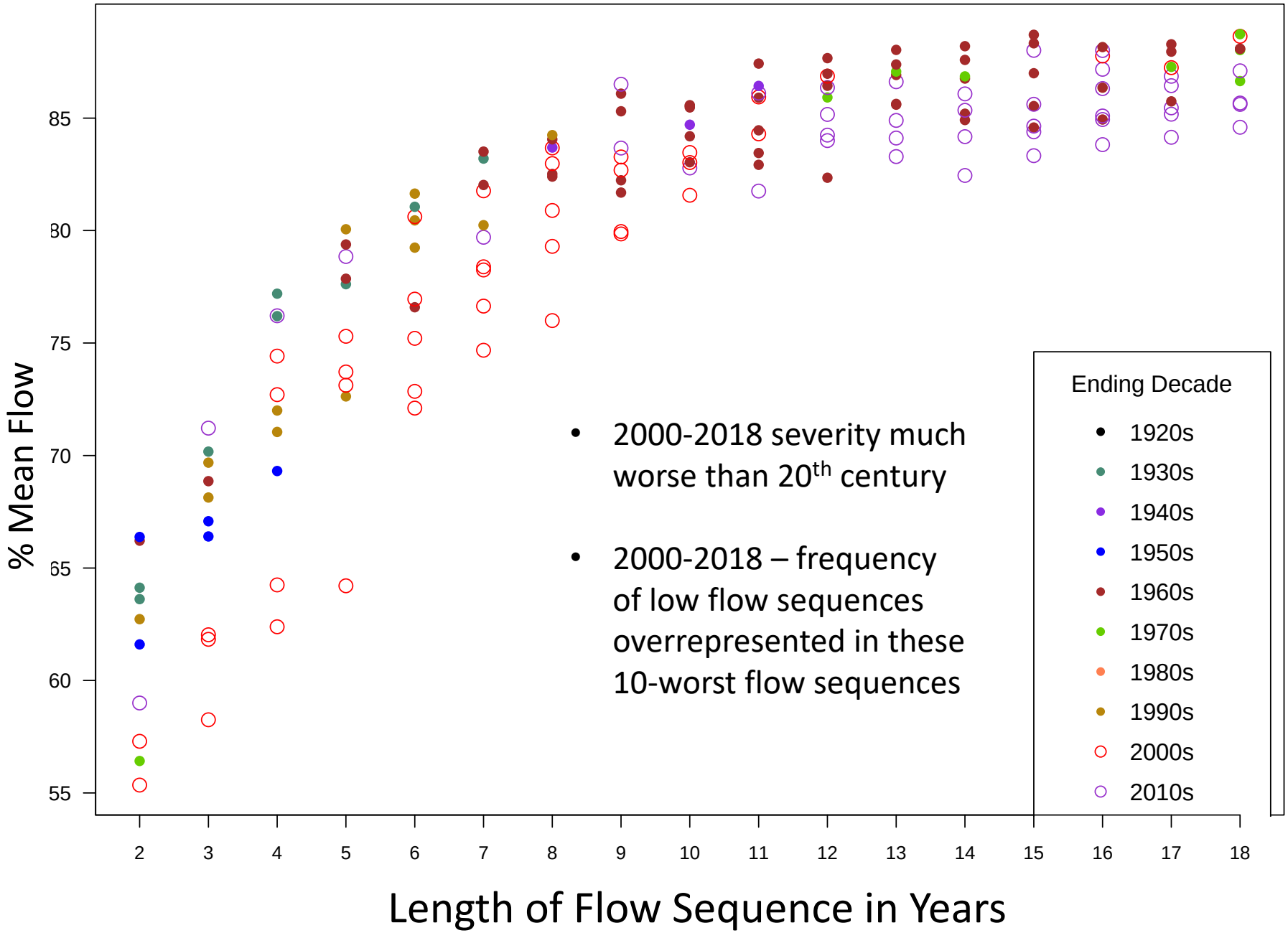
Most Severe Colorado River N-Year Flow Sequences



Length of Flow Sequence in Years

Most Severe Colorado River N-Year Flow Sequences



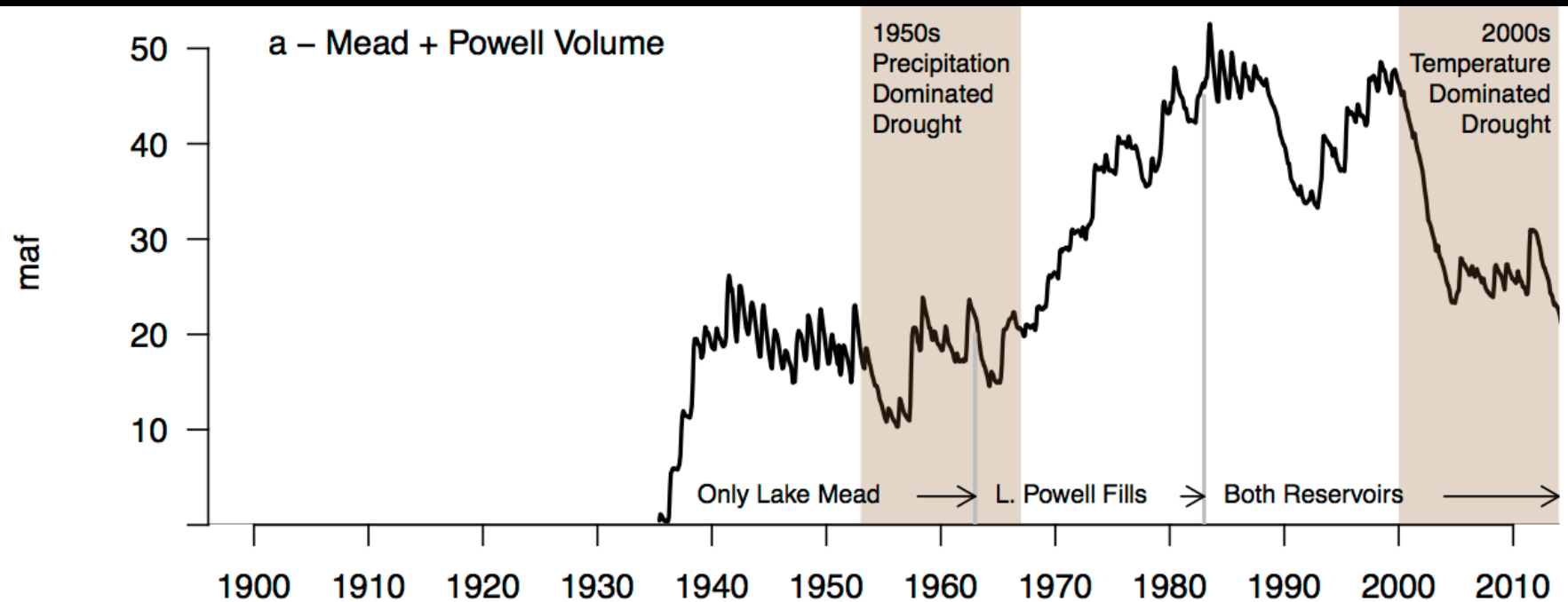
- 2000-2018 severity much worse than 20th century
- 2000-2018 – frequency of low flow sequences overrepresented in these 10-worst flow sequences

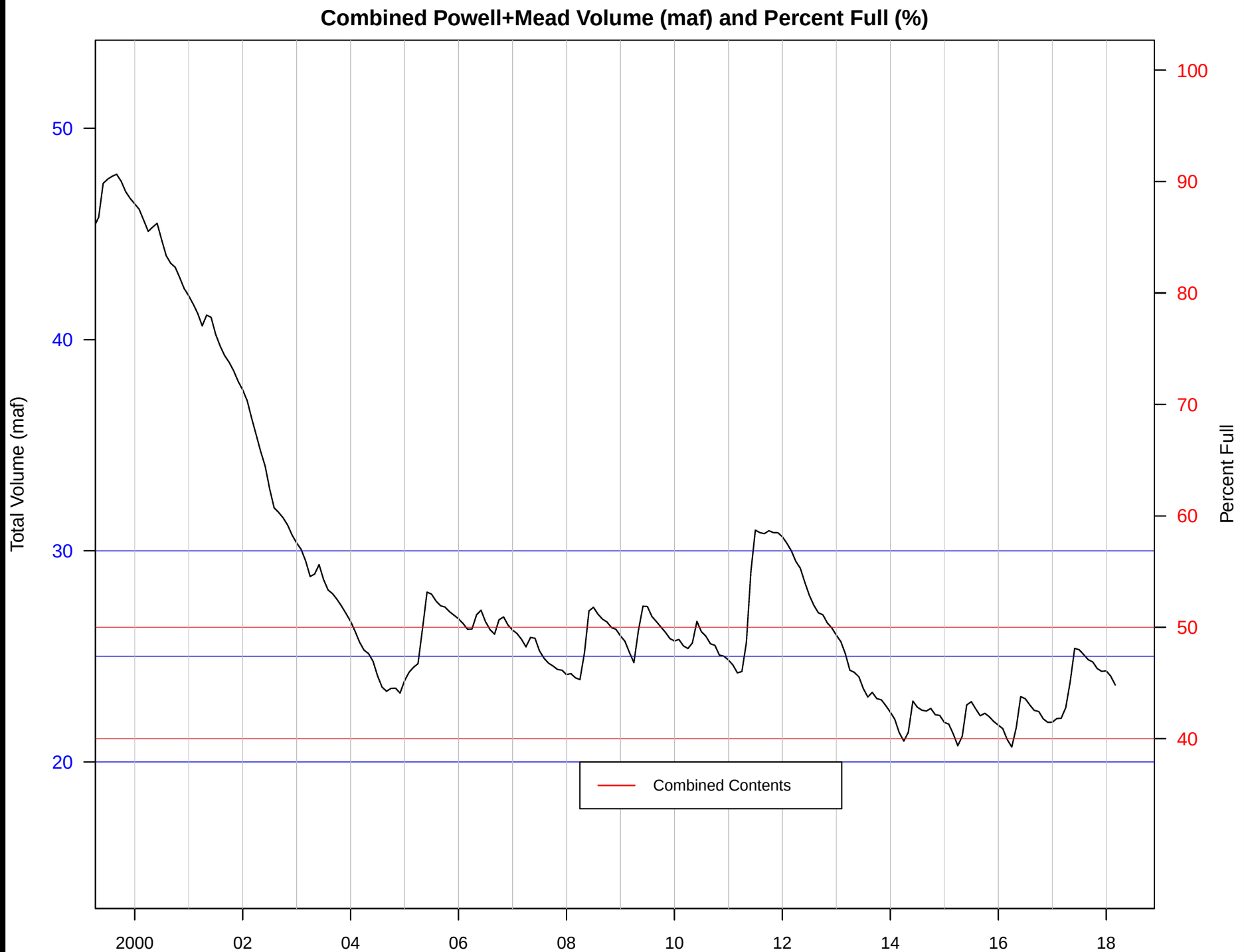
Contents of the Two Largest Reservoirs in the United States

2000 = 90%
2015 = ~ 40%

Most Serious Drought since records kept

Causes…
Lake Powell: Drought
Lake Mead: Structural Deficit ("overuse")




Combined Powell+Mead Volume (maf) and Percent Full (%)
Total Volume (maf)
Percent Full
50
40
30
20
100
90
80
70
60
50
40
2000
02
04
06
08
10
12
14
16
18
Combined Contents

Hydrologic Sensitivities of Colorado River Runoff to Changes in Precipitation and Temperature*

JULIE A. VANO

Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington

TAPASH DAS[+]

Division of Climate, Atmospheric Sciences, and Physical Oceanography, Scripps Institution of Oceanography, La Jolla, California

DENNIS P. LETTENMAIER

Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington

Calculated Temperature Sensitivity and Precipitation Elasticity with 6 different runoff models

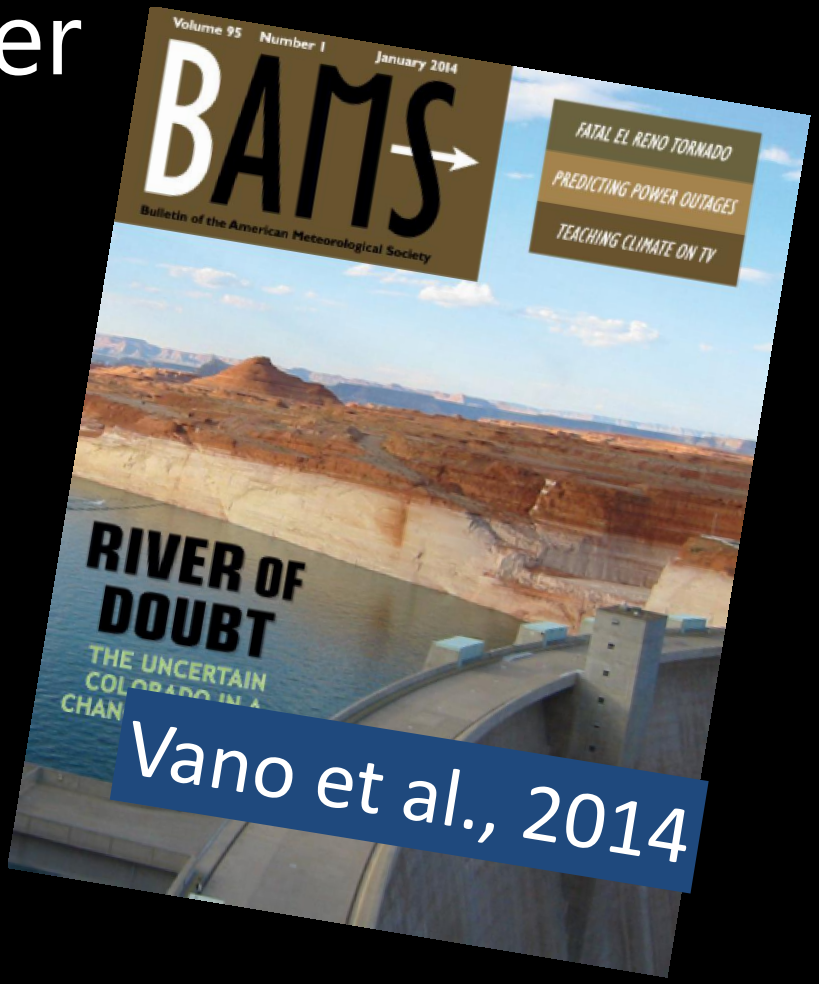
Temperature Sensitivity: Change in Flow per Degree Increase in Temperature. Is a Negative Percent

Precipitation Elasticity: Percent Change in Flow per 1% Change in Precipitation. Is a unit-less number

Temperature Sensitivity and Precipitation Elasticity are roughly additive

An interdisciplinary team reconciled the future of the Colorado River

Warming alone will drive Colorado River flow declines of -6.5% +/- 3.5% per ºC



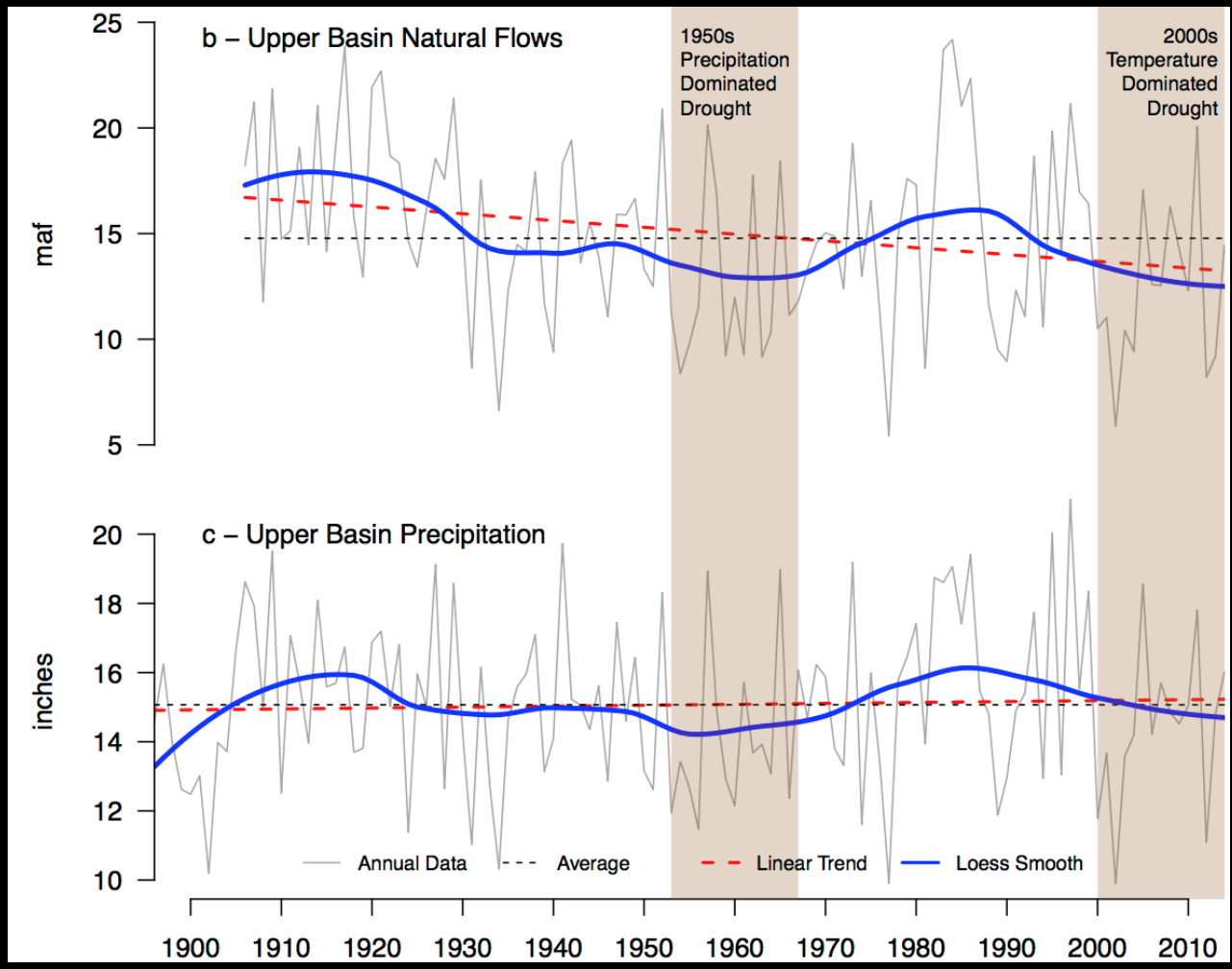
Bulletin of the American Meteorological Society, January 2014 issue

Two Droughts – Two Different Causes

1953-1967 Drought
- 18% Flow Decline
- 6.1% Precipitation

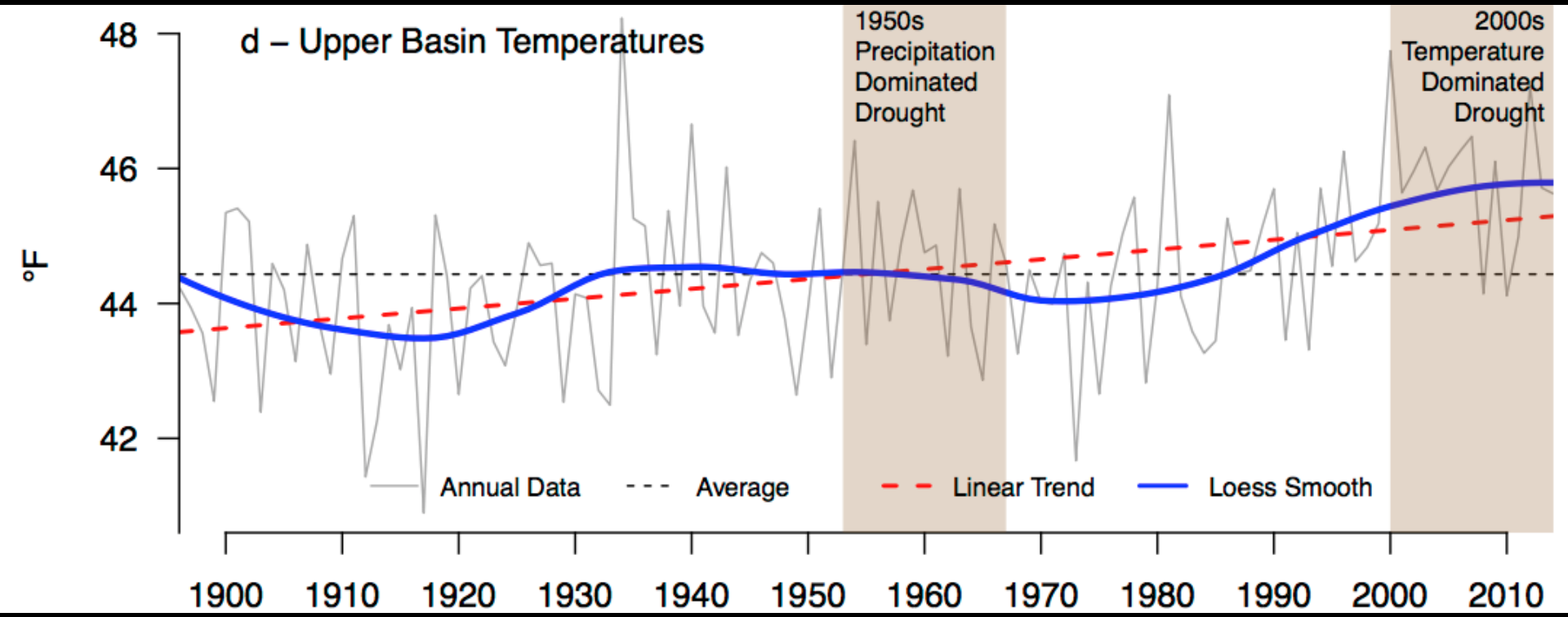
2000-2014 Drought
- 19% Flow Reduction
- 4.6% Precipitation

Note:
2000s Drought is only 75% of the Precipitation Decline in the 1950s Drought



Source: Udall & Overpeck, 2017; flow data from Reclamation, PRISM Precipitation

Temperatures Key to 2000s Decline

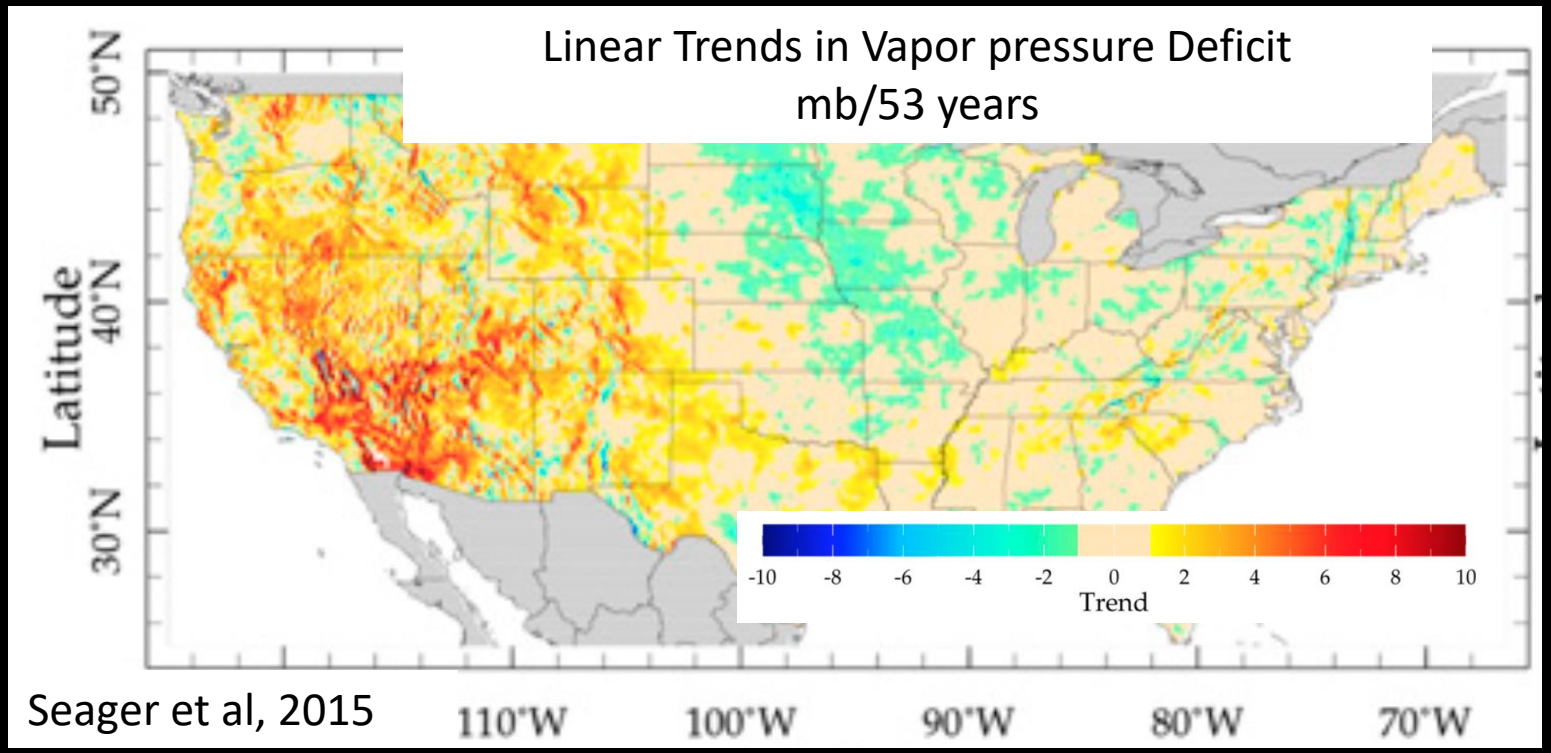


2000-14 Temperatures are 1.6°F above 1906-99 Average

Temperature Sensitivity Explains 1/6 to ½ of the current runoff reduction. 1/3 is mid point of 1/6 and 1/2

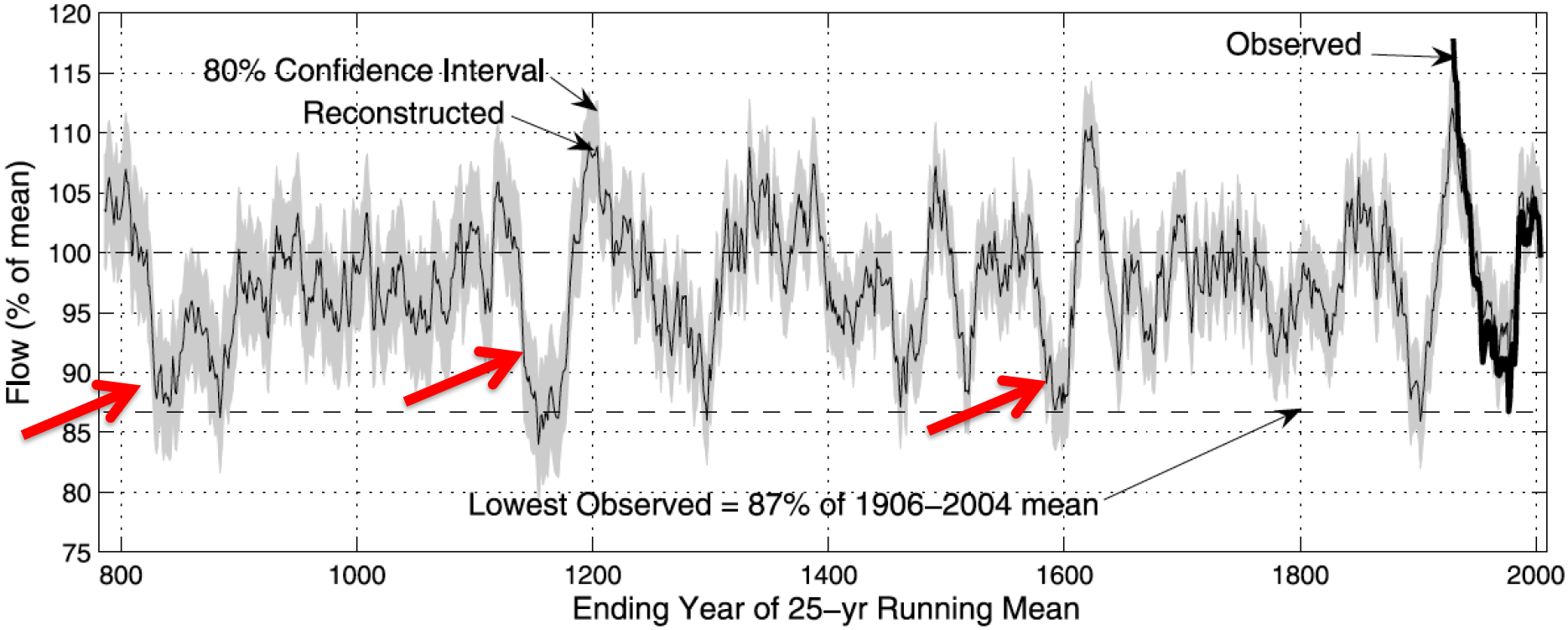
Source: Udall & Overpeck 2017, PRISM Temperatures

- Why less water?
  - Longer Growing Season
  - More Warmth on Any Given Day
  - At some point, possibly more plants and growth upslope
  - More Evaporation from Soils
  - More opportunity for sublimation
  - More atmospheric demand



Seager et al, 2015

The Upper Colorado River Basin is Megadrought Country – 1200 years of Colorado River flow thanks to tree rings



Meko et al., (*Geopysical Research Letters*, 2007)

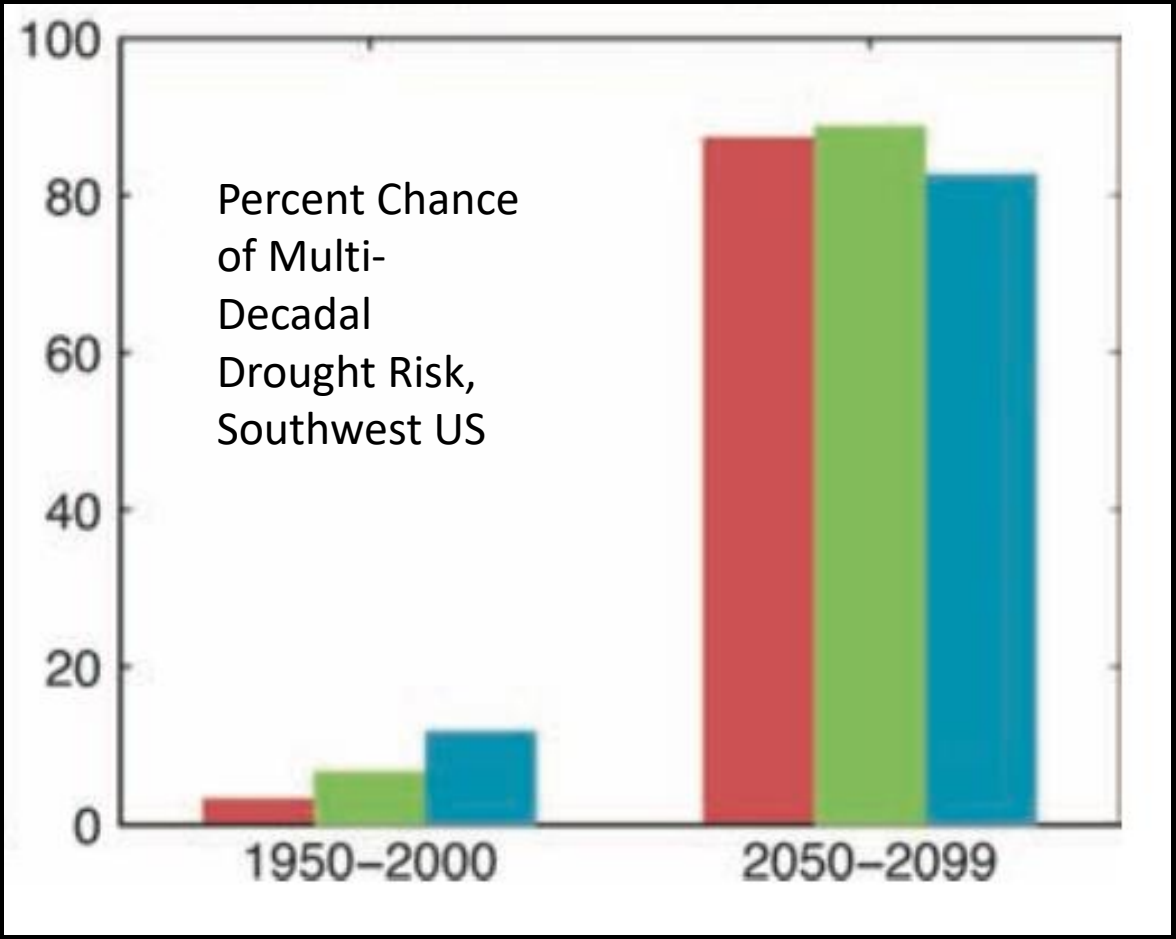
CLIMATOLOGY

Unprecedented 21st century drought risk in the American Southwest and Central Plains

Benjamin I. Cook,[1,2]* Toby R. Ault,[3] Jason E. Smerdon[2]

In both Central Plains and Southwest, Multi-decadal Drought Risk* exceeds 80% in 21st Century

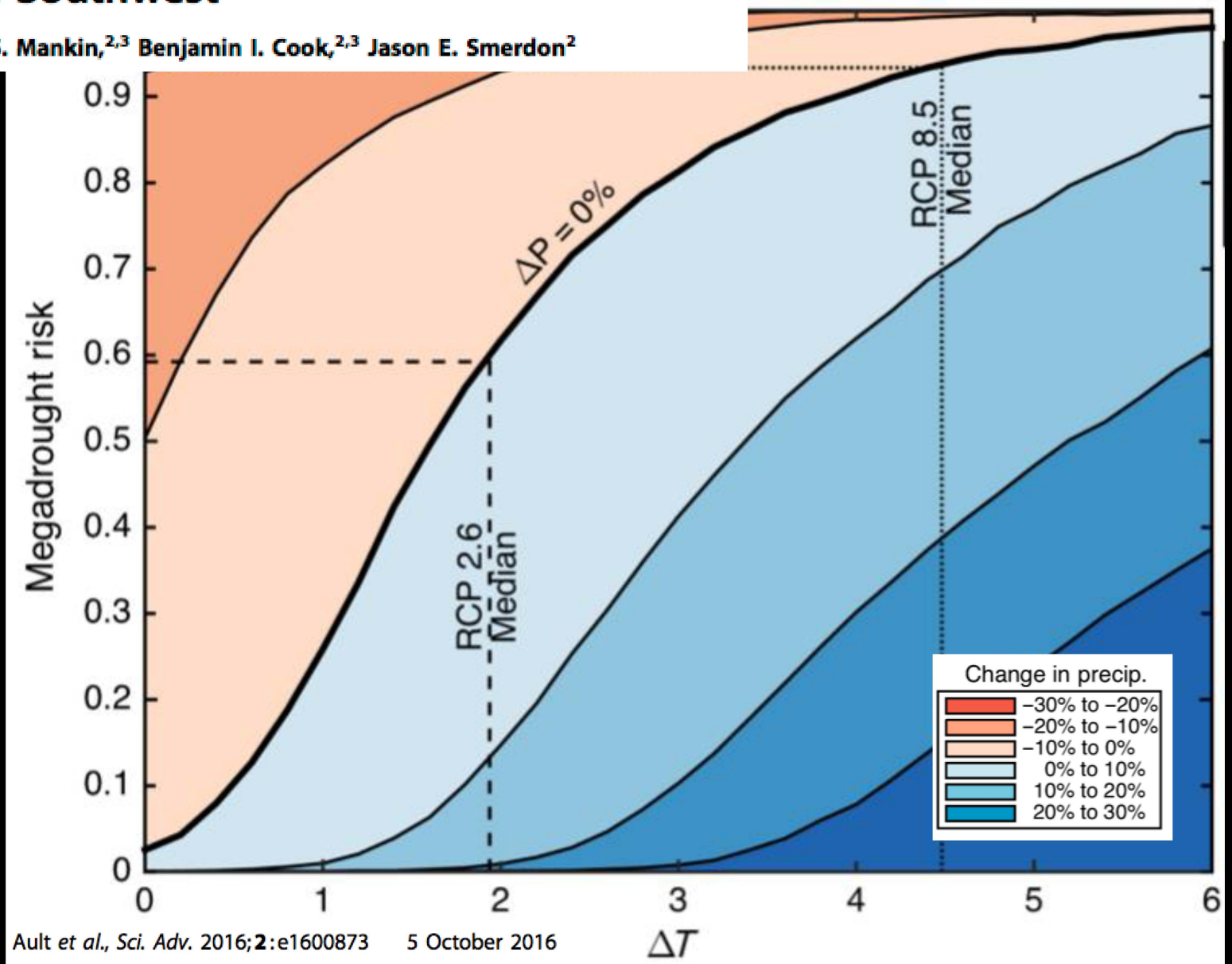
* Defined as Drought lasting 35 or more years



CLIMATOLOGY

Relative impacts of mitigation, temperature, and precipitation on 21st-century megadrought risk in the American Southwest

Toby R. Ault,[1]* Justin S. Mankin,[2,3] Benjamin I. Cook,[2,3] Jason E. Smerdon[2]



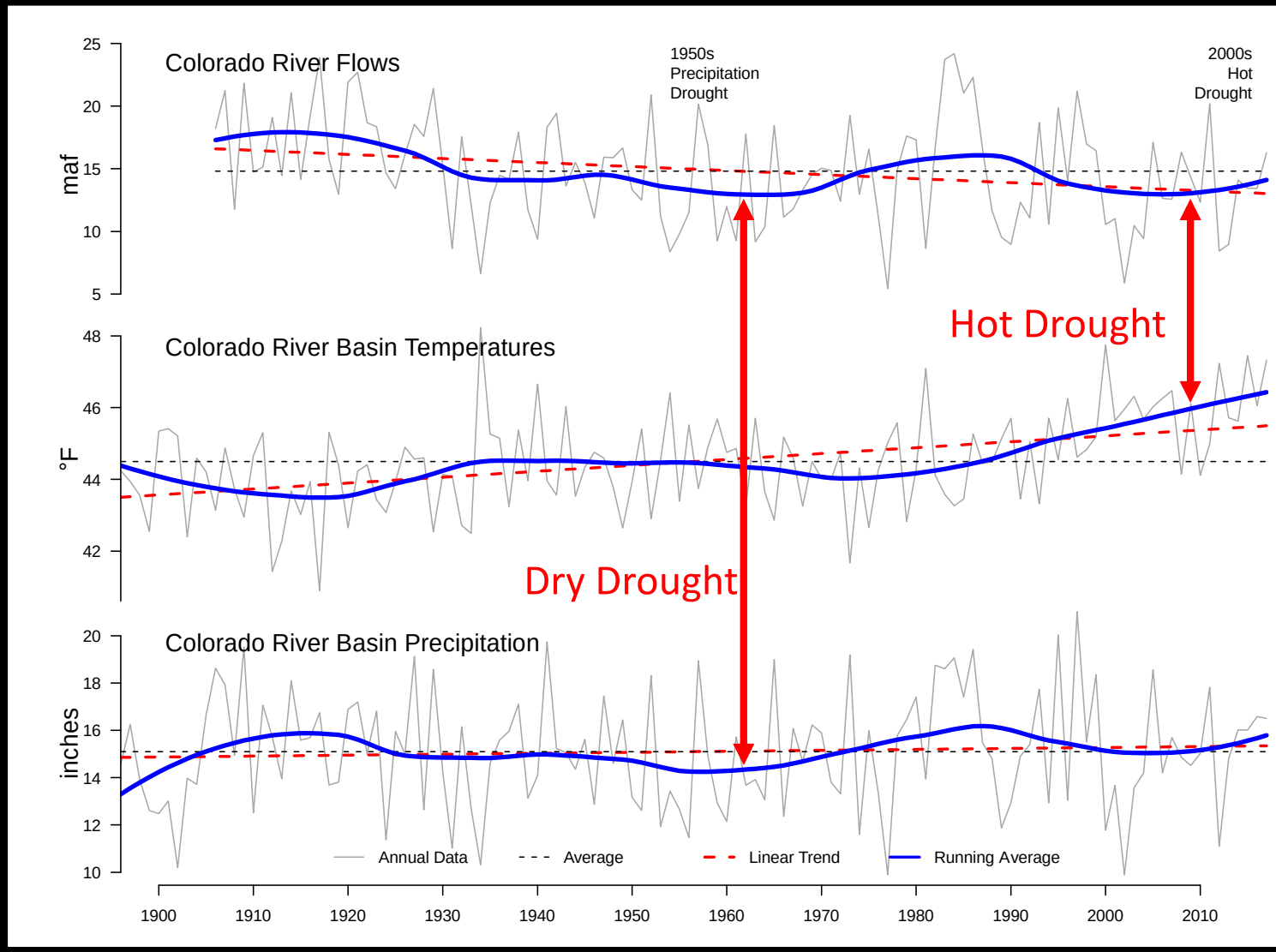
Ault *et al.*, *Sci. Adv.* 2016;**2**:e1600873 5 October 2016

The Complete Picture…

You have to invoke higher temperatures to explain the current drought.

AND….

This does not bode well for the future…

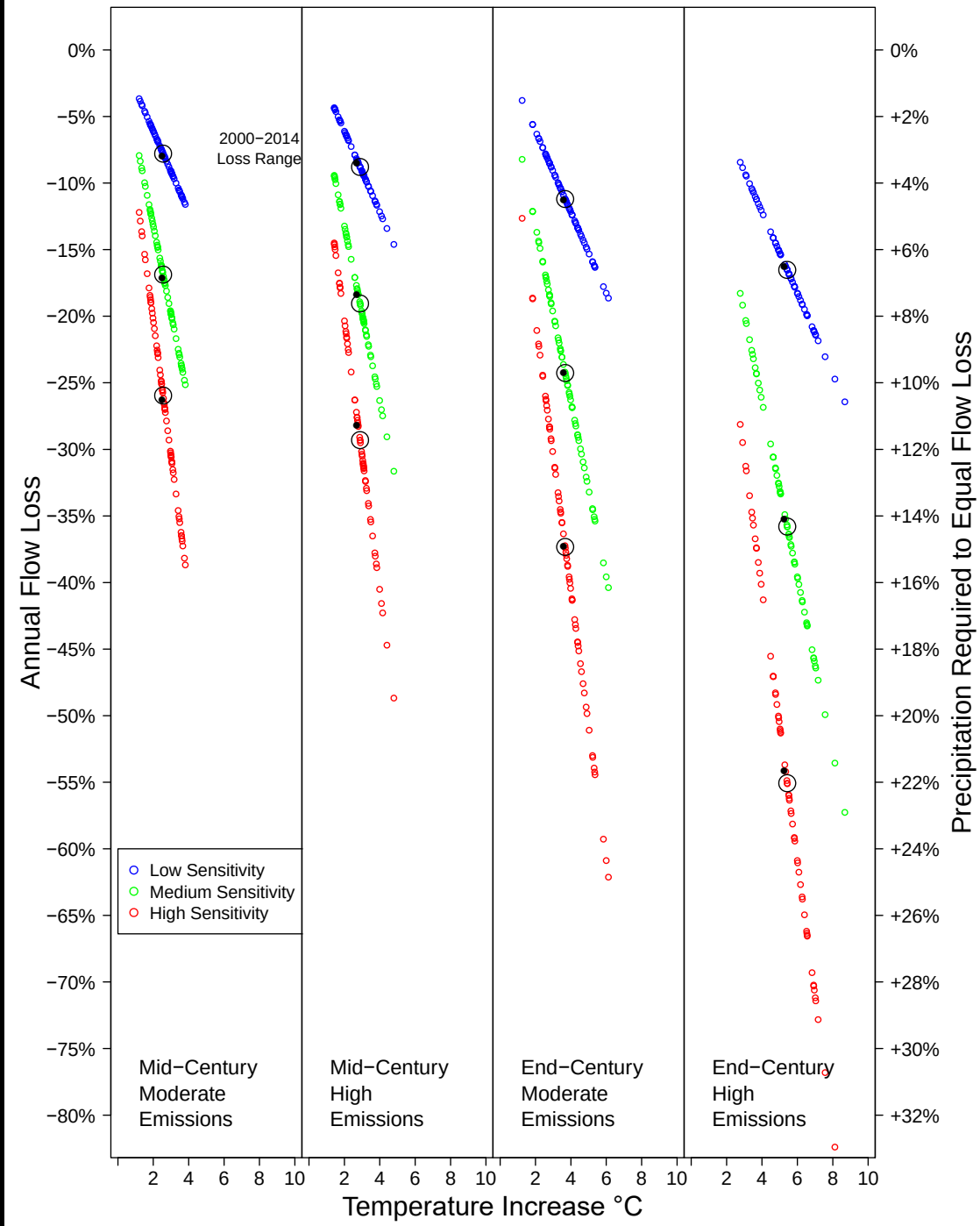


Colorado River Future Flow Losses

Climate Change a combination of …

1. For-Sure Temperature Rise -> Flow Losses

2. Not-Sure Precipitation Change -> Flow Gains or Losses



Key Additional Points

Our results are generally comparable to Reclamation's most recent results when considering the full range of our analysis when both precipitation and temperatures are included. However, our focus and emphasis is on the large near-certain temperature-induced flow declines with a separate analysis of precipitation. Reclamation, by contrast, has a focused on climate multimodel-ensemble median declines, including medians calculated across emission scenarios [*Reclamation*, 2013, 2012]. Decision makers often treat these median outcomes as a proxy for risk despite the fact that the median obscures the wide range of results and lumps wet and dry, warm and hot, large and small emission increases and, most critically, near certain temperature increases and very uncertain precipitation changes.

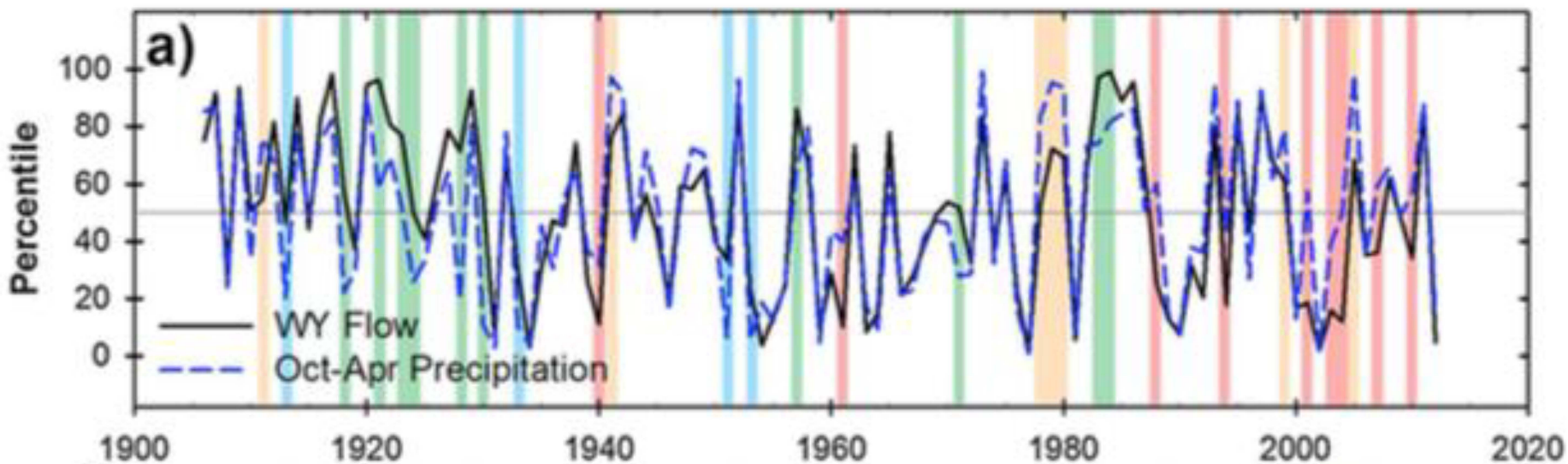
We assert that the large precipitation increases necessary to offset substantial temperature-induced flow decreases appear unlikely to occur for a number of reasons. These reasons include the potential for storm tracks to go north of the basin due to Hadley Cell expansion, the high potential for megadrought to increase evaporation while reducing precipitation and runoff for extended periods, the large size of the needed precipitation increases, especially when compared to decadal historical increases, the consistent identification by global assessments of the Southwest as an area likely to dry, and finally the lack of any trend over the last century or last 16 years (Figure 2c). Hence, we choose to focus on highly likely temperature-induced declines with separate analysis of the precipitation needed to offset these declines.

Increasing influence of air temperature on upper Colorado River streamflow

Connie A. Woodhouse[1,2], Gregory T. Pederson[3], Kiyomi Morino[2], Stephanie A. McAfee[4], and Gregory J. McCabe[5]

Key Points:

- When UCRB flow departs from precipitation, temperature is a major forcing
- Since 1988, flows have often been less than expected given winter precipitation
- Warm temperatures exacerbated modest precipitation deficits in the 2000s drought



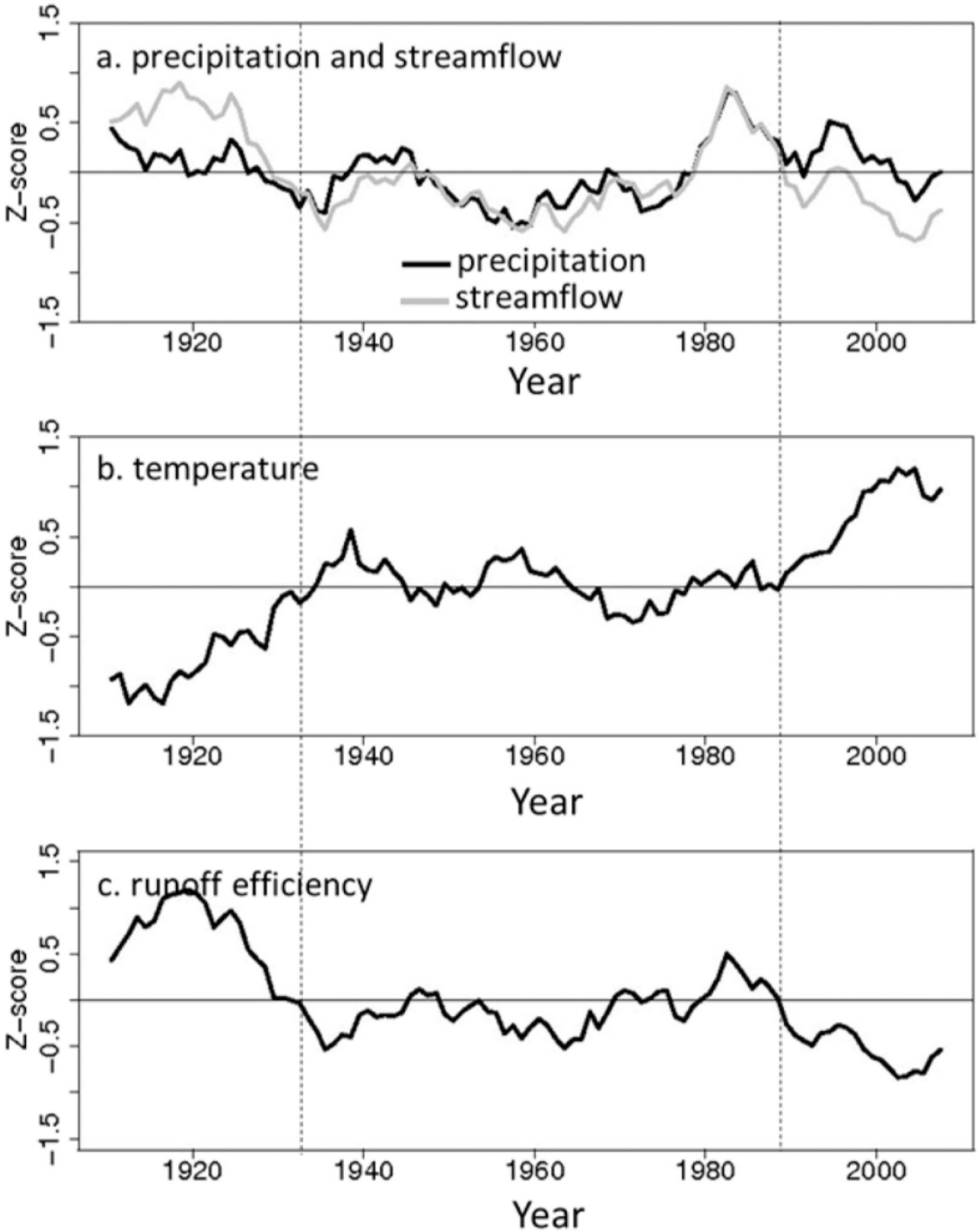
Declining Runoff Efficiency

Most of the year-to-year variability explained by precipitation

Since the late 1980s increases in temperature have caused a substantial reduction in runoff efficiency

Over the last 3 decades temperature has reduced the flow by 7%

McCabe et al, 2017

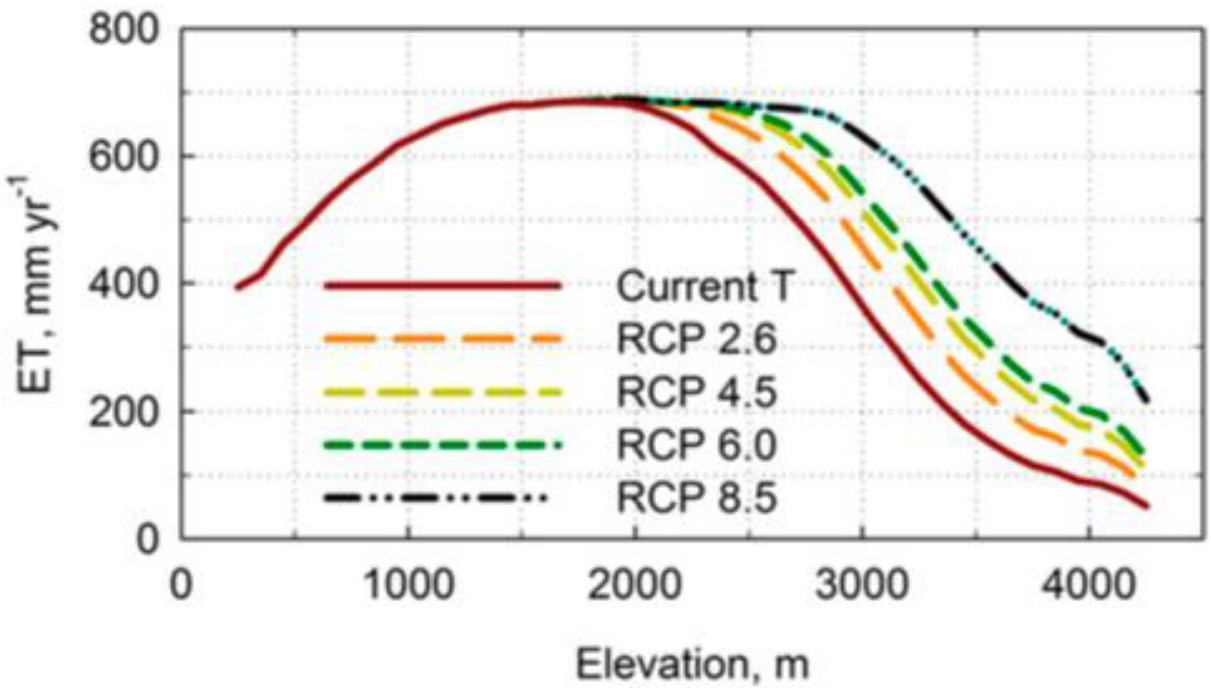


Mountain runoff vulnerability to increased evapotranspiration with vegetation expansion

Michael L. Goulden[a,1] and Roger C. Bales[b,c]

PNAS | September 30, 2014 | vol. 111 | no. 39 |

Kings River basin ET currently peaks at midelevation and declines at higher elevation, creating a cold-limited zone above 2,400 m that is disproportionately important for runoff generation. Climate projections for 2085–2100 indicate as much as 4.1 °C warming in California's Sierra Nevada, which would expand high rates of ET 700-m upslope if vegetation maintains its current correlation with temperature.



Comparison of CMIP3 and CMIP5 projected hydrologic conditions over the Upper Colorado River Basin

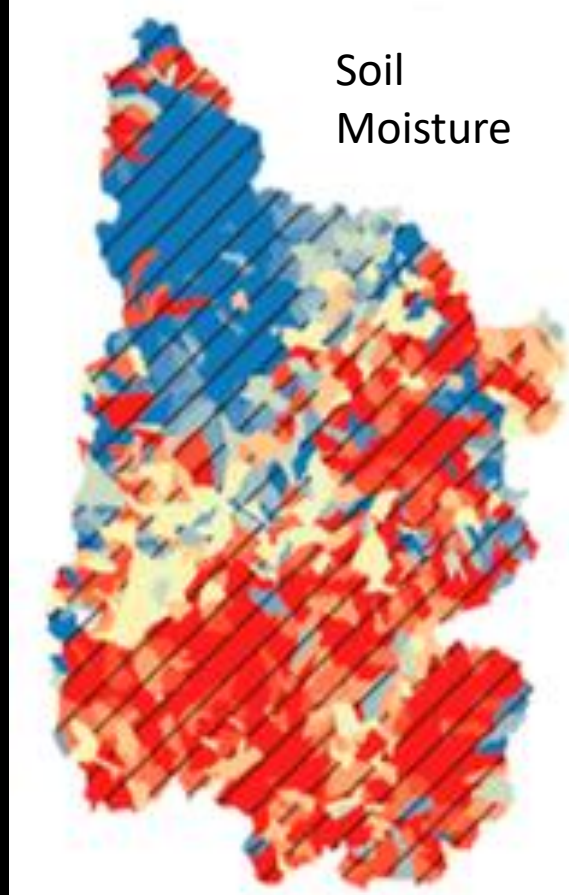
Jessica Ayers,[a] Darren L. Ficklin,[b,c*] Iris T. Stewart[d] and Meredith Strunk[a]

[a] *School of Public and Environmental Affairs, Indiana University, Bloomington, IN, USA*
[b] *Department of Geography, Indiana University, Bloomington, IN, USA*
[c] *Center for Geospatial Data Analysis, Indiana Geological Survey, Bloomington, IN, USA*
[d] *Department of Environmental Studies and Sciences, Santa Clara University, CA, USA*

INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **36**: 3807–3818 (2016)

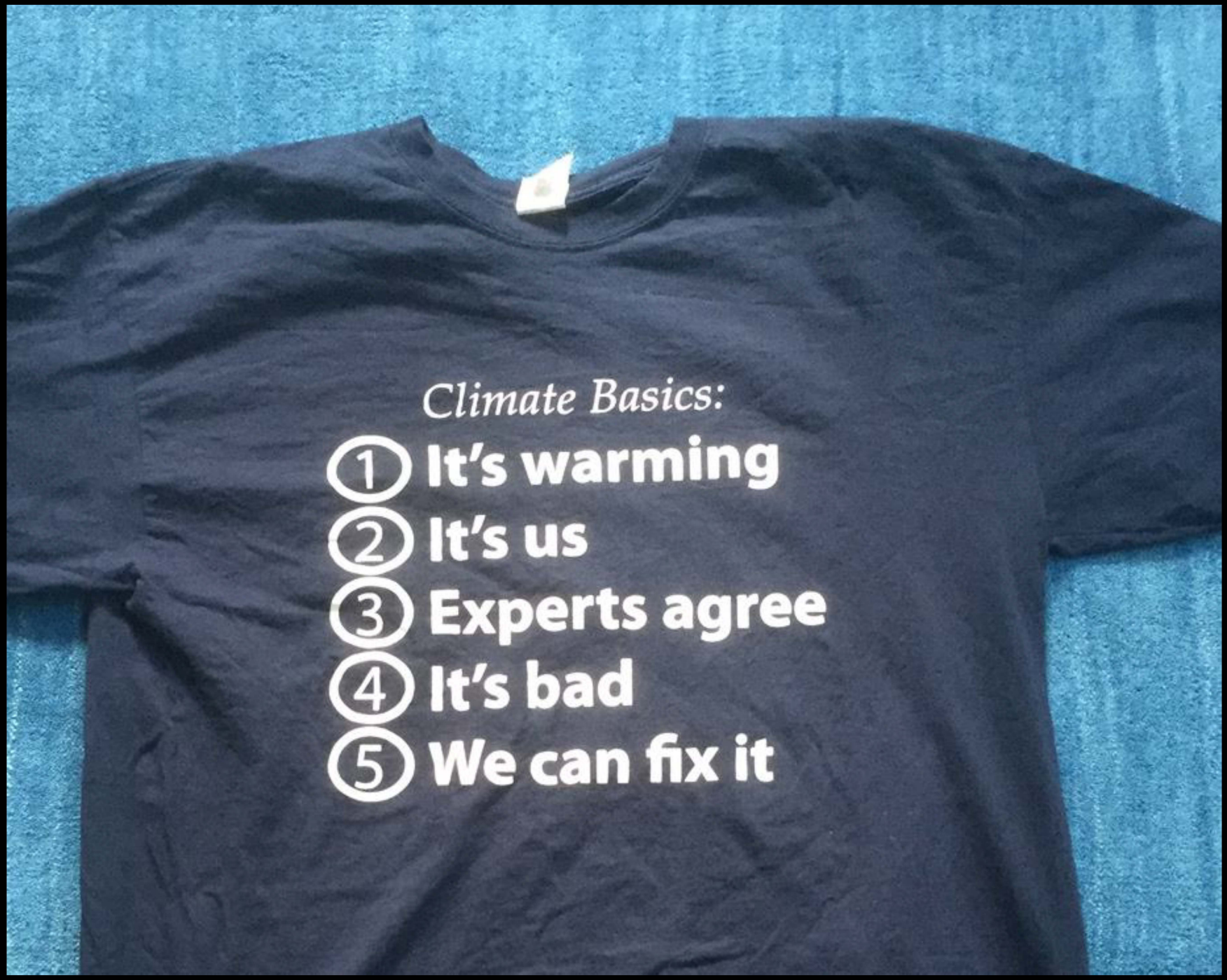
If you believe the climate models, north is wet, and south is dry

Wet: Wind Rivers + Unita
Dry: All of Colorado



Concluding Thoughts

- Temperature is impacting Colorado River Flows
- We’ve lost ~7% already
- We could lose 20% by 2050, 35% by 2100
- Increases in precipitation could reduce these temperature-induced losses
  - But many reasons to doubt this will occur
- We need to deal with greenhouse gasses
  - Must all go away
  - The sooner the better
  - This is everyone’s responsibility


Climate Basics:
1 It's warming
2 It's us
3 Experts agree
4 It's bad
5 We can fix it

End

Perspectives on the causes of exceptionally low 2015 snowpack in the western United States

Philip W. Mote[1], David E. Rupp[1], Sihan Li[1], Darrin J. Sharp[1], Friederike Otto[2], Peter F. Dennis P. Lettenmaier[4], Heidi Cullen[5], and Myles R. Allen[2,6]

AGU PUBLICATIONS

Geophysical Research Letters

Key Points:

- In the 2012-2015 west coast drought, unusually high temperatures played a prominent role in reducing snow accumulation and causing drought
- In much of the westernmost U.S., April snowpack was at its lowest ever in 2015
- Crowd-sourced climate modeling shows that greenhouse gases and SST patterns did more to cause drought in the Northwest than in California

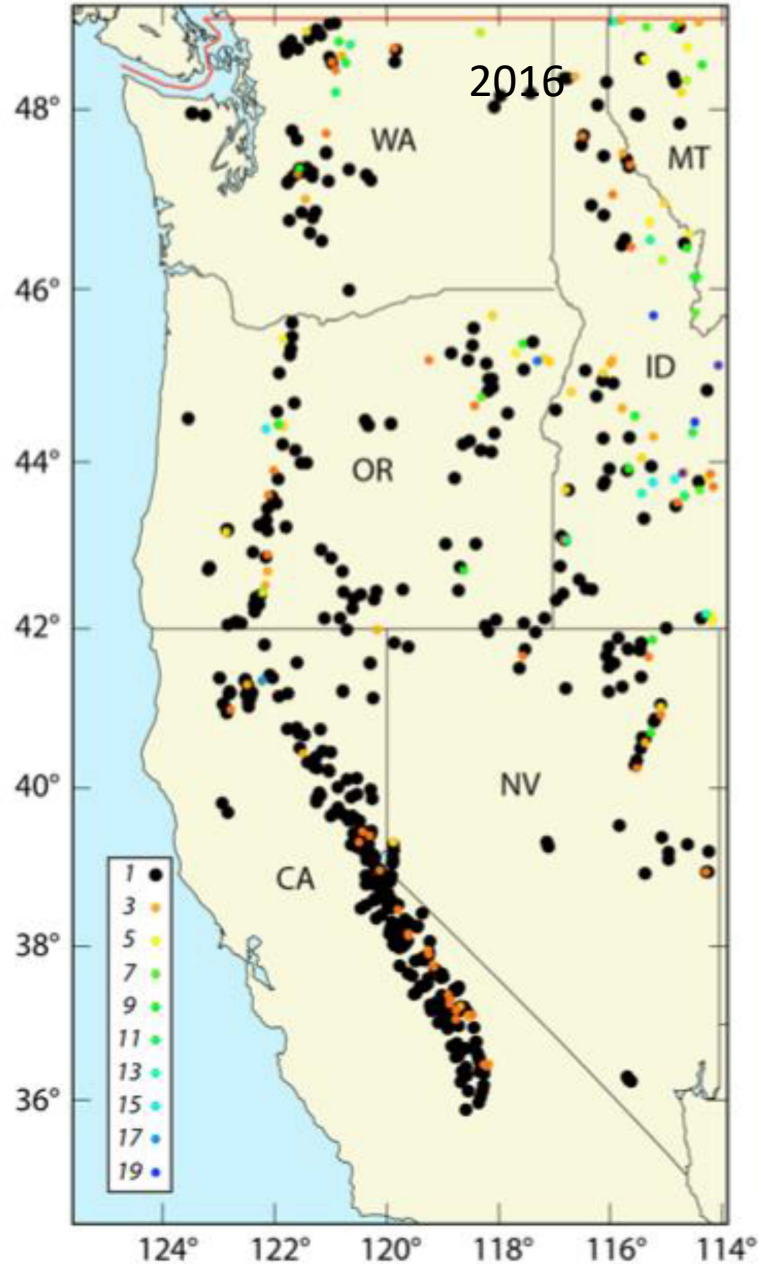


Figure 1. Locations of snow courses with data back to at least 1976 indicating the rank of 2015 against all available years, for 1 April SWE. Symbols and color indicate rank (including ties); filled circle indicates lowest ever.

Colorado snowpack is off to its worst start in more than 30 years; ski areas feel the pinch

AP Associated Press

November 18, 2016 / 1:31 pm / Business, Denver news

The Colorado snowpack is off to its worst start in more than 30 years, said Brian Domonkos, who supervises the U.S. Department of Agriculture snow survey in the state.

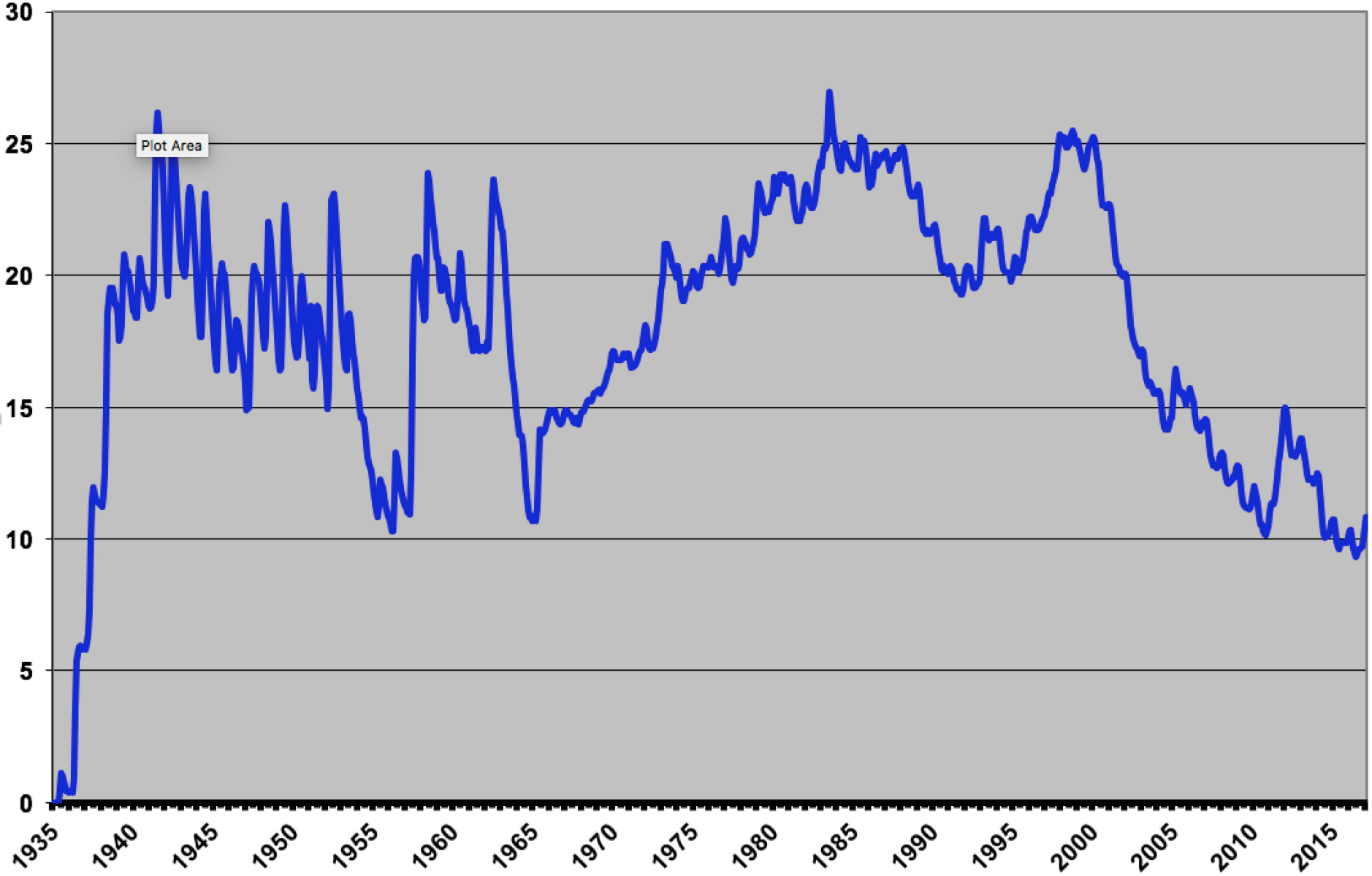
Snowpack boon for Powell

By Todd Glasenapp Sun Correspondent Feb 7, 2017 1

ARIZONA Daily Sun

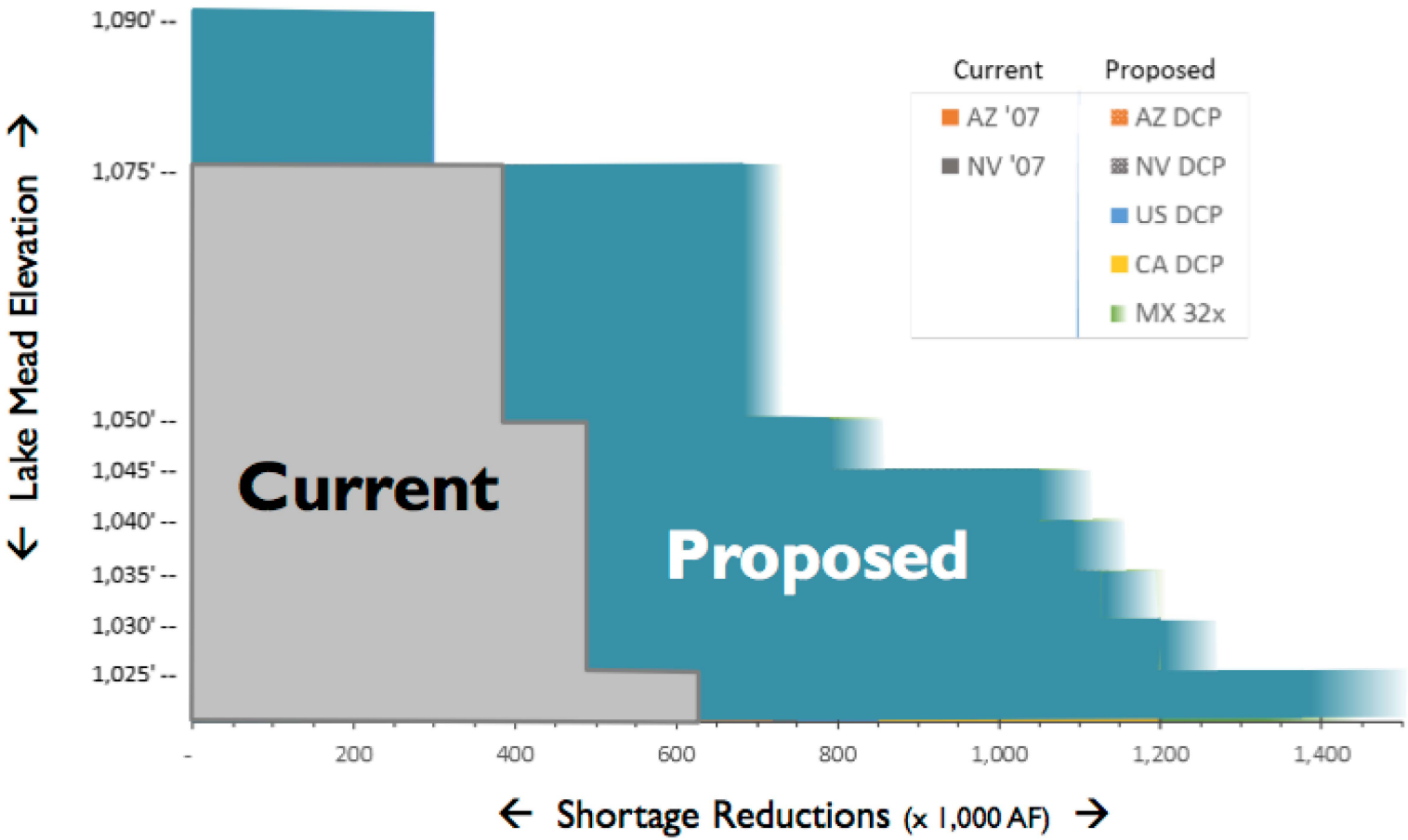
Heavy snowfall on Colorado's Western Slope and Utah's Wasatch Range in December and January boosted snowpack in the five-state Upper Colorado River Basin to 157 percent of average.

Lake Mead Volume in Millions of Acrefeet 1935-2017



Drought Contingency Proposal

Potential Shortage Sharing and Protection Actions, by Lake Mead Elevation and State/Country



Big snowstorms put Colorado River drought plan on ice

By Tony Davis Arizona Daily Star Mar 19, 2017 Updated Mar 20, 2017

"The improved hydrology has changed the landscape and given us a reprieve," said Suzanne Ticknor, CAP's water-policy director

Other water users disagree with this position, including the Arizona Department of Water Resources (DWR), the Tucson and Phoenix water utilities and the Gila River Indian Community, which controls the largest share of CAP water.

Lake Mead to get above-average flow of Colorado River water

By Dan Elliott The Associated Press
April 18, 2017 - 8:51 am

LAS VEGAS REVIEW-JOURNAL

The federal government plans to release an above-average amount of Colorado River water into Lake Mead this year, but it's less than many hoped after a healthy snow season across much of the West.

The Bureau of Reclamation, which manages dams and reservoirs on the Colorado River, said Monday that it will release 9 million acre-feet (enough water to cover an acre of land one foot deep) from Lake Powell, sending it down the Colorado to Lake Mead, where it will be tapped by Arizona, California and Nevada.

Last month, the agency projected it could release 11.1 million acre-feet from Lake Powell, but a dry early March reduced the amount of snow in the mountains that feed the river.

CLIMATE CHANGE

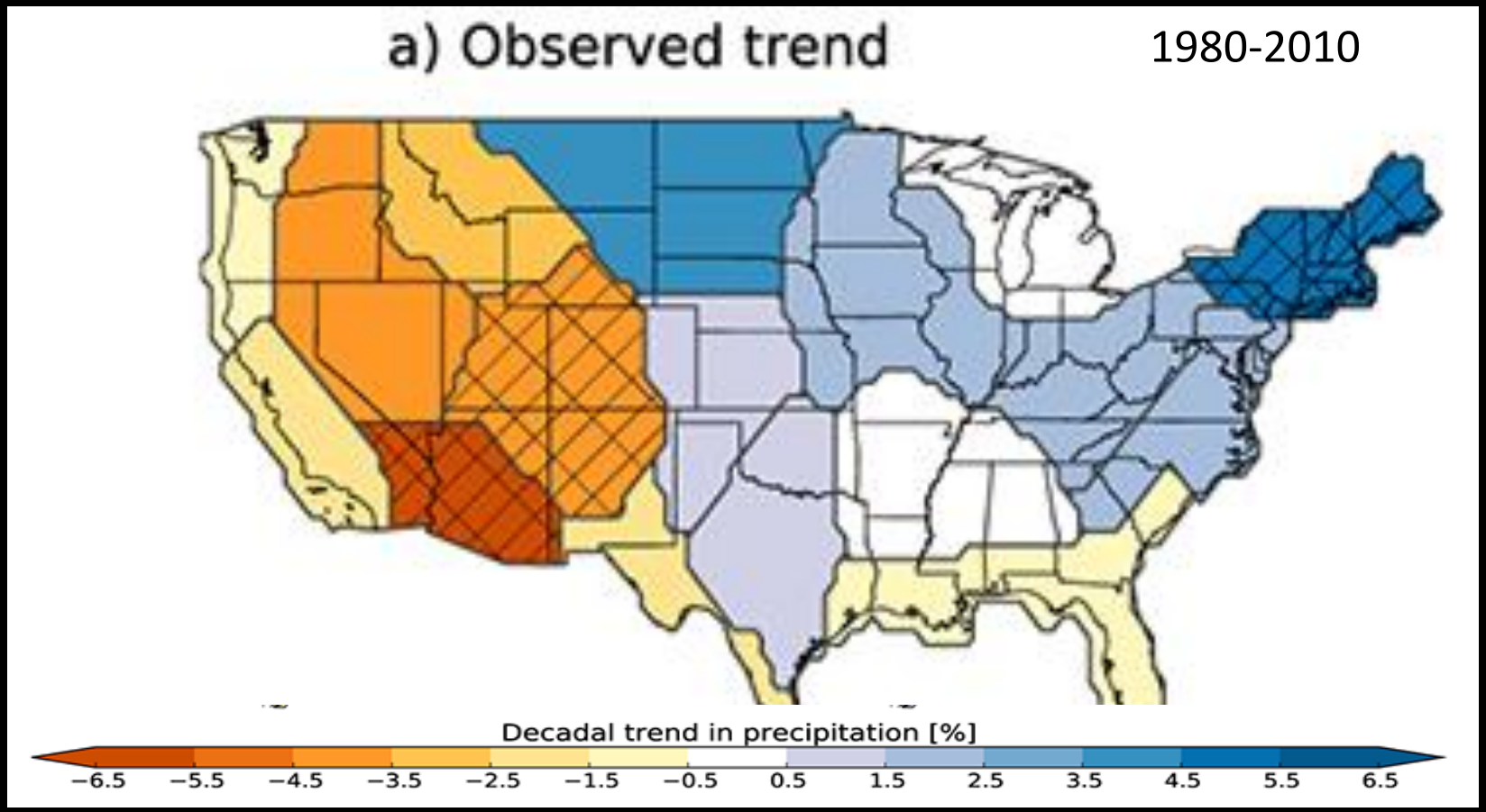
Dry Times Ahead

Jonathan Overpeck[1] and Bradley Udall[2]

The climate of the western United States could become much drier over the course of this century.

- 2F Warming since 1900
- Snowpack Reductions and Changes in Runoff Timing Already Present
- Most Severe Drought since records kept
- Powell and Mead at 50% of capacity now, full 2000
- Tree Mortality Rates High
- Increase in Wildfire Frequency
- Drought may be natural, but exacerbated by higher temperatures
- Snowpack Reductions and Runoff Timing attributed to climate change
- Continued drying likely as temperatures increase and storm tracks shift
- Megadroughts independent of climate change a possibility with severe consequences if combined with warming

Running dry: The U.S. Southwest's drift into a drier climate state



Weather Patterns that provide winter precipitation are becoming less frequent due to Hadley Cell Expansion. Southwest Precipitation has declined by 25%.

Prein et al, 2016

Anthropogenic warming has increased drought risk in California

Noah S. Diffenbaugh[a,b,1], Daniel L. Swain[a], and Danielle Touma[a]

[a]Department of Environmental Earth System Science and [b]Woods Institute for the Environment, Stanford University, Stanford, CA 94305

Edited by Jane Lubchenco, Oregon State University, Corvallis, OR, and approved January 30, 2015 (received for review November 22, 2014)

- No change in precipitation over last few decades
- But the occurrence of drought has increased in last two decades over previous century
- The probability that precipitation deficits occur with warm temperatures has increased