The Colorado River Millennium Drought: the relative impacts of higher temperatures vs. other causes

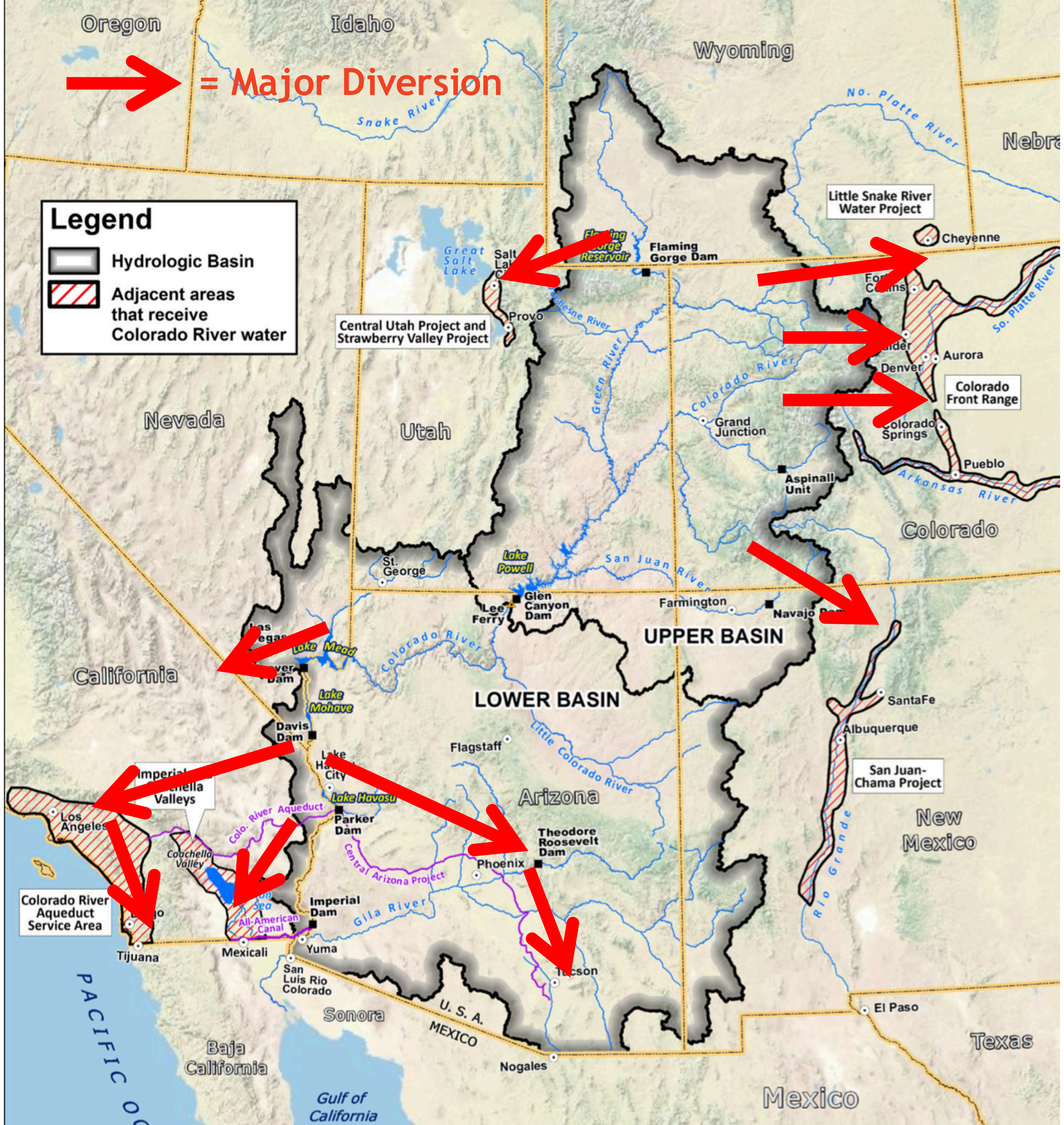
When the Rain Stops: Drought on Subseasonal and Longer Timescales
Aspen, CO
September 13, 2018

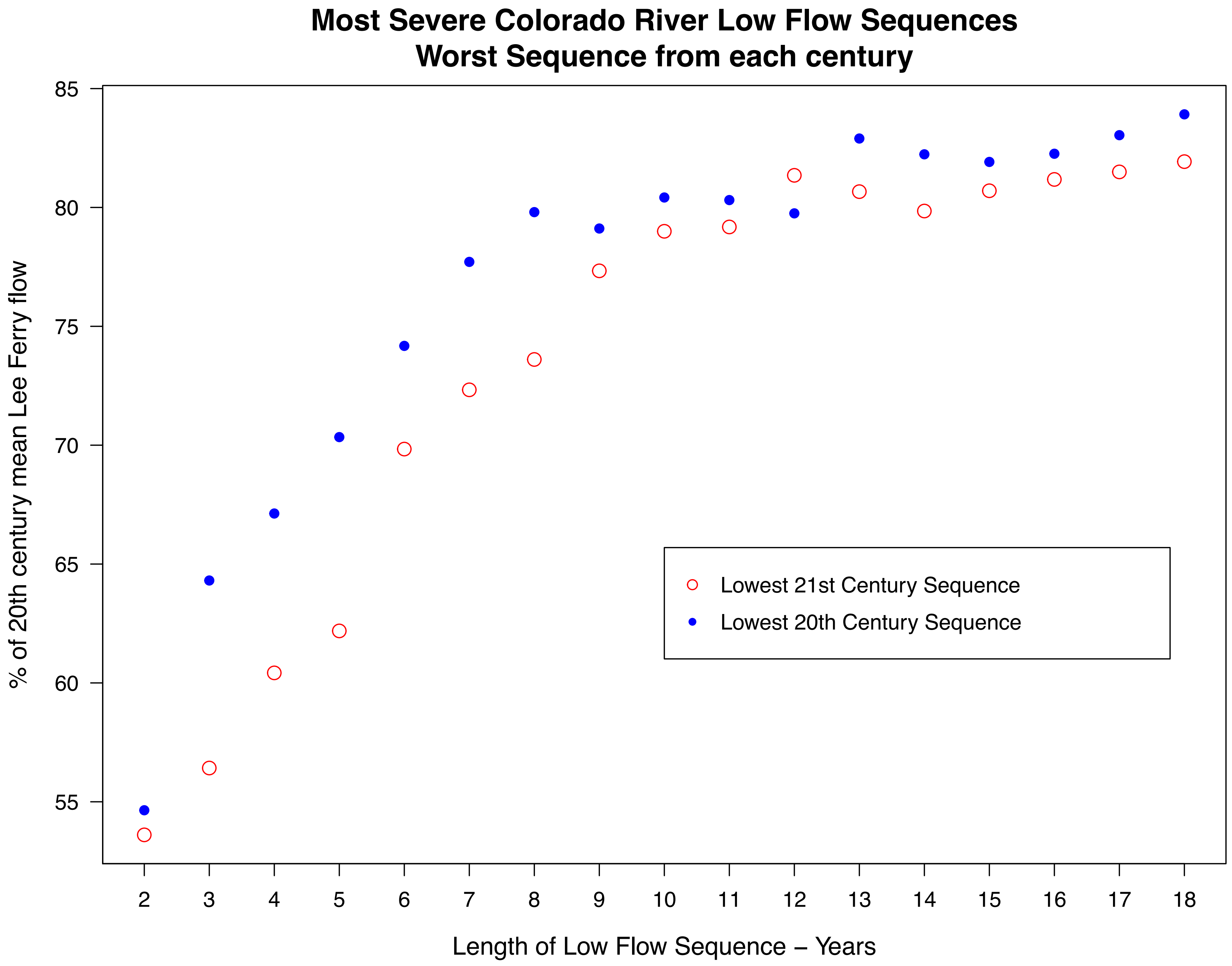
Brad Udall
Senior Scientist/Scholar
Colorado State University
Bradley.Udall@colostate.edu

Lake Creek, Colorado
September 8, 2018

Colorado River

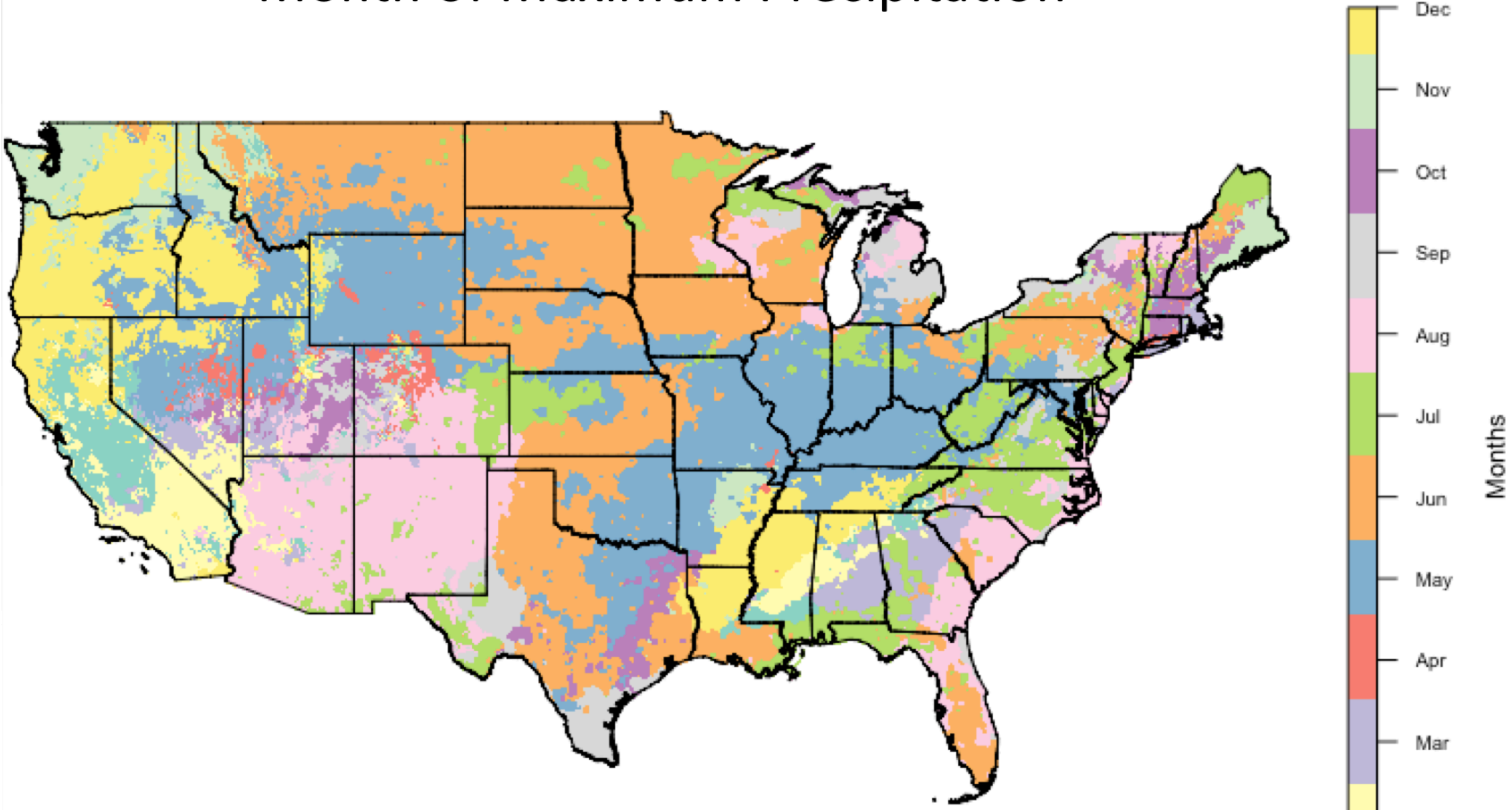
- 7 States, 2 Nations
- 8% of area of the Lower 48
- Annual Flow 16.4 MAF
  = Hudson River
- 40 M People
- All of the Major Cities in Southwest
- 4.5m Irrigated Acres
- Fully Allocated in 1922
- Withdrawals equaled Supplies ~2000
- Large New Projects still contemplated
- No longer reaches the ocean





Most Severe Colorado River Low Flow Sequences
Worst Sequence from each century
% of 20th century mean Lee Ferry flow
85
80
75
70
65
60
55
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Length of Low Flow Sequence – Years
Lowest 21st Century Sequence
Lowest 20th Century Sequence

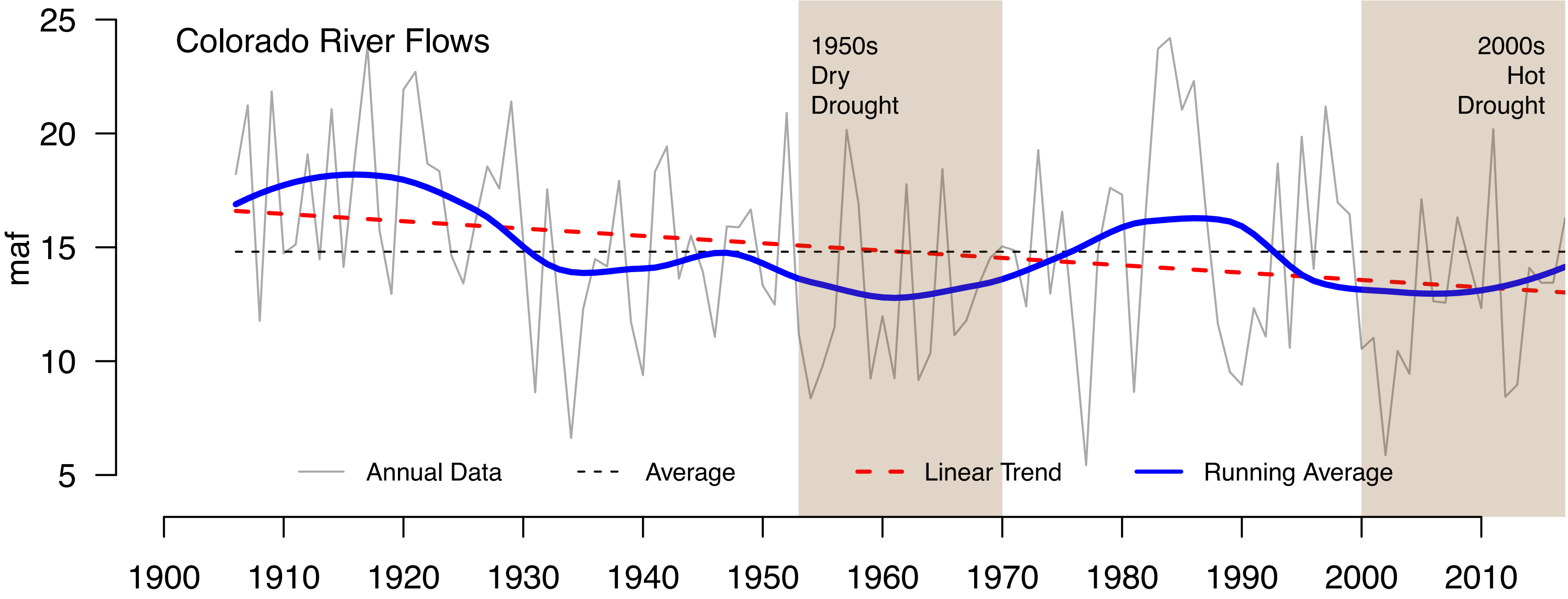
Month of Maximum Precipitation



Udall, 2017 - PRISM 30-Year Normals

Millennium Drought 2000—2018

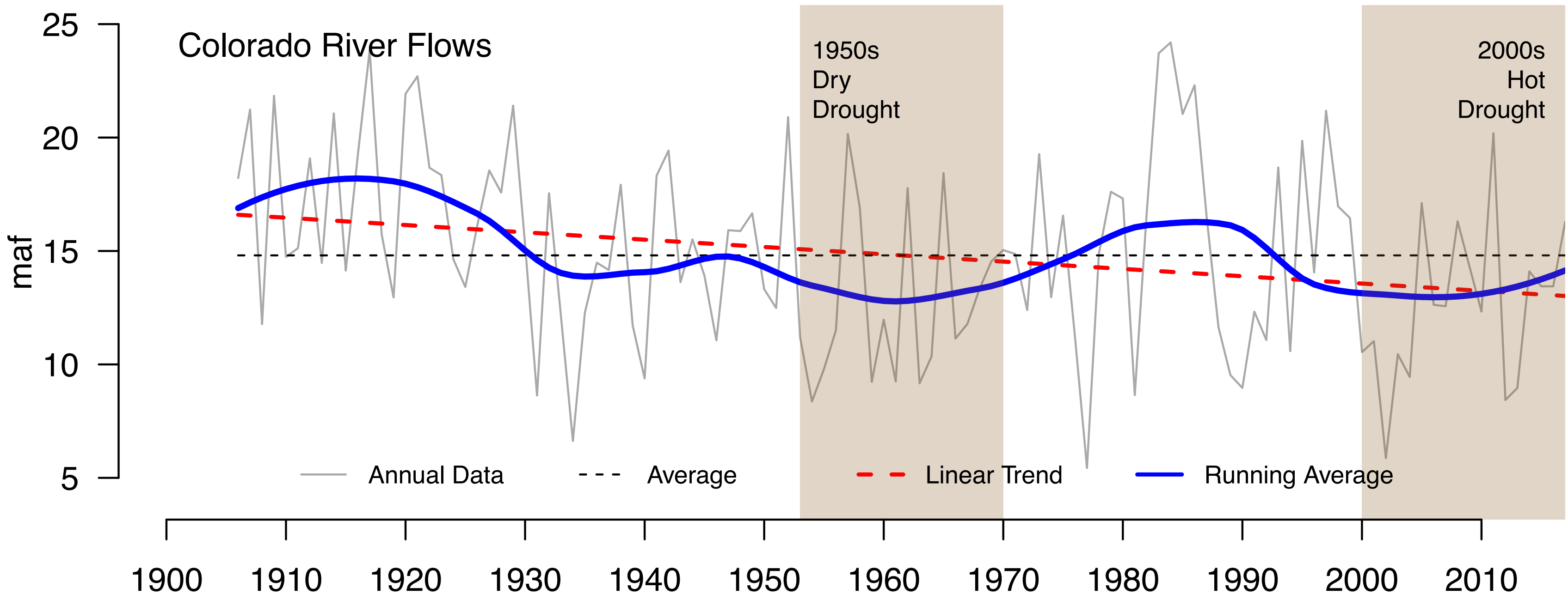
- 2000-2017 is the worst drought in the gaged record
- ~ 20%/yr decline
- Long-term trend, too



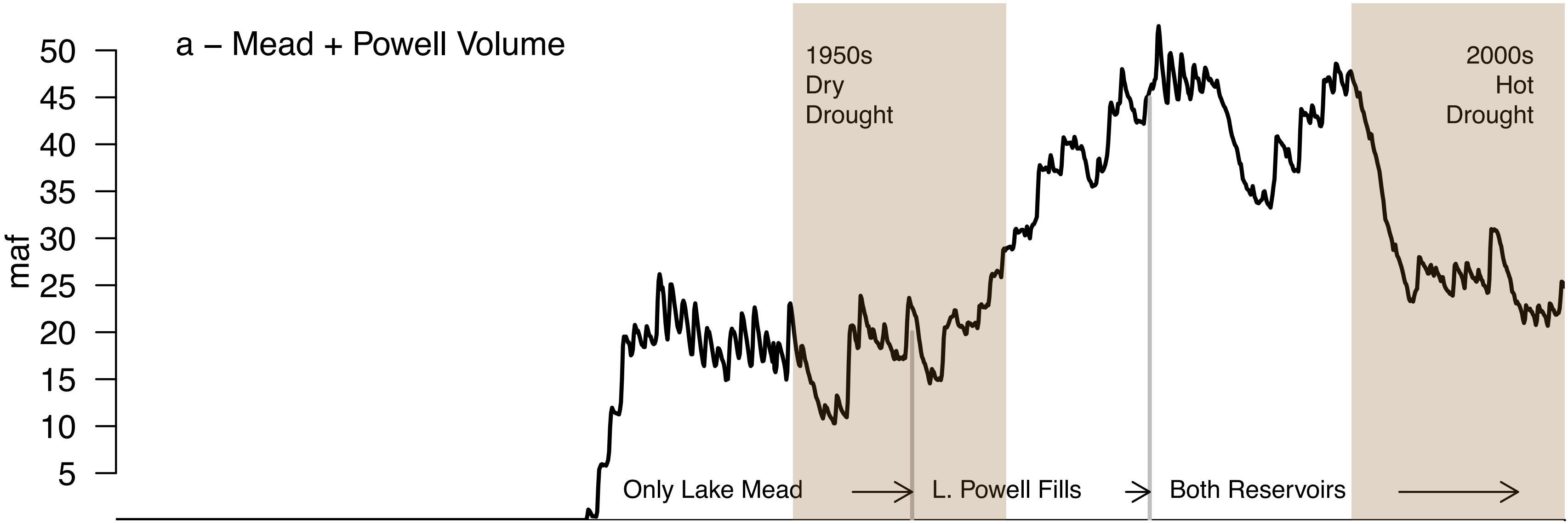
Udall and Overpeck, WRR, 2017

Millennium Drought 2000—2018

- 2000-2017 is the worst drought in the gaged record
- ~ 20%/yr decline
- Long-term trend, too



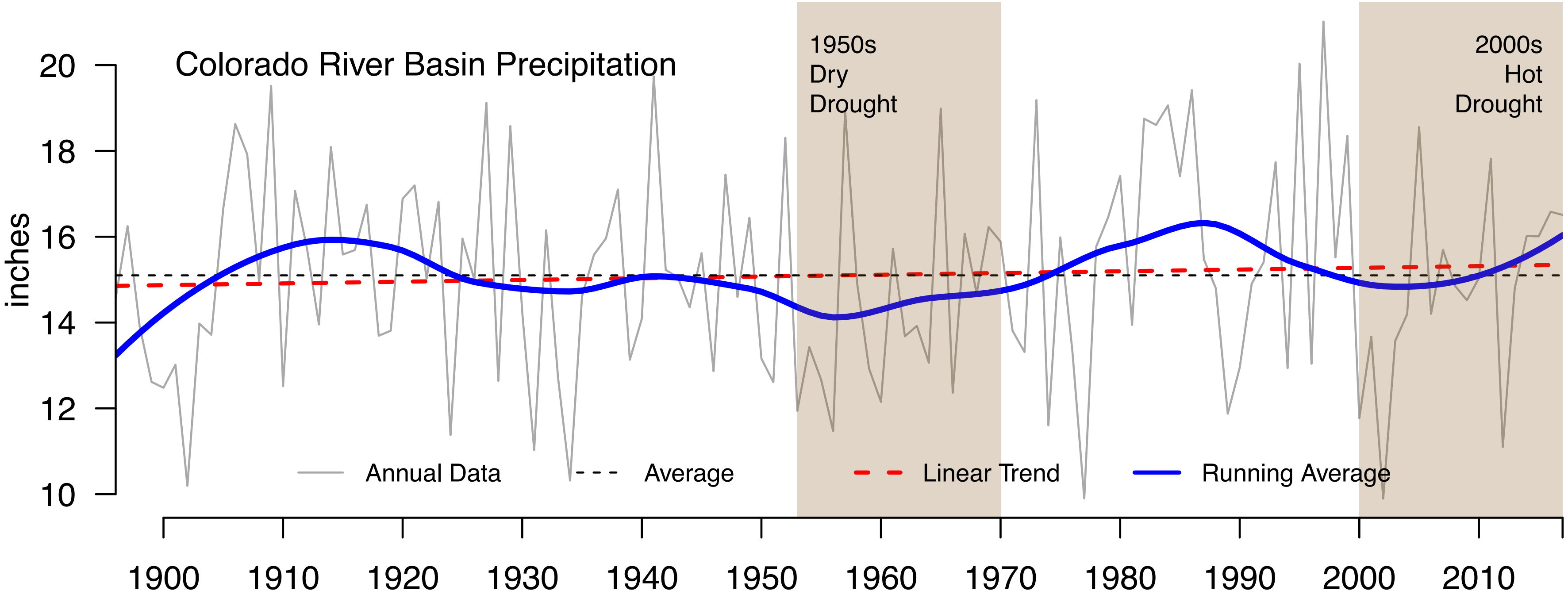
- Lakes Powell and Mead have lost 50% of their volume



Udall and Overpeck, WRR, 2017

Millennium Drought 2000—2018

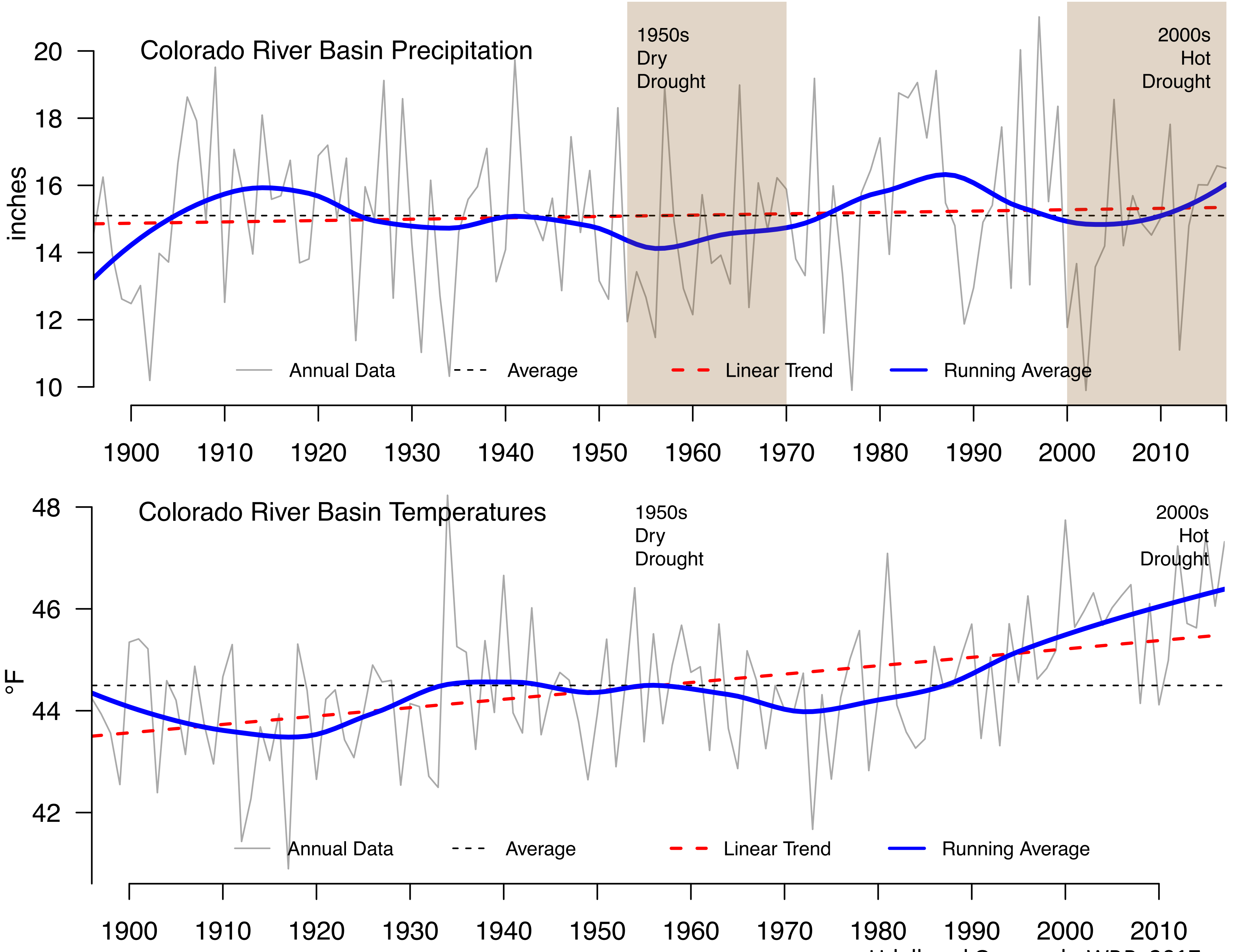
- Precipitation declines only partially explain
- ~ 66% of the loss



Udall and Overpeck, WRR, 2017

Millennium Drought 2000—2018

- Precipitation declines only partially explain
  - ~ 66% of the loss
- Temperature increases explain the remainder
  - ~ 33% of the loss
- Why?
  - More Evaporation
- Temperature-Induced Losses
  - Now = ~6%
  - 2050 = ~20%
  - 2100 = ~35%



Udall and Overpeck, WRR, 2017

On the causes of declining Colorado River streamflows

Mu Xiao, Bradley Udall, Dennis P. Lettenmaier

First published: 30 August 2018 | https://doi.org/10.1029/2018WR023153

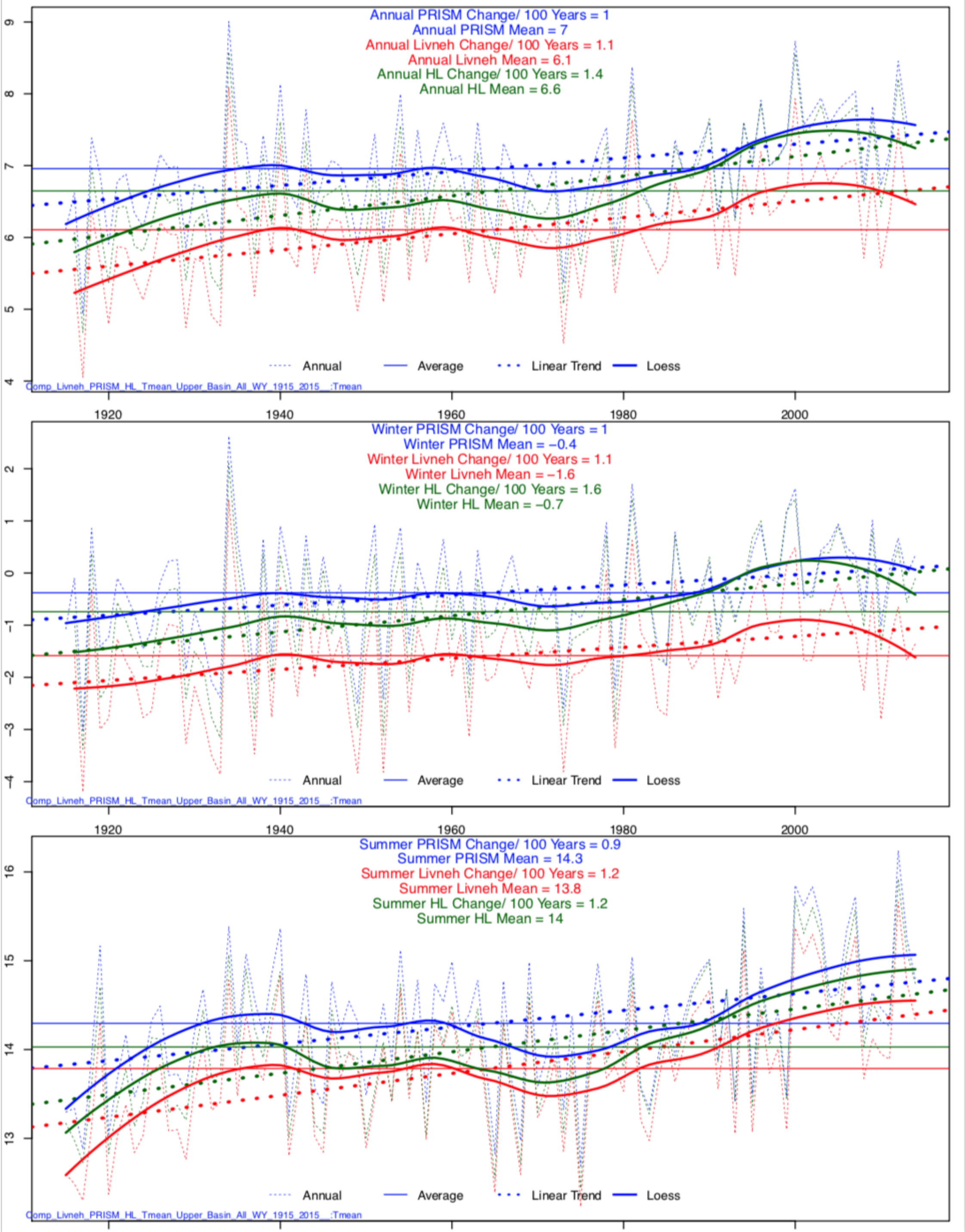
Water Resources Research
AN AGU JOURNAL

Research Article

Model-based Study using Historical Data

- Long-term Trend Analysis
- 1950s vs 2000s Drought Analysis
- 2017 Forecast Analysis

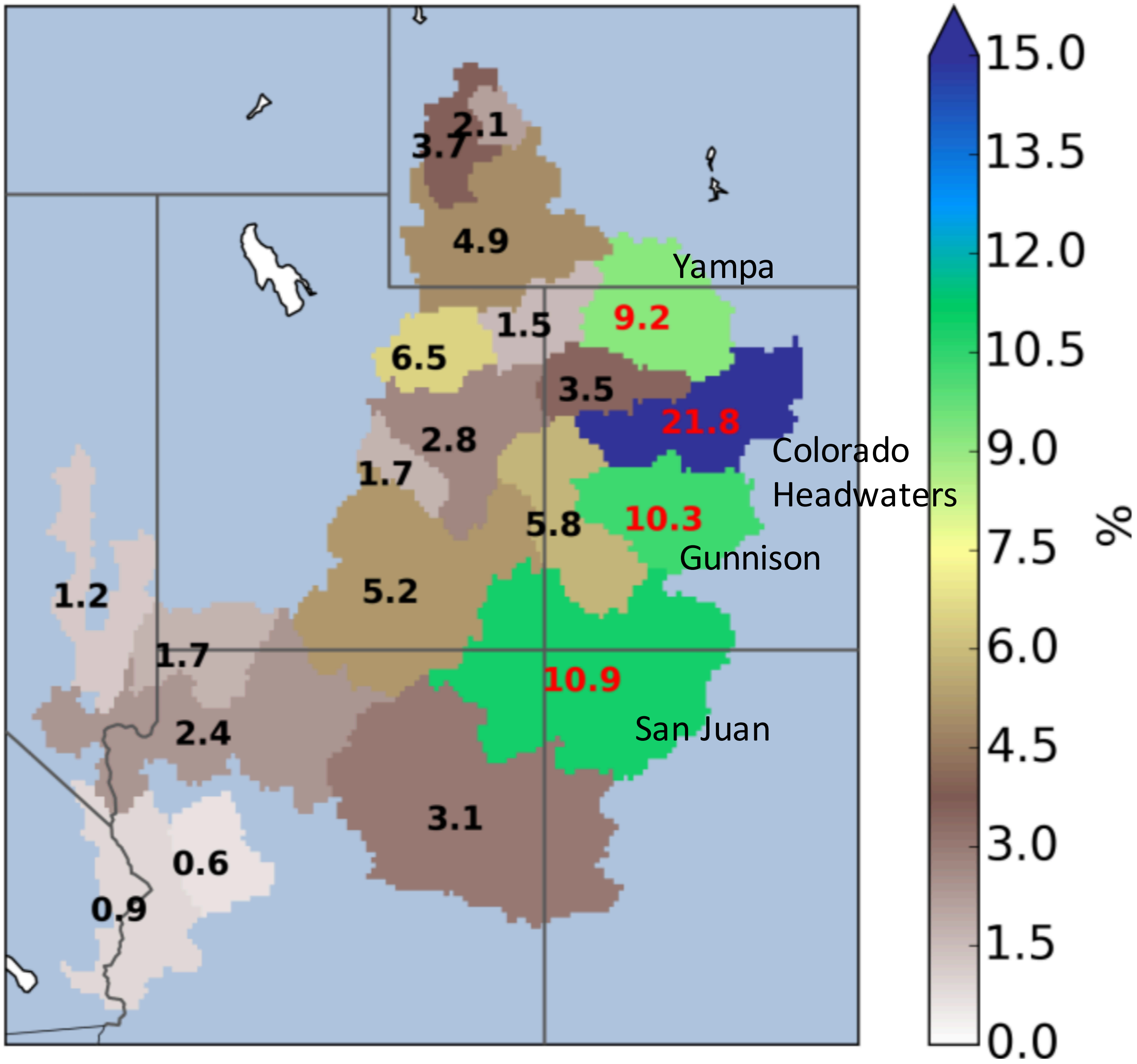
- VIC Model Experiments
  - Daily Model at 1/16 Degree
  - Different Dataset from U&O, 2017
  - Temperature Detrend Run
    - Fixed Precipitation Run



VIC Percent of Annual Runoff at Imperial Dam

4 Key Basins (Green + Blue) produce ~55% of all runoff

All located primarily in Colorado



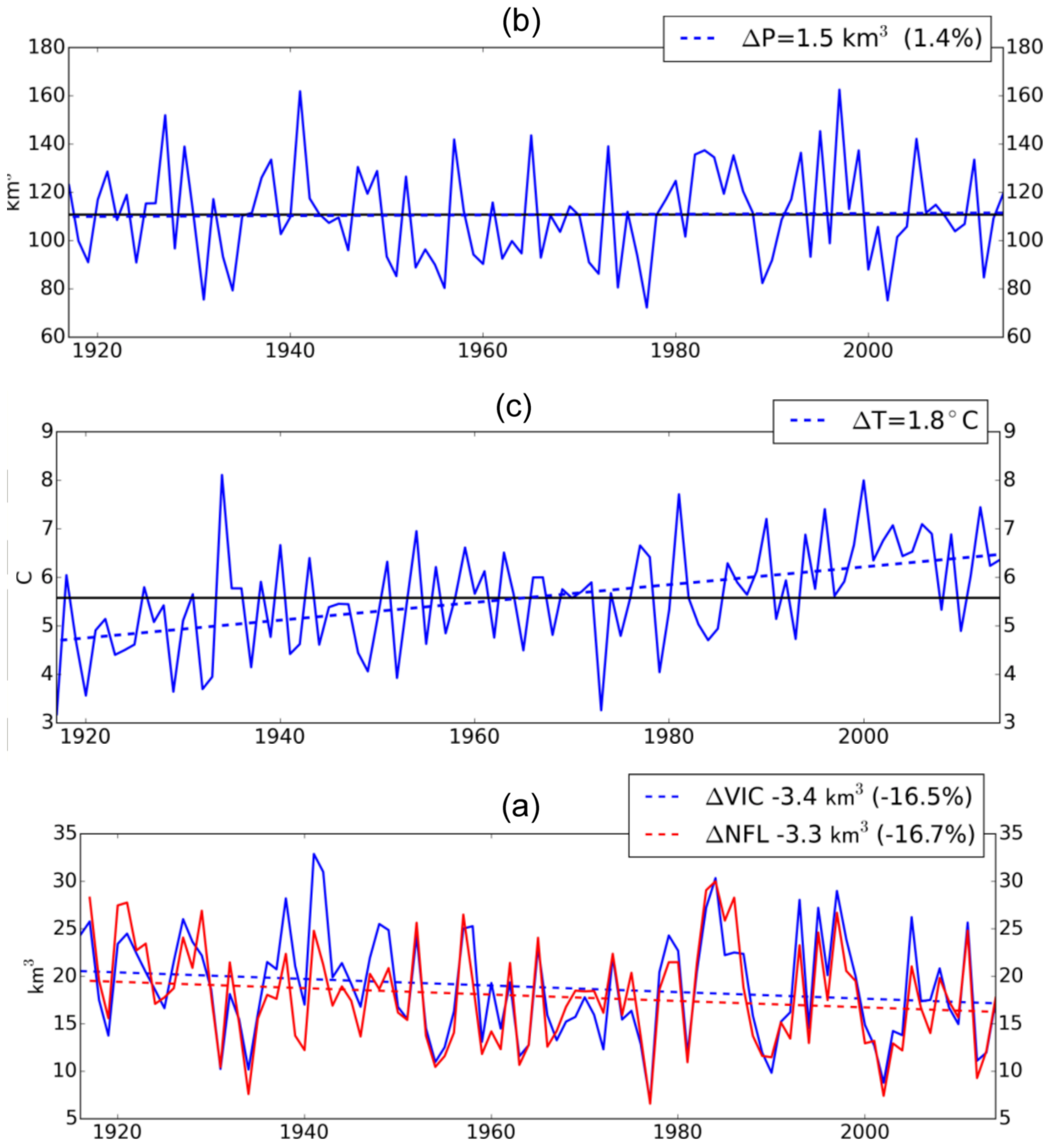
VIC Forcing Data / Calibration

UCRB Precipitation
1.4% Increase

Temperature
1.4 ^{o}C input data
1.8 ^{o}C output data

”Full Energy Balance” Mode

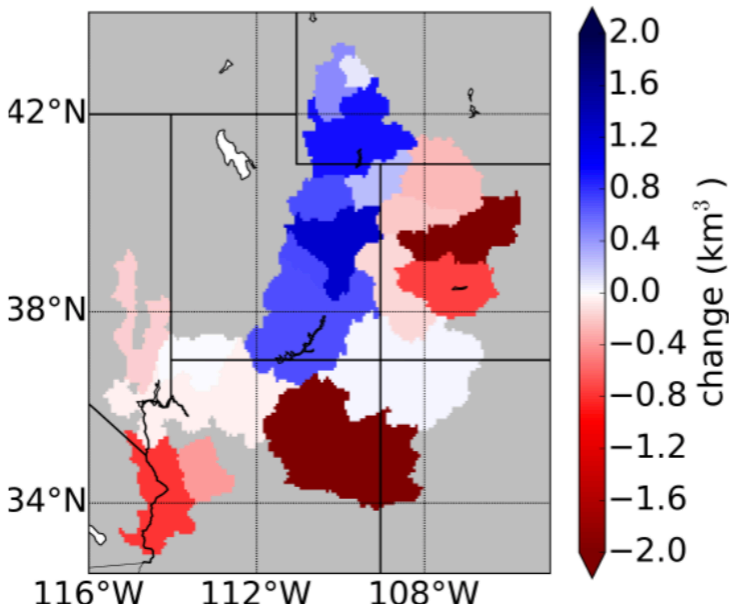
Natural Flows vs VIC
$R^2 = 0.75$



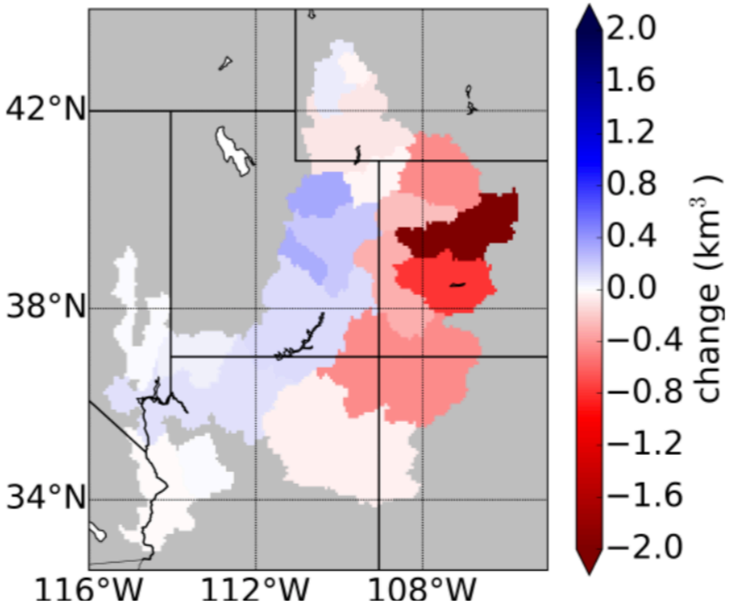
Long Term Trend Findings

- -16.5% decline over 99 years
- 53% of the decline due to warming temperatures
- Remainder due to changing precipitation patterns
- Winter ET Increases reduce SWE leading to reductions in Apr-Sept streamflow

Precipitation Trend



Runoff Trend



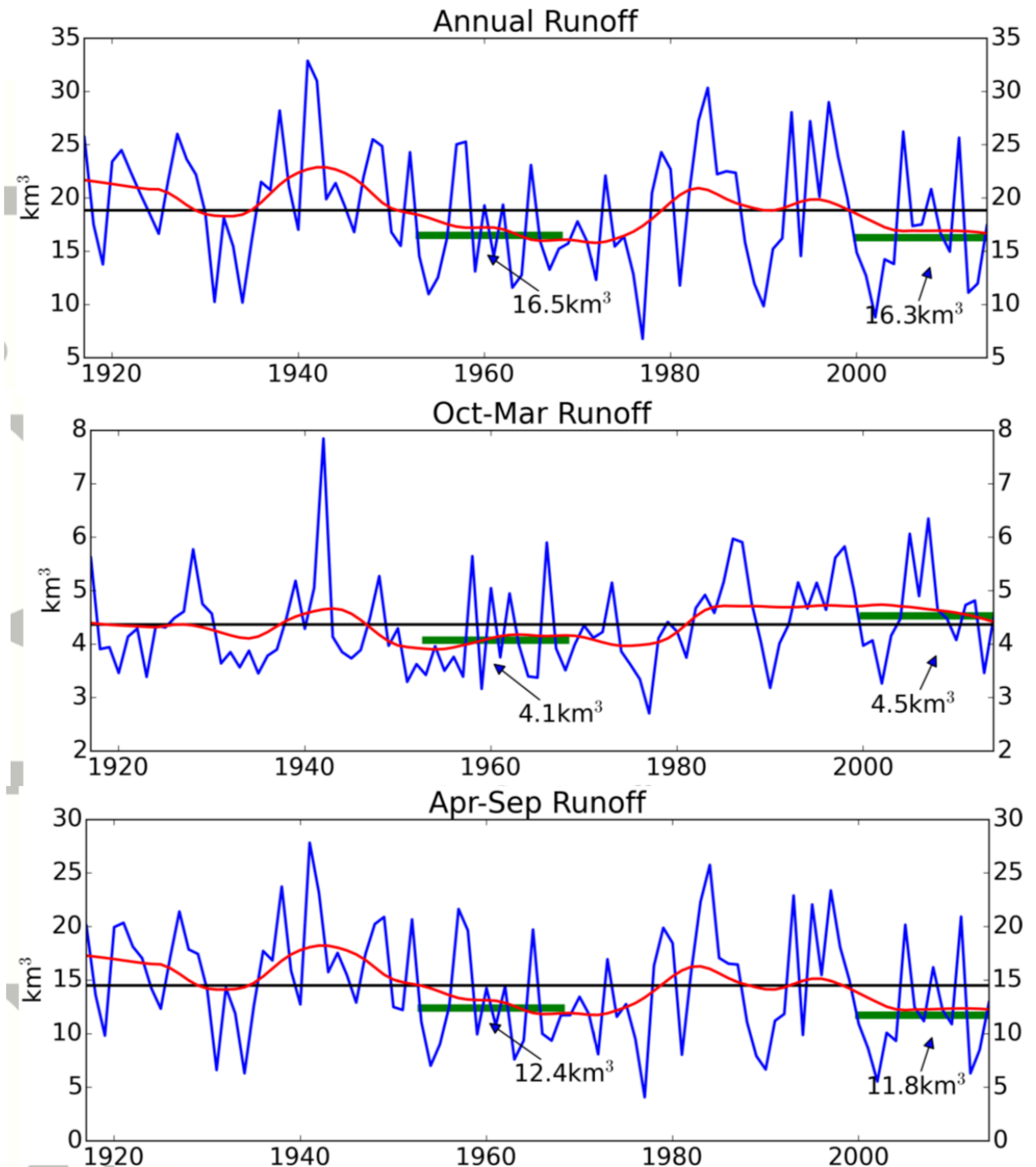
Two Droughts – 1950s vs 2000s

Longterm Average Runoff = 18.9 km^3

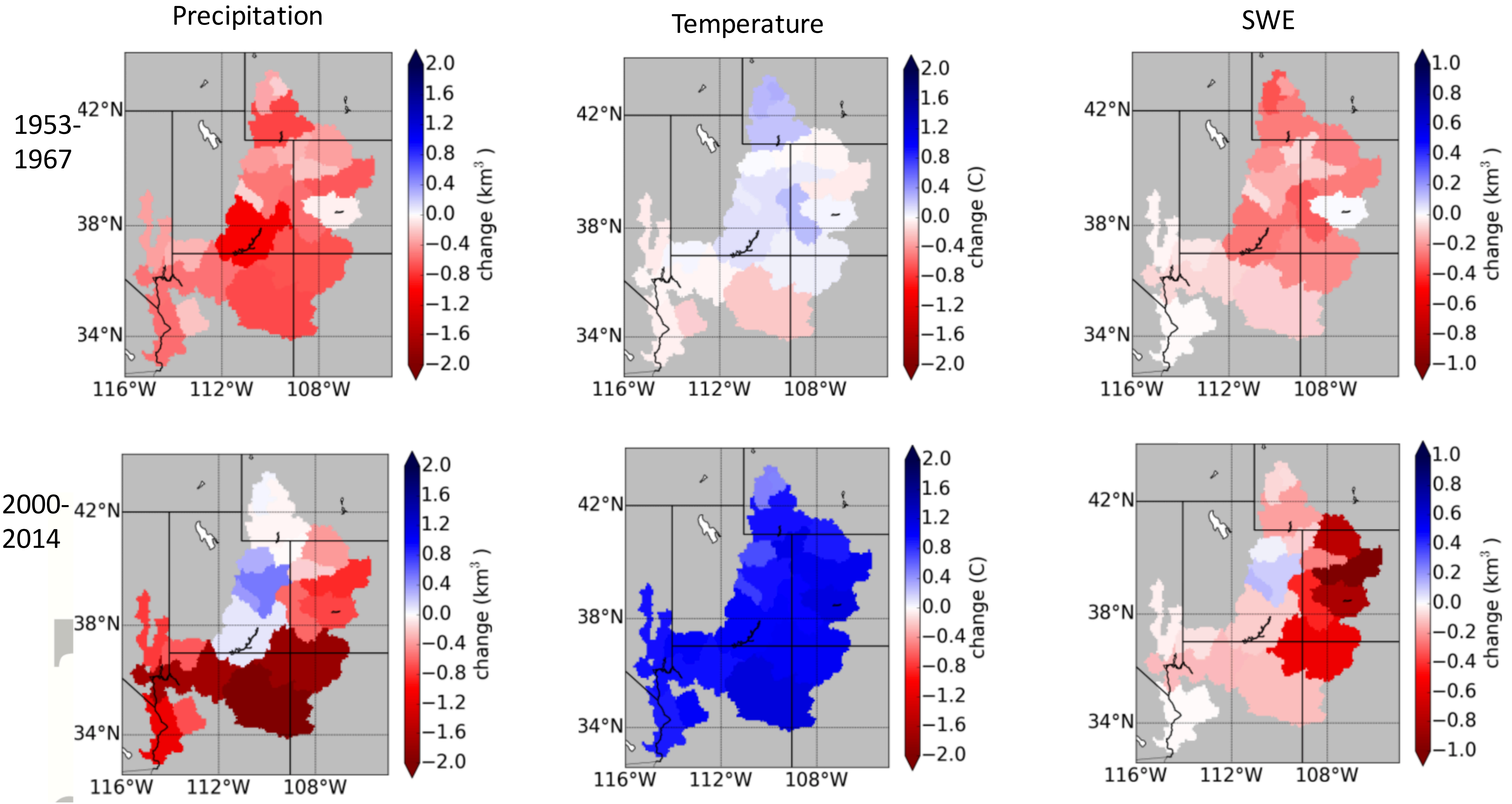
2000s slightly worse annually
16.5 km^3 vs 16.3km^3

2000s Slight Increase in Winter
4.1 km^3 vs 4.5 km^3

2000s Decrease in Summer
12.4 km^3 vs 11.8 km^3



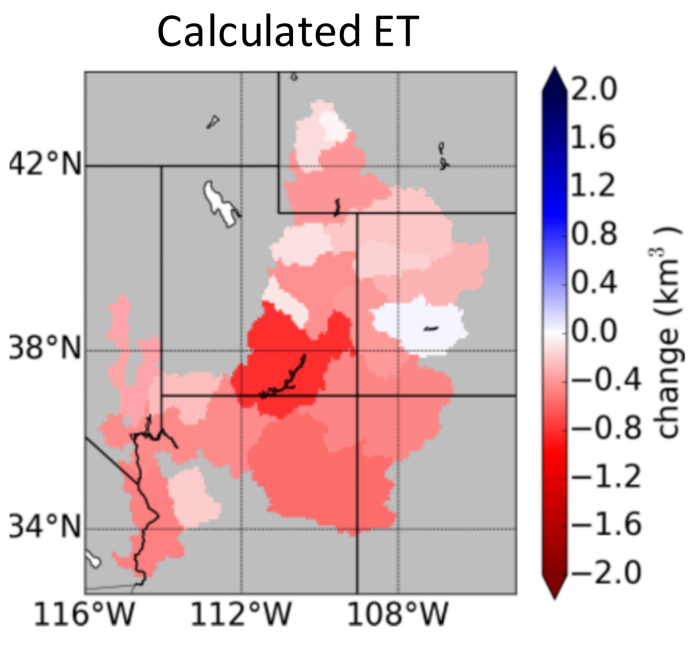
Two Droughts: P, T & SWE
Anomalies relative to mean

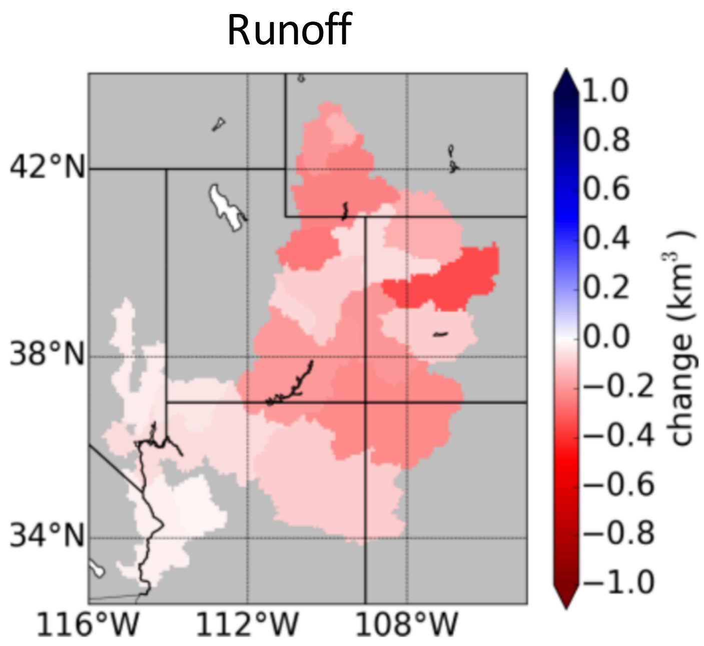


Two Droughts: ET and Runoff
Anomalies relative to mean

1953-1967

ET declines almost everywhere evenly

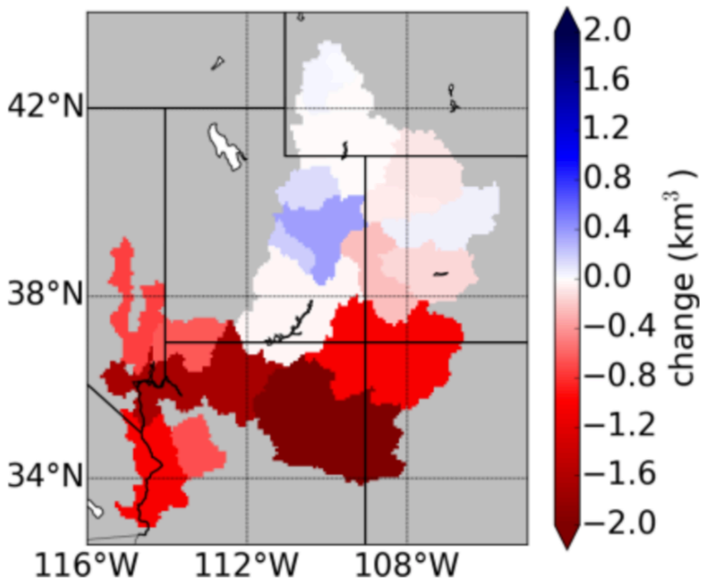


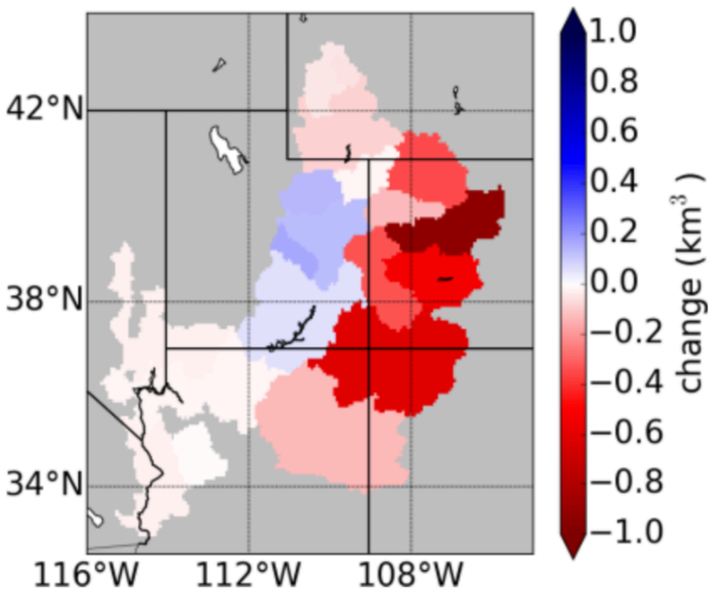


Runoff
Declines uniformly everywhere

2000-2014

ET spatially heterogenous



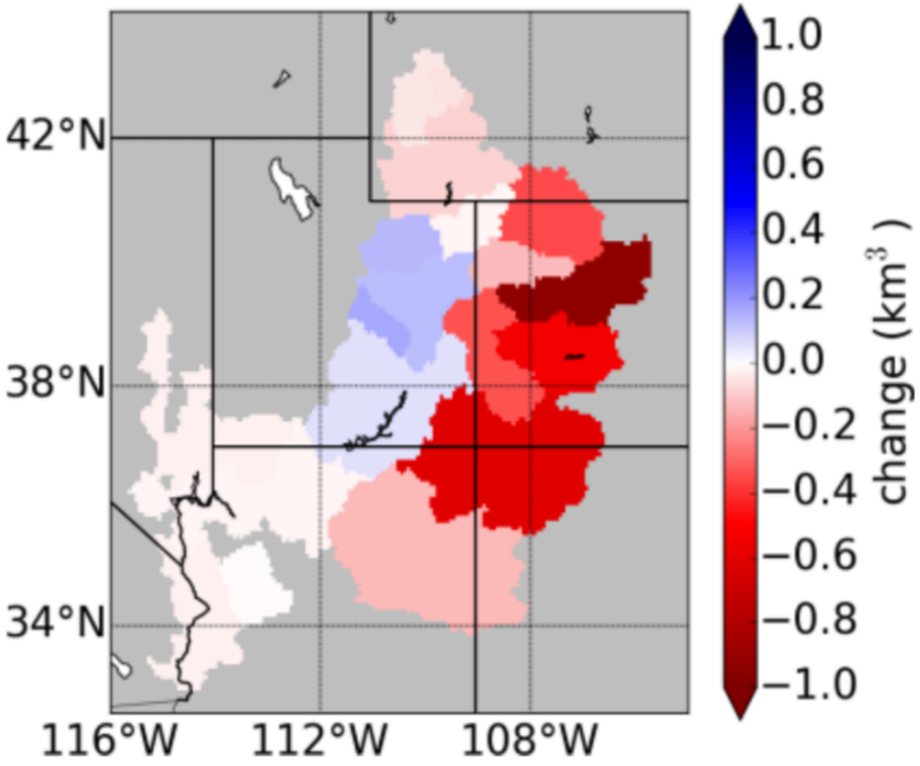


Runoff
- Increases in Utah
- Decreases in Colorado

Two Droughts Findings

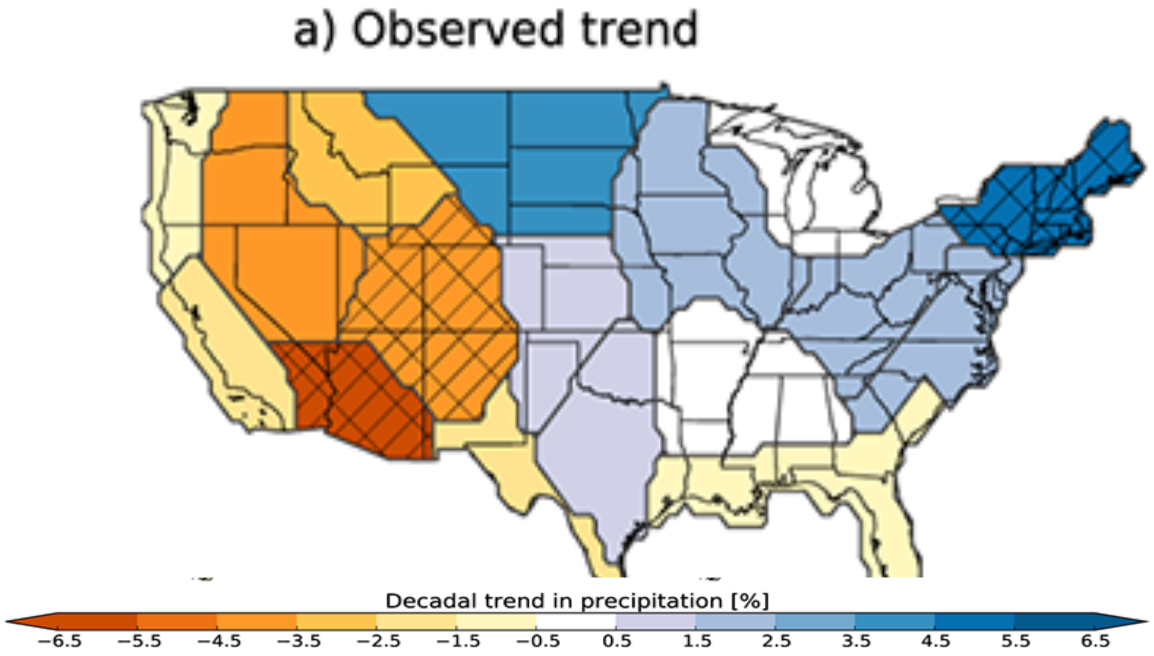
- Similar to Long Term Findings
- 2000s have half of the UCRB precipitation reduction of the 1950s
  - -6.1 km^3 vs -3.2 km^3
- 2000s have higher Winter ET
  - 0.4 km^3 vs 1.8 km^3
- 2000s have higher Winter Flows
- ~50% due to higher UCRB temps
  - 0.1 ^{o}C vs 1.0 ^{o}C
  - T-detrend run provides comparison
- ~50% due to changing precipitation locations

2000-2014 Runoff Anomalies



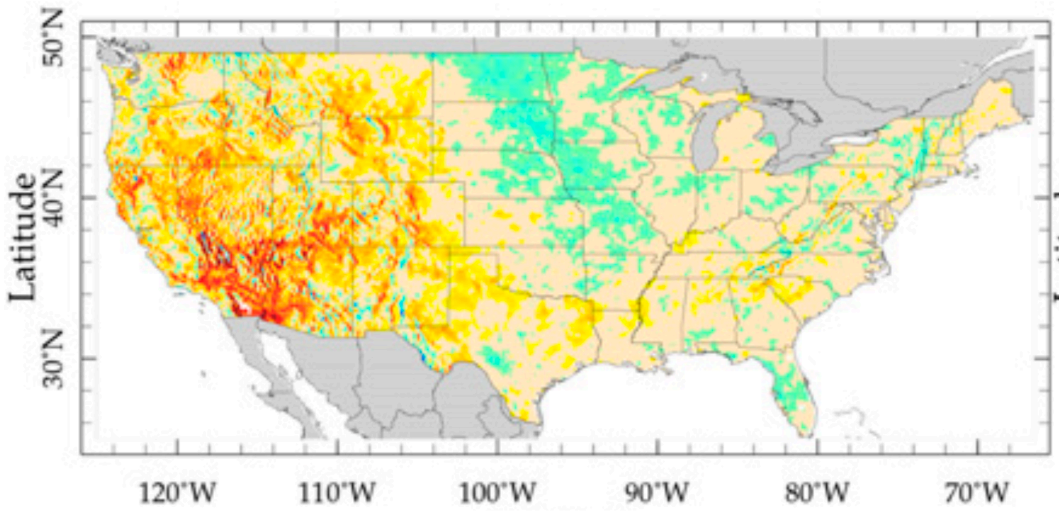
Other Studies

- Hydrologic Sensitivities of Colorado River Runoff to changes in Precipitation and Temperature
    - Vano et al., 2014
- Increasing Influence of air temperature on Colorado River Streamflow
    - Woodhouse et al., 2016
- Mountain Runoff Vulnerability to increased evapotranspiration with vegetation expansion
    - Goulden and Bales, 2014
- Running Dry: The US Southwest's Shift to a drier climate
    - Prein et al., 2016
- Climatology, Variability, and Trends in the U.S. Vapor Pressure Deficit, an Important Fire-Related Meteorological Quantity
    - Seager et al, 2015
- Evidence that Recent Warming is Reducing Upper Colorado River Flows
    - McCabe et al., 2017
- Comparison of CMIP3 and CMIP5 Projected hydrologic conditions over the Upper Colorado River Basin
    - Ayers et al., 2016



Prein et al., 2016

Vapor Pressure Deficit Trends



Seager et al., 2015

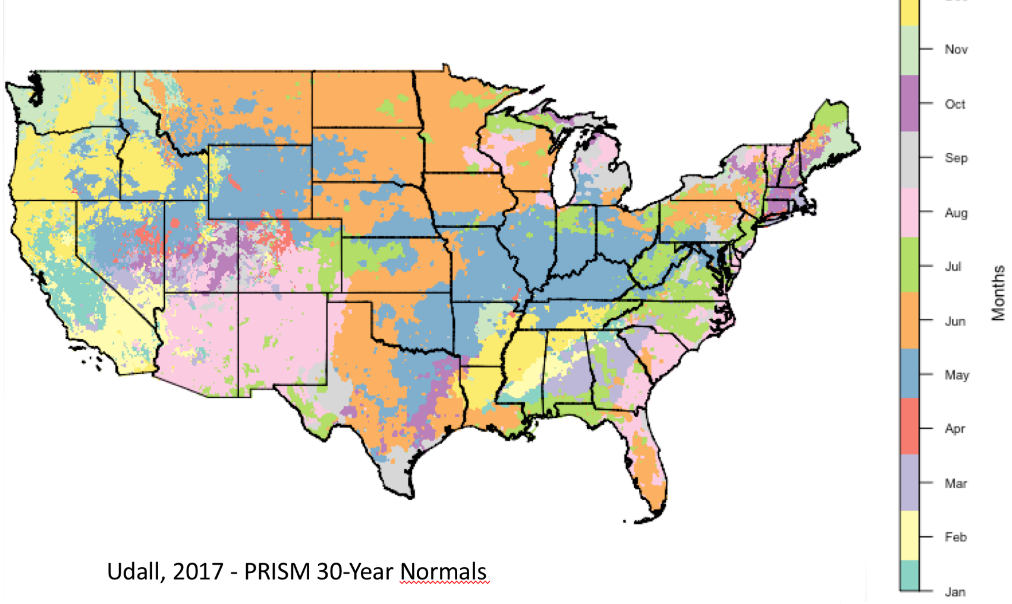
Concluding Thoughts

Hot Drought has been a factor in the last 19 years in the CRB. Precipitation reductions can not explain flow loss.

Temperature is an known, significant and forecastable driver of river flows.

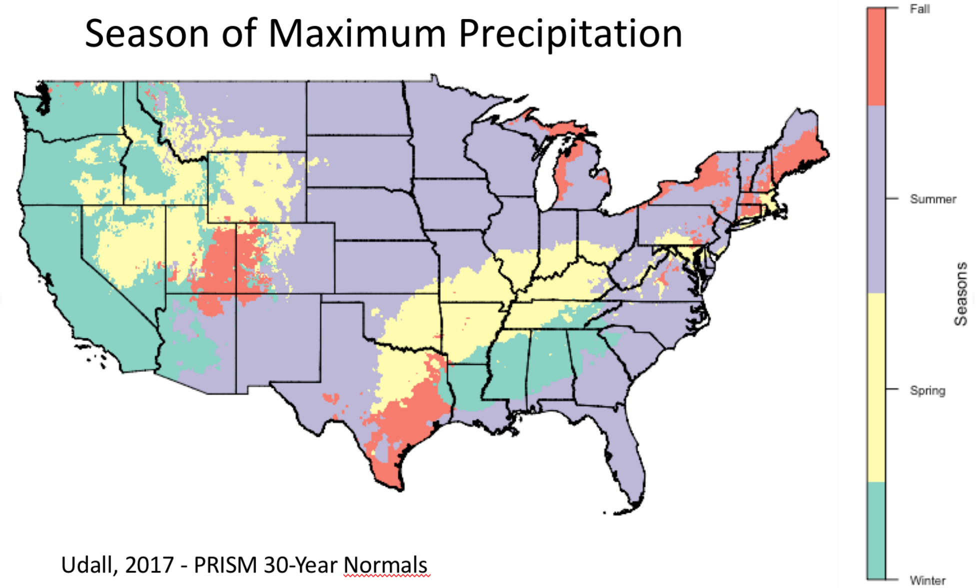
Precipitation is hard to forecast on almost all meaningful time scales for water managers. This is especially true in the Colorado River Basin.

Month of Maximum Precipitation



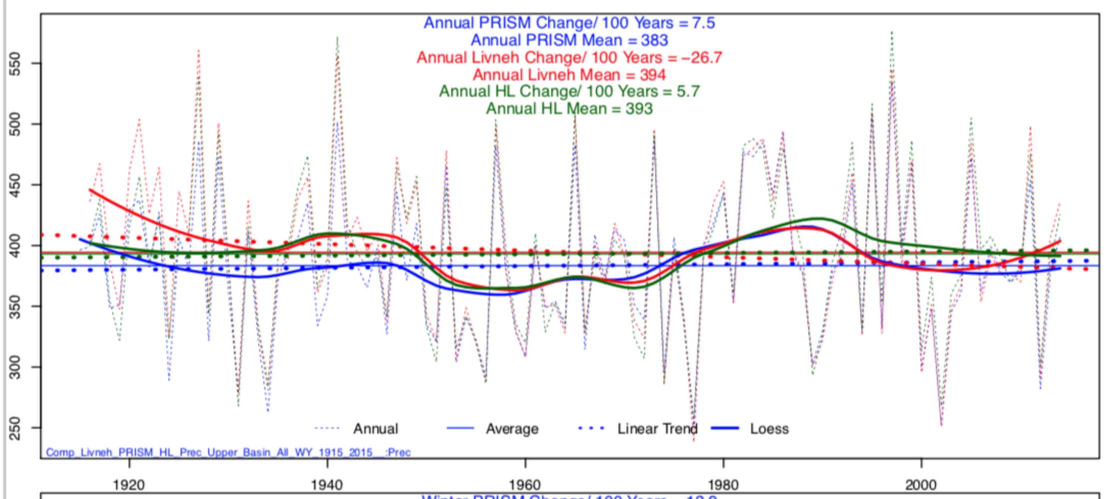
Udall, 2017 - PRISM 30-Year Normals

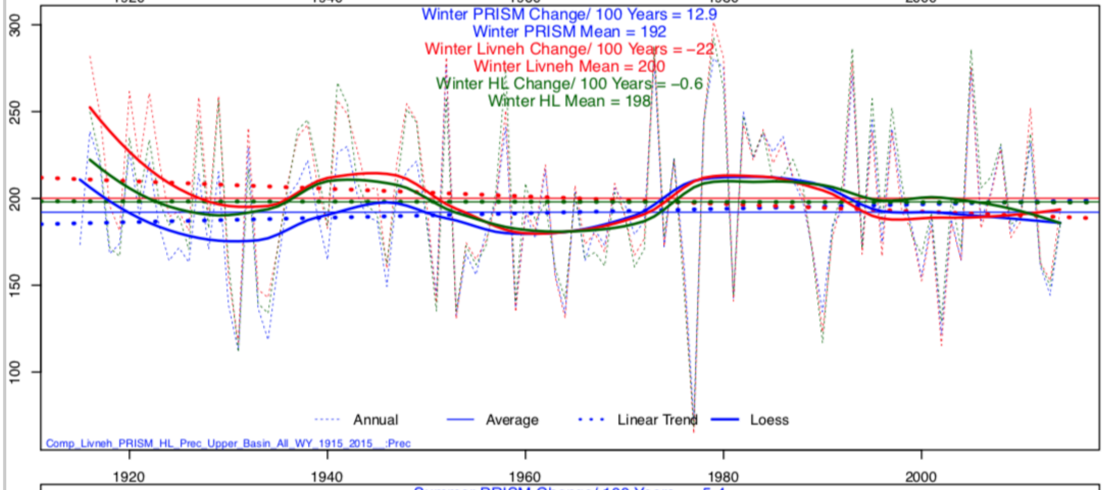
Season of Maximum Precipitation

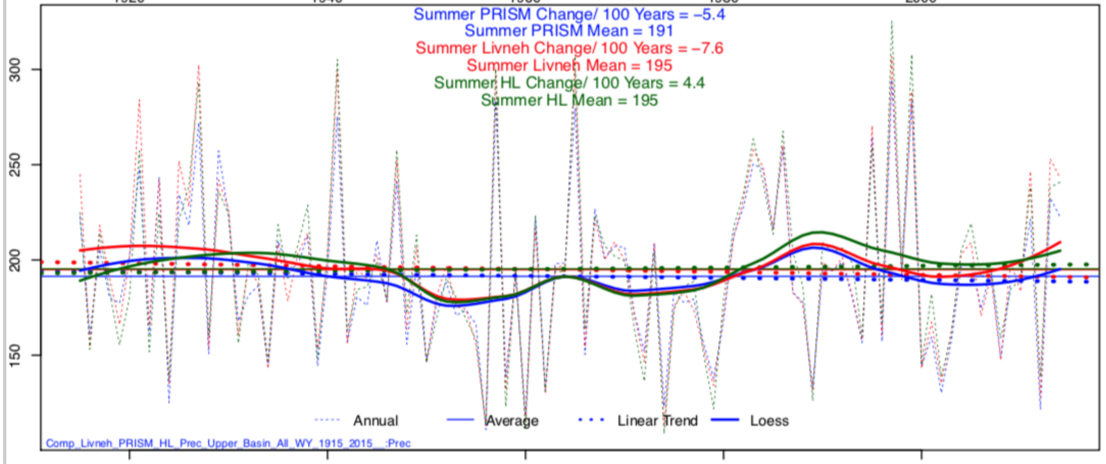


Udall, 2017 - PRISM 30-Year Normals

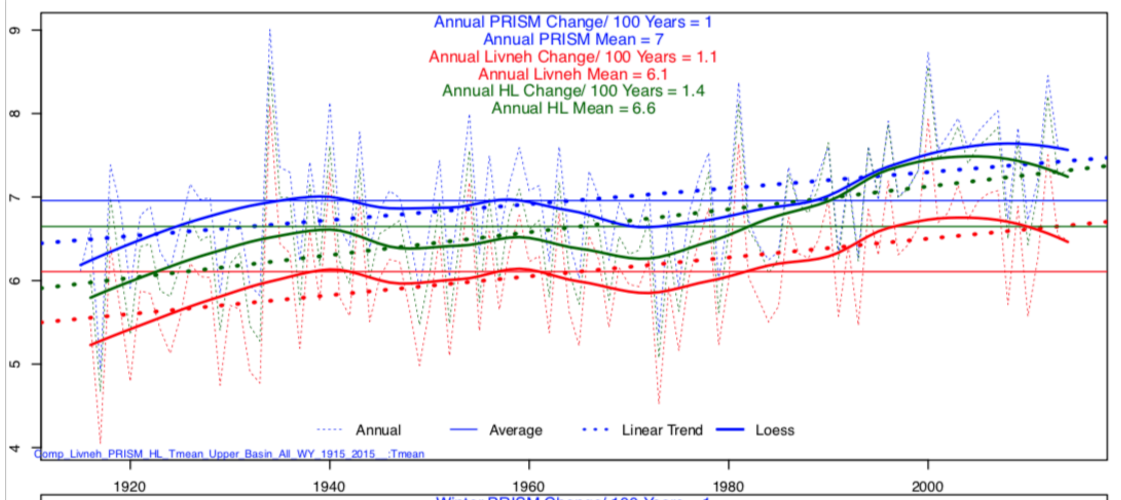
Precipitation

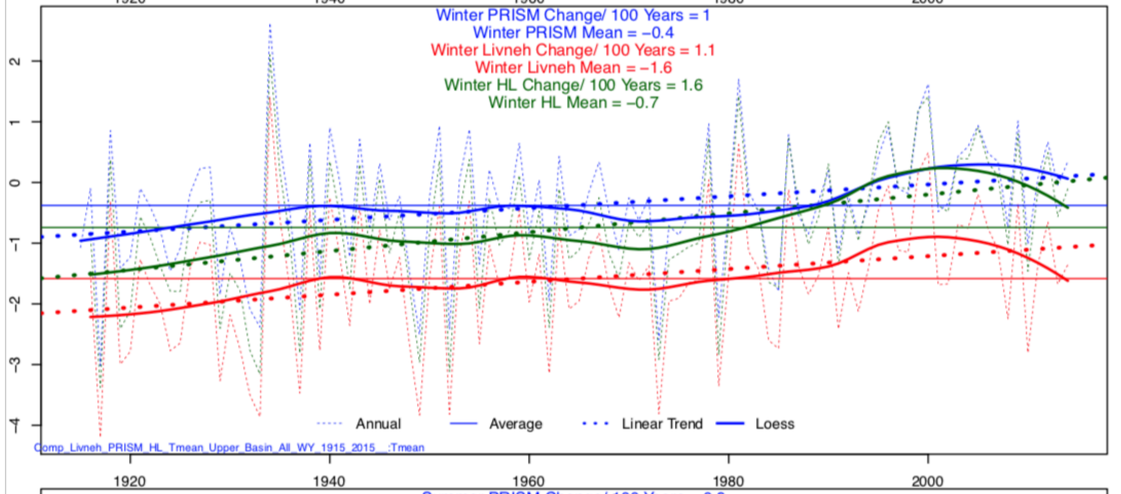


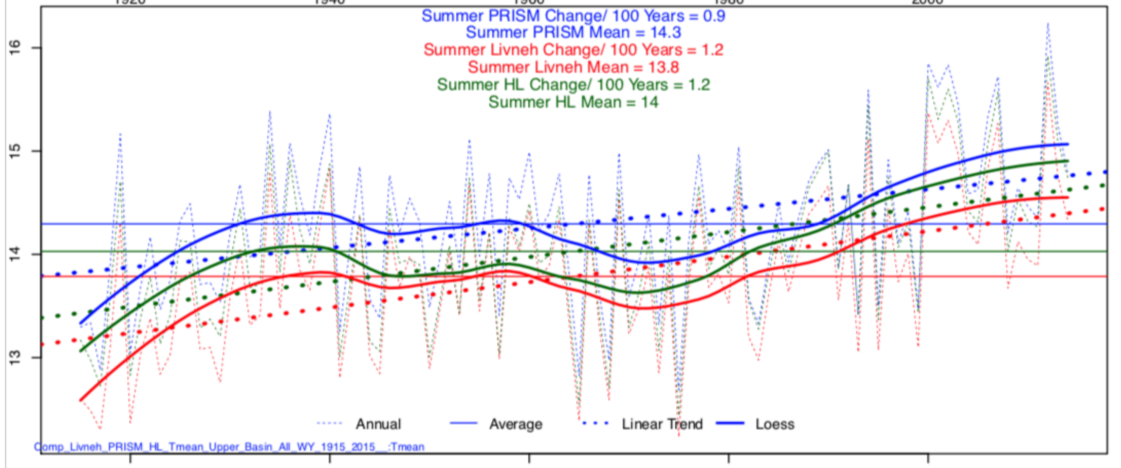


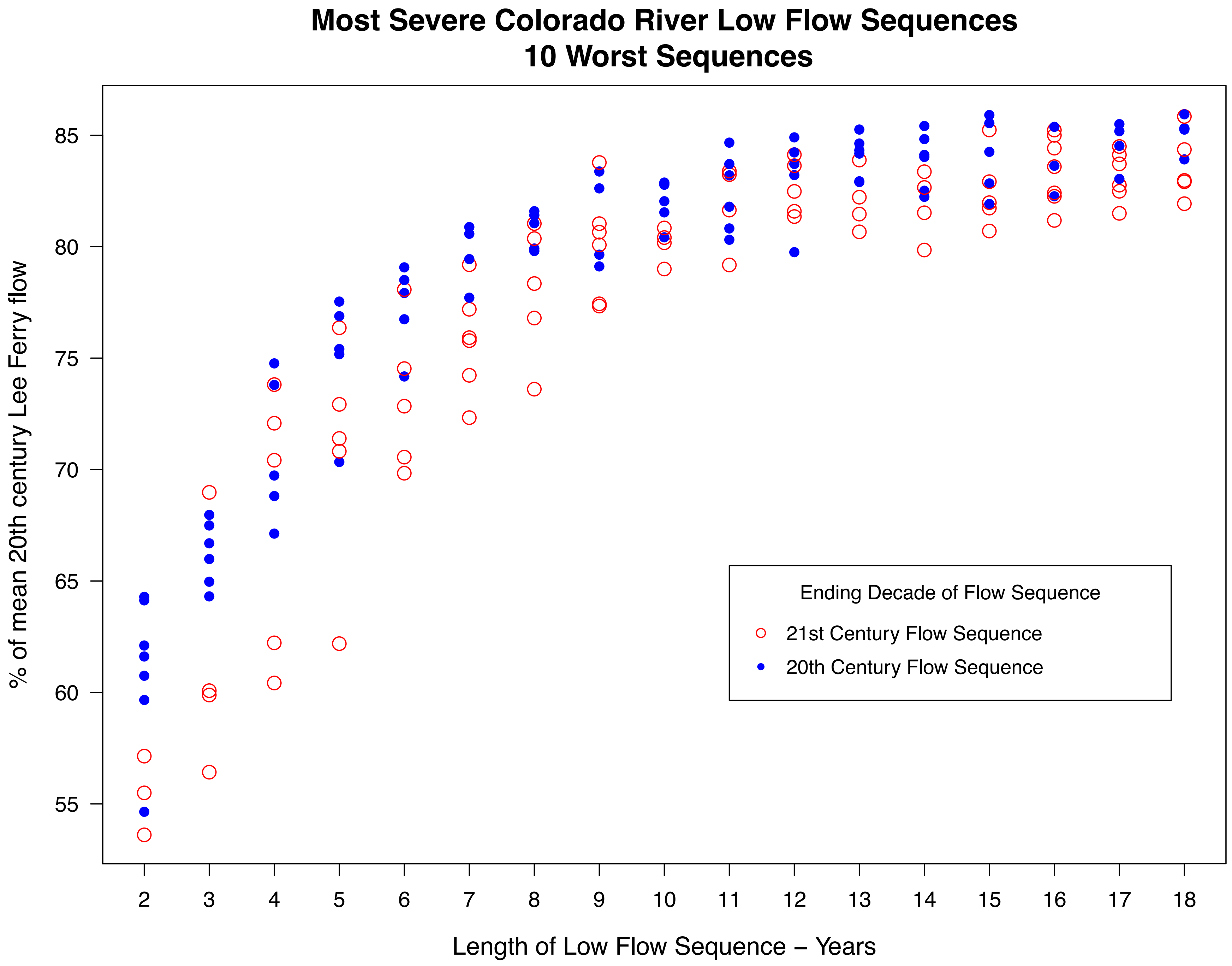


Temperature



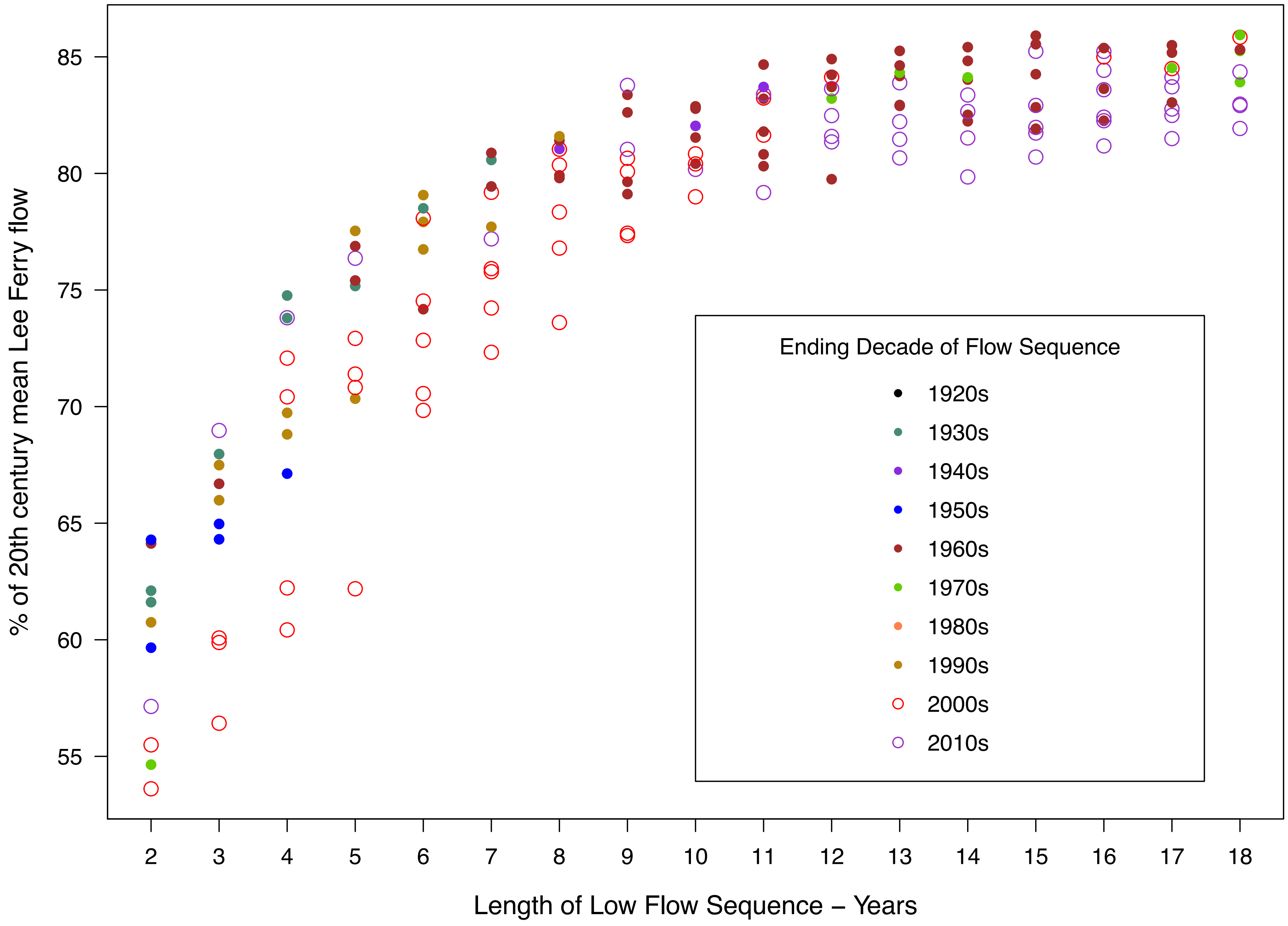


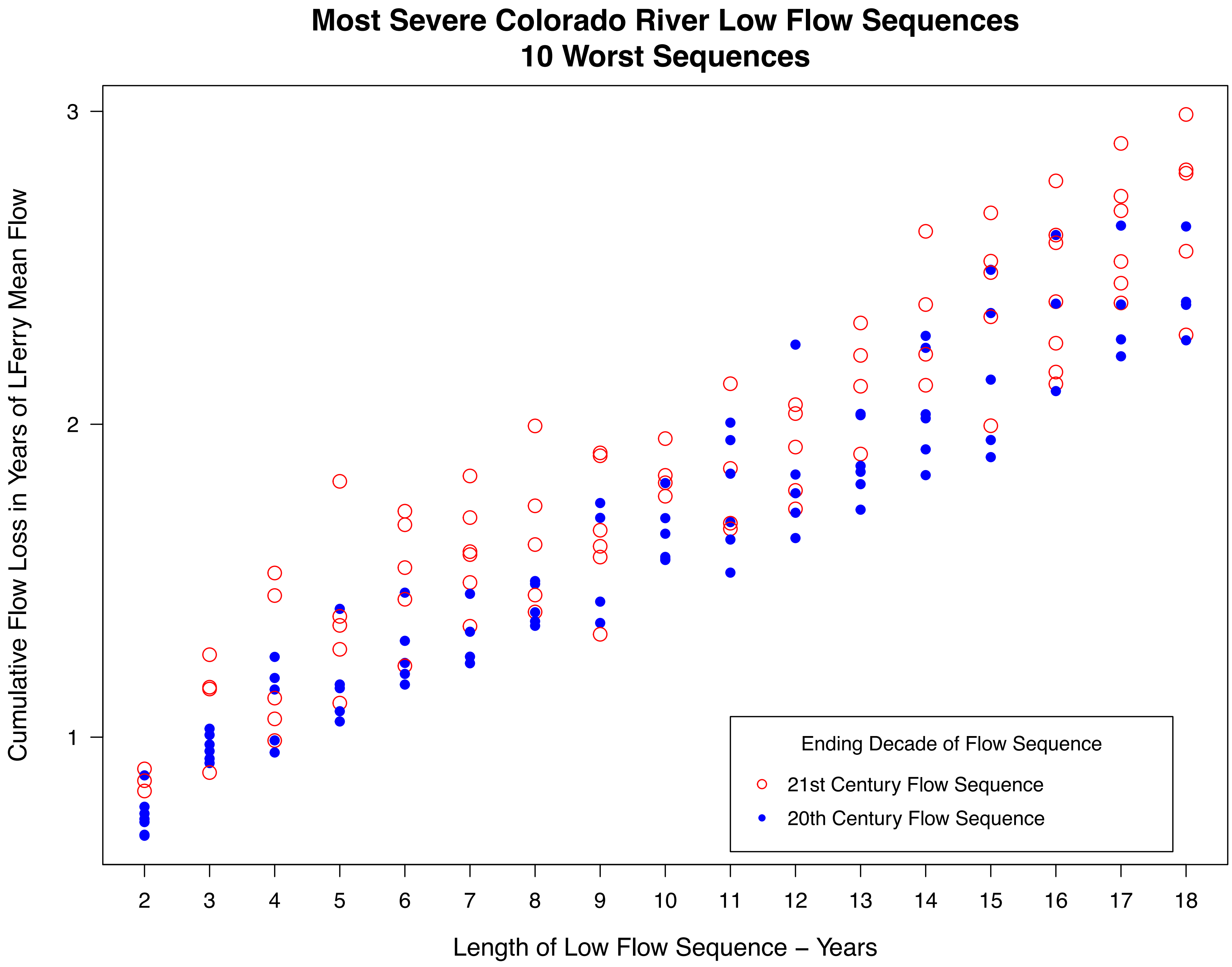




Most Severe Colorado River Low Flow Sequences
10 Worst Sequences
% of mean 20th century Lee Ferry flow
55
60
65
70
75
80
85
Length of Low Flow Sequence – Years
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Ending Decade of Flow Sequence
21st Century Flow Sequence
20th Century Flow Sequence

Most Severe Colorado River Low Flow Sequences
10 Worst Sequences





Most Severe Colorado River Low Flow Sequences
10 Worst Sequences
Cumulative Flow Loss in Years of LFerry Mean Flow
Length of Low Flow Sequence – Years
Ending Decade of Flow Sequence
21st Century Flow Sequence
20th Century Flow Sequence
1
2
3
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18