Aqua Incognita in the Colorado River in 1922 and Beyond

Climate Challenges to Sustainability

GRAD 592
Professor Jennifer Gimbel
Colorado State University
November 29, 2021

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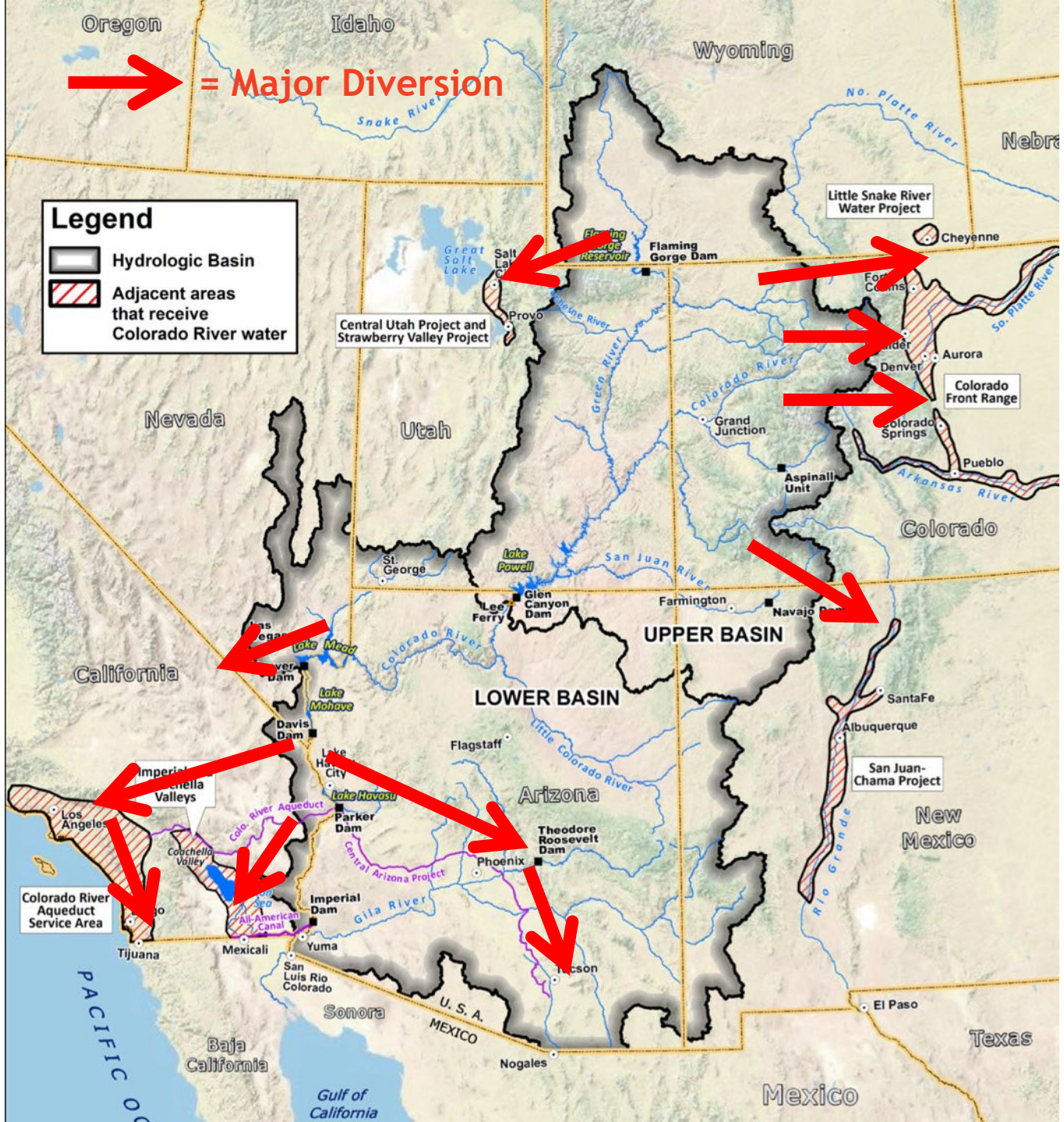
End of Ramp

FERRY CLOSED

Photo Credits: Brad Udall
Oct 2, 2021

Colorado River

- 7 States, 2 Nations, 30 Tribes
- 8% of area of the Lower 48
- 20C Annual Flow ~15.2 MAF
  = Hudson River
- Worst drought in gaged record started 2000 ~12.3 MAF/yr
  = ~19% decline annually
- 40 M People
- All of the Major Cities in SW US
- 4.5m Irrigated Acres
- Fully Allocated in 1922
- Complex Use Agreements
- Withdrawals equaled Supplies ~2000
- New Projects still contemplated
- No longer reaches the ocean



Talk Outline

- Current Basin Status
  - Reservoir Levels, Shortage Status
- Unusual River Flows since 2000
- South to North Flow Decline Pattern
- Recent 20 Month Period Contribution to Drought
- Role of Heat in Reducing Flows
- Role of Precipitation in Reducing Flows
- No longer a drought – aridification
- IPCC AR6 Findings

Lake Mead will fall below 1075’ on January 1, 2022, triggering first-ever ‘Tier 1’ water shortage in Lower Basin…..

circle of blue
where water speaks

Podcasts Great Lakes Drying American West Water Debt WASH WaterNews Special Features Choke Point About Donate

The Colorado River Basin’s Daunting New Math

The basin’s big reservoirs have fallen to uncharted territory. The forecast isn’t any better.

August 13, 2021

The Economist

Menu Weekly edition Search

United States
Aug 21st 2021 edition ›

Low and dry

The American West is drying up

The effects of climate change are being exacerbated by a century of bad policy

August 21, 2021

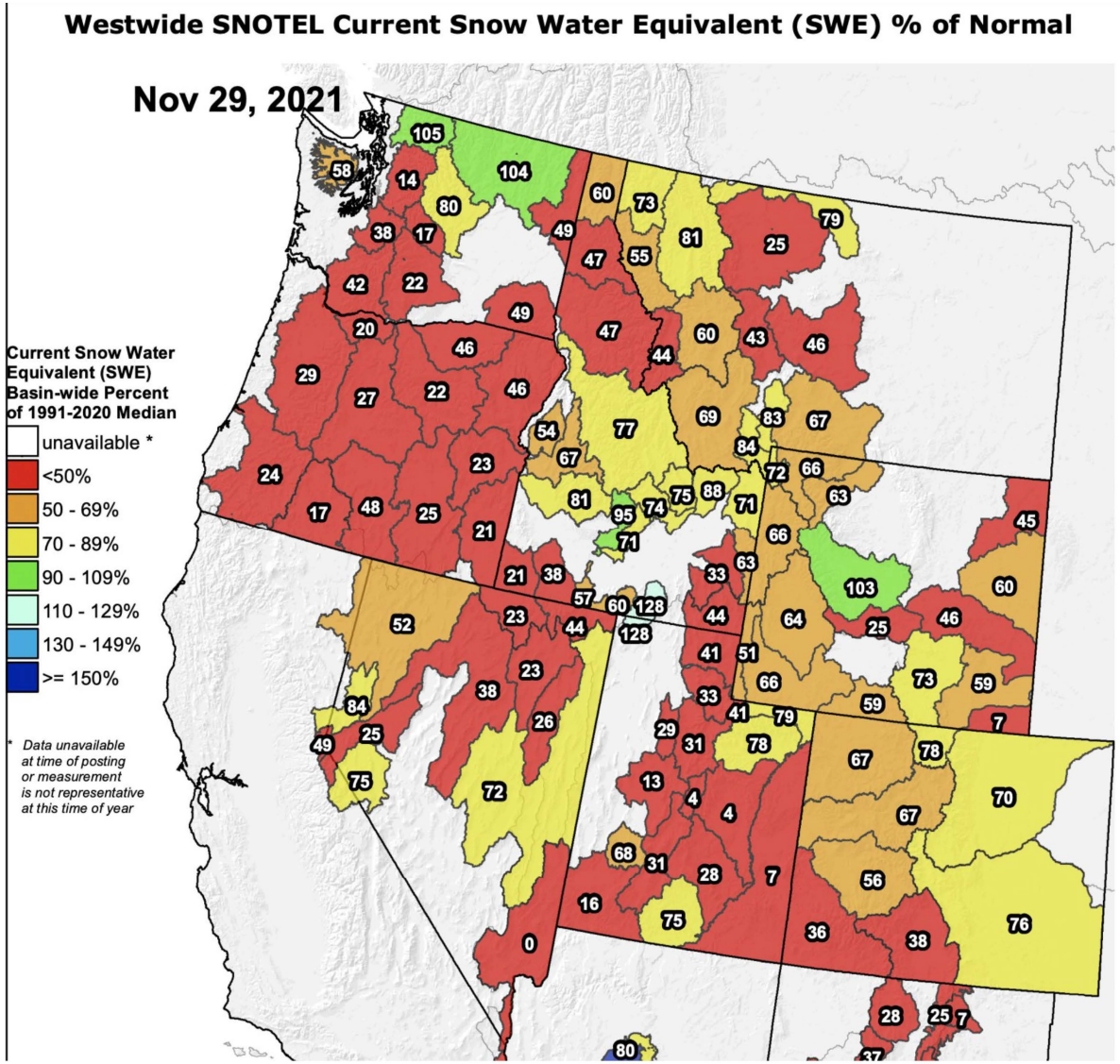
The Washington Post
Democracy Dies in Darkness

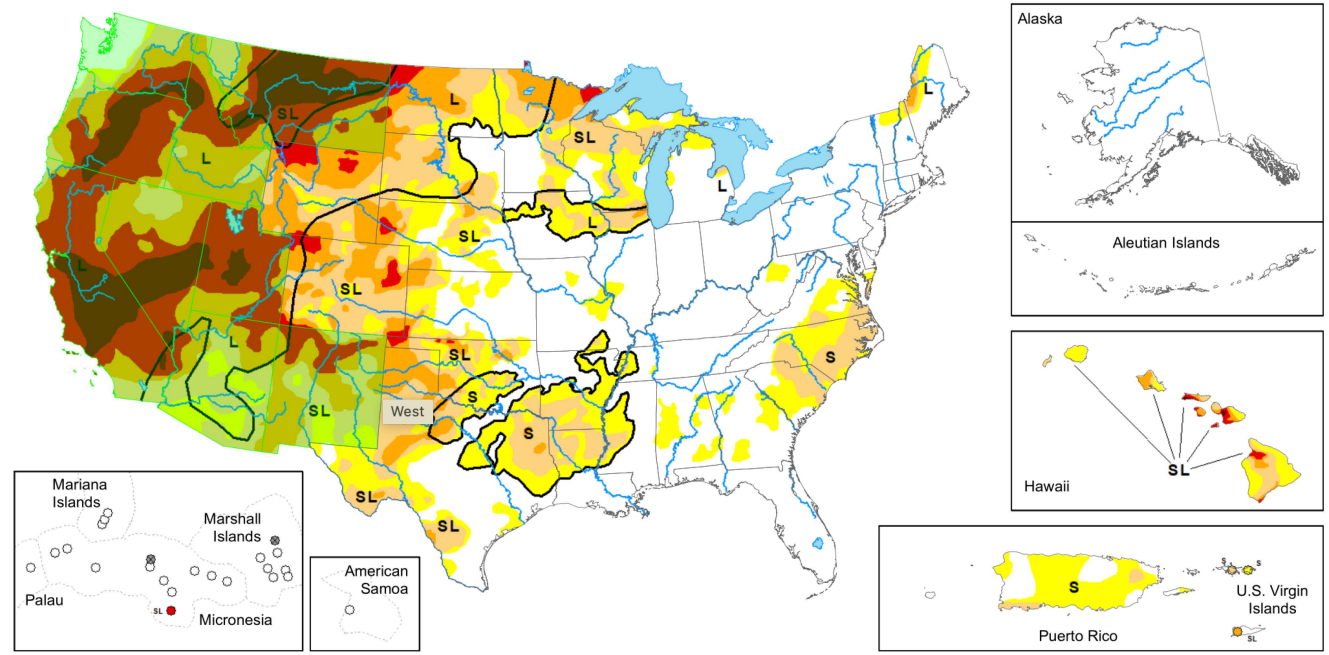
National

First-ever water shortage declared on the Colorado River, triggering water cuts for some states in the West

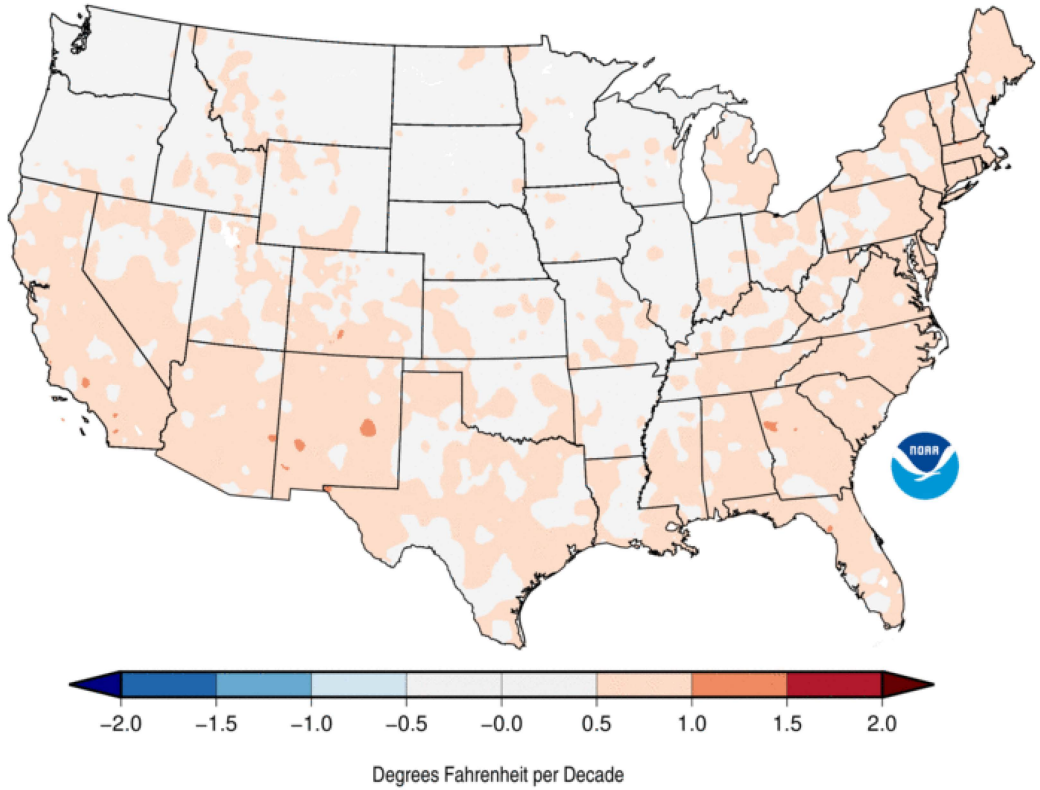
August 16, 2021

August 21, 2021


Westwide SNOTEL Current Snow Water Equivalent (SWE) % of Normal
Nov 29, 2021
Current Snow Water Equivalent (SWE) Basin-wide Percent of 1991-2020 Median
unavailable *
<50%
50 - 69%
70 - 89%
90 - 109%
110 - 129%
130 - 149%
>= 150%
* Data unavailable at time of posting or measurement is not representative at this time of year


Map released: November 24, 2021
Data valid: November 23, 2021
West
Alaska
Aleutian Islands
Hawaii
Mariana Islands
Marshall Islands
Palau
Micronesia
American Samoa
Puerto Rico
U.S. Virgin Islands

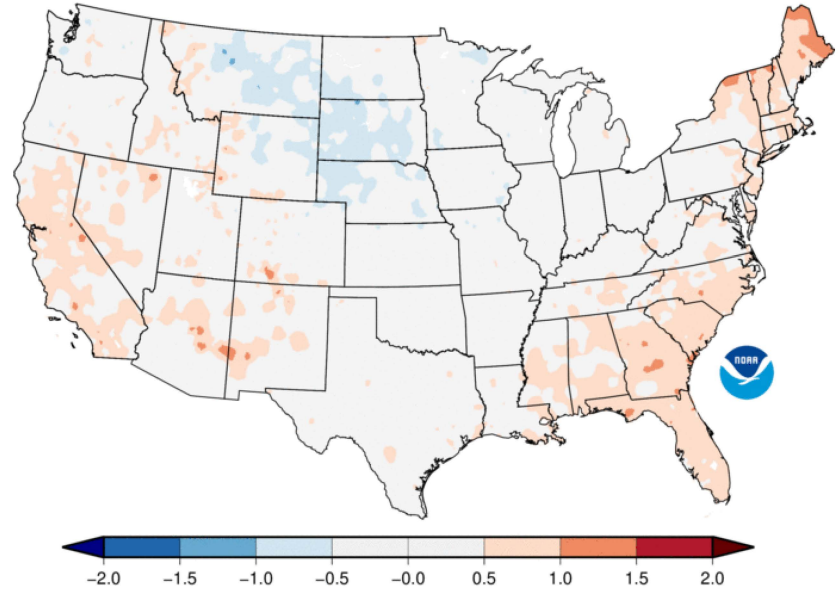
Average Temperature Trends
Annual 1991–2020 (30 years)



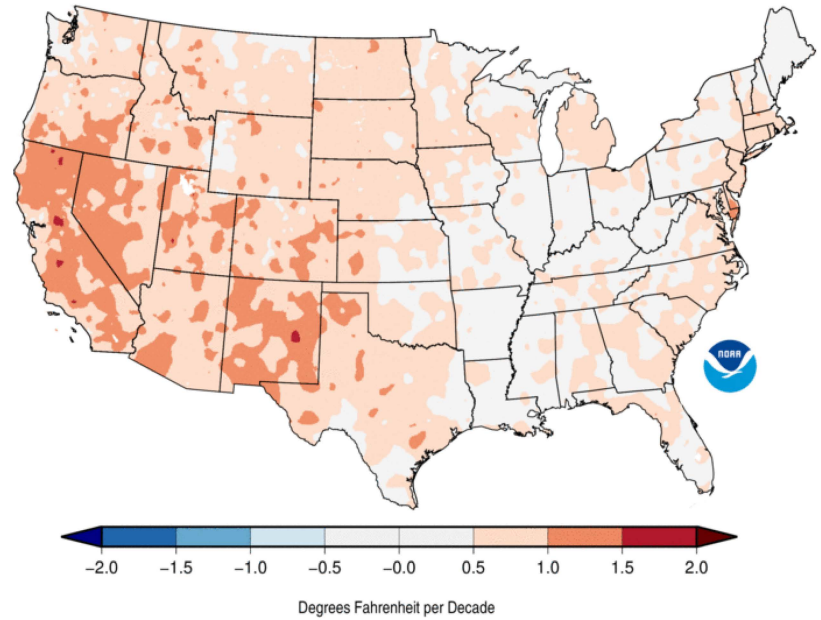
Data Source: 5km Gridded Dataset (nClimGrid)

National Centers for Environmental Information

Average Temperature Trends
Winter 1991–2020 (30 years)



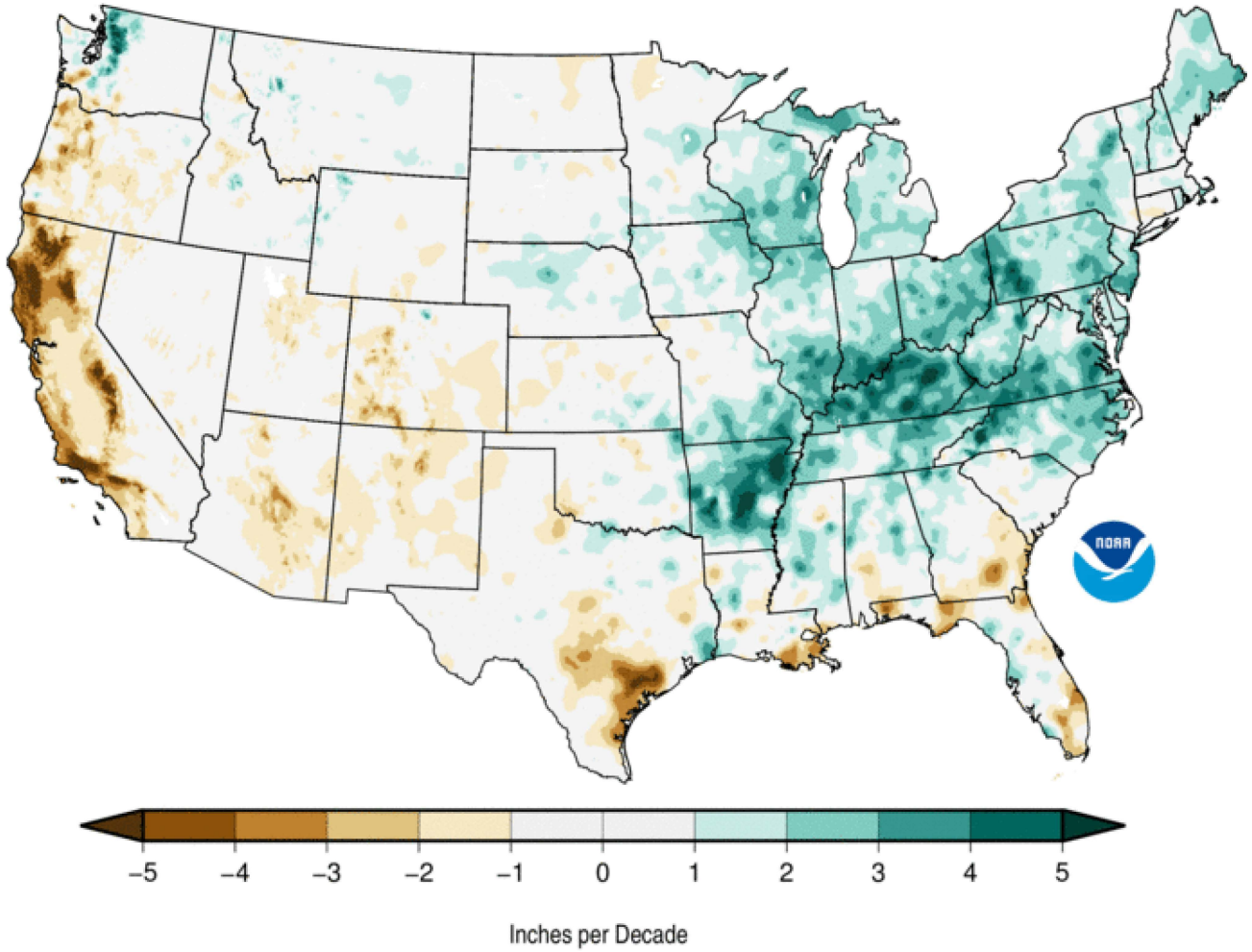
Average Temperature Trends
Summer 1991–2020 (30 years)



Data Source: 5km Gridded Dataset (nClimGrid)

National Centers for Environmental Information

Precipitation Trends
Annual 1991–2020 (30 years)



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National Centers for Environmental Information

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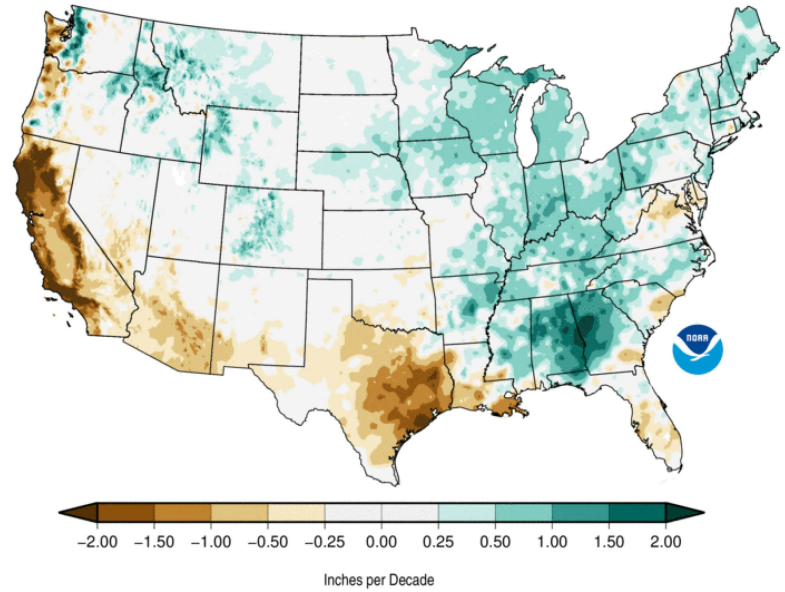

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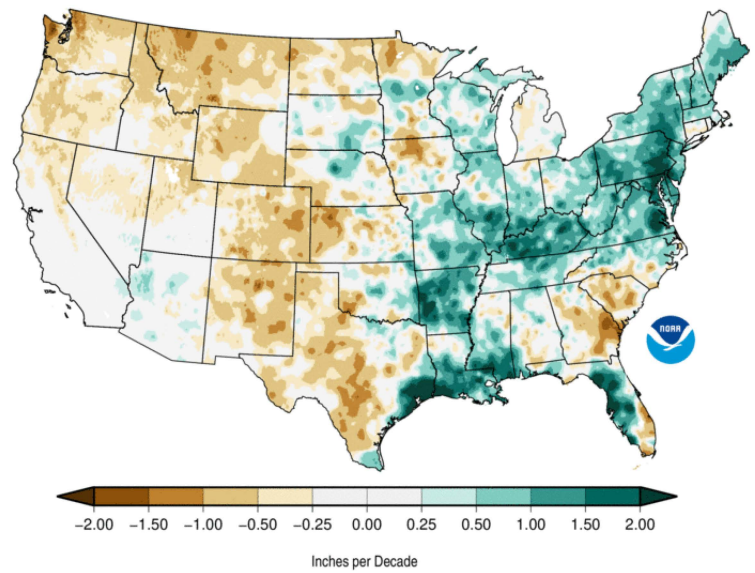


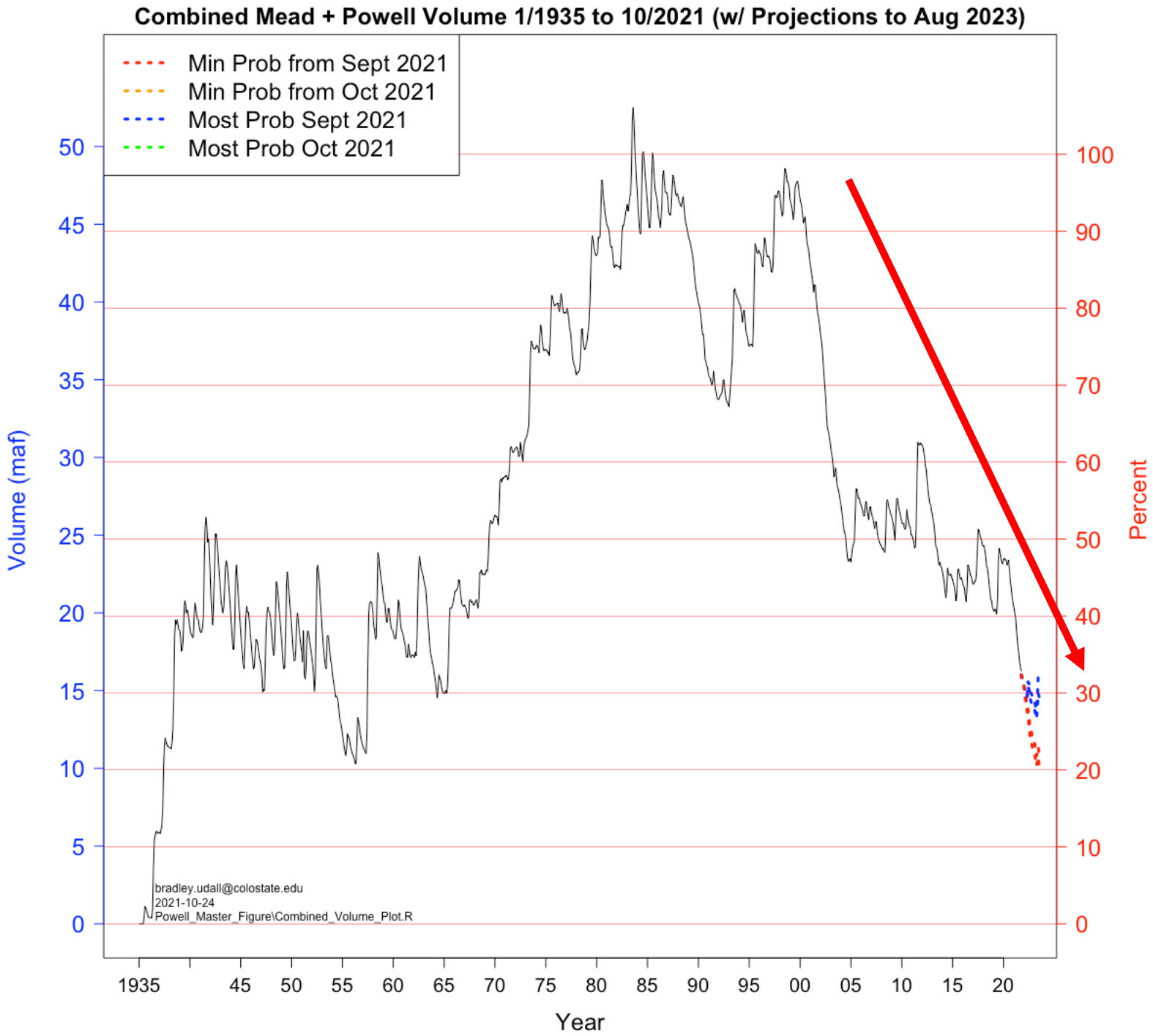
Data Source: 5km Gridded Dataset (nClimGrid)

National Centers for Environmental Information

Jan 2000:
Powell+Mead 95% Full,
47 MAF

April 2022:
Powell+Mead less than
30% Full, 15 MAF

Loss of 32 MAF or 1.4
MAF/Year



Paired Lake Powell Photos near Hite, UT, 22 Years Apart

Lake Powell ~2000 Full Pool

Lake Powell October 2021 155’ Low

2 Kinds of Flows: (1) Natural Flows

Last 22 Years: How Different from 1906-99?

Mean: 15.2 maf vs 12.3 maf (-19%)

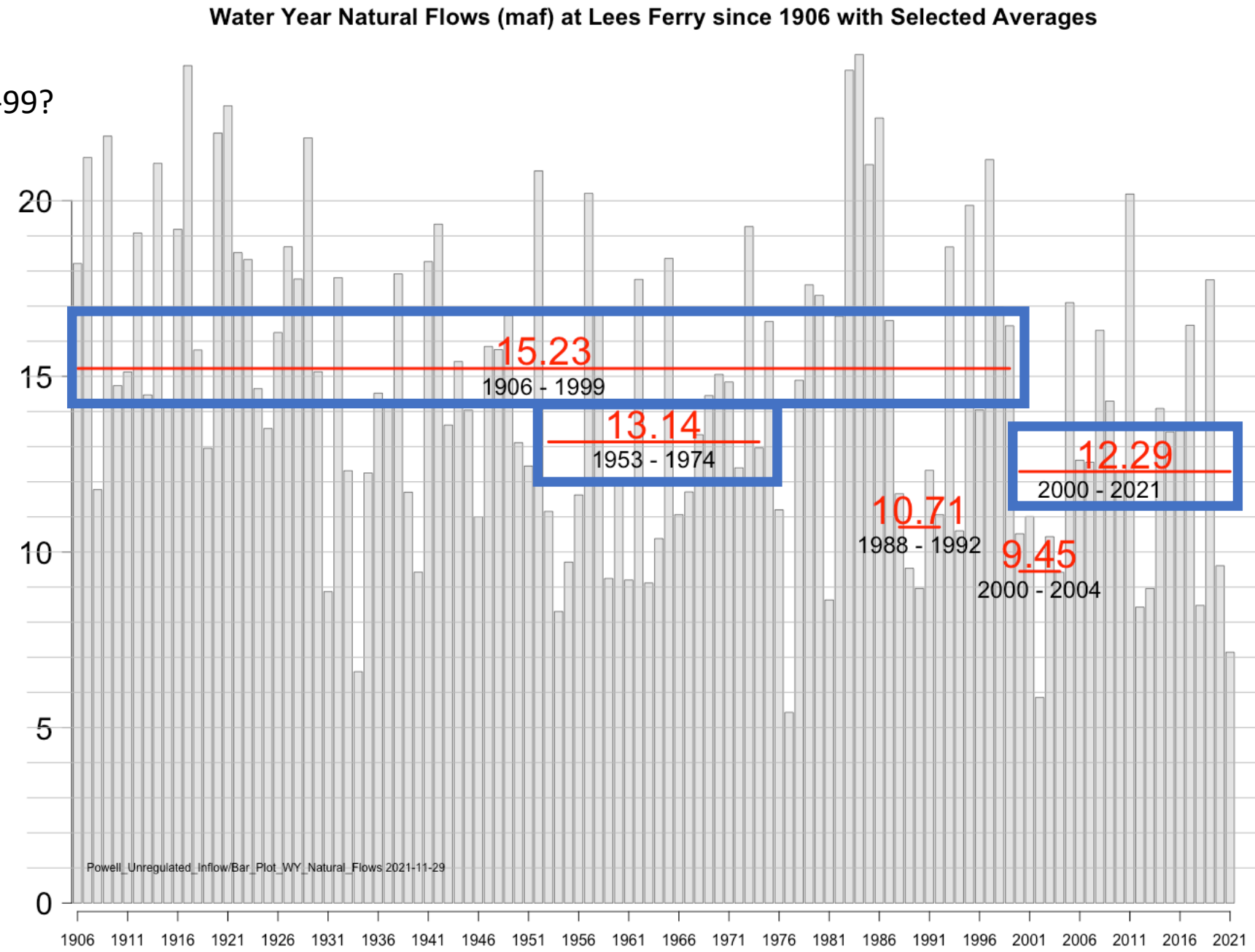
High Flow Years (>15 maf) ½ as many

Low Flow Years (<10 maf) 2.5x as many

1 in 1500 Years if using 1906-99

Worst 22-Year Period
in 1906-99: 13.1 maf
in 2000-21: 12.4 maf
(-700 kaf/yr or 15.4 maf total)

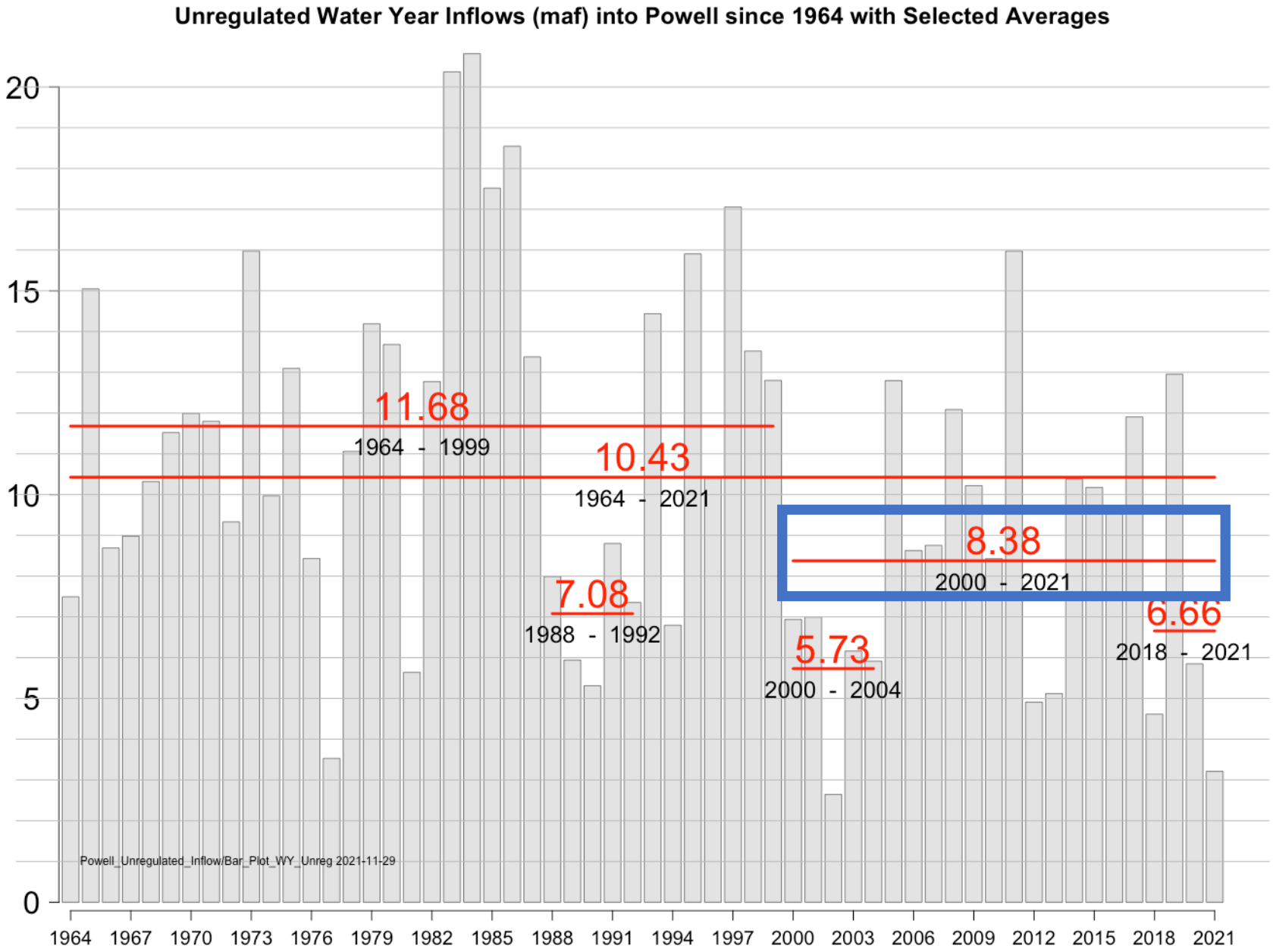
Take Home: Last 22 Years has no 20th C Analog. It is completely different.



2 Kinds of Flows: (2) Unregulated Inflows

- Actual Inflows into Powell with effects of Upstream Reservoir Operations Removed
- If you added Upper Basin Demands to these flows you'd have ~ "Natural Flows"
- 2000-2021 Average is 8.4 maf/year
- Powell inflows tie Directly to Compact Section III D Non-Depletion Provision
- Can not release from Powell more than Inflow - Evaporation over time
- Take Home:

8.38 maf – 500 kaf evap is ~ 7.9 maf/yr.
This is less than annualized III D plus MX non-depletion amount (8.23 maf/yr).



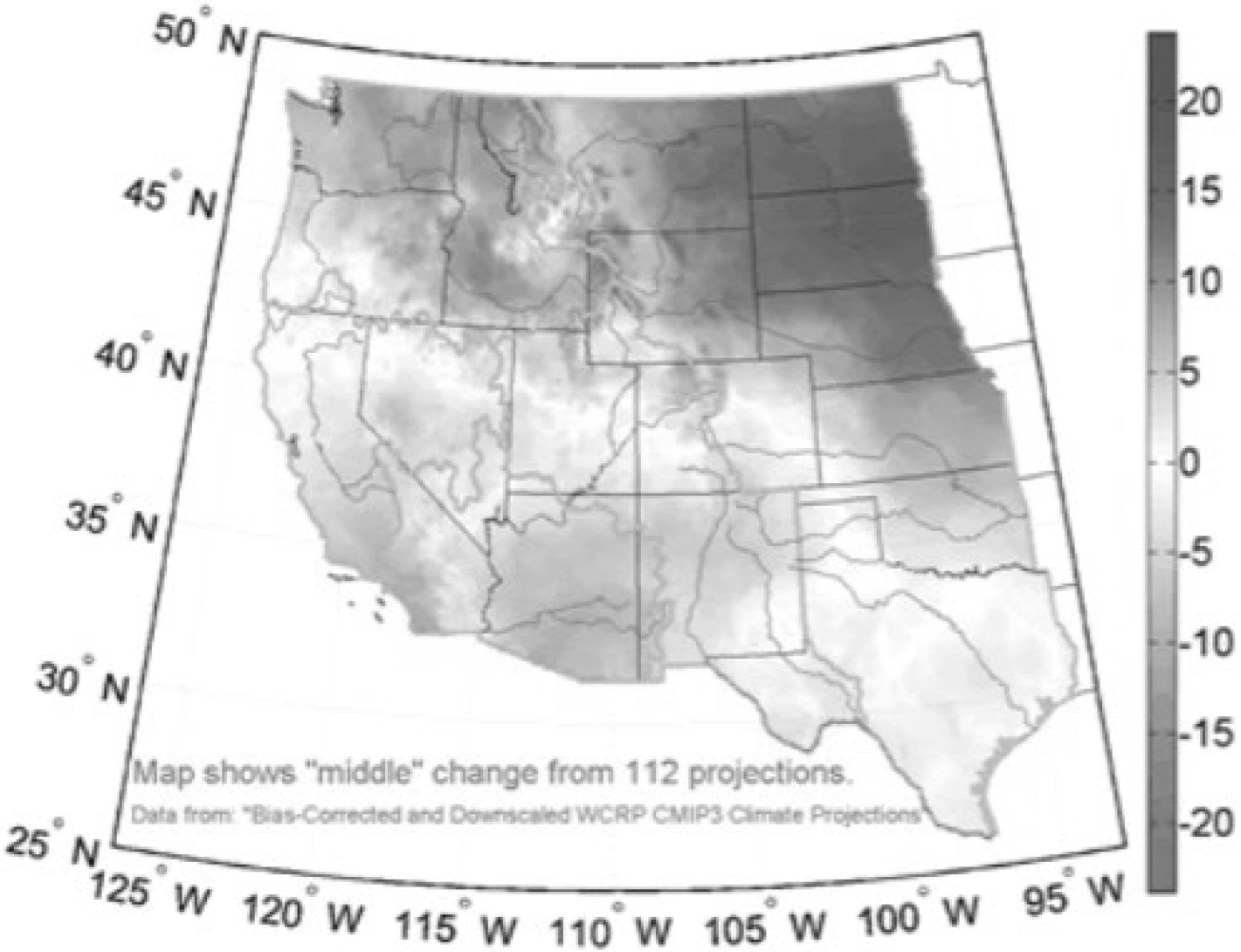
Reclamation Downscaled Precipitation CMIP3 Projections
End of 21st Century

Wet– Dry North-South Gradient Across the Basin

Take Home Point:

Precipitation Changes are small in Colorado with a North-South Gradient

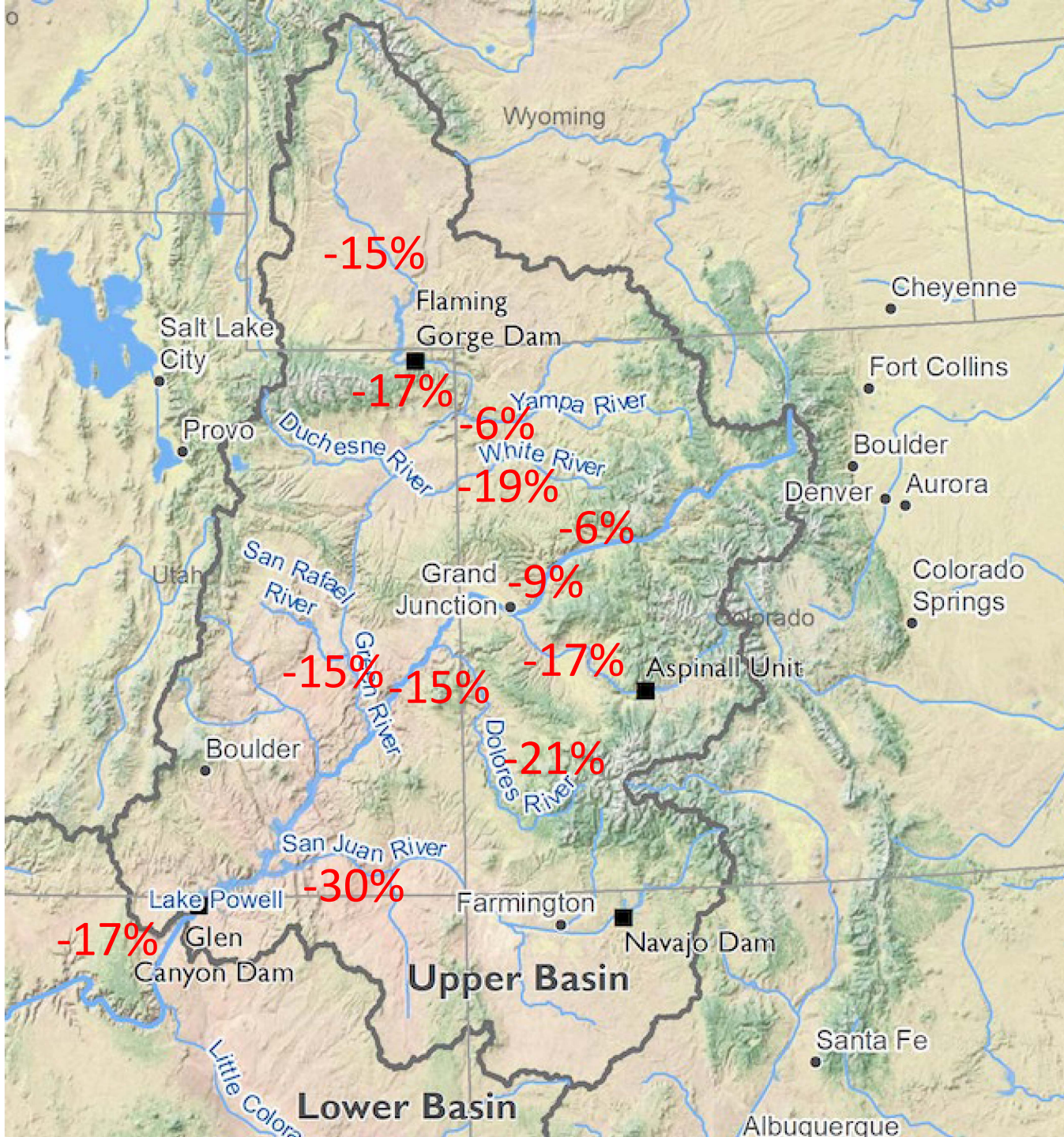
Southern Colorado at significant risk of Precipitation (and runoff) declines



South to North Flow Losses
2000-2019 vs 1906-1999

- Colorado @ Lees Ferry - 17%
- San Juan near Bluff - 30%
- Green River @ GR UT - 15%
- Colorado River near Cisco - 15%
- Dolores near Cisco - 21%
- Colorado near Cameo - 9%
- Gunnison near GJ - 17%
- Colorado @ Glenwood - 6%
- White near Watson - 19%
- Yampa near Maybell - 6%
- Green near Greendale - 17%
- Green below Fontenelle - 15%

Outliers in S-N Decreasing Pattern
- White
- Mainstem Green (2 gages)



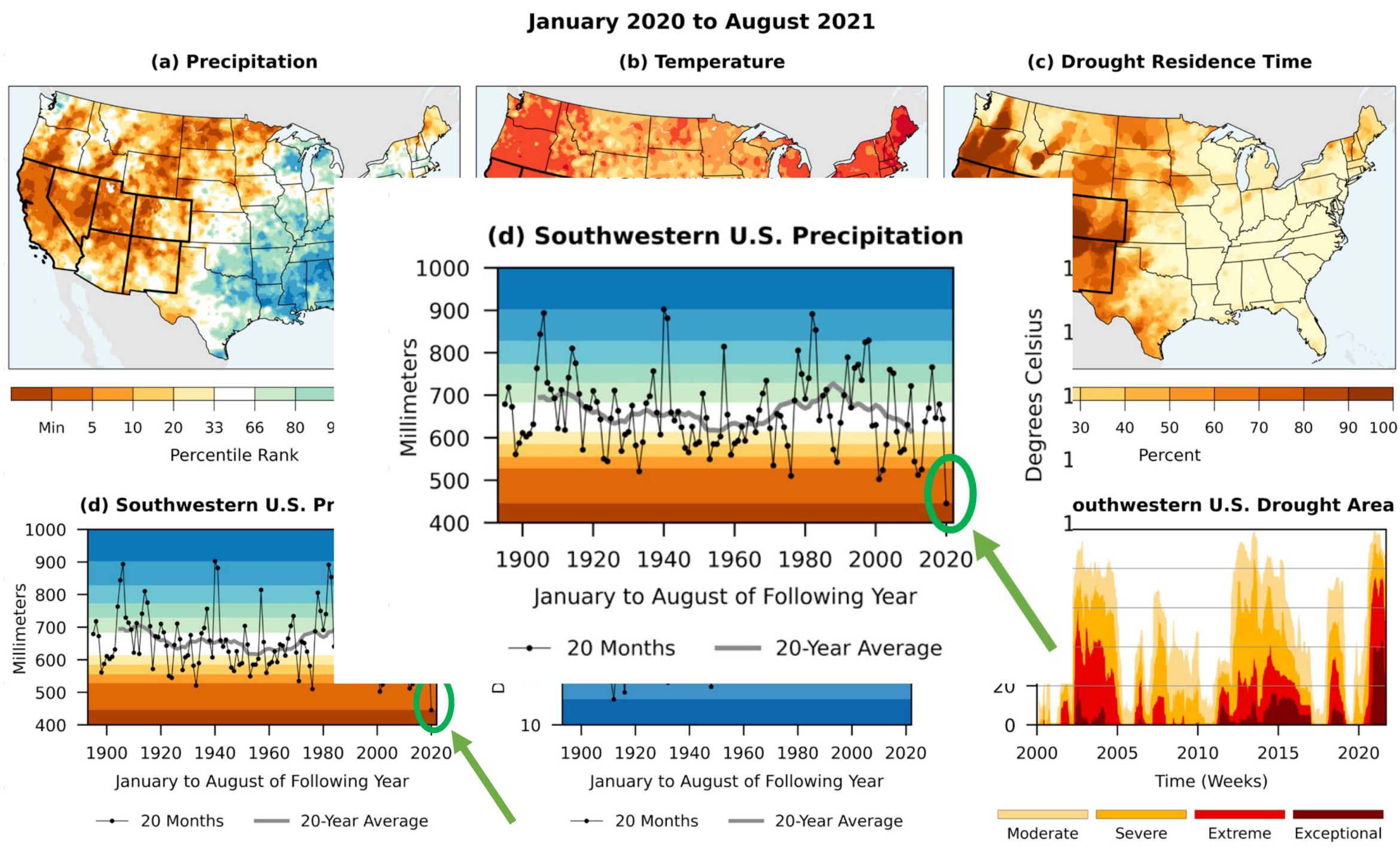
September 2021 NOAA Drought Report

20 Month Period January 2020 to August 2021 had..

- Lowest Total Precipitation since 1895
- 3rd Highest Daily Average Temperatures since 1895
- Record High Vapor Pressure Deficit

Low Precipitation “appears largely natural”

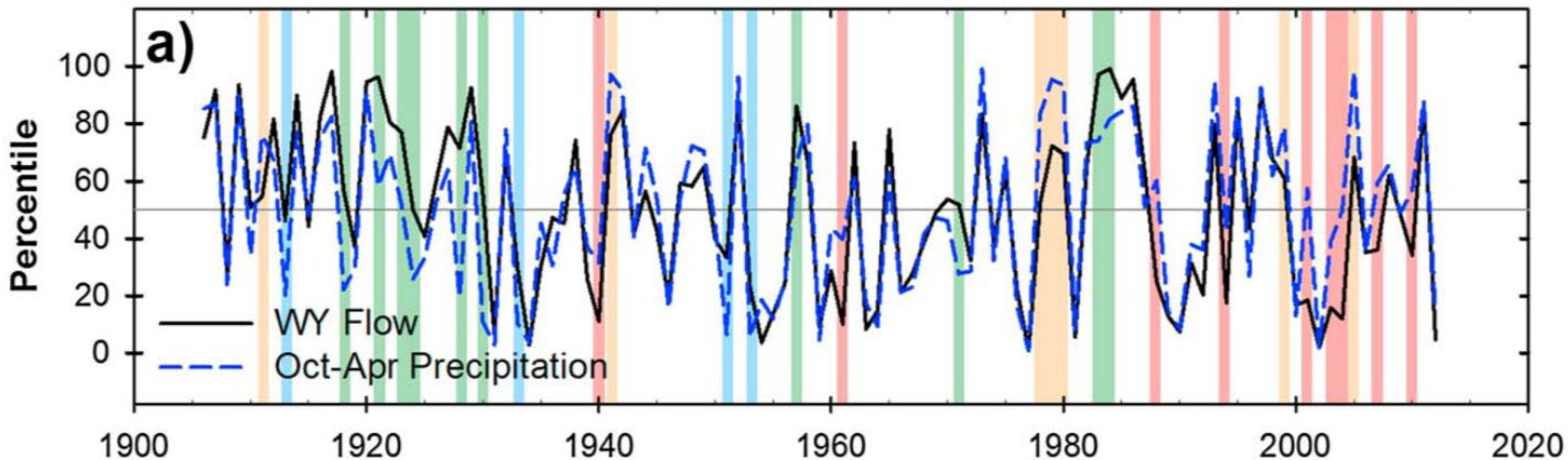
“Warm temperatures that helped to make this drought so intense and widespread will continue (and increase) until stringent climate mitigation is pursued”


January 2020 to August 2021
(a) Precipitation
(b) Temperature
(c) Drought Residence Time
Min 5 10 20 33 66 80 9
Percentile Rank
(d) Southwestern U.S. Precipitation
Millimeters
1000 900 800 700 600 500 400
1900 1920 1940 1960 1980 2000 2020
January to August of Following Year
20 Months
20-Year Average
Degrees Celsius
30 40 50 60 70 80 90 100
Percent
(d) Southwestern U.S. Pr
outhwestern U.S. Drought Area
2000 2005 2010 2015 2020
Time (Weeks)
Moderate
Severe
Extreme
Exceptional

Increasing influence of air temperature on upper Colorado River streamflow - 2016

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

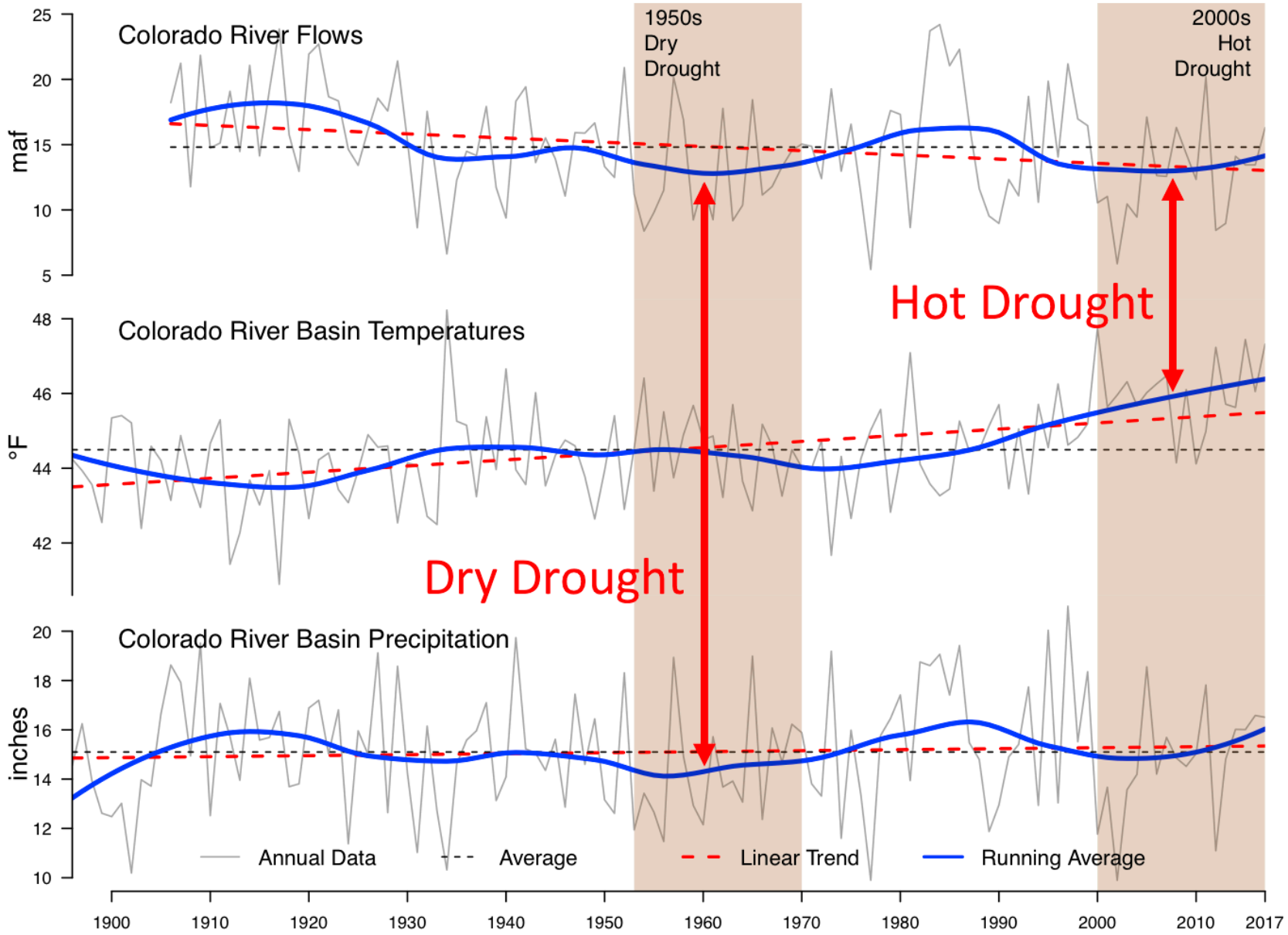
- Temperature can be a major flow driver (normally we just think about precipitation)
- Since 1988 flows have been less than expected given winter precipitation
- Warm temperatures exacerbated modest precipitation deficits in the Millennium Drought



The twenty-first century Colorado River hot drought and implications for the future - 2017

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

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



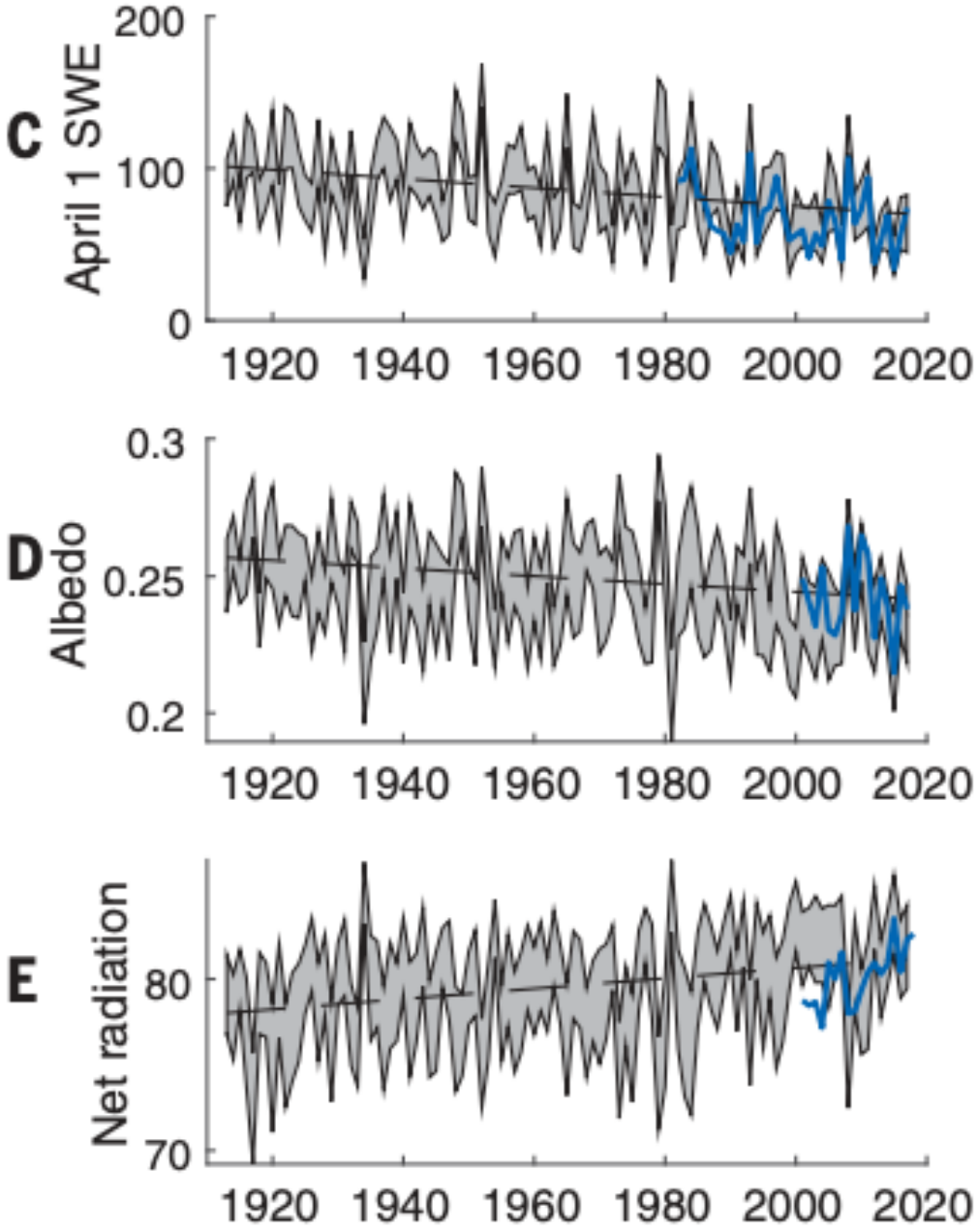
Udall and Overpeck, WRR, 2017

WATER RESOURCES

Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation

P. C. D. Milly* and K. A. Dunne

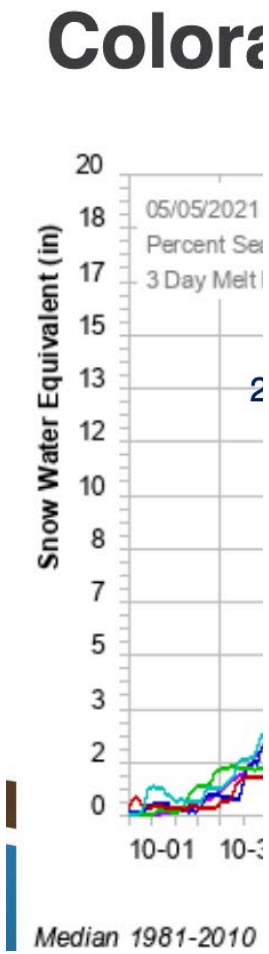
- Attempt to ‘reconcile’ the wide range of CR Temperature Sensitivities
- Answer: -9.3 %/°C !
- Mid-century flow loss (only Temps)
  - -14% to -26% Low GHG Emissions
  - -19% to -31% High GHG Emissions
- Mid-century flow loss (both Temps & Precip)
  - +5% to -24% Low GHG Emissions
  - +3% to -40% High GHG Emissions
- Key Finding: As shiny, reflective snow declines, absorbed radiation goes up (2/3 of the cause)

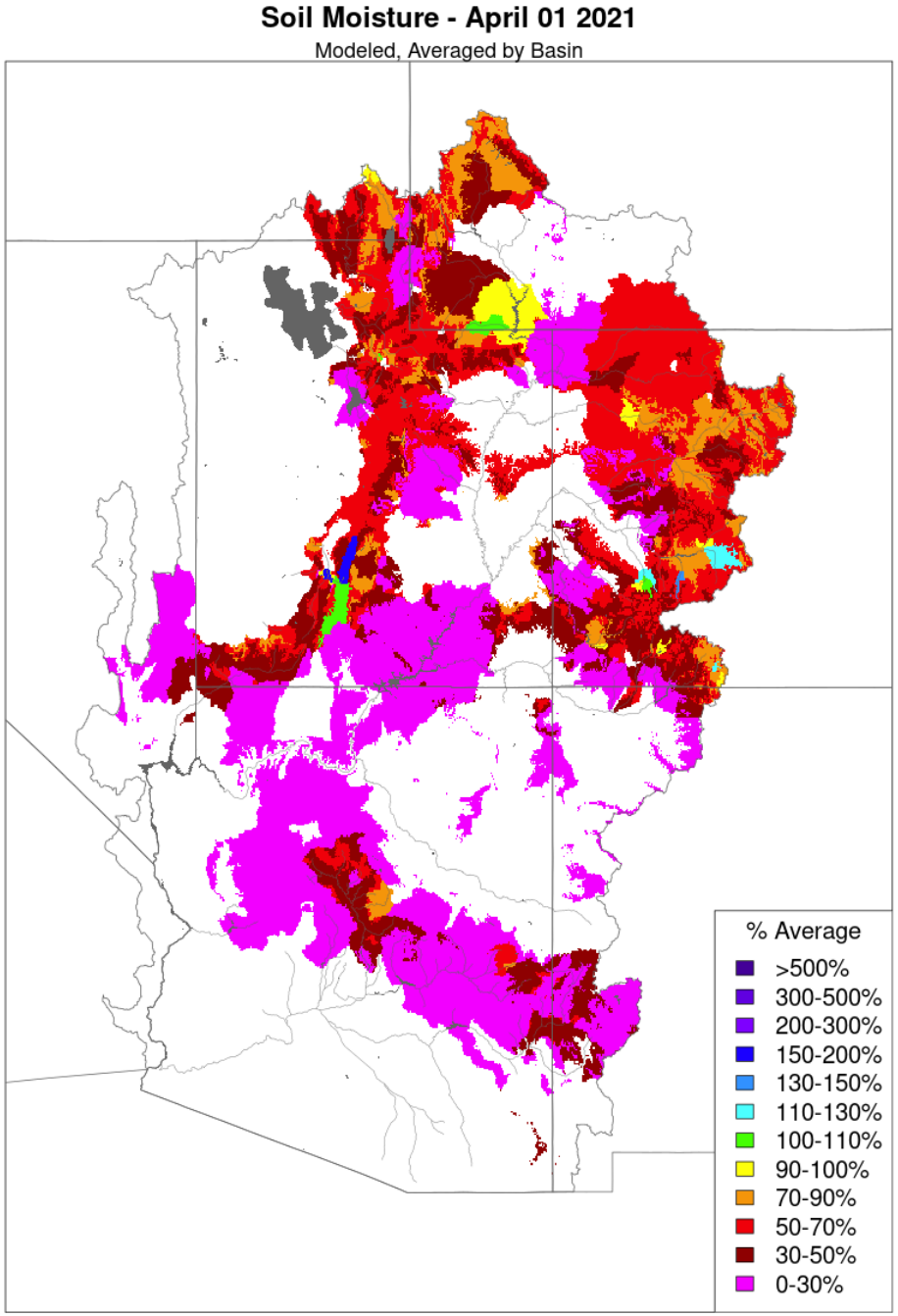


Milly *et al.*, *Science* **367**, 1252–1255 (2020) 13 March 2020

How can average April 1 CRB snowpack turn into low runoff?

- Last 2 CRB Winters
  - 2021: 90% SWE -> 30% Runoff
  - 2020: 100% SWE -> 50% Runoff
- Close to Average Winter Precip
- But….
- Large Spring Precip reductions
  - early melt means early greenup
- Hot, Dry Summers reduce soil moisture
- Result:
  - Next Year's Spring Runoff fills soil moisture deficit first resulting in low flows



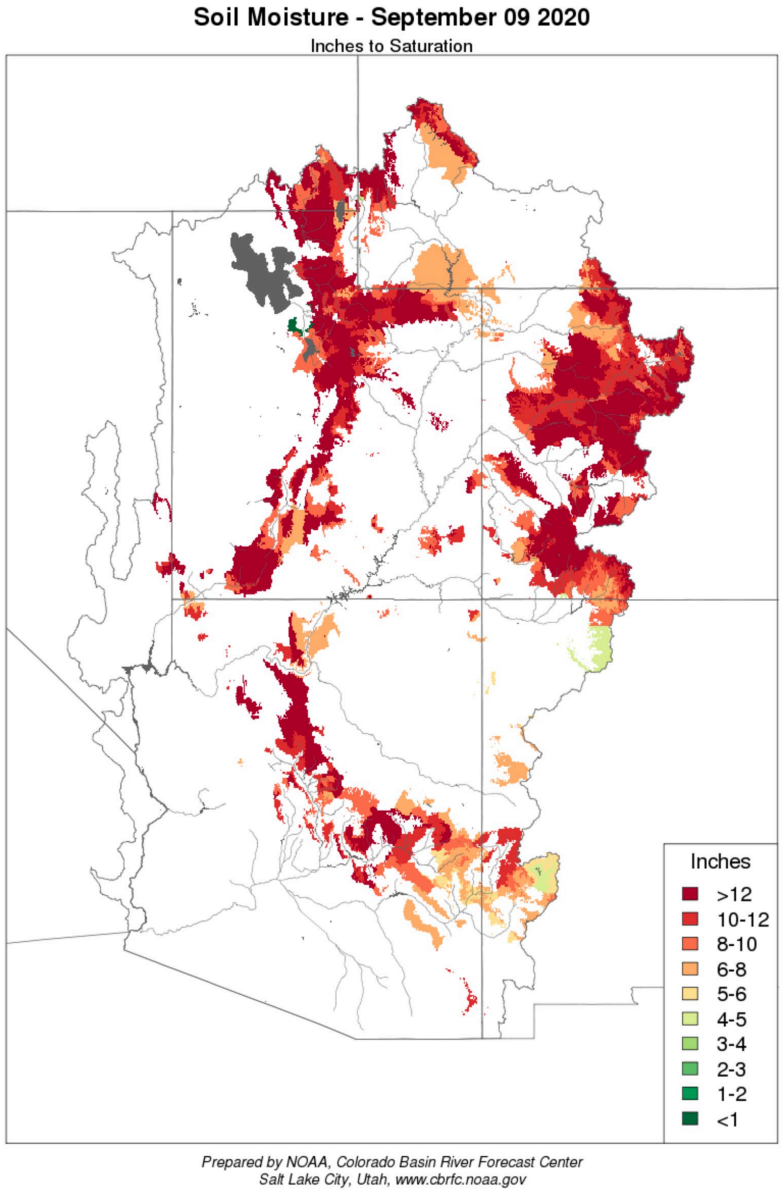


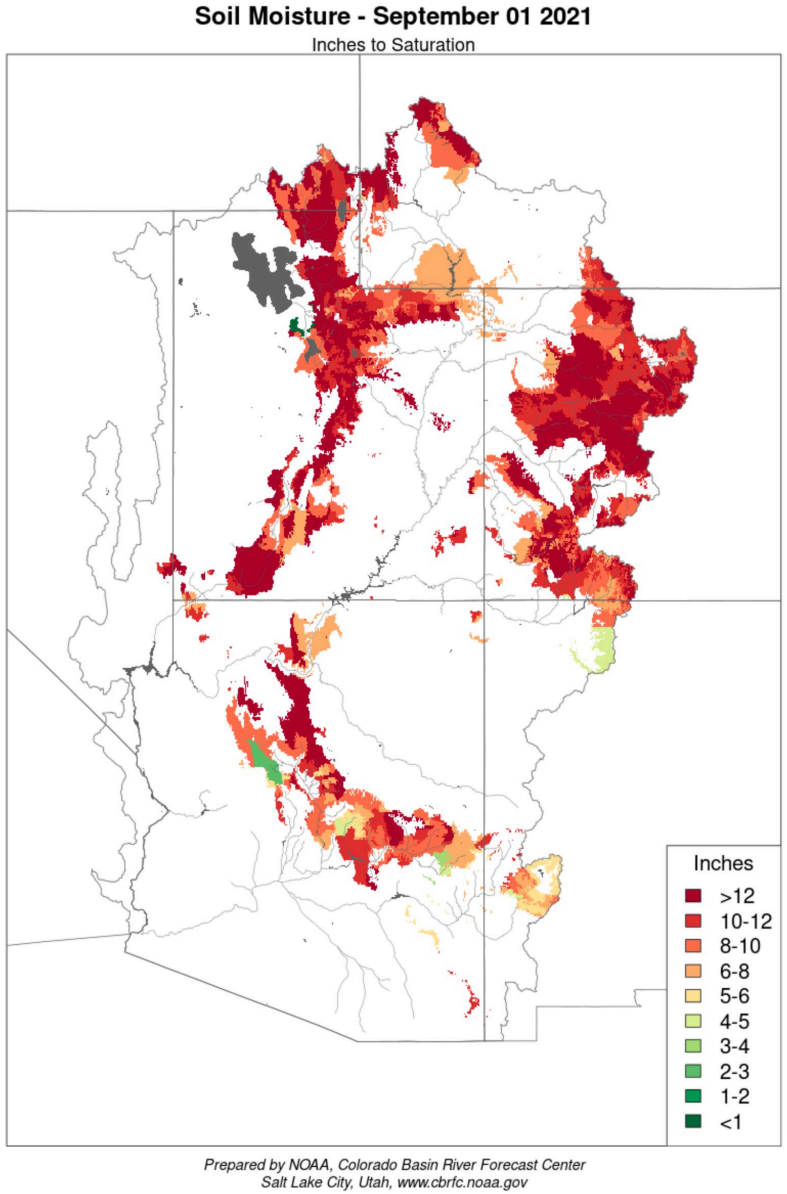
Das et al., 2012

Soil Moisture Comparison September 2020 vs September 2021

Despite good 2021 monsoon, soil moisture deficits persist.

2022 Runoff likely impacted.





Emerging Megadrought

Science, April 2020

DROUGHT

Large contribution from anthropogenic warming to an emerging North American megadrought

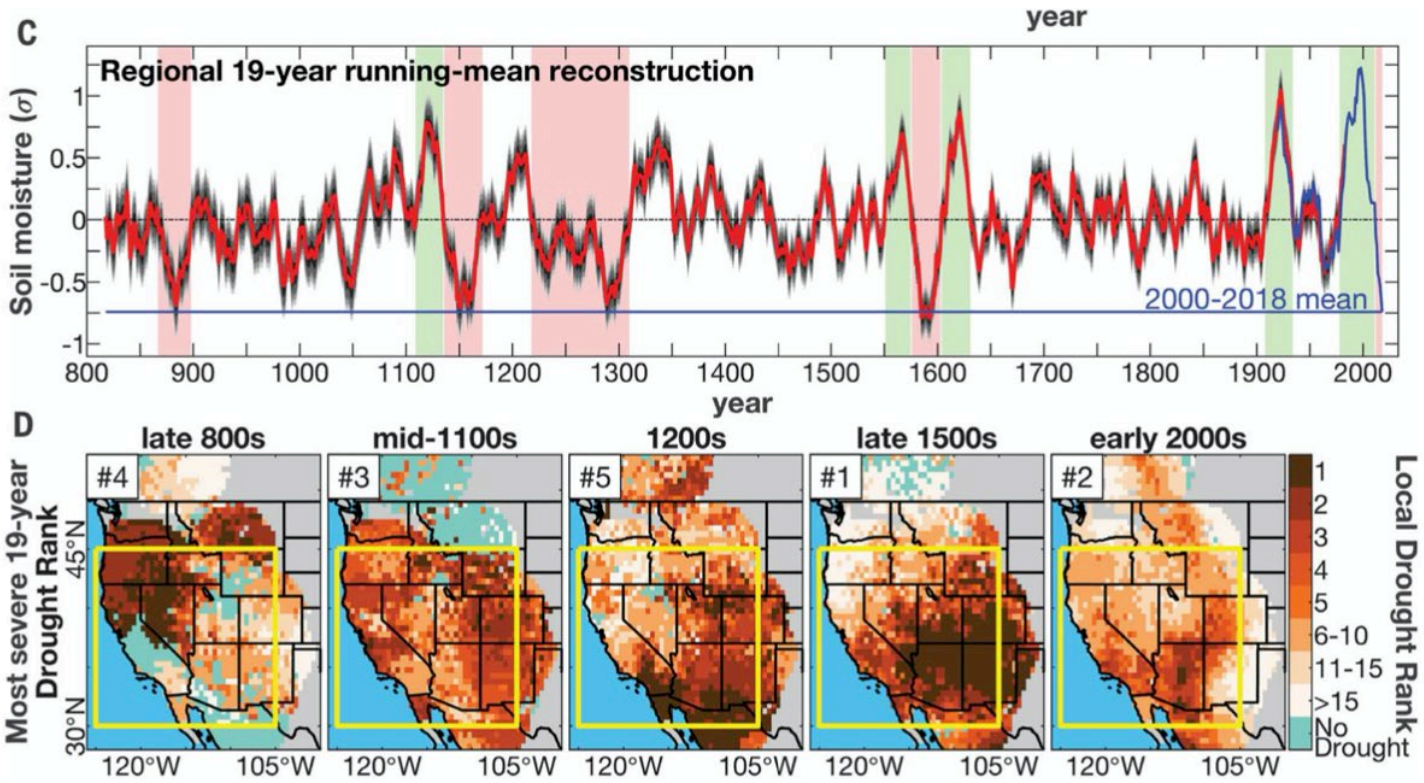
A. Park Williams[1]*, Edward R. Cook[1], Jason E. Smerdon[1], Benjamin I. Cook[1,2], John T. Abatzoglou[3,4], Kasey Bolles[1], Seung H. Baek[1,5], Andrew M. Badger[6,7,8], Ben Livneh[6,9]

2000—2018 2nd Driest 19-year period since 800 AD as measured by JJA Soil Moisture

Caused by Natural Variability aided by anthropogenic drying

About 50% due to humans

Without anthropogenic drying, would be a moderate drought



Westwide Aridification – Not a Drought

- Declining Snowpacks
- Earlier runoff
- More rain, less snow
- Higher Temperatures: >1.25°C
- Drying Soils
- Severe Fires
- Forest Mortality
- Warm Thirsty Atmosphere (holds more moisture)
- Northward moving storm tracks (less certain, but a worry)
- Shorter Winter
- Megadrought

COMMENTARY

Climate change and the aridification of North America

Jonathan T. Overpeck[a,b,1] and Bradley Udall[b,c]

Discussions of droughts and their impacts often center on the lack of precipitation, just as assessments of hydrologic impacts under a changing climate most often focus on how average precipitation in a given locale is likely to change in the future. Within climate science, however, focus has begun to include the growing role warming temperatures are playing as a potent driver of greater aridity: hotter climate extremes; drier soil conditions; more severe drought; and the impacts of hydrologic stress on rivers, forests, agriculture, and other systems. This shift in the hydrologic paradigm is most clear in the American Southwest, where declining flows in the region's two most important rivers, the Colorado (Fig. 1) and Rio Grande, have been attributed in part to increasing temperatures caused by human activities, most notably the burning of fossil fuels (1–5). Warmer summers are also likely to reduce flows in the Columbia River, as well as in rivers along the Sierra Nevada in California (6). Now, an important study (7) documents how warming is also causing flow declines in the northern Rocky Mountains and in the largest river basin in the United States, the Missouri. This work further highlights the mechanisms behind the temperature-driven river flow declines and places more focus on how anthropogenic climate warming is progressively increasing the risk of hot drought and more arid conditions across an expanding swath of the United States.

The work by Martin et al. (7) on the temperature-driven flow reductions in the Upper Missouri River has broader implications. As they note, many aspects of river management could be increasingly impacted by a more arid river basin, including agricultural water deliveries, river management and navigation, and ecosystem services associated with the river; economies of a large region will likely suffer if the aridification continues. This mirrors the change occurring in the Southwest, where rivers provide the only large sustainable water supply to the region and more than 40 million water users, yet flows have already declined significantly since just the late 20th century (3, 4).

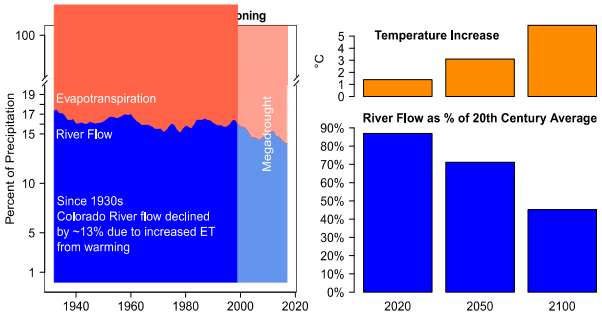


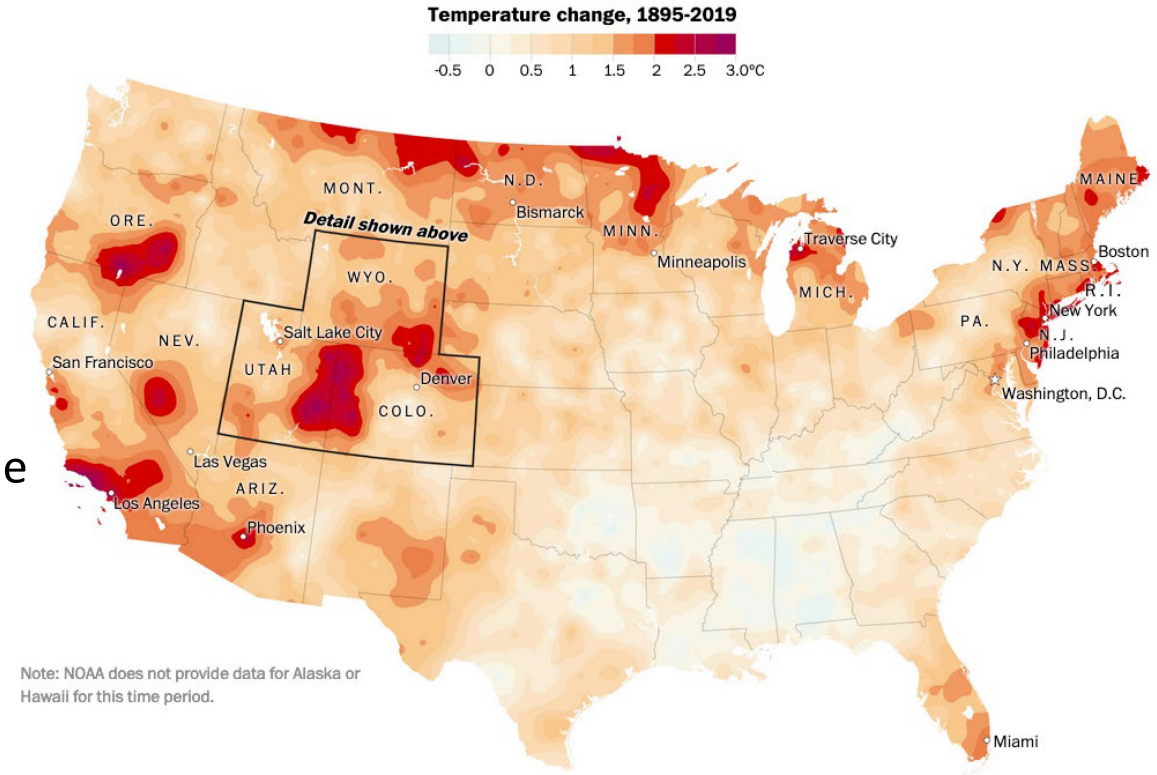
Fig. 1. Climate change is causing the Southwest to aridify. (*Left*) Since the 1930s, increasing temperatures have caused the percentage of precipitation going to evapotranspiration (ET) to increase at the expense of precipitation going to Colorado River flow, resulting in an unprecedented and still ongoing megadrought (shading) starting in 1999 (8). (*Right*) Higher temperatures have already reduced Colorado River flow by 13%, and projected additional warming, assuming continued high emissions of greenhouse gases, will increase ET while reducing river flow even more through the 21st century. Data on *Left* are 20-y running means from ref. 5, and data on *Right* are calculated from Representative Concentration Pathways (RCP) 8.5 multimodel Coupled Model Intercomparison Project–Phase 5 (CMIP5) ensemble temperature increases projected for the Upper Colorado River Basin combined with temperature sensitivity of −9.3%/°C estimated by ref. 5, assuming no change in precipitation.

Across the US West, warming is also contributing to drier soils (8), widespread tree death (9), and more severe wildfires (10). The recent unprecedented drought conditions in California also have been tied to human-caused warming (11). Greater aridity is redefining the West in many ways, and the costs to human and natural systems will only increase as we let the warming continue.

Martin et al. (7) also highlight how increasing temperature-driven aridity is more often framed in the West in terms of episodic drought. Just as in the Southwest, where an unprecedented drought began in 1999 and has continued through 2020 with drier-than-normal soils, reduced river flows, and low levels in major reservoirs, the worst drought of the instrumental era gripped the Upper Missouri River Basin

Why are the 21st Century flows so different?

- 1. Temperature Increases
  - Increased Evaporation / Transpiration
    - Evaporation + Transpiration reduces flow this year
    - Soil Moisture reduces flow next year
  - Proven Connection to Climate Change (-9% / °C Increase ?)
- 2. Precipitation Decreases
  - New Findings
    - 2000-20 tied with worst 20th C 21-Year Period for Precipitation
    - Until recently, precip declines were not extreme
    - 3 of Last 4 years especially bad
  - Key Seasons / Months
    - More Summer declines than Winter
      - summer declines deplete soil moisture
    - March, April worrisome, too
      - early snow melt bad
  - Hints of Connection to Climate Change
    - Hoerling et al., 2019

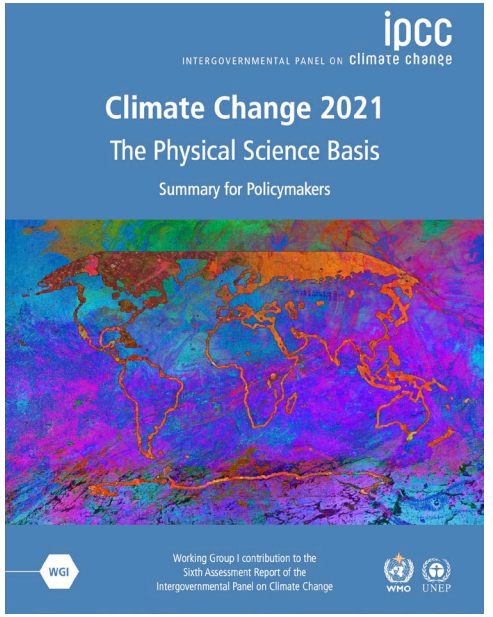


The Washington Post

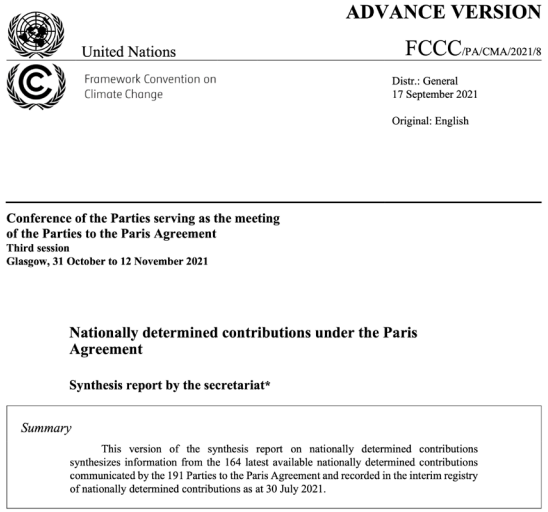
IPCC 6th Assessment Major Findings plus IPCC NDCs

- Humans have warmed all parts of our climate system
- Widespread and rapid changes have occurred
- Change is unprecedented over centuries to 1000s of years
- Weather and Climate Extremes across the globe affected
- Temperature will increase to at least mid-century
- 1.5°C and 2°C will be exceeded unless deep GHG reductions occur soon
- More warming means more harmful impacts
- Warming will intensify the hydrologic cycle
  - more floods and droughts
- Many changes are irreversible for centuries to millennia
- Low likelihood, high impact events can not be ruled out
- Lower emissions lead to noticeable temperature changes within 20 years

- Headed towards 2.7°C warming by 2100



August 7, 2021



ADVANCE VERSION

United Nations

Framework Convention on Climate Change

FCCC/PA/CMA/2021/8

Distr.: General
17 September 2021

Original: English

Conference of the Parties serving as the meeting of the Parties to the Paris Agreement
Third session
Glasgow, 31 October to 12 November 2021

Nationally determined contributions under the Paris Agreement

Synthesis report by the secretariat*

Summary

This version of the synthesis report on nationally determined contributions synthesizes information from the 164 latest available nationally determined contributions communicated by the 191 Parties to the Paris Agreement and recorded in the interim registry of nationally determined contributions as at 30 July 2021.

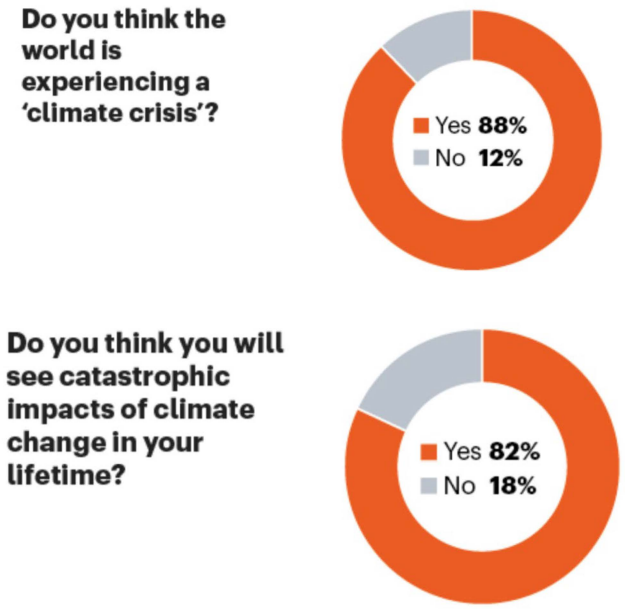
September 17, 2021

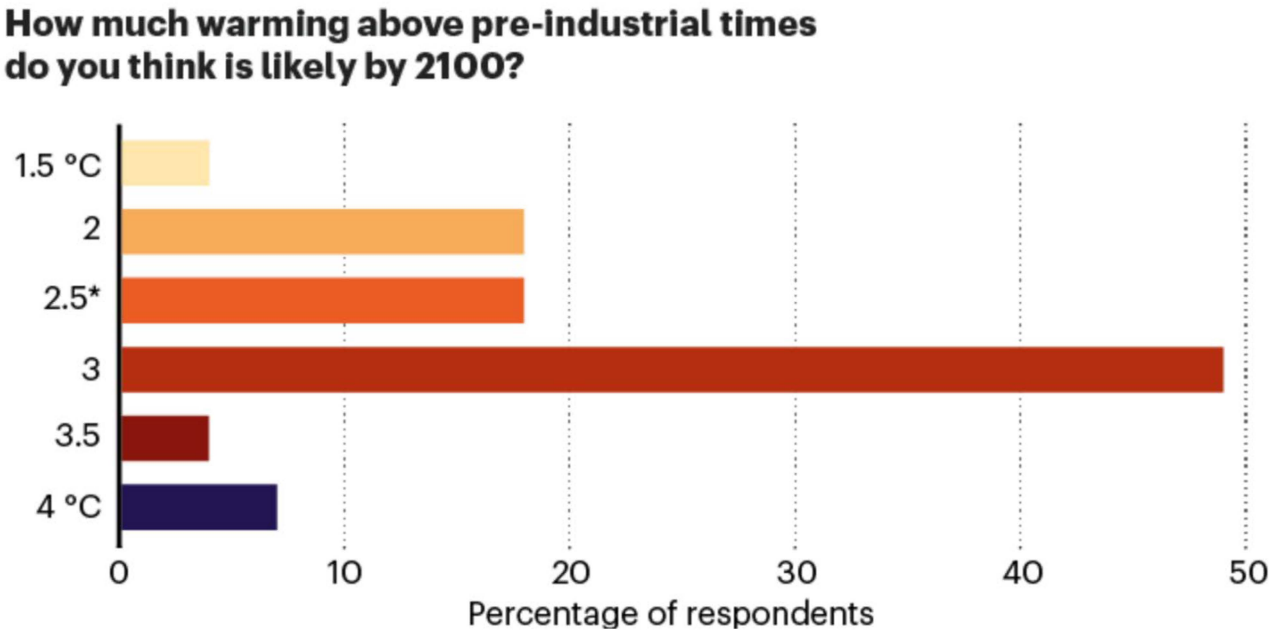
nature

NEWS FEATURE | 01 November 2021

Top climate scientists are sceptical that nations will rein in global warming

A *Nature* survey reveals that many authors of the latest IPCC climate-science report are anxious about the future and expect to see catastrophic changes in their lifetimes.





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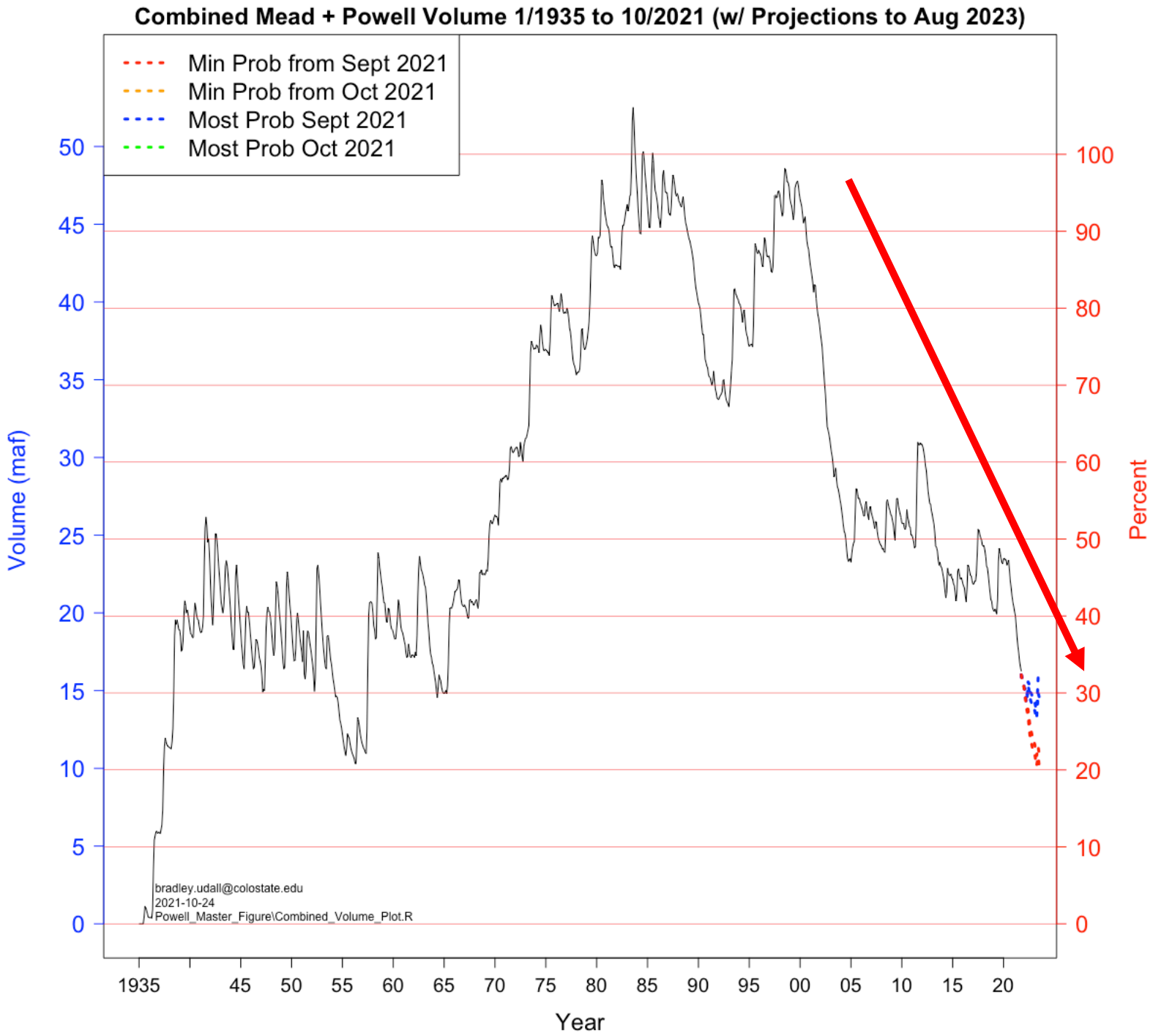
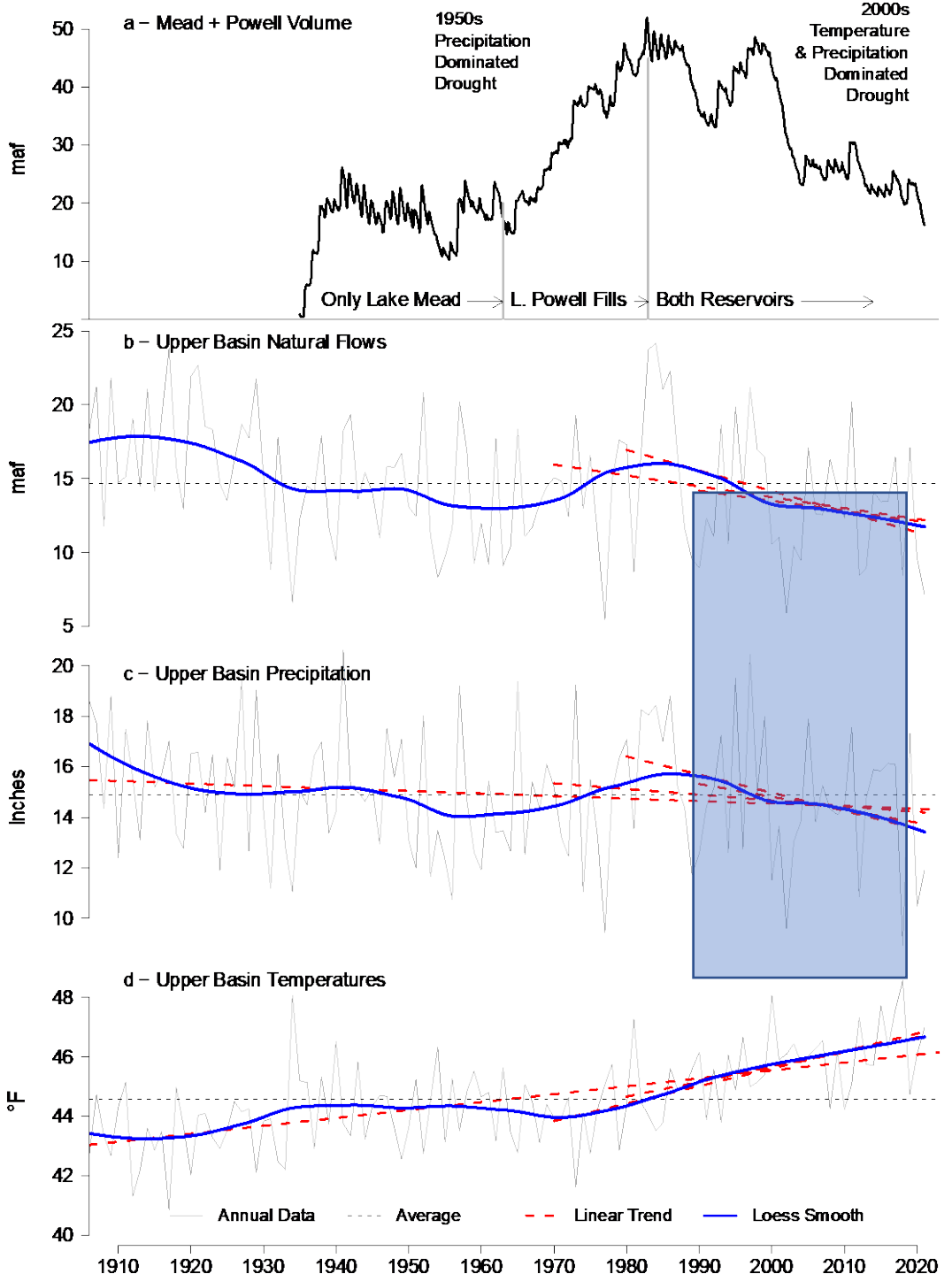
Loss of 32 MAF or 1.4
MAF/Year



Colorado River Basin Trends

- All Trend Lines in Wrong Direction
- Tier 1 Shortage in 2022
- Projections of up to 40% flow loss by Mid-Century
- 2027 New Management Rules in Place
- 2000-2021 Flows/Precip Downward shift in Highs and Lows

Udall and Overpeck, 2017
Milly and Dunne, 2020



2007 Interim Guidelines Shortage Reductions and Incremental DCP Contributions

Lake Mead Elevation	AZ 2007	AZ DCP	AZ TOTAL	NV 2007	NV DCP	NV TOTAL	CA 2007	CA DCP	CA TOTAL	BOR DCP	MX Min 323	MX BWSCP	MX Total	TOTAL
≤1090 >1075	0	192K	192K	0	8K	8K	0	0	0	100k	0	41k	41k	341k
≤1075>1050	320K	192K	512K	13K	8K	21K	0	0	0	100k	50k	30k	80k	713k
≤1050>1045	400K	192K	592K	17K	8K	25K	0	0	0	100k	70k	34k	104k	821k
≤1045>1040	400K	240K	640K	17K	10K	27K	0	200K	200K	100k	70k	76k	146k	1,113k
≤1040>1035	400K	240K	640K	17K	10K	27K	0	250K	250K	100k	70k	84k	154k	1,171k
≤1035>1030	400K	240K	640K	17K	10K	27K	0	300K	300K	100k	70k	92k	162k	1,229k
≤1030>1025	400K	240K	640K	17K	10K	27K	0	350K	350K	100k	70k	101k	171k	1,288k
≤1025	480K	240K	720K	20K	10K	30K	0	350K	350K	100k	125k	150k	275k	1,475k

2022

Los Angeles Times

California, Arizona and Nevada in talks on new plan to save Colorado River water

BY IAN JAMES | STAFF WRITER

NOV. 17, 2021 5 AM PT

The 500+ Plan

CA, NV, AZ trying to save additional 500 kaf in 2022 and 2023

Would Boost Mead by 16 Feet over 2 years

Ideally, 5-Year Plan Through 2026 (End of DCP+IG)

$100m / Year = $200 / AF

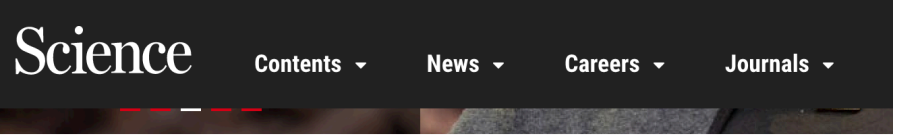
Colorado River states balk at adjusting water shares to deal with crisis

tucson.com

Tony Davis Nov 27, 2021 Updated 6 hrs ago

"Our challenge now is not reallocating water," wrote Arizona Department of Water Resources Director Tom Buschatzke. "Our challenge is to collaborate to address the increasing hydrologic risks by developing additional innovative and proactive measures, including either voluntary or mandatory conservation."

Reasonable Worst Case Planning



Contents

28 MAY 2021
VOL 372, ISSUE 6545

THIS WEEK IN *SCIENCE*

Research in *Science* journals.

SCIENCE | 28 MAY 2021 : 929 |

Full Text PDF

EDITORIAL

Managing Colorado River risk

BY JOHN FLECK, BRAD UDALL

SCIENCE | 28 MAY 2021 : 885 |

Summary Full Text PDF

Managing Colorado River Risk Science May 28, 2021

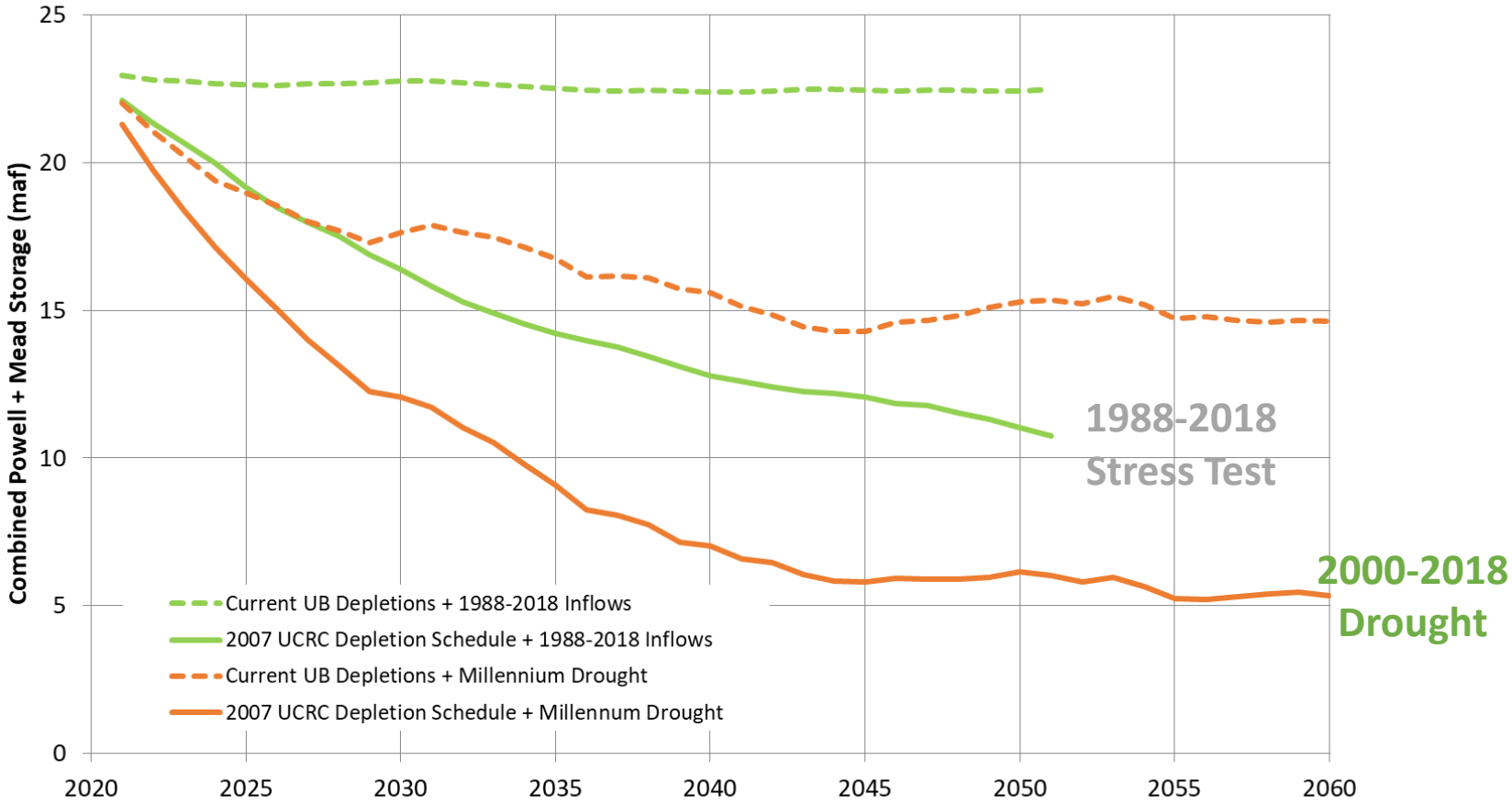
"As the basin's water management community prepares for a new round of negotiations over the water allocation rules, how bad of a "worst case scenario" should be considered and who will get less water as a result? It is tempting to use today's 20% flow decline as the new baseline—that is, modeling future reductions on the basis of what has already been observed. But only by planning for even greater declines can we manage the real economic, social, and environmental risks of running low on a critical resource upon which 40 million North Americans depend."

Existing Supply – Demand Balance is tenuous

MAIN MESSAGE:
If Upper Basin demands do not increase
AND
recent flows are representative of future runoff, then the system would stay at "sustainable" but low levels

Wheeler et al., 2021

Combined Mead + Powell Storage



With UCRC Projections

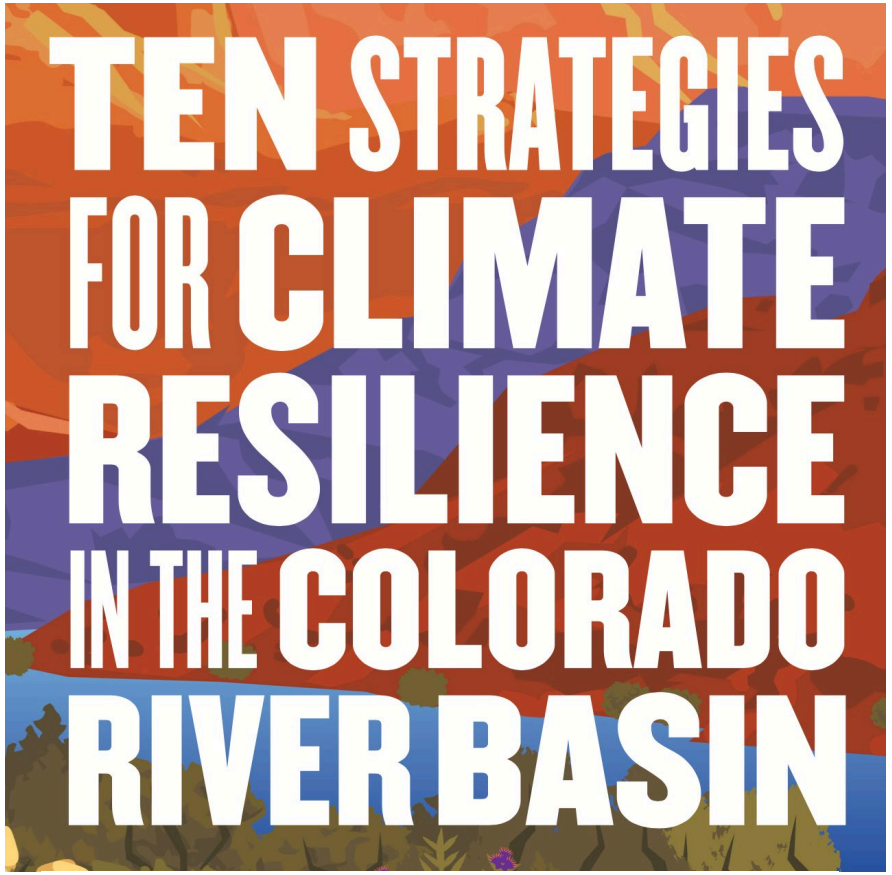
No Upper Basin Increase

Potential CRB Solutions

Solution Lens: adapt, reduce, mitigate, strengthen

1. Forest Management and Restoration
2. Natural Distributed Storage
3. Regenerative Ag
4. Upgrade Ag Infrastructure + Operations
5. Crop Alternatives
6. Urban Conservation and Reuse
7. Industrial Conservation and Reuse
8. Coal Plant Retirement Water
9. Reduce Dust on Snow
10. Covering Reservoirs and Canals

www.tenstrategies.net



REPORT TEAM

MARTIN & McCOY

Culp & Kelly LLP

The Nature Conservancy

EDF Environmental Defense Fund — Finding the ways that work

Audubon

Western Resource Advocates — Protecting the West's Land, Air & Water

American Rivers — Rivers Connect Us

Trout Unlimited

Theodore Roosevelt Conservation Partnership

Brad Udall
Bradley.Udall@colostate.edu
@bradudall

Dan McCool Op-Ed

3 Fundamental Errors
1. Flawed Data
2. Fixed Allocations
3. No Native American Participation

Proposed Solution
Use Percentages based on 5-year rolling average

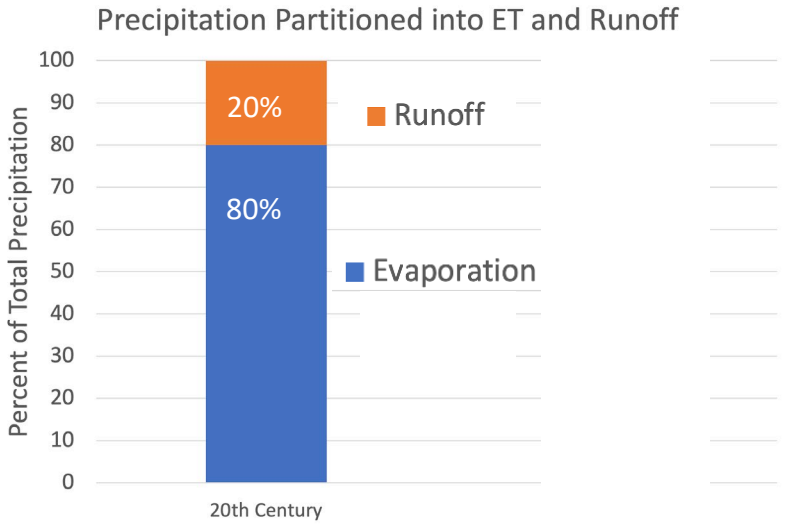
As climate change parches the Southwest, here's a better way to share water from the shrinking Colorado River

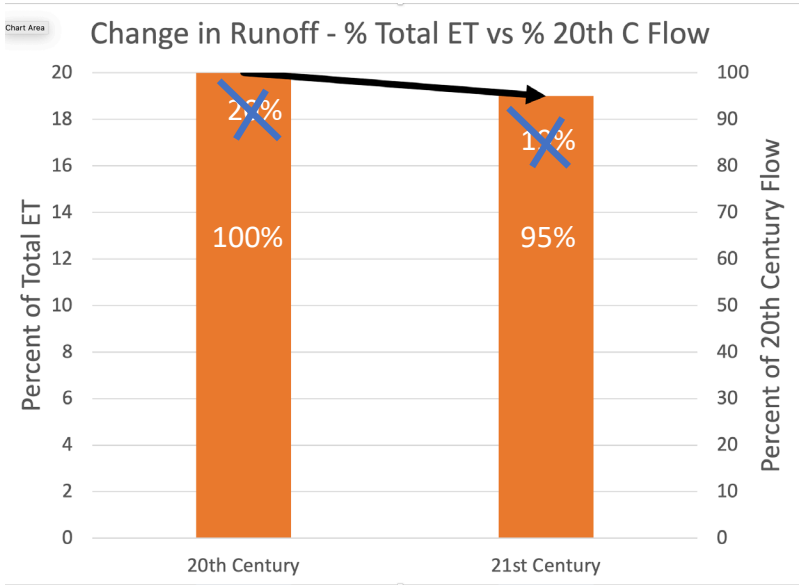
November 17, 2021 8.18am EST

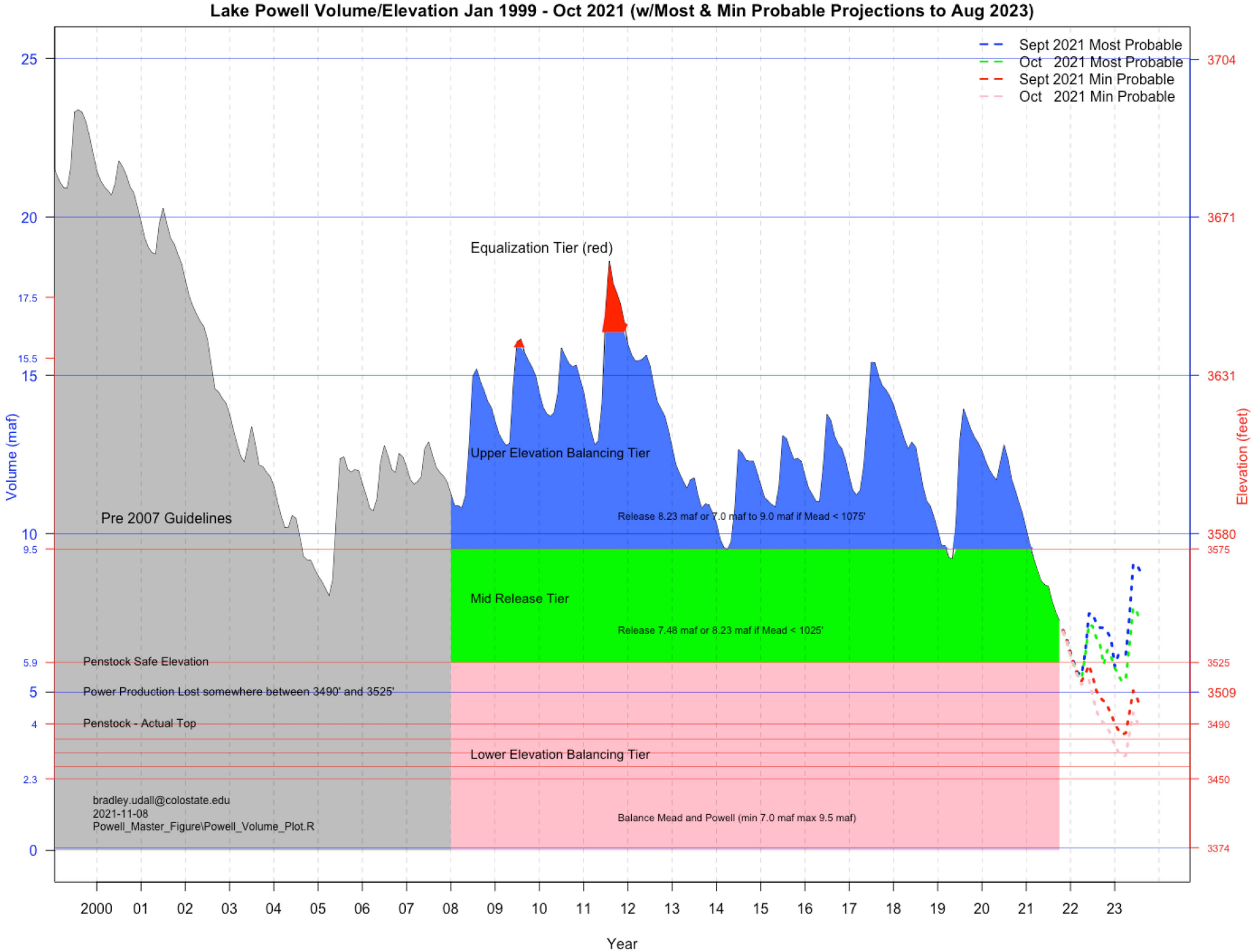
Why does Increased Evaporation / Transpiration lead to lower River Flow ? A thought experiment

- In CRB 80% of Precipitation Evaporates/Transpires (ET) back to atmosphere
- Remaining 20% is river flow
- In hotter world, any given day hotter, longer growing season, thirstier atmosphere
  - 80% can easily increase to 81% or more
  - But that means the remainder for river flow is 19% or less
- 1% increase in ET / 1% decrease in river flow seems small
- But river users don't know / don't care about river flow in terms of % of ET
- All they know is that now they have 19/20 (95% or -5%) of previous flow

- Take Home: Small 1% increase in ET makes for large 5% decrease in river flow






Lake Powell Volume/Elevation Jan 1999 - Oct 2021 (w/Most & Min Probable Projections to Aug 2023)
Sept 2021 Most Probable
Oct 2021 Most Probable
Sept 2021 Min Probable
Oct 2021 Min Probable
Equalization Tier (red)
Upper Elevation Balancing Tier
Release 8.23 maf or 7.0 maf to 9.0 maf if Mead < 1075'
Pre 2007 Guidelines
Mid Release Tier
Release 7.48 maf or 8.23 maf if Mead < 1025'
Penstock Safe Elevation
Power Production Lost somewhere between 3490' and 3525'
Penstock - Actual Top
Lower Elevation Balancing Tier
Balance Mead and Powell (min 7.0 maf max 9.5 maf)
bradley.udall@colostate.edu
2021-11-08
Powell_Master_Figure\Powell_Volume_Plot.R
Volume (maf)
Elevation (feet)
Year
25
20
17.5
15.5
15
10
9.5
5.9
5
4
2.3
0
3704
3671
3631
3580
3575
3525
3509
3490
3450
3374
2000
01
02
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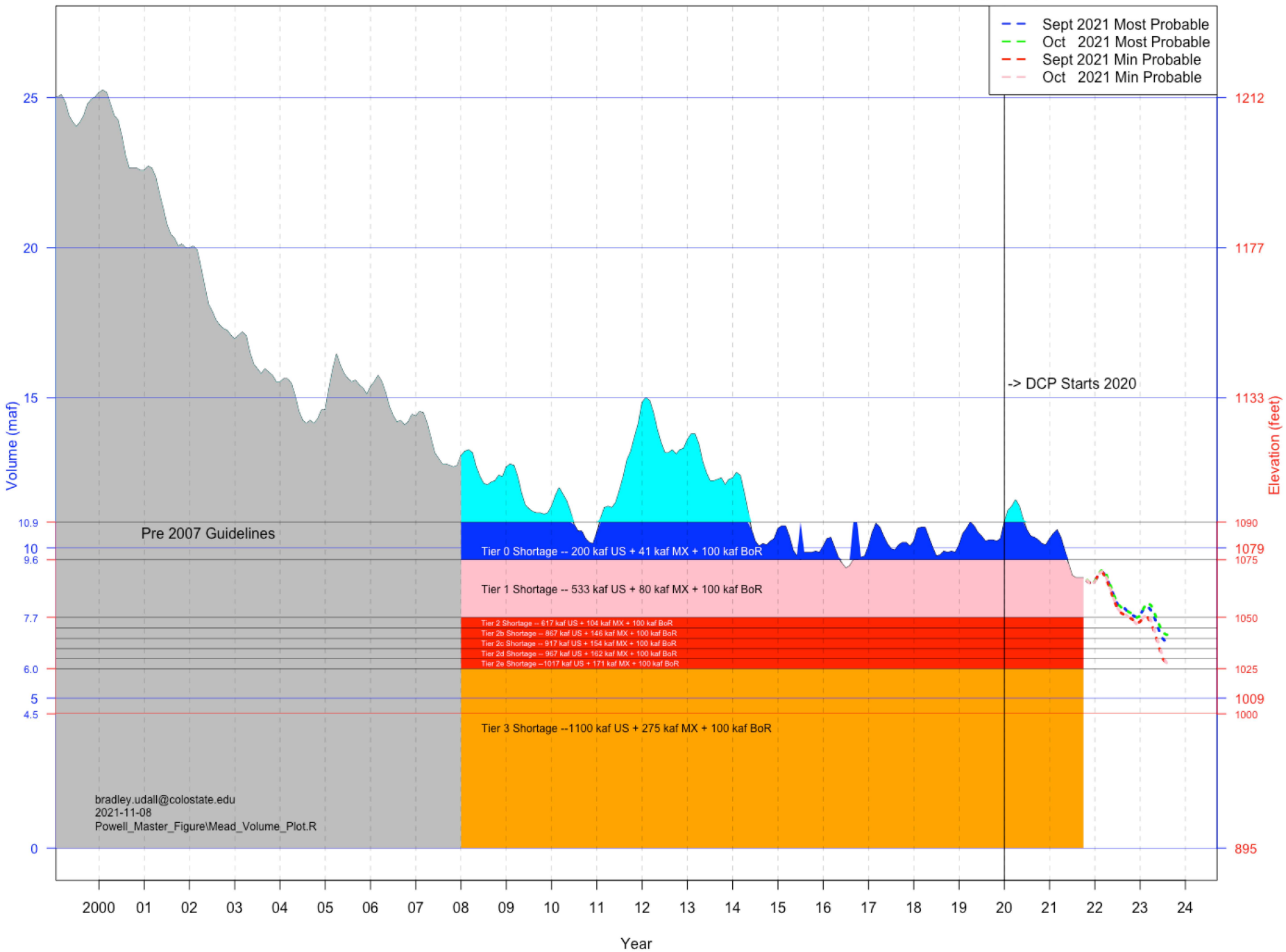
Lake Mead Volume Jan 1999- Sep 2021 (w/ Most & Min 24-Month Study Projections to Aug 2023)
Sept 2021 Most Probable
Oct 2021 Most Probable
Sept 2021 Min Probable
Oct 2021 Min Probable
-> DCP Starts 2020
Pre 2007 Guidelines
Tier 0 Shortage -- 200 kaf US + 41 kaf MX + 100 kaf BoR
Tier 1 Shortage -- 533 kaf US + 80 kaf MX + 100 kaf BoR
Tier 2 Shortage -- 617 kaf US + 104 kaf MX + 100 kaf BoR
Tier 2b Shortage -- 867 kaf US + 146 kaf MX + 100 kaf BoR
Tier 2c Shortage -- 917 kaf US + 154 kaf MX + 100 kaf BoR
Tier 2d Shortage -- 967 kaf US + 162 kaf MX + 100 kaf BoR
Tier 2e Shortage --1017 kaf US + 171 kaf MX + 100 kaf BoR
Tier 3 Shortage --1100 kaf US + 275 kaf MX + 100 kaf BoR
bradley.udall@colostate.edu
2021-11-08
Powell_Master_Figure\Mead_Volume_Plot.R
Volume (maf)
Elevation (feet)
Year
25
20
15
10.9
10
9.6
7.7
6.0
5
4.5
0
1212
1177
1133
1090
1079
1075
1050
1025
1009
1000
895
2000
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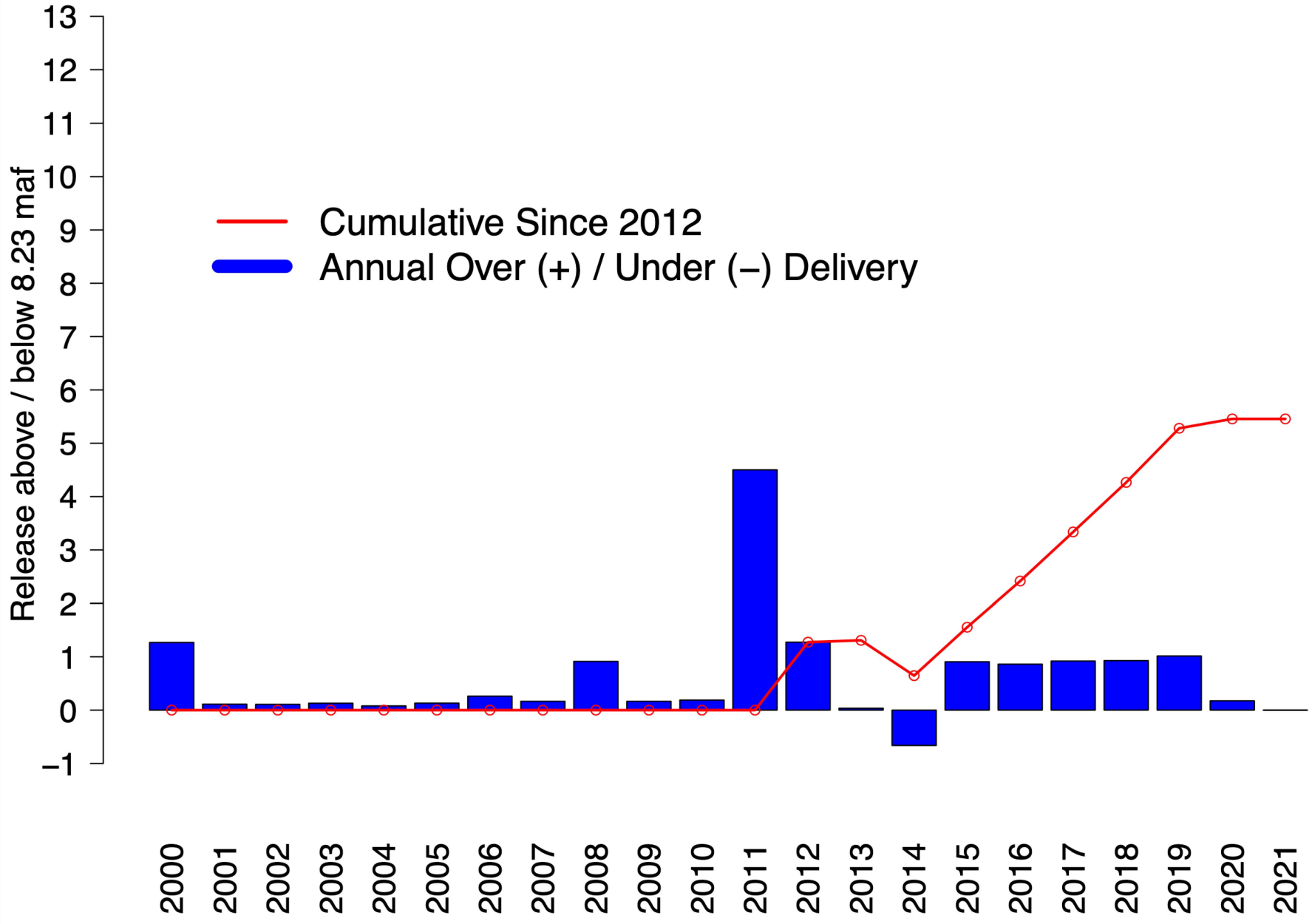
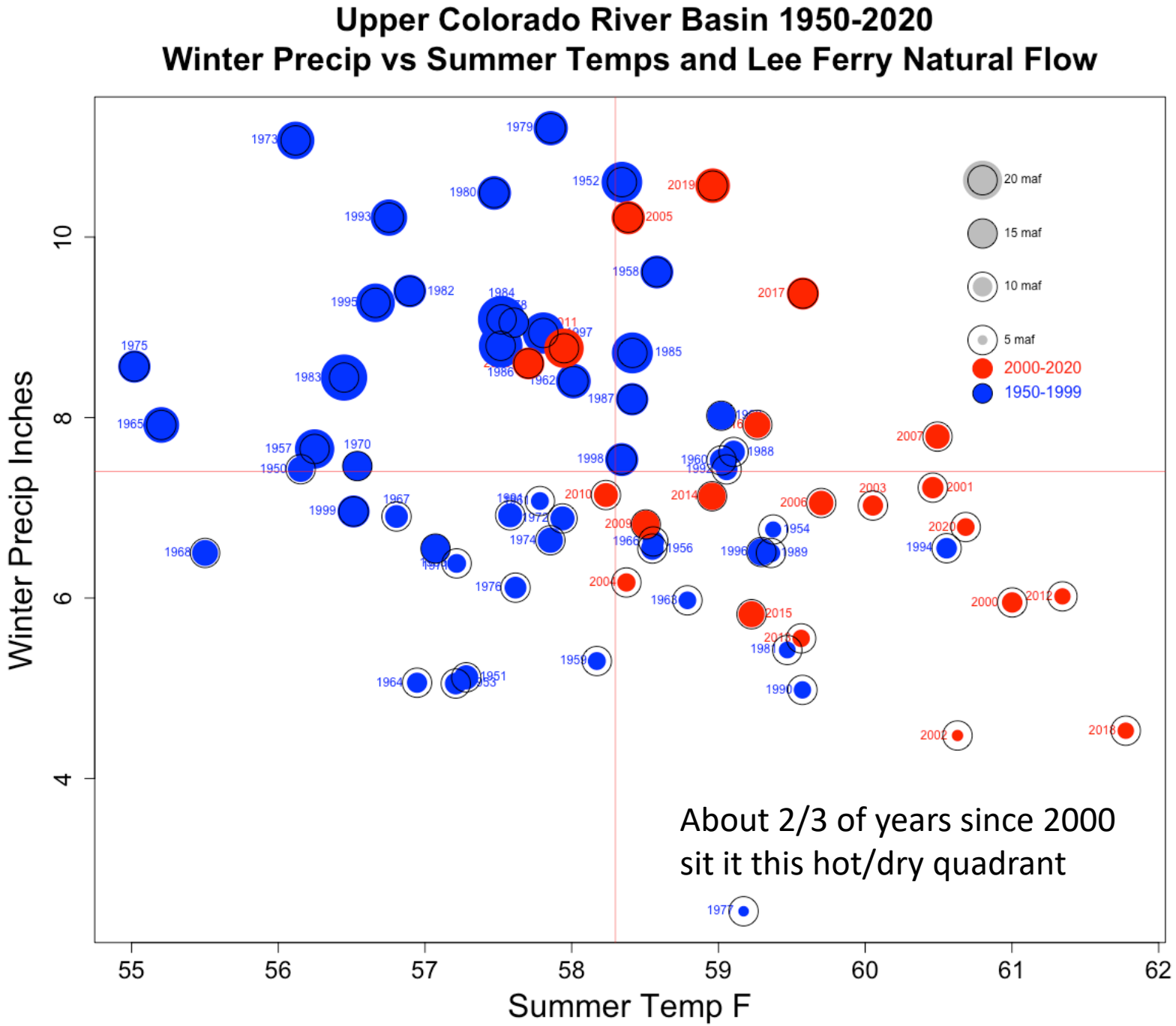
Lee Ferry Flow Above/Below 8.23 maf/year
2000 – 2021



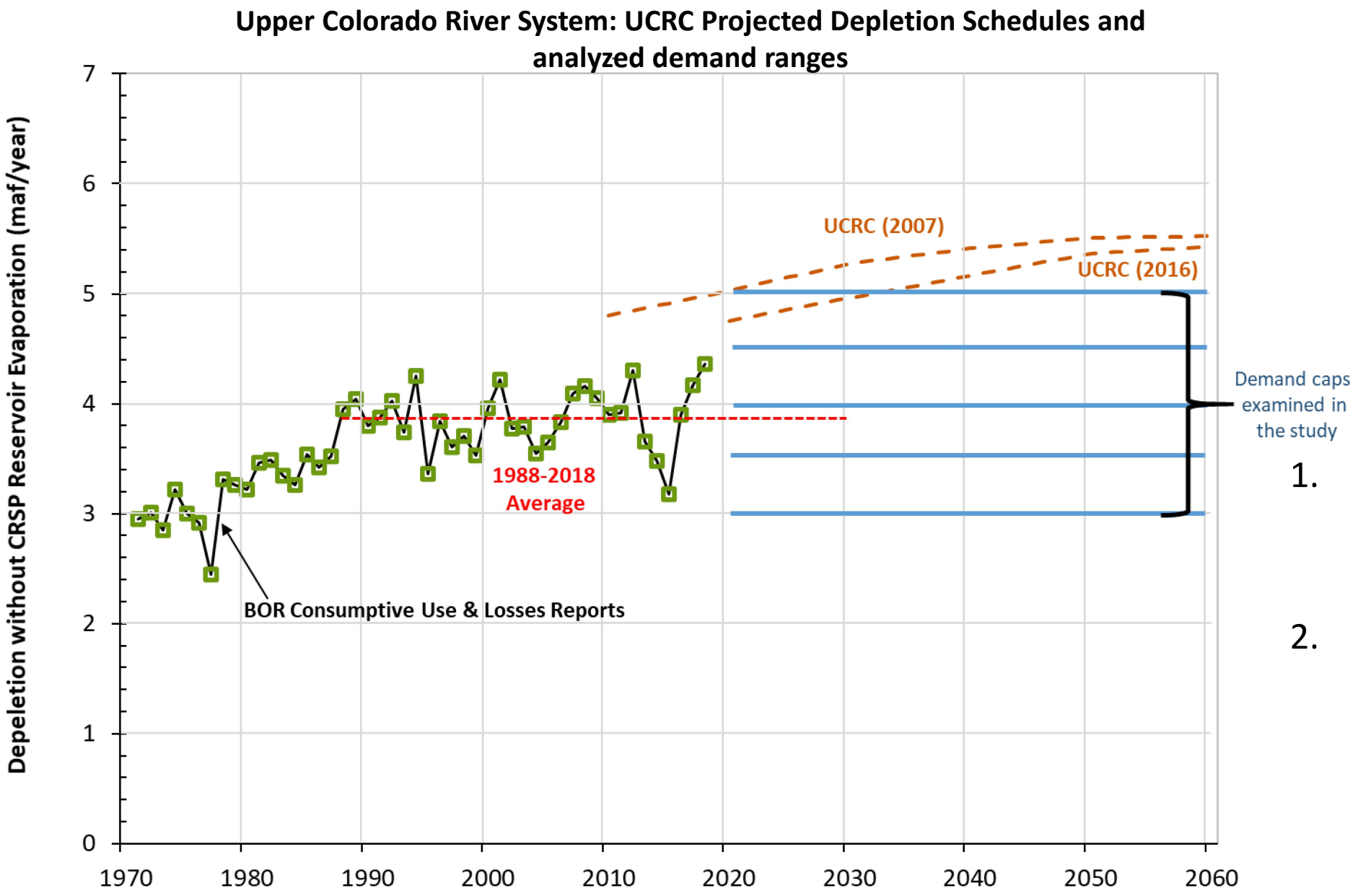
Colorado River: Non-Stationarity Evident

- Warming Everywhere
- Record Setting Drought
- Temperature Induced Losses
- Snow Loss
- Earlier Runoff
- Less Productive Runoff
- Recent precipitation declines
- Dust



Prudent Planning and “Reasonable Worst-Case Future”

- What scenarios should we be modeling for?
  - Water-supply policy is ultimately a political / policy decision, informed by science
  - **We suggest: “Reasonable Worst-Case Future”**
    - Definition: Future that is both politically possible to plan for, and climatologically possible, without being on the extreme tail of any distribution
- What science should inform that decision?
  - Known Science
    - Past 21 years of flows, precipitation and temperature
    - Temperature impacts on flow
    - Future temperature projections
    - **All evidence points to declining flows**
  - Unknown Science – mostly precipitation
    - Low confidence in projected increases
    - Might save the day, but is it prudent to count on this?
    - Precipitation might also decrease – see Hoerling et al, 2019
- **Ultimately a Policy Decision of What is Prudent and Possible to Plan For**
  - Balancing of politically Possible and climatologically Problematic
  - **Prudence dictates modeling using flows less than last 21 years, <u>but how much less</u>?**



1. Small difference between 2007 and 2016 UCRC Schedules
2. We analyzed a wide range of Upper Basin capped depletions
   - 5.0 maf
   - 4.5 maf
   - 4.0 maf
   - 3.5 maf
   - 3.0 maf

On the causes of declining Colorado River streamflows

Mu Xiao, Bradley Udall, Dennis P. Lettenmaier

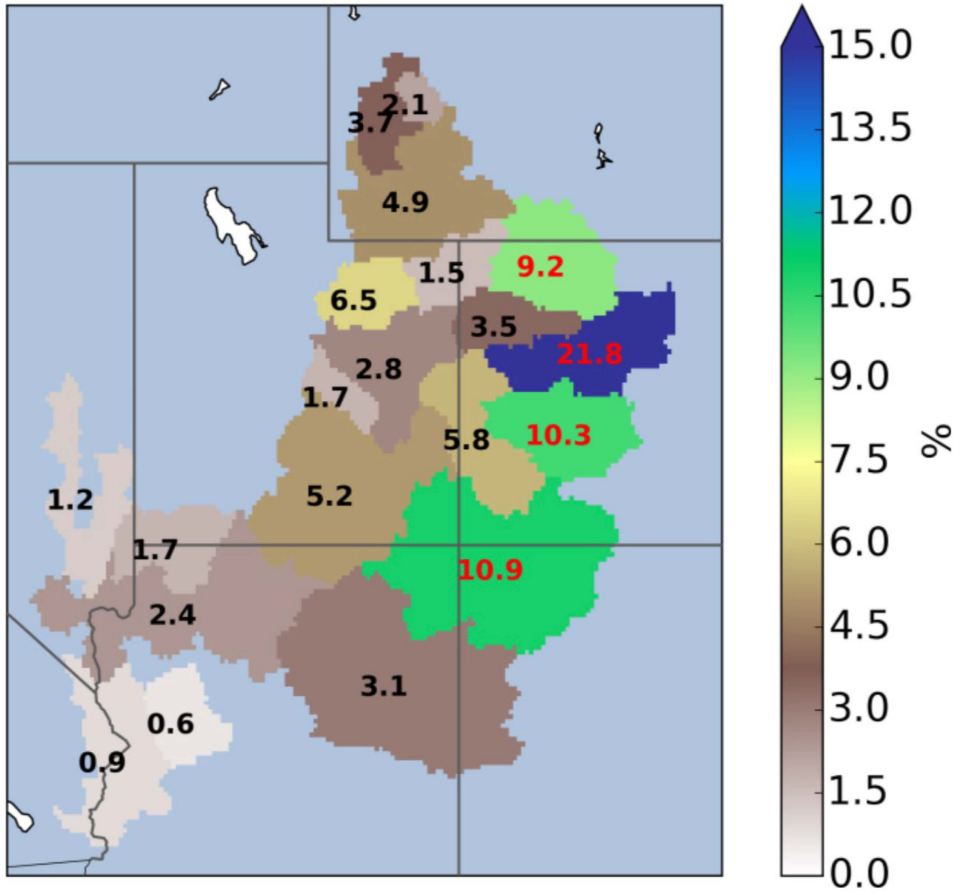
First published: 30 August 2018 | https://doi.org/10.1029/2018WR023153

Model-based Study using Historical Data

Findings

- ~50% of Decline due to Higher Temperatures
- More Evaporation of all kinds

- ~50% of Decline due to Changing Precipitation Patterns
- Shift to less productive basins



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

Water Resources Research
AN AGU JOURNAL
Research Article

Is the Colorado River "Stress Test" stressful enough?

Posted by jfleck on 22 July 2021, 5:57 pm

BY BRAD UDALL AND JOHN FLECK

Earlier this year, we argued in a Science magazine editorial that Colorado River forecasting must take the growing risk of climate change seriously. The latest five-year projections from the U.S. Bureau of Reclamation offer a practical example of the challenge.

Published July 8 (see here and here) with an accompanying news release, the projections suggested that if the trends of the last 30-plus years continues, there is a 79 percent chance that Lake Powell could drop next year below elevation 3,525 – a danger zone for managing power production and releases to the Lower Basin going forward. With the reservoirs behind Hoover and Glen Canyon dams expected to drop below 30% by early 2022, these projections take on a new importance — we no longer have a huge water buffer to protect us from future low flow years.

It is stark news. But perhaps not stark enough.

This forecast takes advantage of an important new tool Reclamation has invested in called the "Stress Test" to give us a sense of the future risks we face.

The Stress test goes beyond the old "the future will be like the past" scenario building we have used in the past on the Colorado River. This new tool takes an important step toward incorporating climate change. But we are concerned that it doesn't go far enough.

Causes for the Century-Long Decline in Colorado River Flow

Hoerling, Barsugli, Livneh, Eischeid, Quan, Badger, 2019

Sophisticated Multi-model Multi-Ensemble GCM Effort with and without added greenhouse gasses

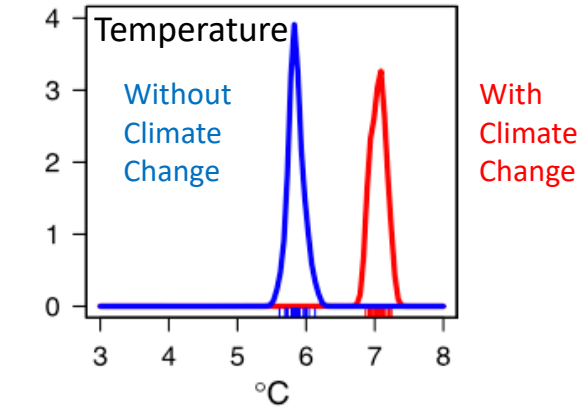
- 20% Flow Decline over last century
- 50% of that due to climate change (i.e. 10% flow loss)
- Climate models show 1.2°C warming and 3% precip decline

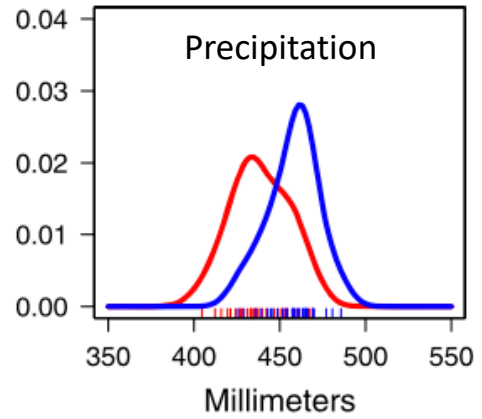
- Precipitation Elasticity of ~ 2
- Temperature Sensitivity of ~ -2.5% to -7% /°C

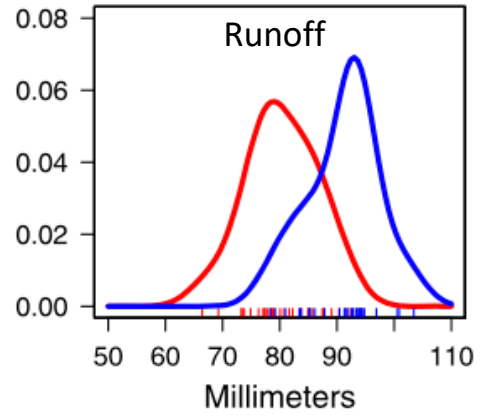
- Warming is 1/3 of the decline (~3 % of flow)
- Precipitation Loss is 2/3 of decline (~7 % of flow)

- What's New:
- 1. Attribution of 1981- 2010 precipitation decline to climate change
- 2. Lower Temperature Sensitivity

Climate Model Results 1981-2010







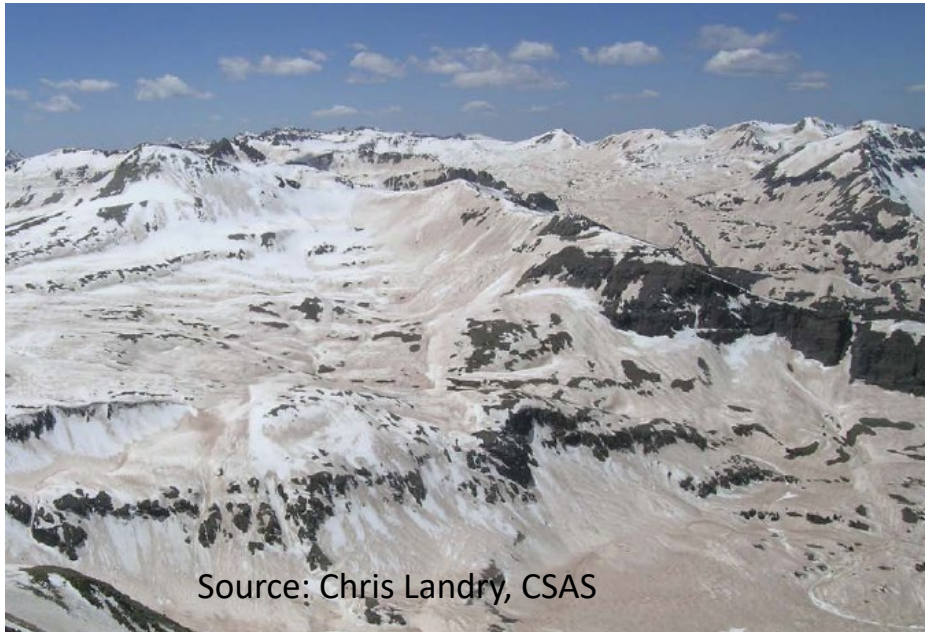
Dust on Snow Reduces Runoff, Shifts Timing

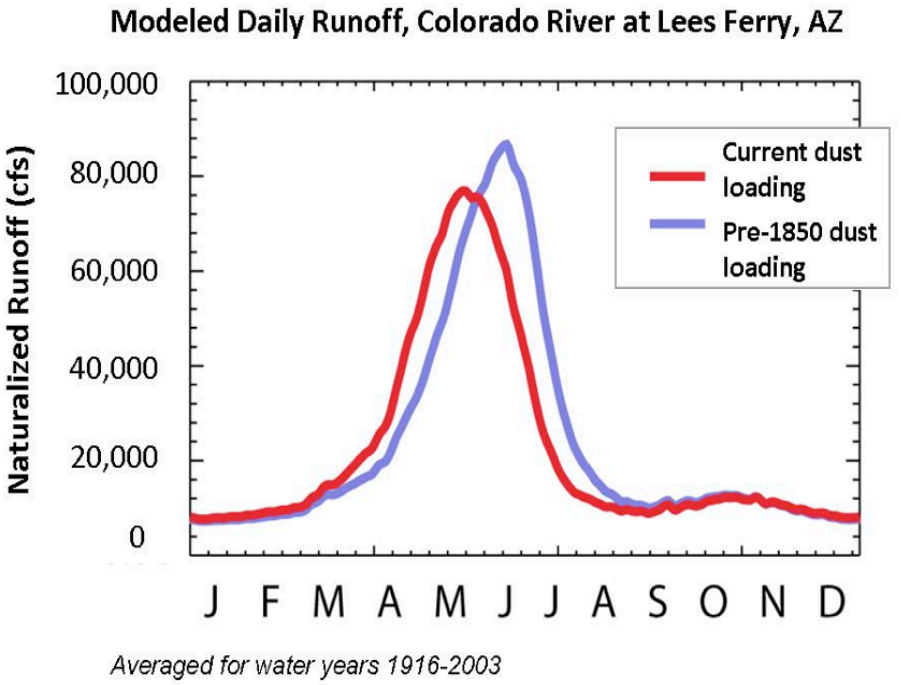
- Dust is causing earlier snowmelt
- Runoff occurring 3 weeks earlier
- Reduced UCRB flow by ~5%
- Super Dusty Conditions advance runoff by 6 weeks, reduce flow by about ~6%

Why: dark surface absorbs more energy

Dust Source: NE Arizona, S. Utah

Sources: Painter et al., 2010, Deems et al., 2013





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