Climate change's complex effects on the water cycle

Boulder County Nature Association

September 23, 2023

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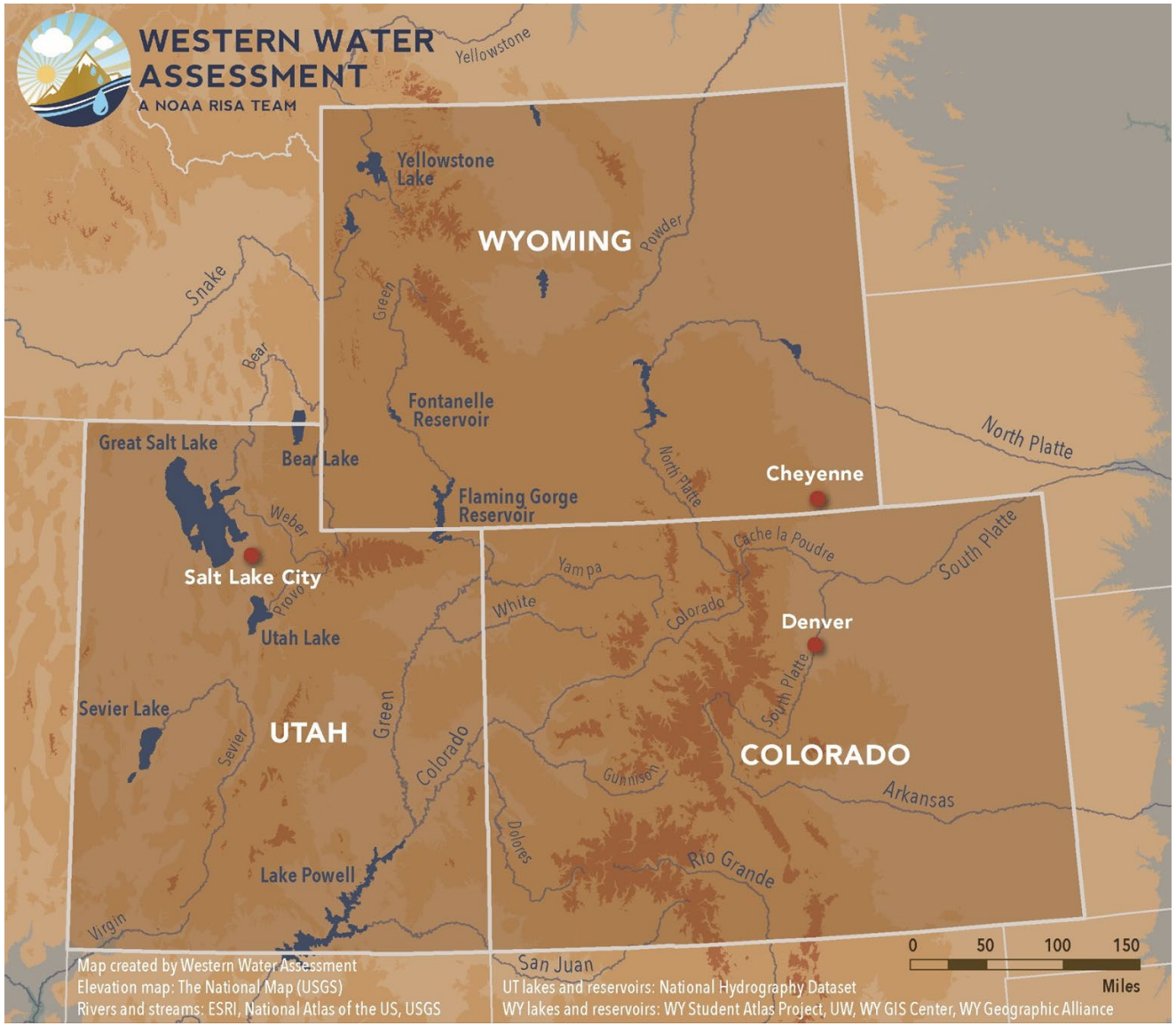
Western Water Assessment

Cooperative Institute for Research in Environmental Sciences

University of Colorado Boulder

Photo: Missouri Lakes, Sheelah Brennan, https://unsplash.com/photos/xd0KIcVHsYk

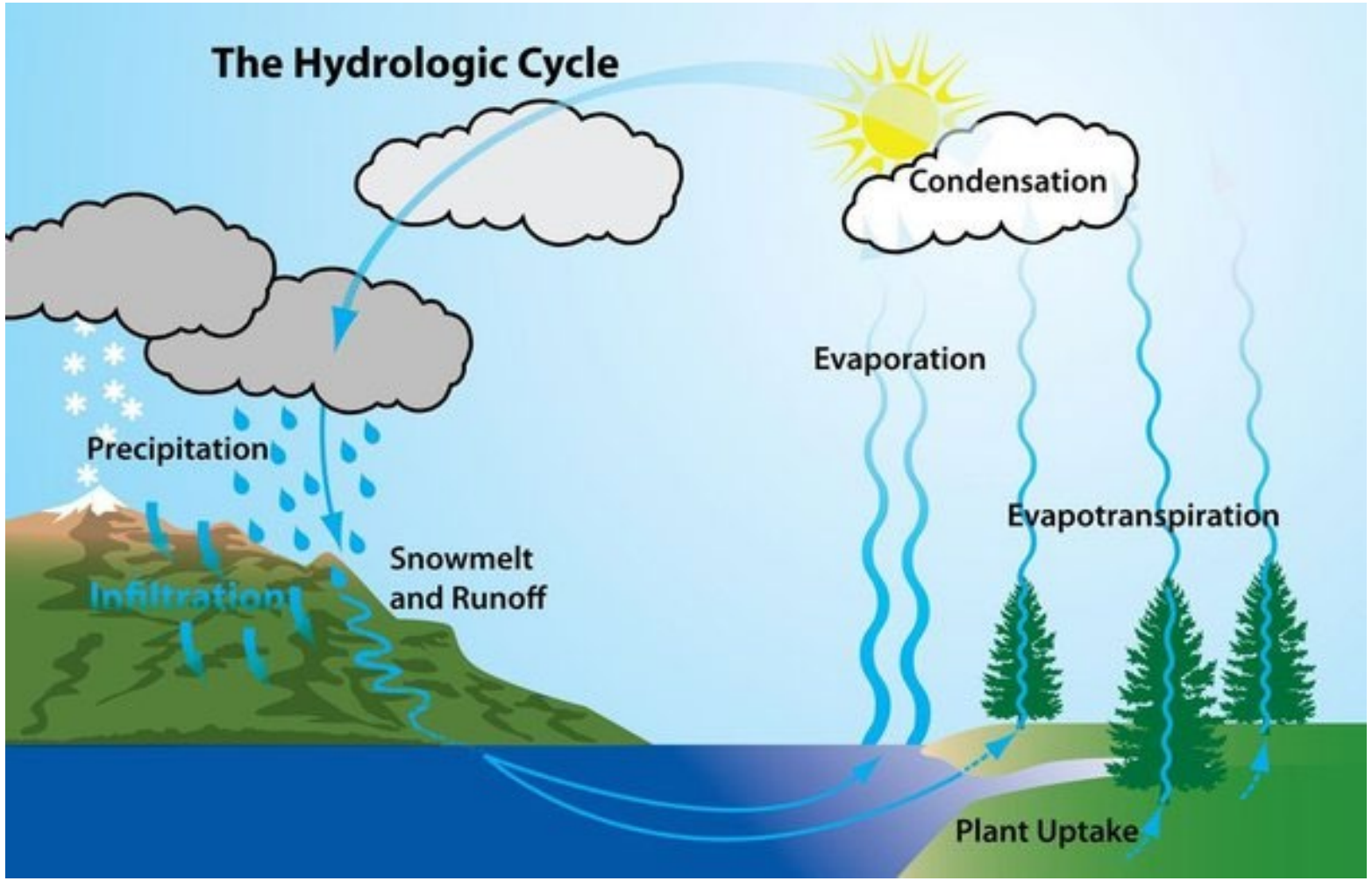


Western Water Assessment

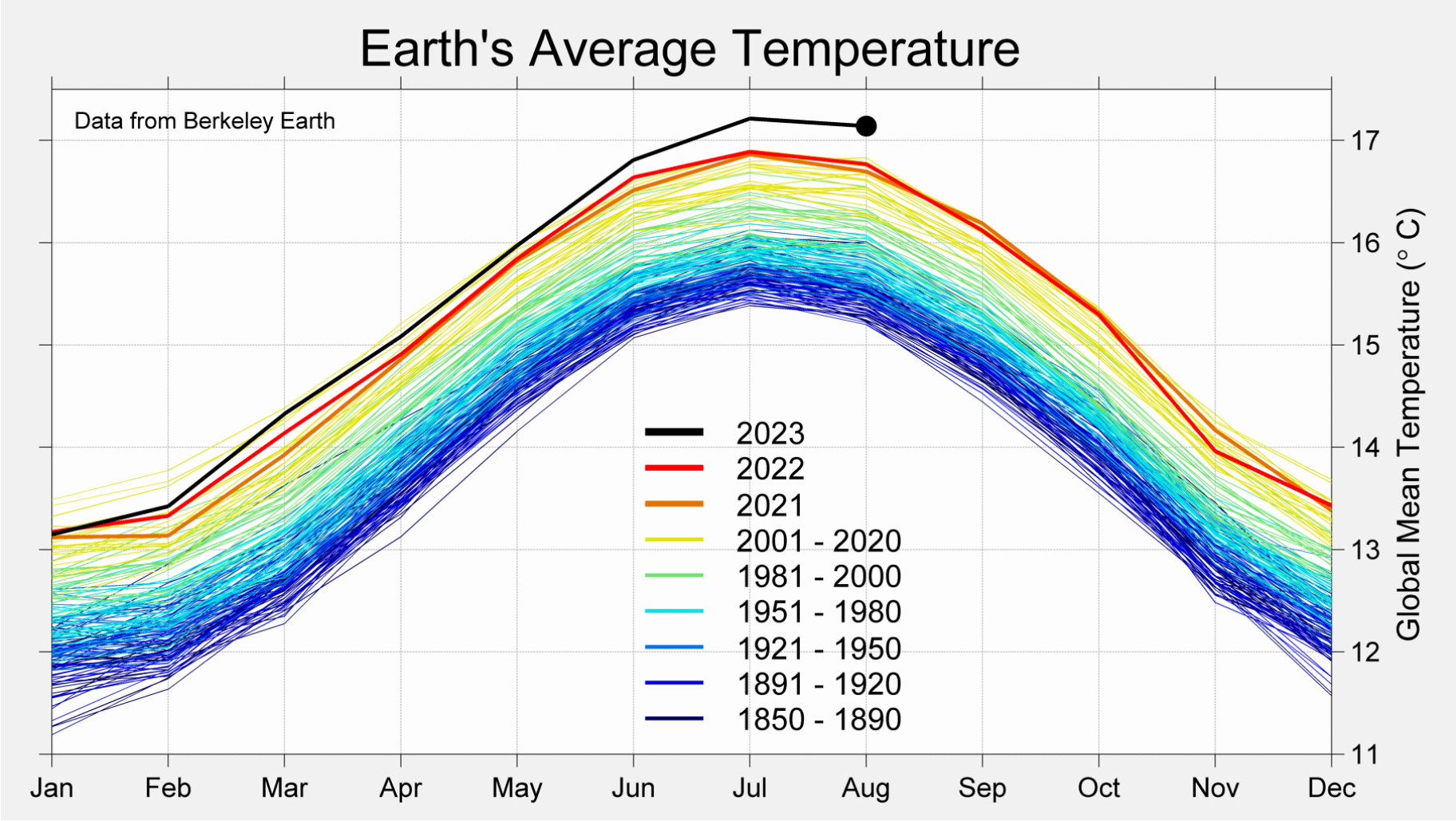
- NOAA-supported applied research team
- CO-WY-UT region
- Hosted by CIRES at CU
- Focus: Societal vulnerabilities to climate variability and climate change, particularly those related to water resources

https://wwa.colorado.edu/

Climate change intensifies the water cycle



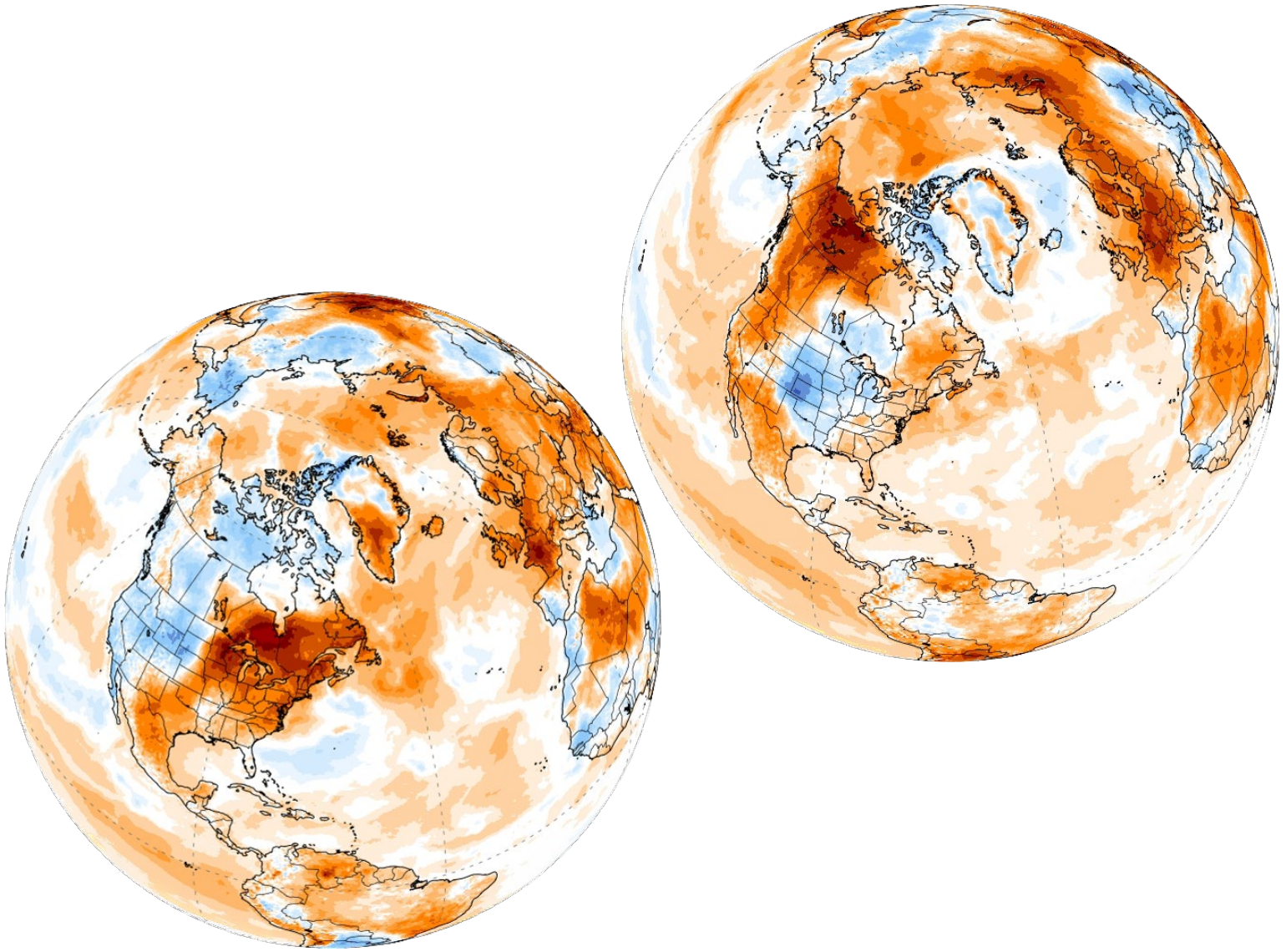
- The water cycle is the movement of water from the Earth to the atmosphere and back
- Global warming intensifies this cycle
- Both average conditions and extreme events are changing
- "Non-stationarity"



Warming is changing the climate in three big ways:

- Atmospheric and ocean circulation
- Atmospheric moisture
- Patterns and magnitude of variability

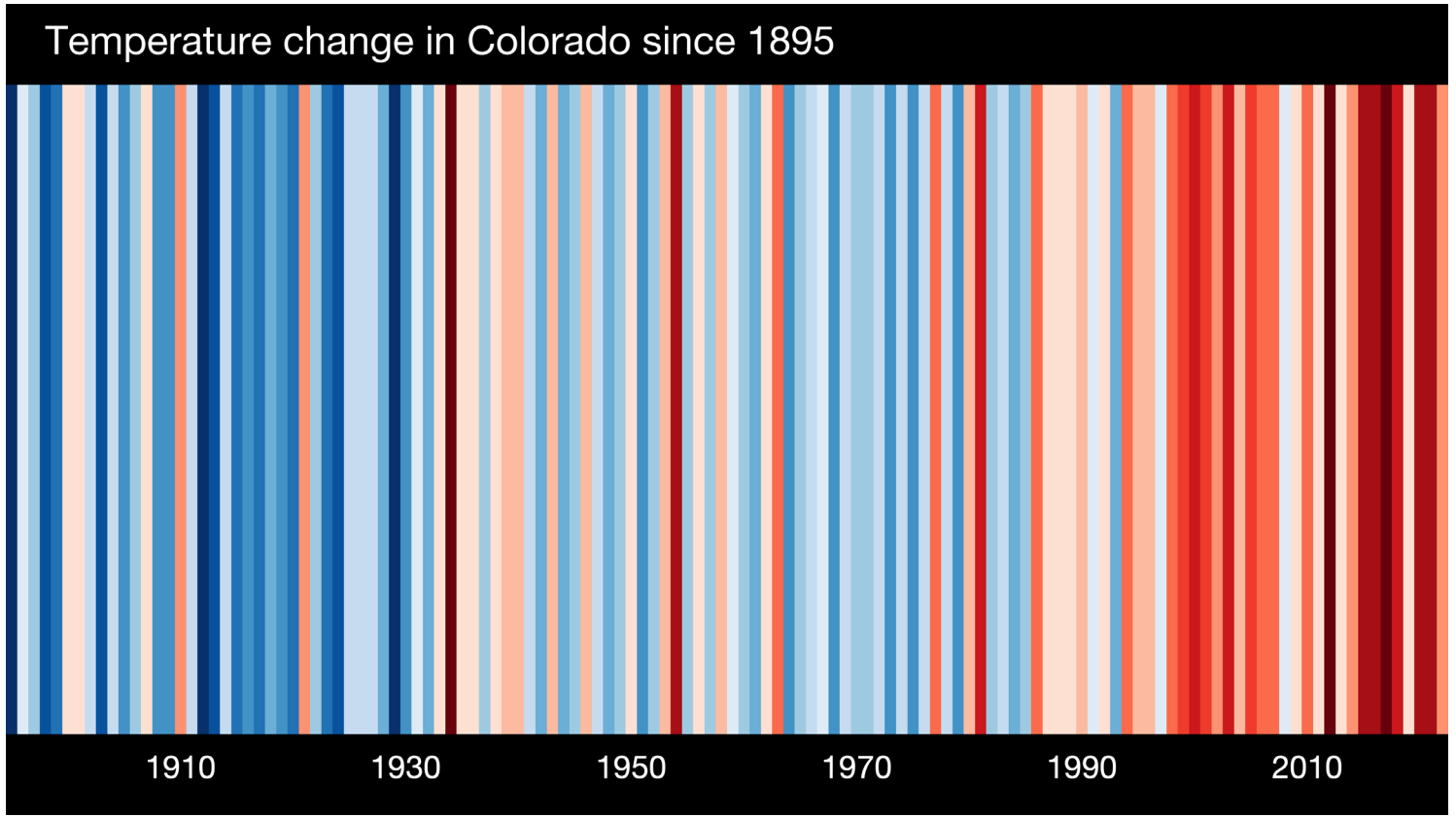
https://berkeleyearth.org/august-2023-temperature-update/



- The poles are warming faster than the lower latitudes
- Loss of sea ice affects radiation reflection and ocean circulation
- The temperature gradient from poles to equator is flattening
- Greater warming over land than over the ocean alters atmospheric circulation patterns
- Changes in circulation patterns affect where and how often extremes occur.
- Jet streams and storm tracks are moving toward the poles

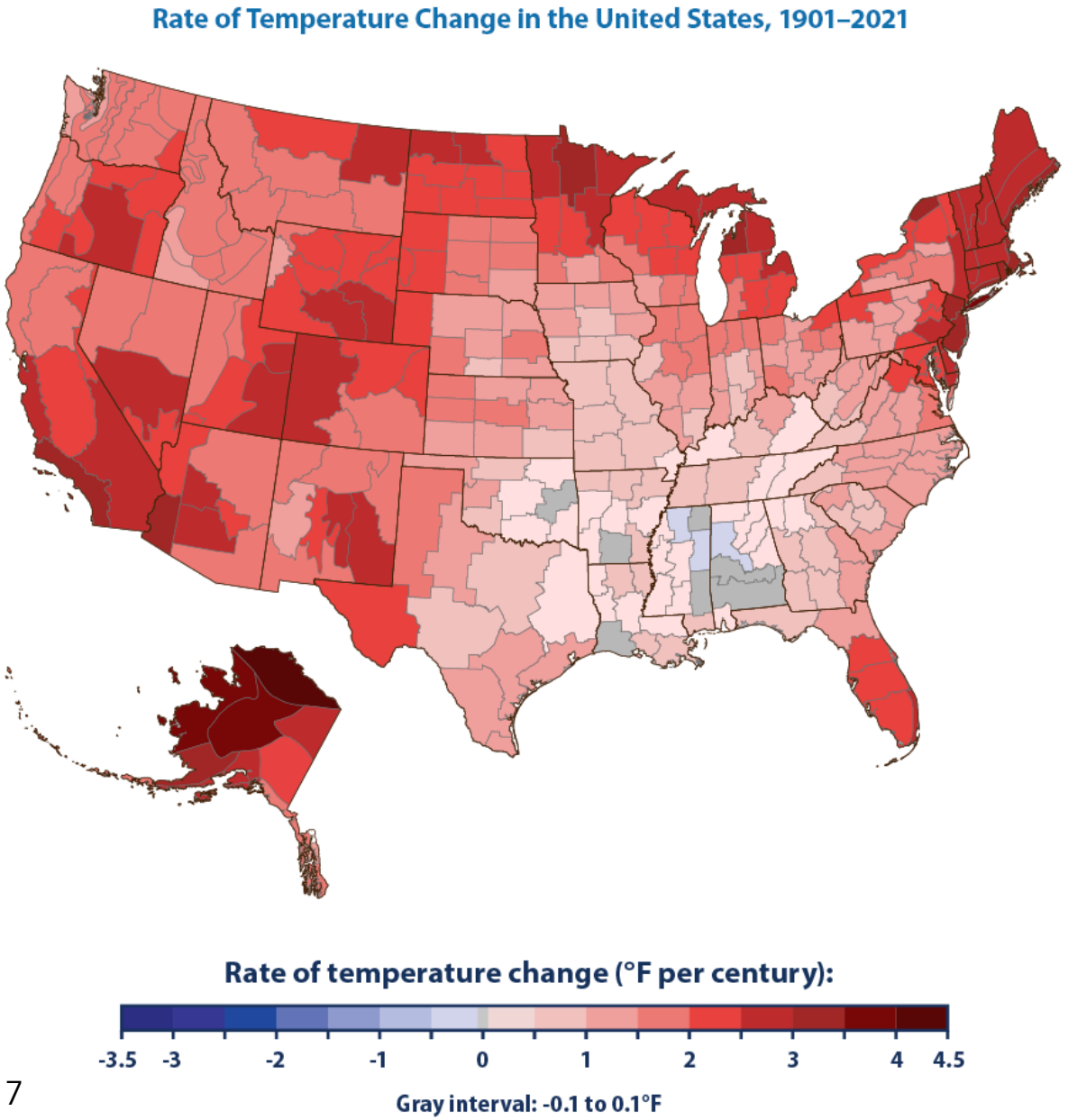
Climate Reanalyzer: https://climatereanalyzer.org/
IPCC Technical Summary: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_TS.pdf
Zhou et al. 2022 https://journals.ametsoc.org/view/journals/clim/35/16/JCLI-D-21-0723.1.xml

Natural variability



- Fluctuations in climate variables
- Results from chaotic behavior of the coupled atmosphere-ocean system
- Often obscures climate change detection, especially extreme events
- By the end of the 21st century, background trends are expected to dominate natural variability in water variables like precipitation

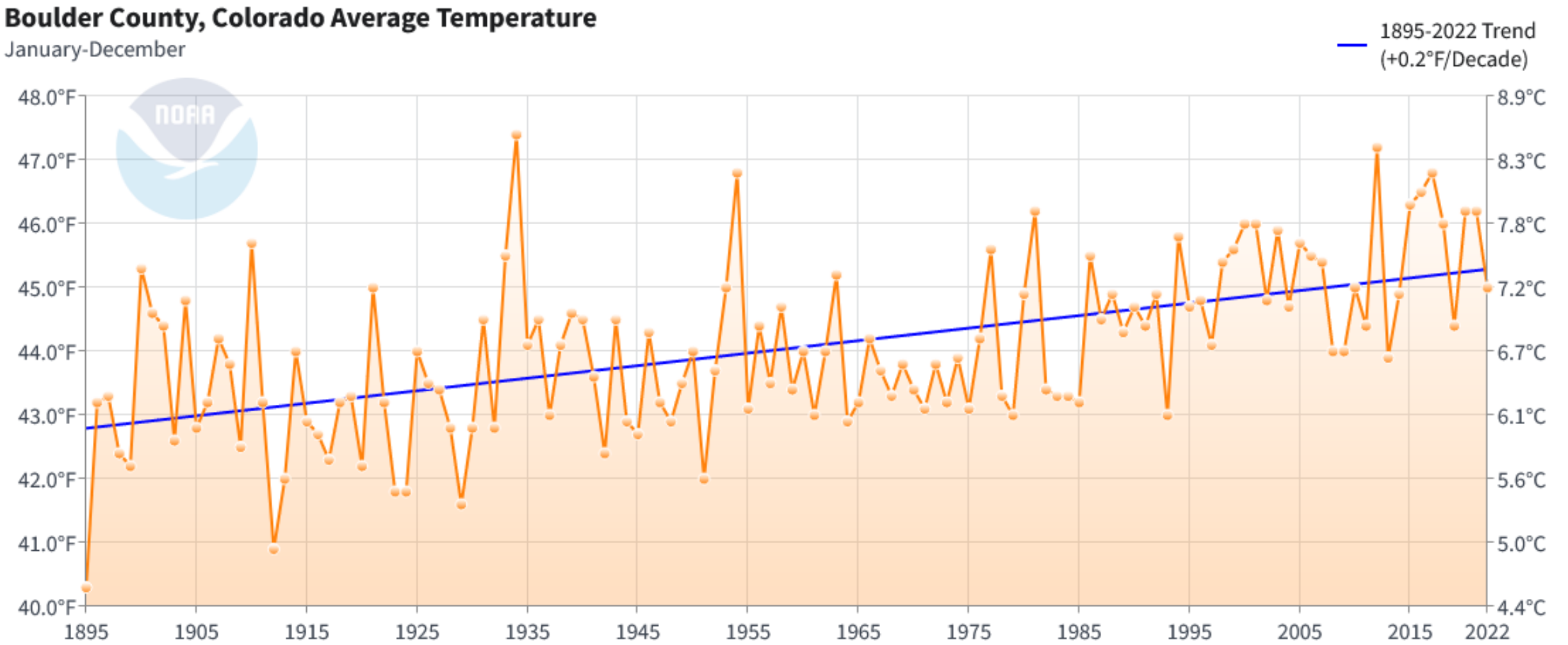
https://showyourstripes.info
Stevenson et al. 2022. https://www.pnas.org/doi/full/10.1073/pnas.2108124119



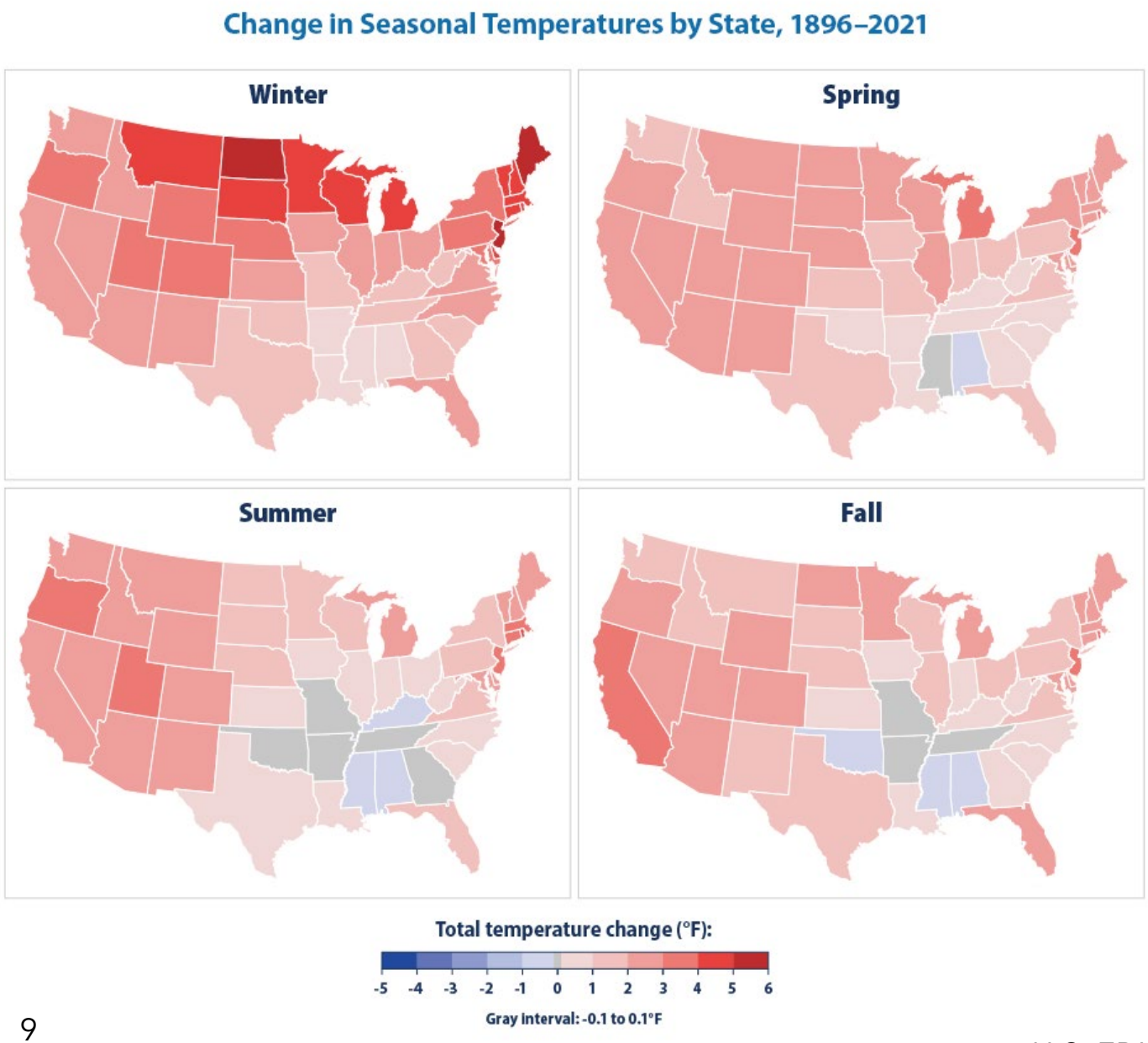
Temperature

- The US has been warming about 60% faster than the planet as a whole
- Colorado temperature rise per century per basin from 1901-2021:
  - Platte River 2.27° F
  - Arkansas River 1.53° F
  - Rio Grande 1.61° F
  - Kansas River 2.41° F
  - Colorado River 2.80° F
- North Slope of Alaska 4.01° F

U.S. EPA, 2022 Climate Indicators: https://www.epa.gov/climate-indicators



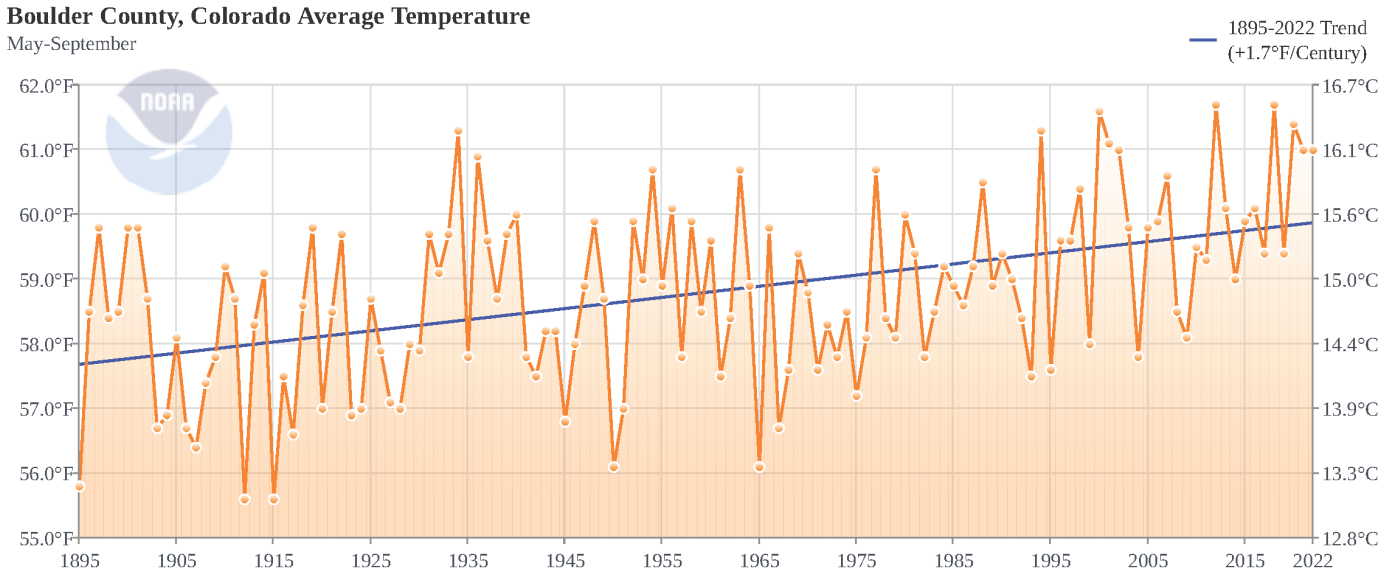
NOAA NCEI Climate at a Glance https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/

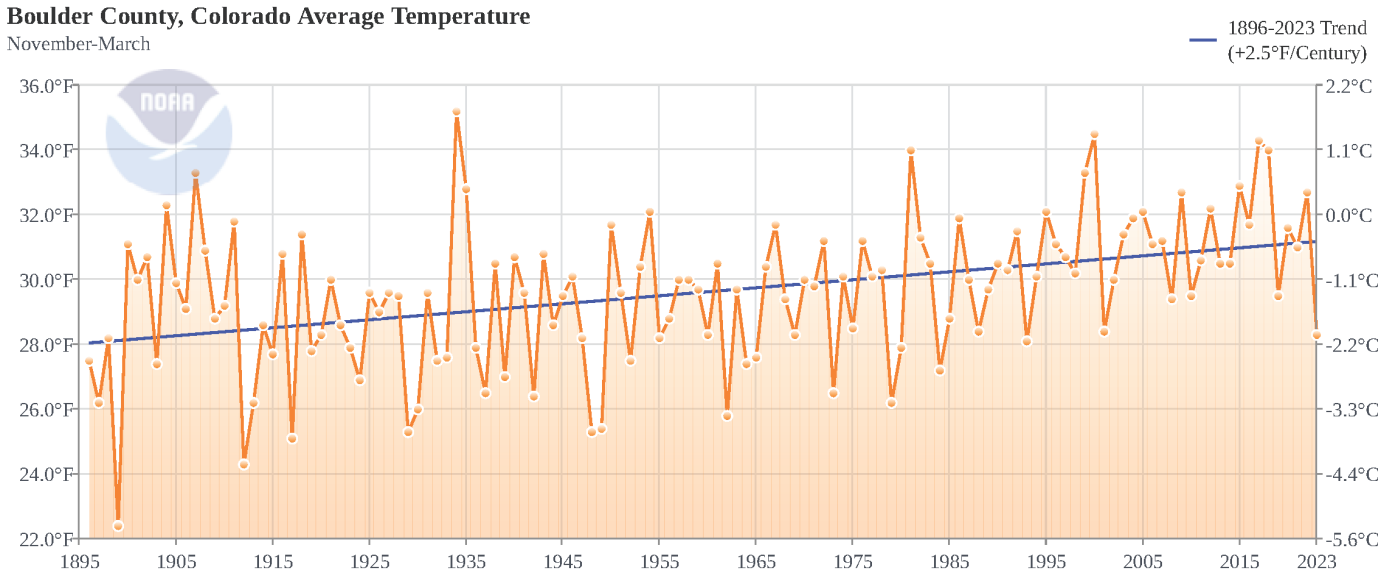


Seasonal temperatures

- Warming is not occurring evenly across seasons
- Trends are consistent with climate models that project greater warming in winter than in summer
- Colorado temperature change by season over 1896-2021:
  - Winter +3.24°F
  - Spring +2.72°F
  - Summer +2.58°F
  - Fall +2.09°F

U.S. EPA Climate Change Indicators https://www.epa.gov/climate-indicators





- Winter months are warming faster than summer months (°F/century)
  - January: 2.9
  - February: 2.7
  - March: 3.8
  - April: 1.0
  - May: 1.1
  - June: 2.0
  - July: 2.6
  - August: 1.3
  - September: 1.4
  - October: 0.7
  - November 1.6
  - December: 1.9
- Spring warming is attributed, in part, to less snow cover in those months

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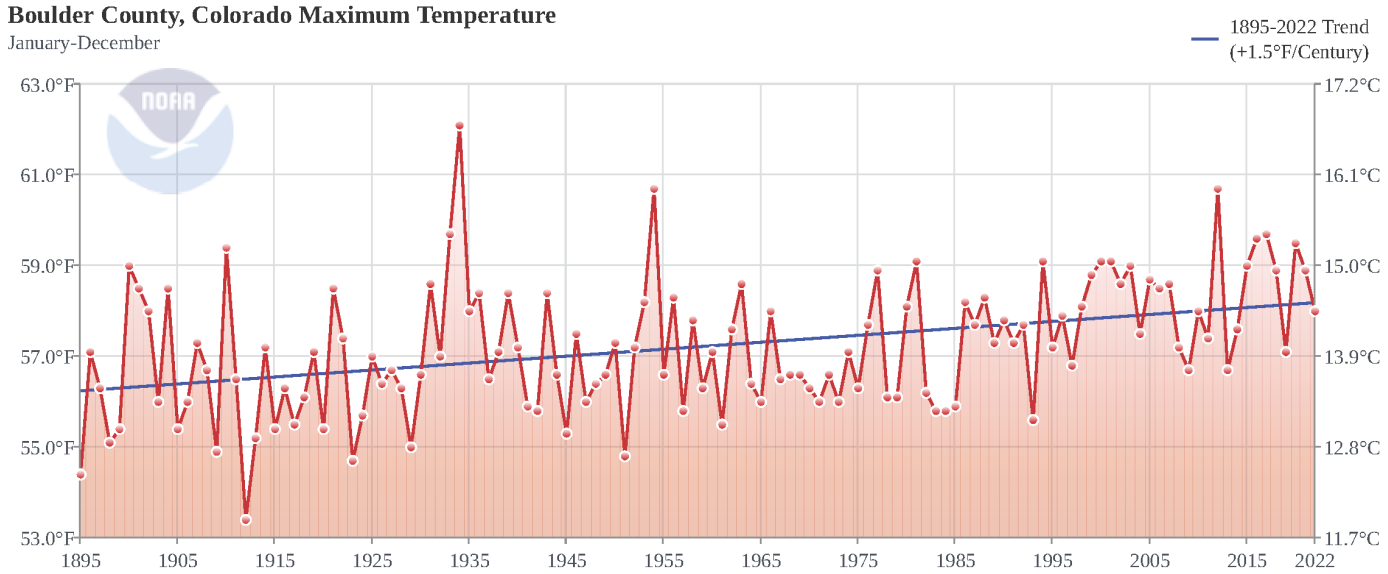
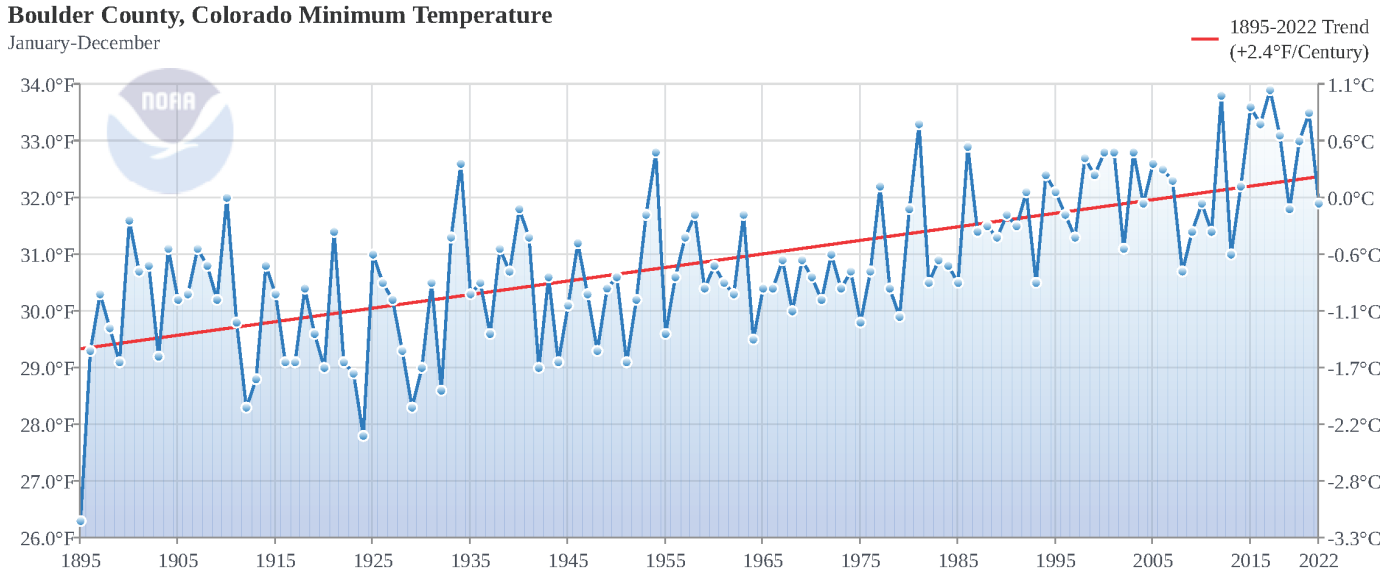


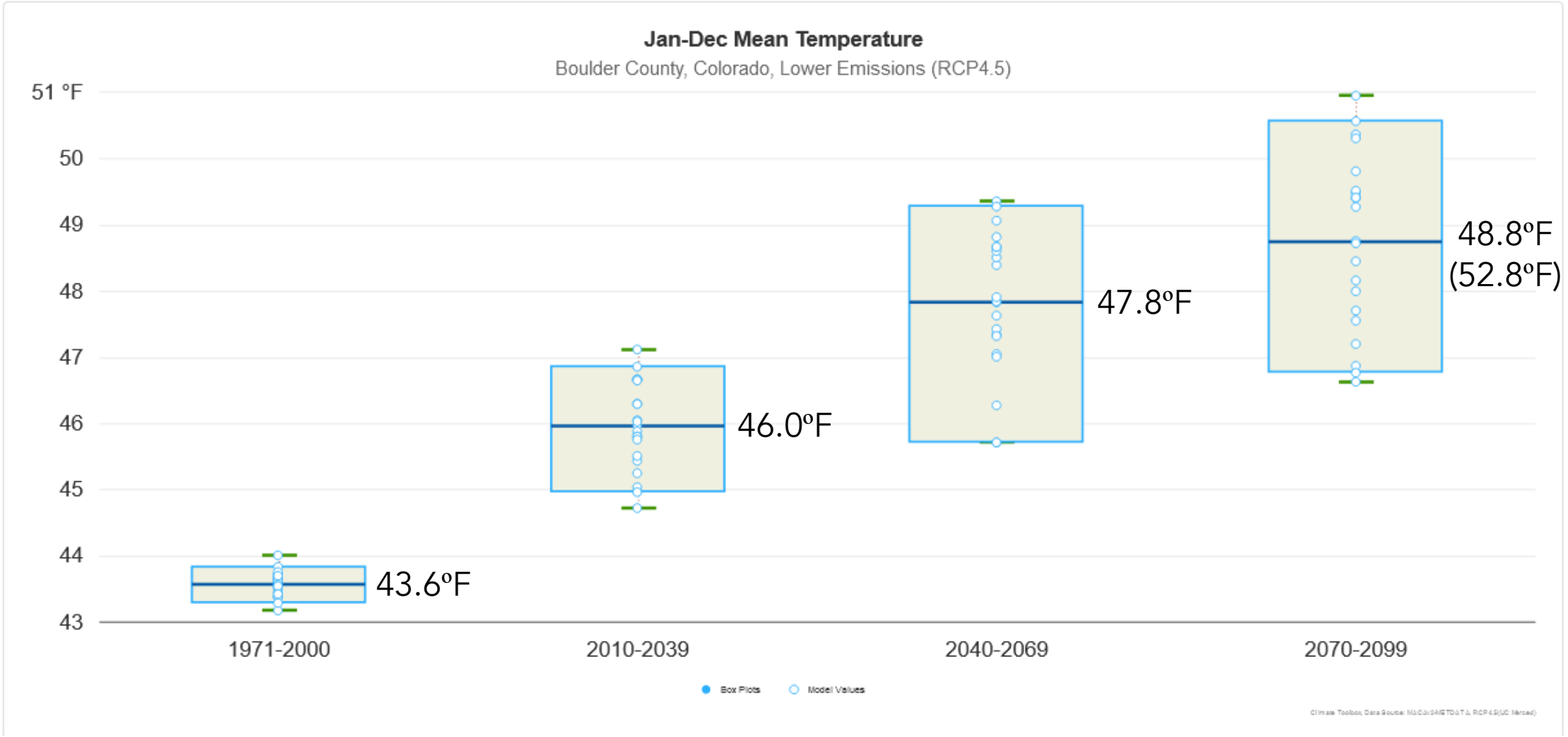


Daytime vs nighttime temperatures

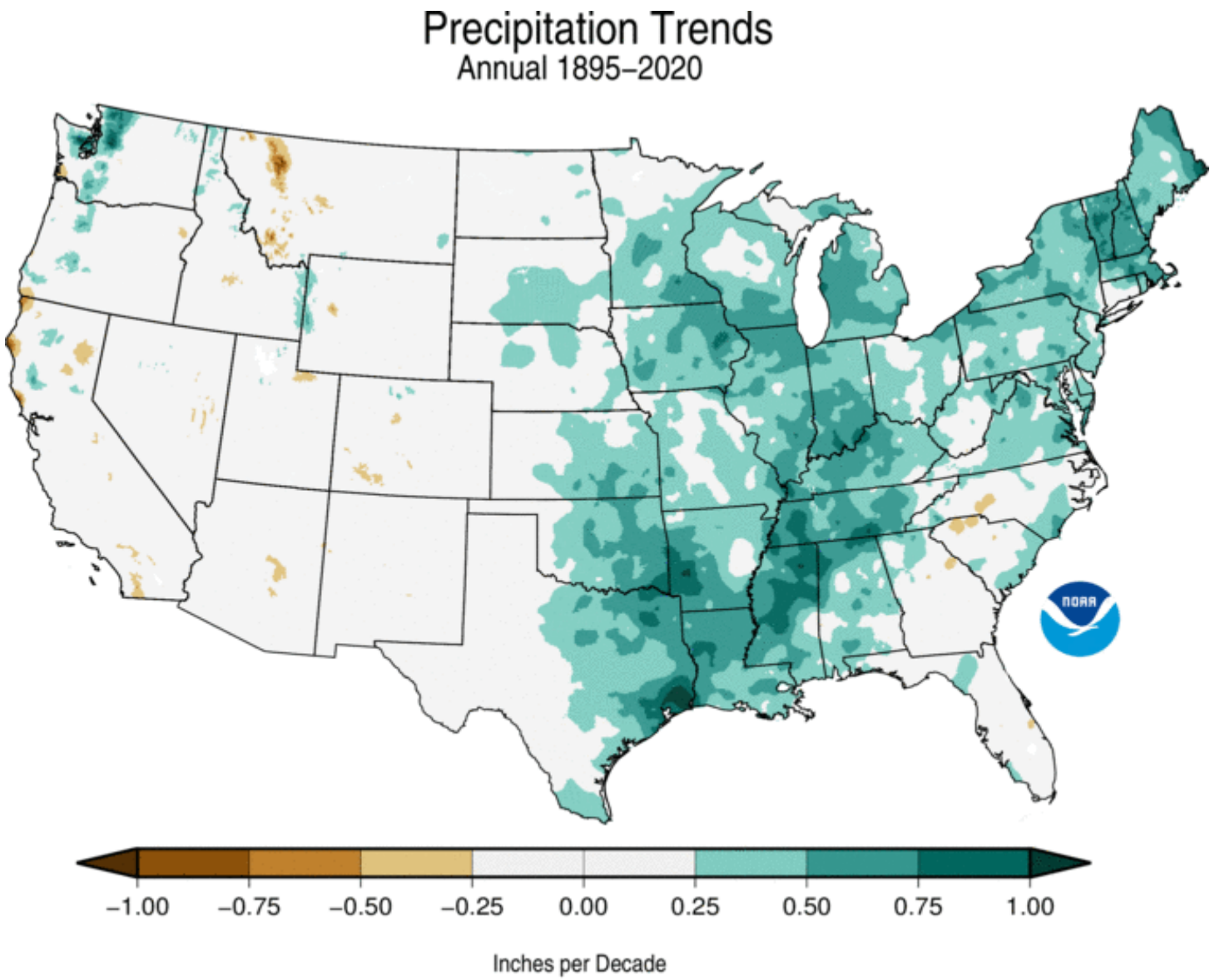
- Minimum temperatures are rising faster than maximum temperatures
- In Boulder County:
  - Max has increased ~1.5° F
  - Min has increased ~ 2.4° F
- Consistent with increases in night-time low temperatures. We don't cool off at night as much as we used to

NOAA NCEI Climate at a Glance https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/

Temperature projections



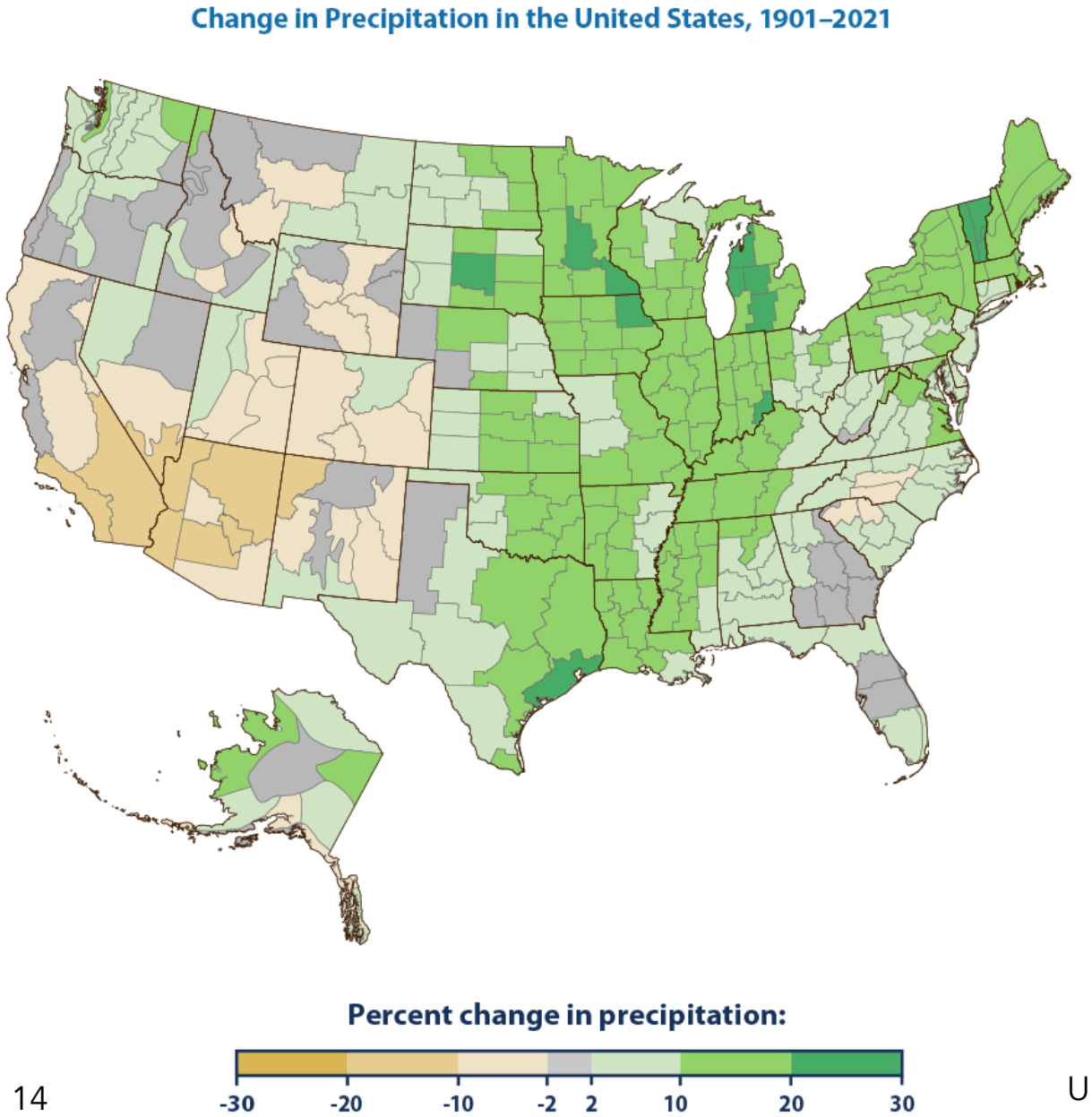
https://climatetoolbox.org/tool/Future-Boxplots



Precipitation

- Warmer air holds more water (a thermodynamic response to climate change)
- The jetstreams and storm tracks are shifting (a dynamic response to climate change)
- Air can hold about 7% more water per degree C
- Depends on unlimited water supply, so applicable over oceans, mostly
- Convection can create storms that exceed the moisture predicted by the thermodynamic response, so it isn't an upper bound

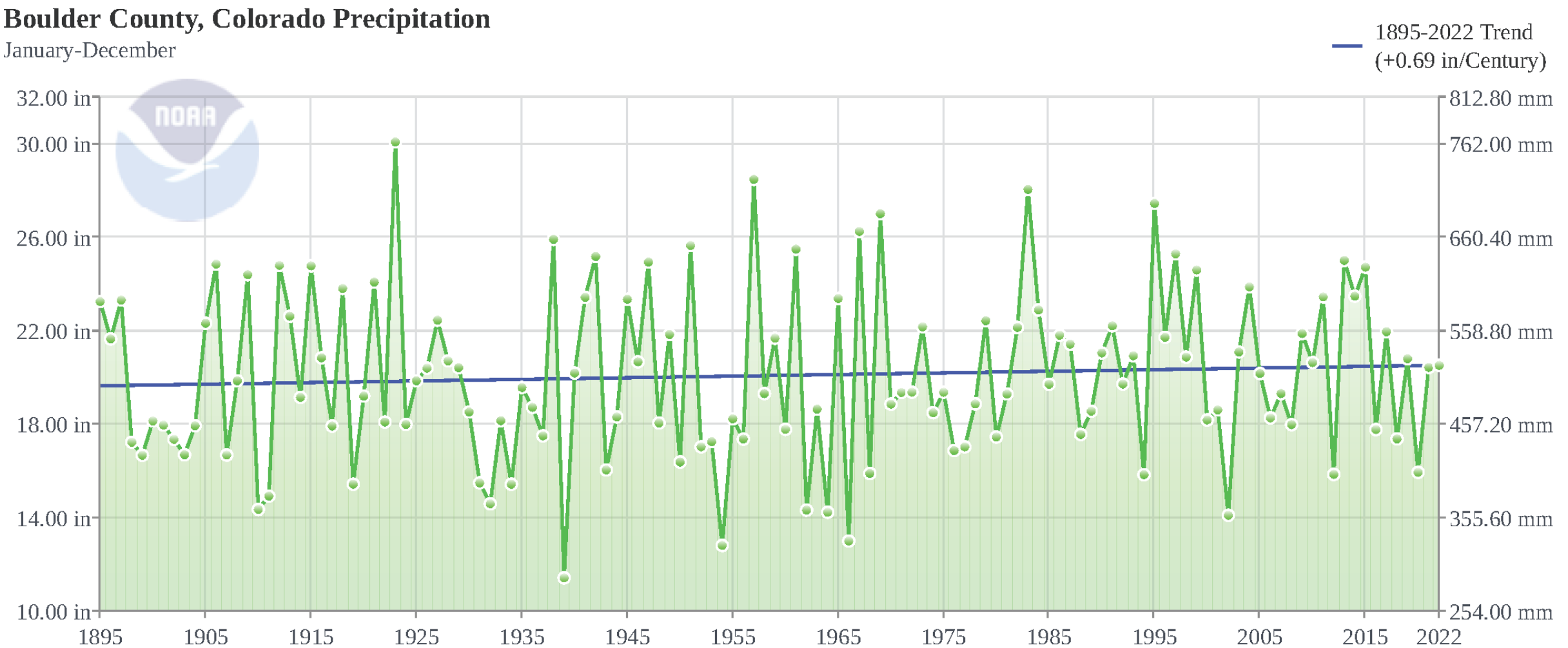
https://www.ncei.noaa.gov/access/monitoring/us-trends/prcp/ann



Colorado precipitation change per basin from 1901-2021

- Platte River +3.54%
- Arkansas River -2.40%
- Rio Grande -6.21%
- Kansas River -4.35%
- Colorado River -3.57%

U.S. EPA Climate Change Indicators https://www.epa.gov/climate-indicators
Adam 2023 https://www.pnas.org/doi/10.1073/pnas.2304077120



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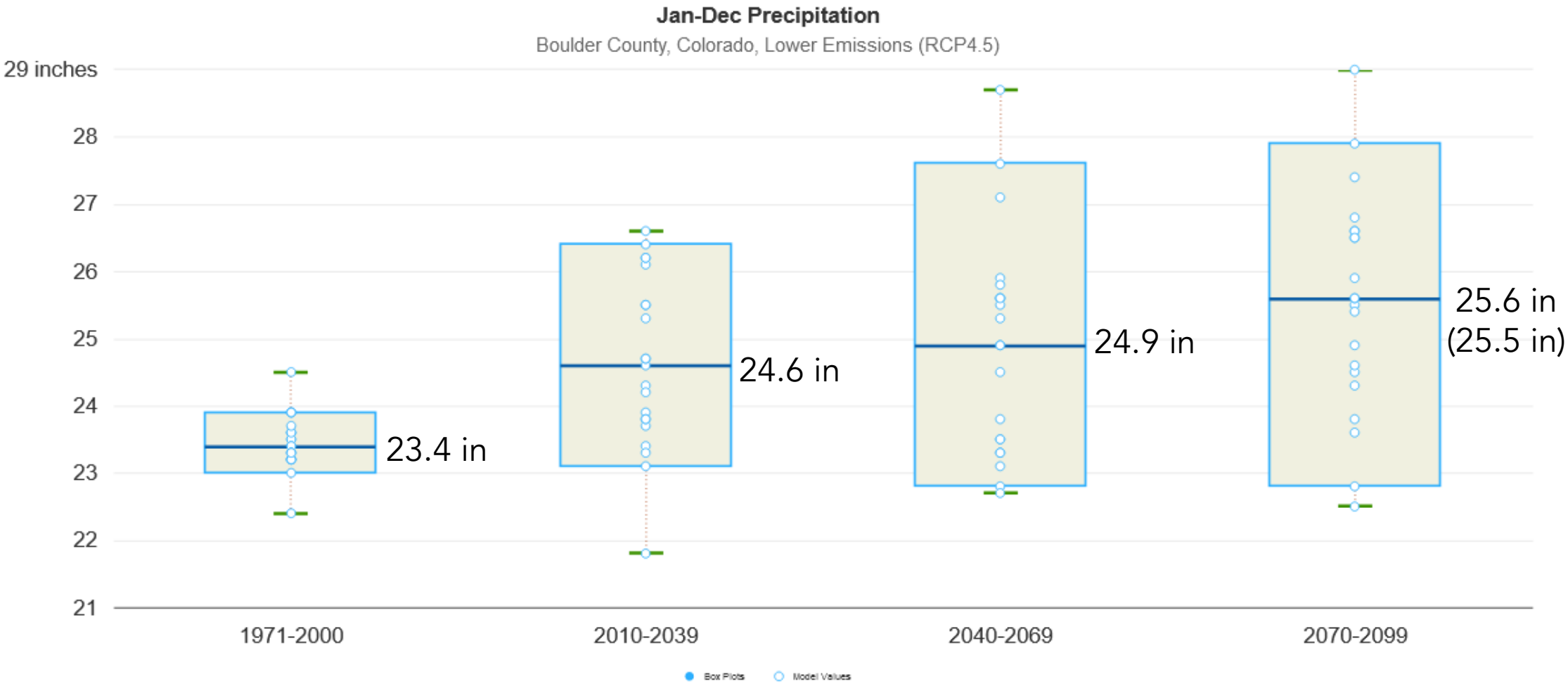
Precipitation projections



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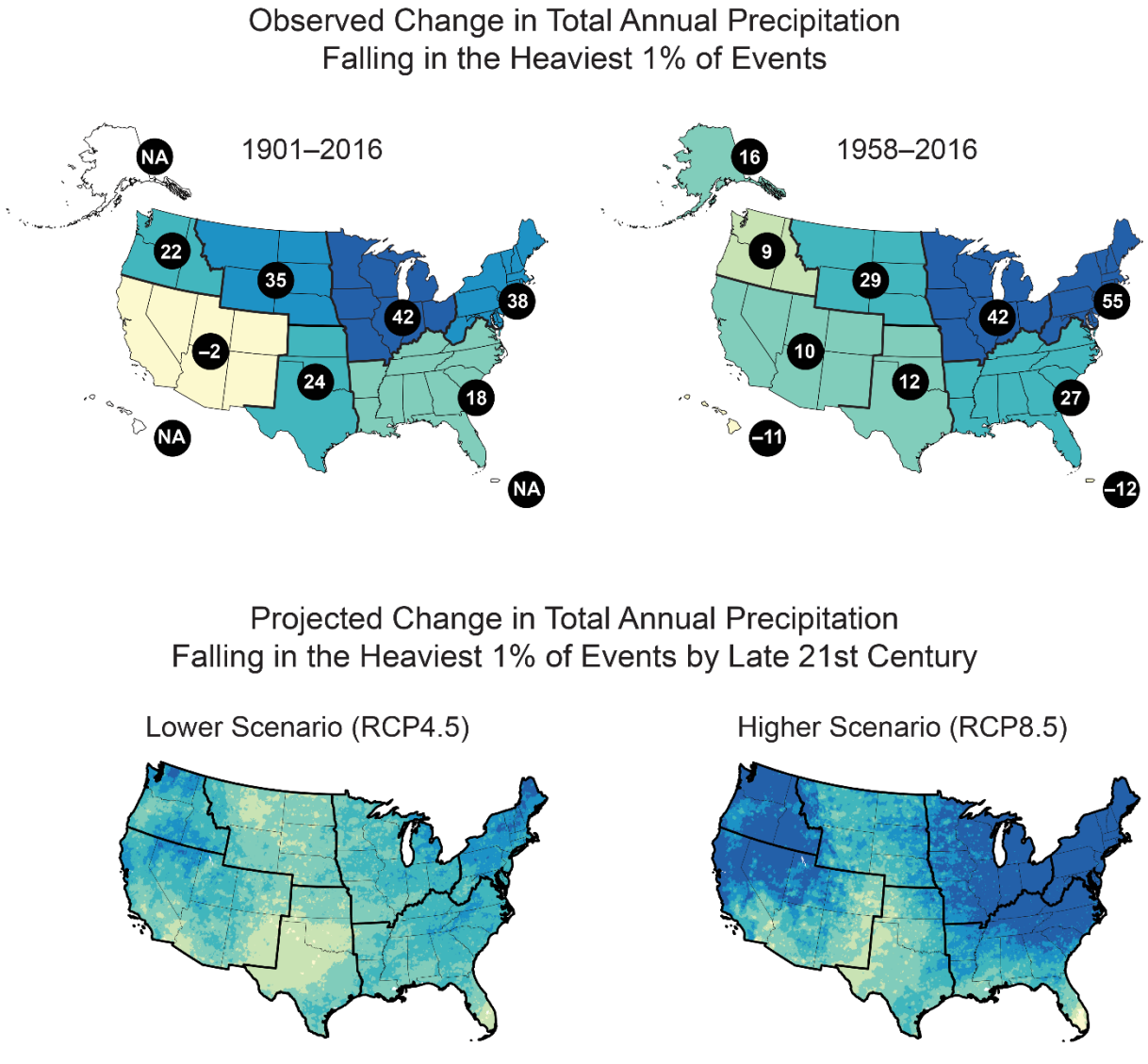
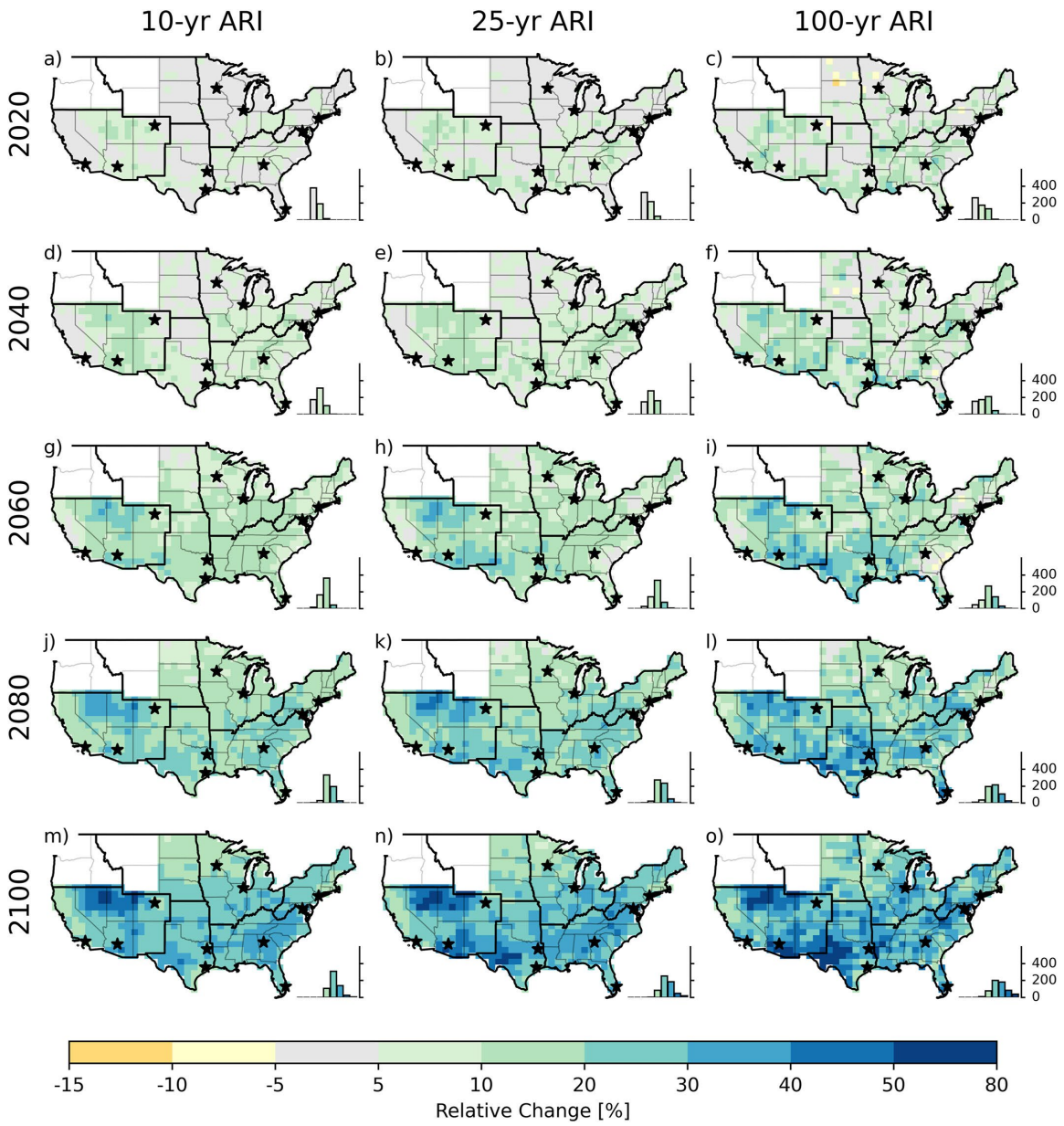


Extreme precipitation

- Climate change makes the extremes greater
- Warmer climate causes more energetic convective storms
- Warming tropics will intensify atmospheric rivers and tropical storms, key sources of moisture
- Tropical cyclones are decaying more slowly and therefore extending further inland
- Increases in extreme precipitation may not raise annual totals

https://nca2018.globalchange.gov/chapter/2/#fig-2-6
IPCC: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_TS.pdf

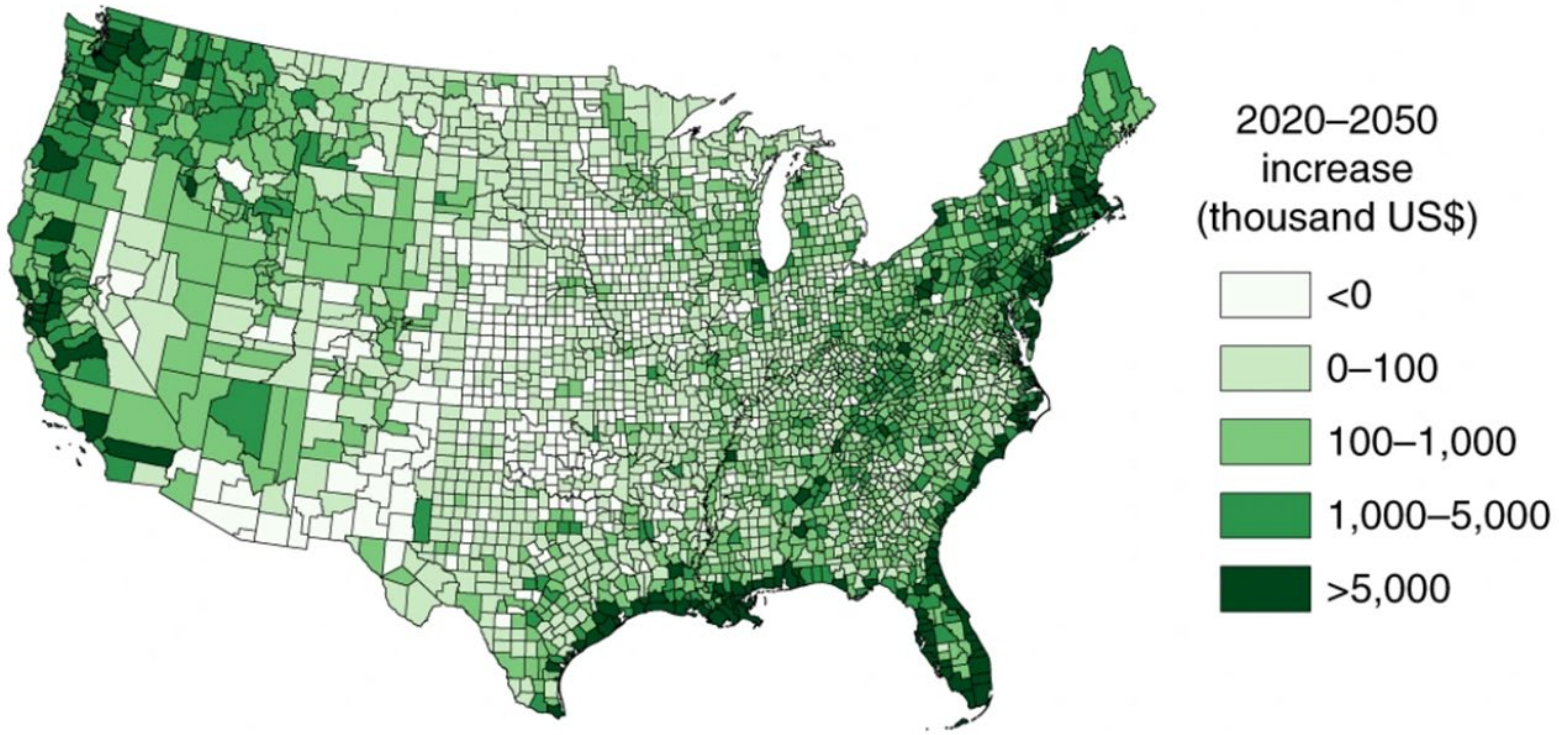


Projected extreme precipitation

- Figure shows percent change in daily precipitation for average return intervals and planning horizons, relative to current planning assumptions
- The 100-yr event in Denver is projected to become a 30-40-yr event
- Expect less moderate precipitation and more extreme precipitation
- Extreme events will make up a larger fraction of total precipitation and moderate events will become less common

Coelho et al. 2022 https://doi.org/10.1029/2021WR031432
Zhou et al. 2022 https://doi.org/10.1175/JCLI-D-21-0723.1

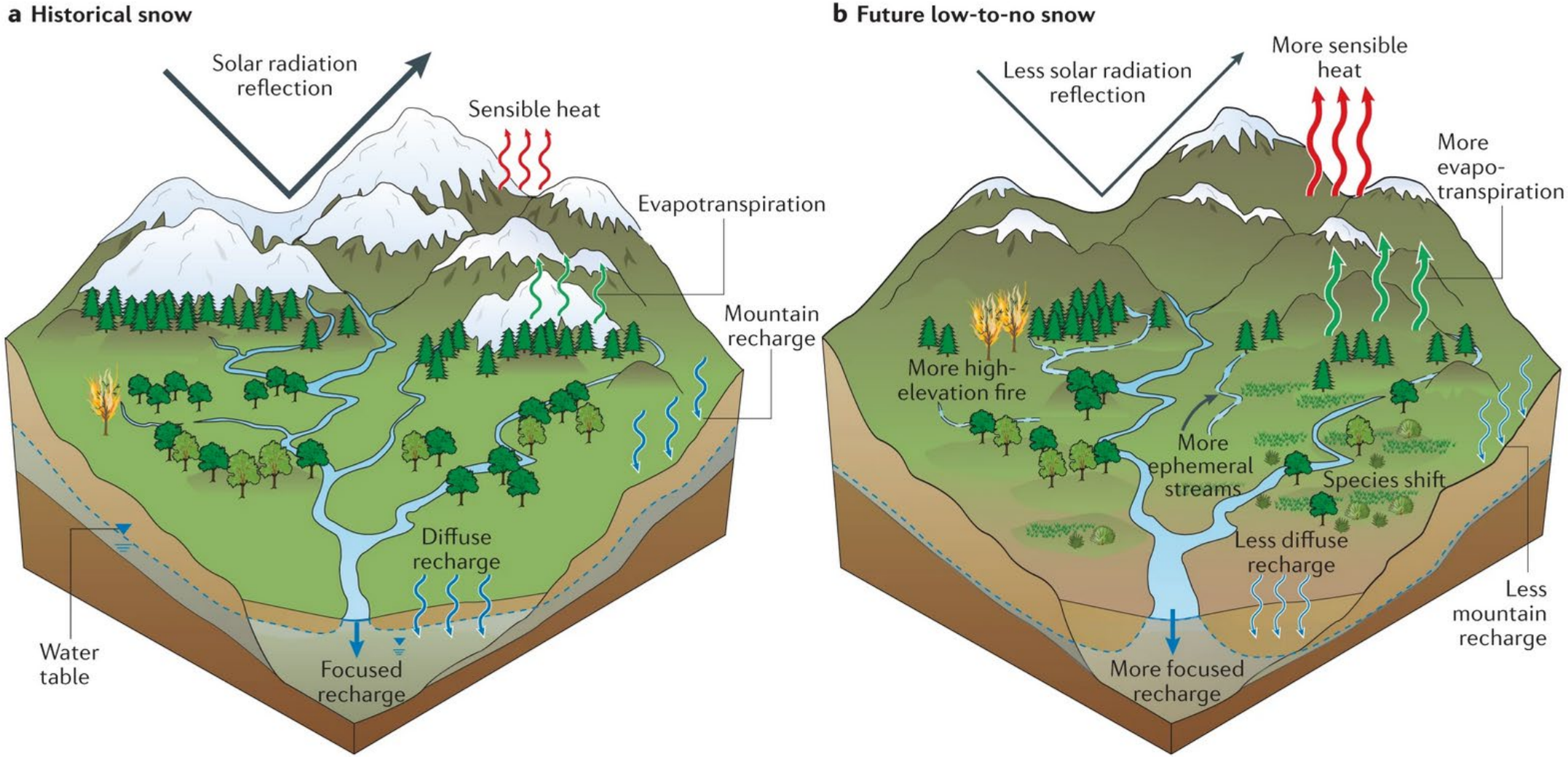
Projected flooding



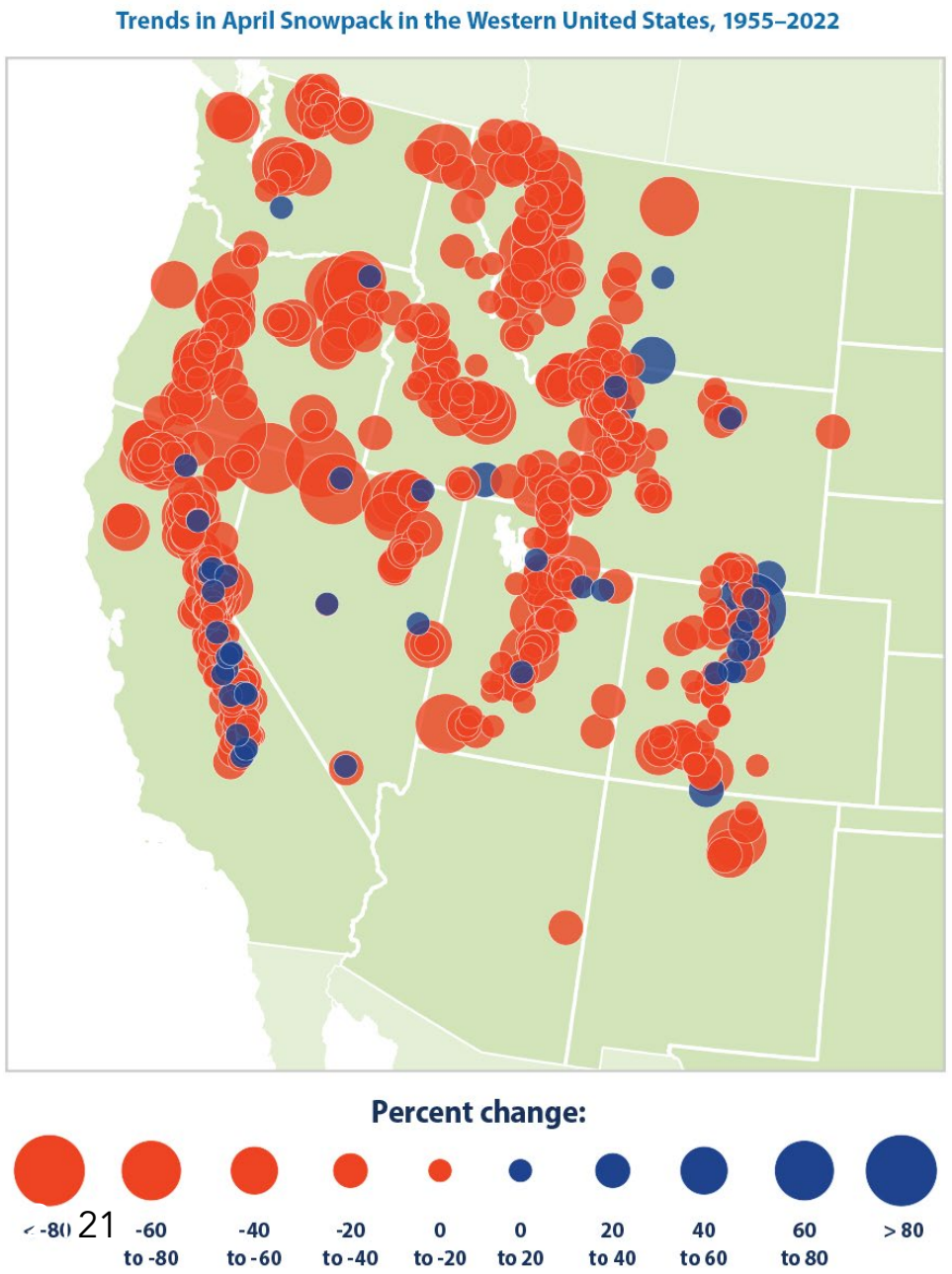
- Risk of damaging flooding (losses) is expected to increase
- Increases with urbanization
- Modulated by climate change impacts to soils and vegetation
- Smaller catchments (under ~200 square miles) will experience a much larger rise than medium and large catchments
- Disproportionate impacts to frontline communities

Wing et al. 2022 https://doi.org/10.1038/s41558-021-01265-6
Fagihih and Brissette 2023 https://doi.org/10.1016/j.jhydrol.2023.130101

Snow



Siirila-Woodburn et al. 2021 https://doi.org/10.1038/s43017-021-00219-y

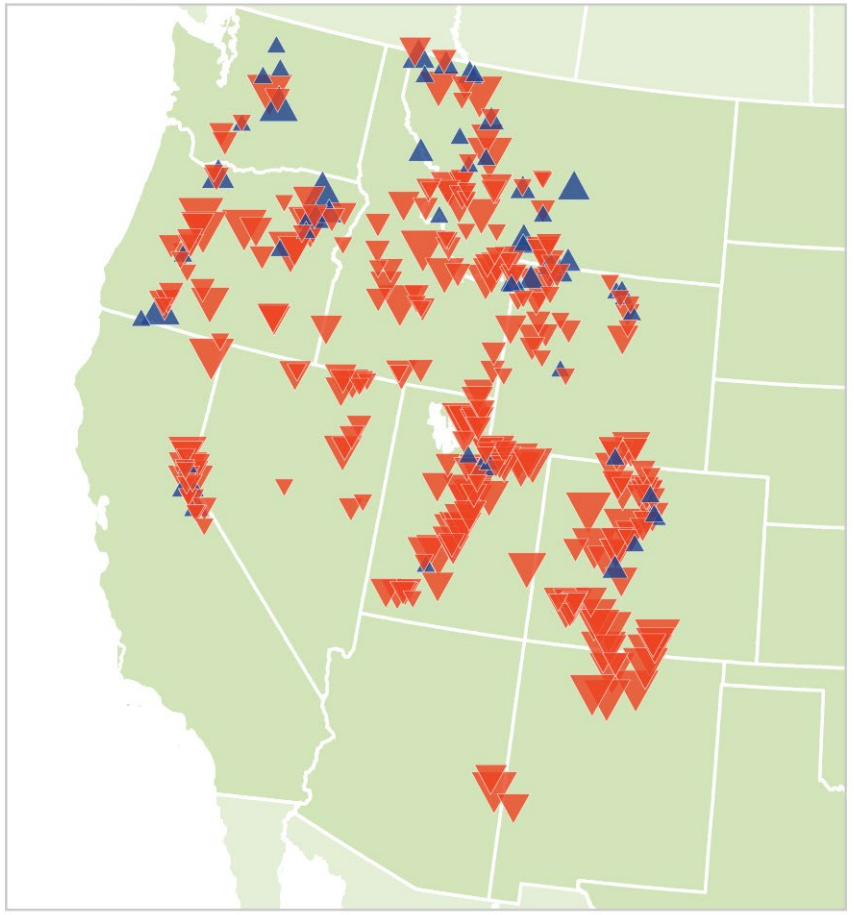


Trends in April snowpack

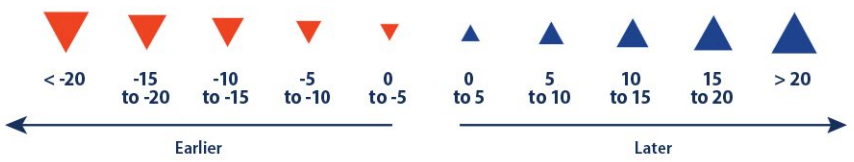
- Figure shows changes in the magnitude of snow water content in the snowpack measured on April 1
- The average decline has been 23%
- Boulder stations:
  - Boulder Falls: -14%
  - University Camp: -20%
  - Niwot: -25%
- More precipitation is falling as rain instead of snow

U.S. EPA Climate Change Indicators https://www.epa.gov/climate-indicators

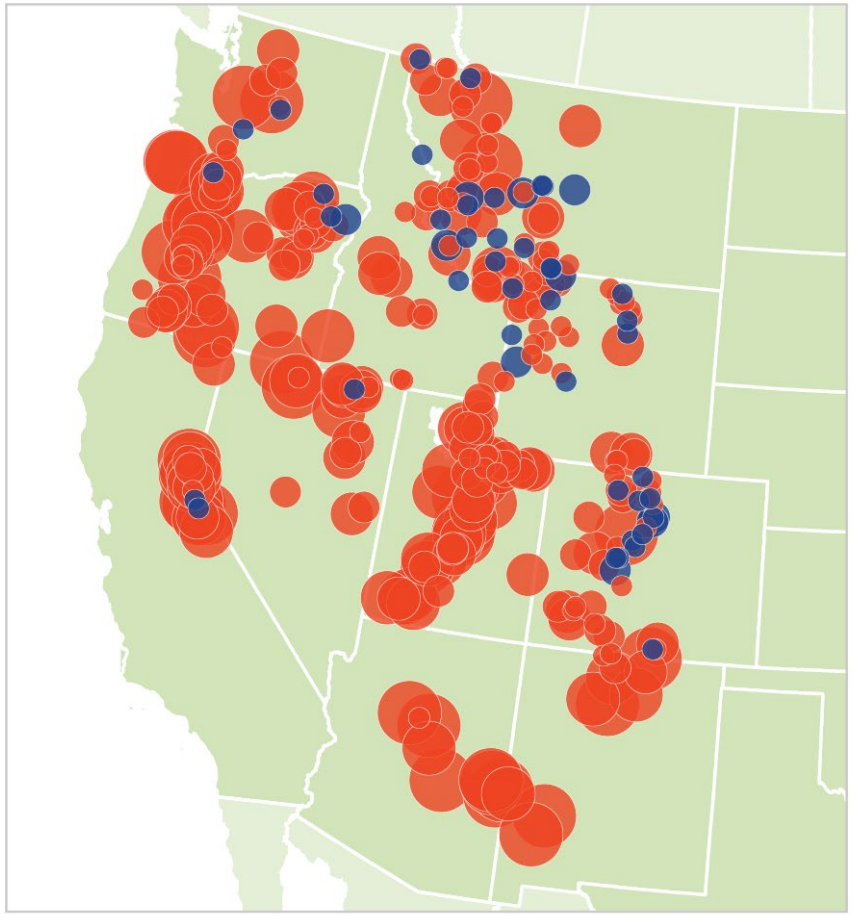
Change in Peak Snowpack Timing in the Western United States, 1982–2021



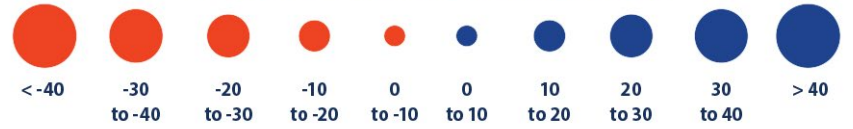
Peak snowpack timing change (days):



Change in Snowpack Season Length in the Western United States, 1982–2021



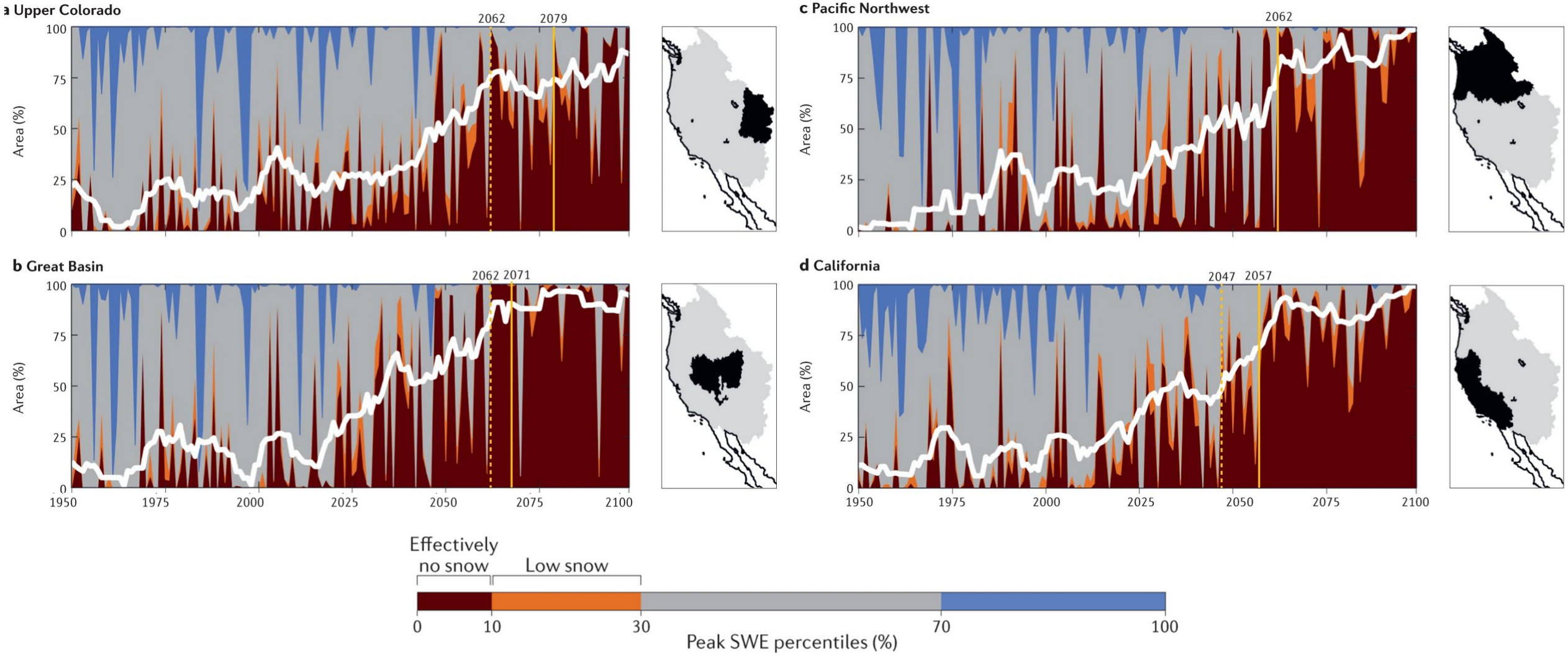
Snowpack season length change (days):



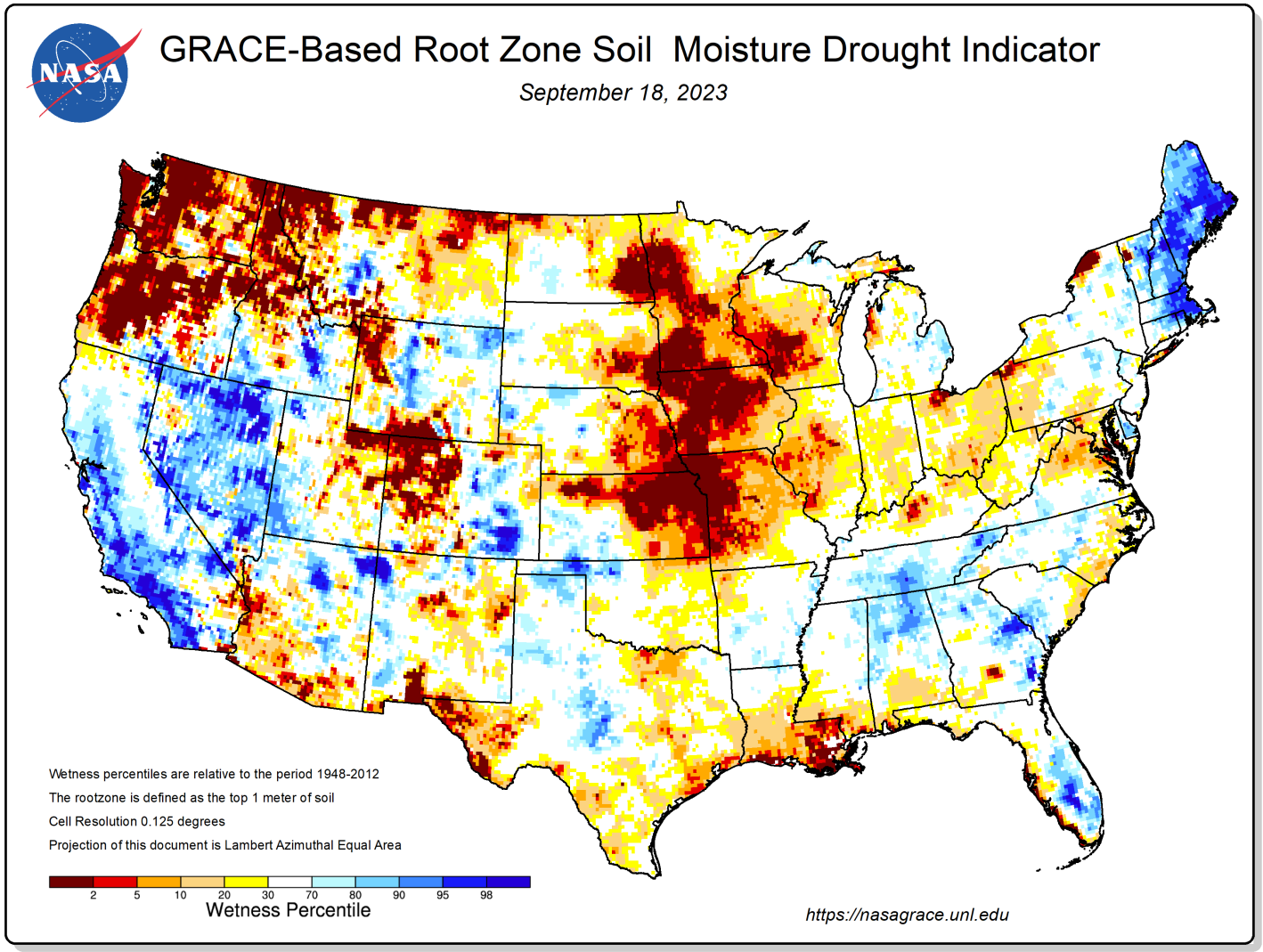
- Peak snowpack is 8 days earlier on average
- Boulder stations:
  - Niwot +3.7 d (later)
  - University Camp +6.3 d (later)
  - Lake Eldora -12.7 d (earlier)
- Snowpack season is 18 days shorter on average
- Boulder stations:
  - Niwot +10.9 d
  - University Camp +5.0 d
  - Lake Eldora +10.5 d

U.S. EPA Climate Change Indicators https://www.epa.gov/climate-indicators

Projected snow disappearance



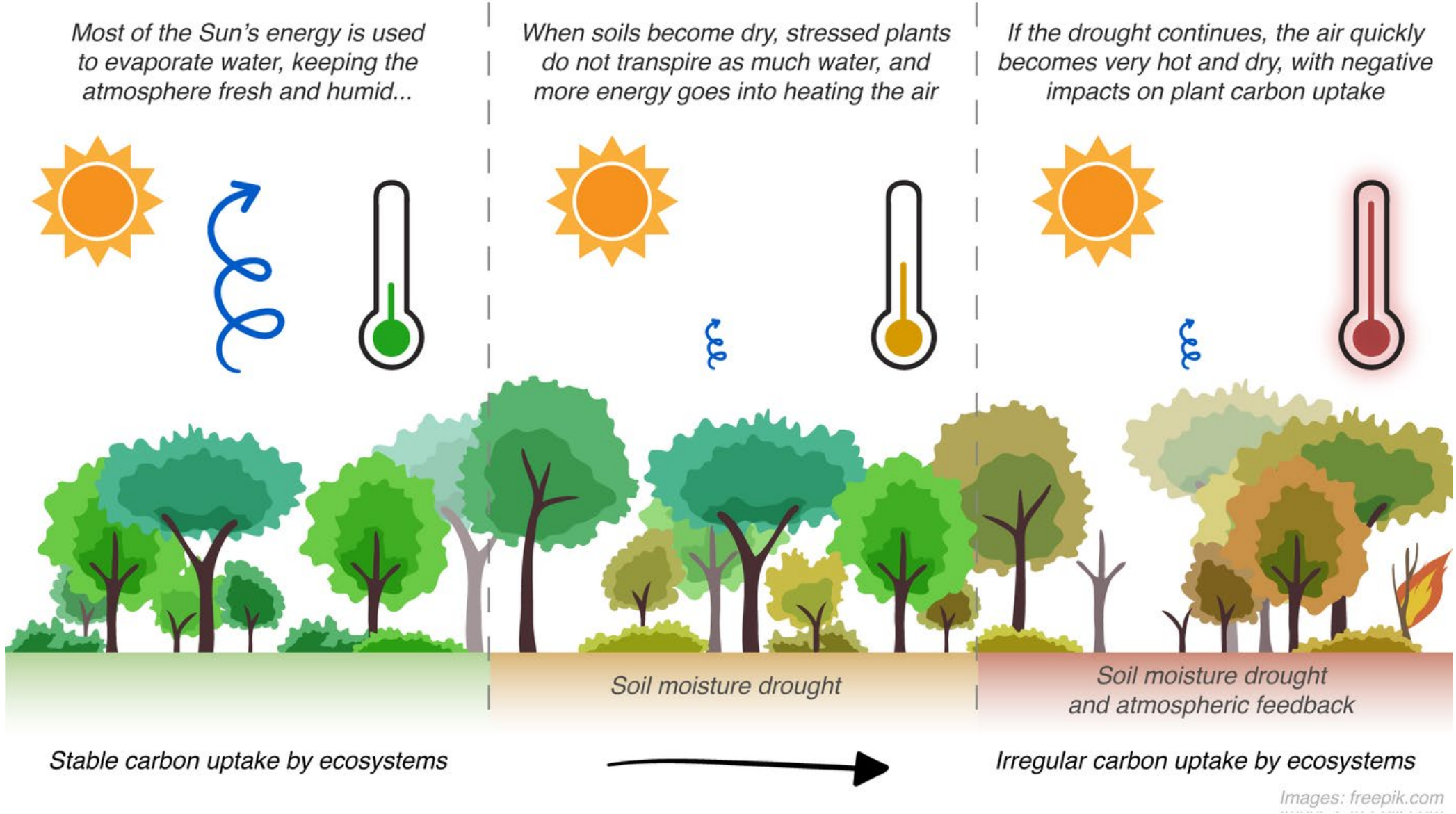
Siirila-Woodburn et al. 2021 https://doi.org/10.1038/s43017-021-00219-y



Soil moisture

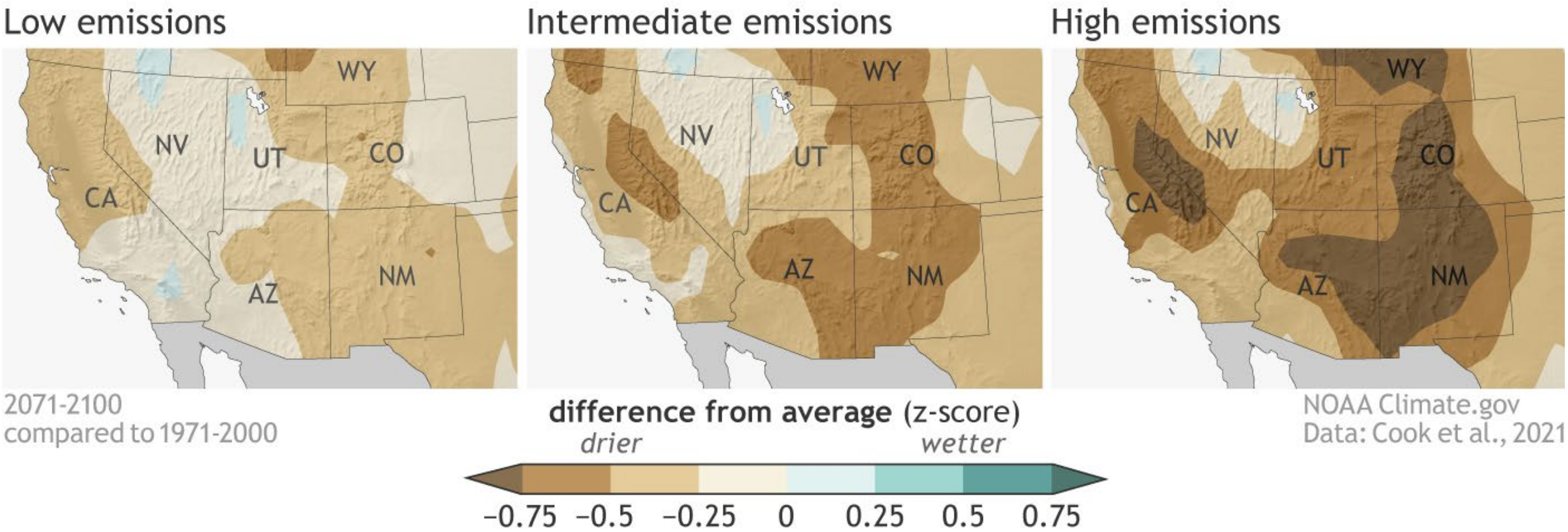
- Thirstier atmosphere pulls moisture from the soil, plants, and open water
- The soil moisture—atmosphere feedback influences local temperatures
- Droughts can self-propagate due to a strong positive feedback of increased air temperature near the surface, which further dries out the soil

NASA Grace: https://nasagrace.unl.edu/Default.aspx

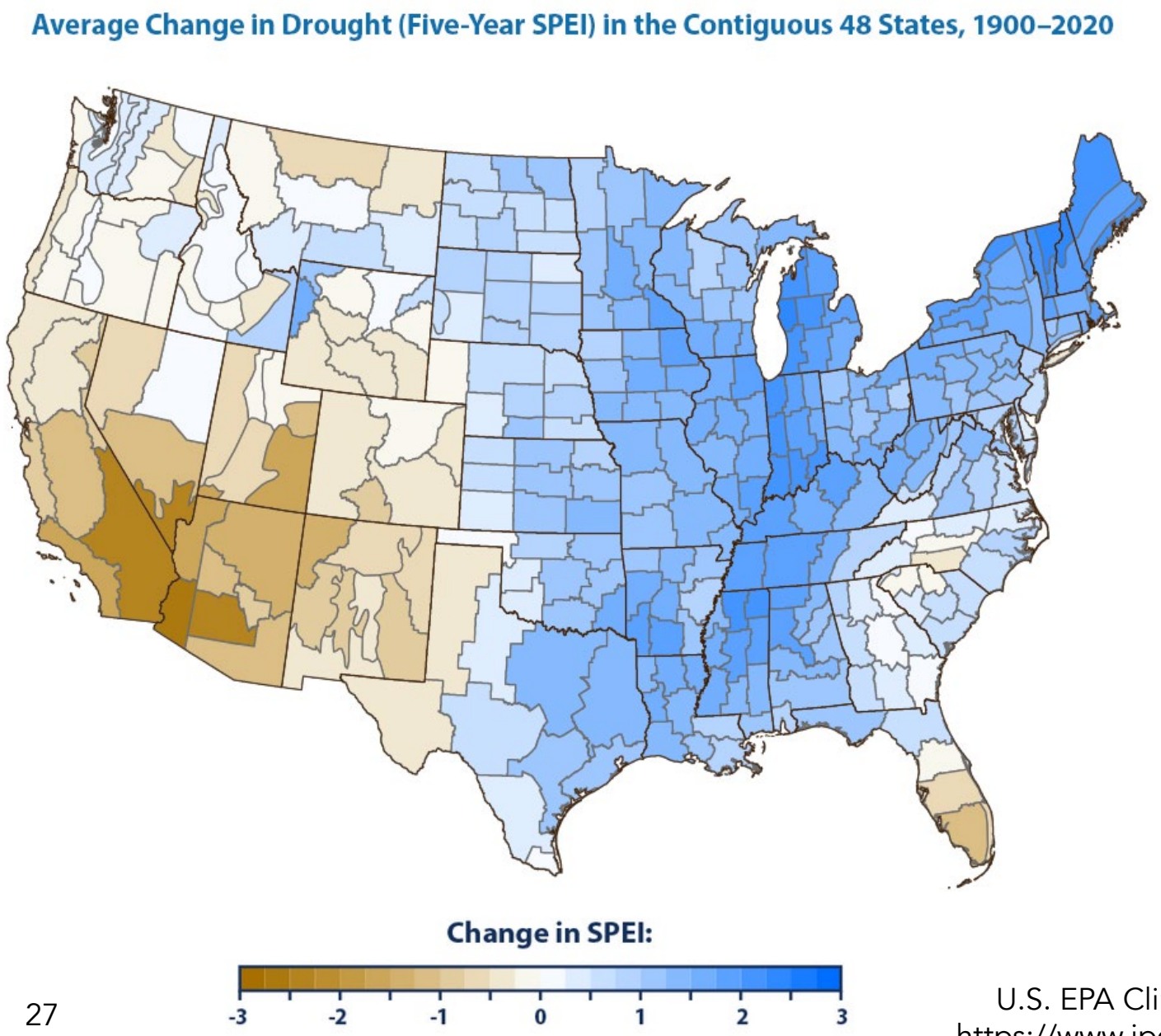


https://www.caltech.edu/about/news/soil-moisture-drives-year-to-year-change-in-land-carbon-uptake

Change in summer soil moisture, late 21st century



https://www.climate.gov/news-features/featured-images/even-small-additional-increases-greenhouse-gases-will-make-decades

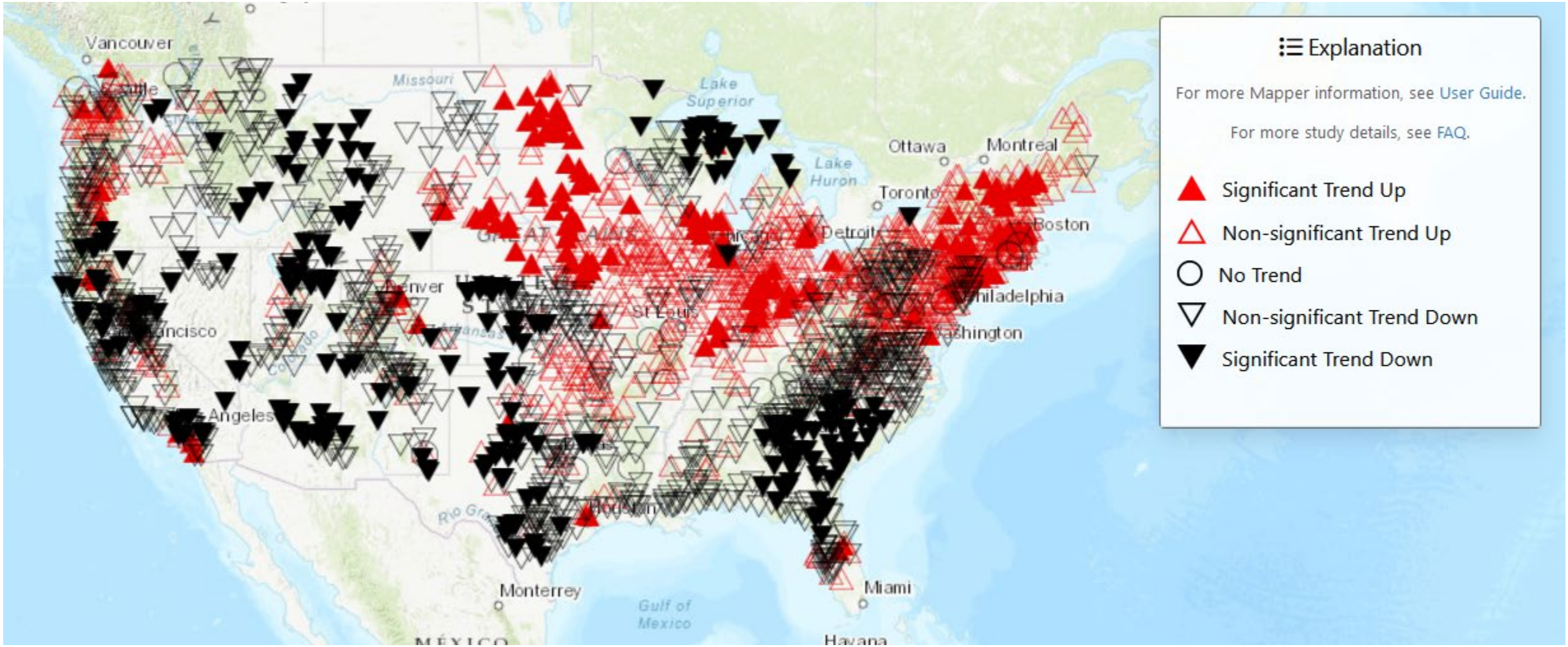


Drought

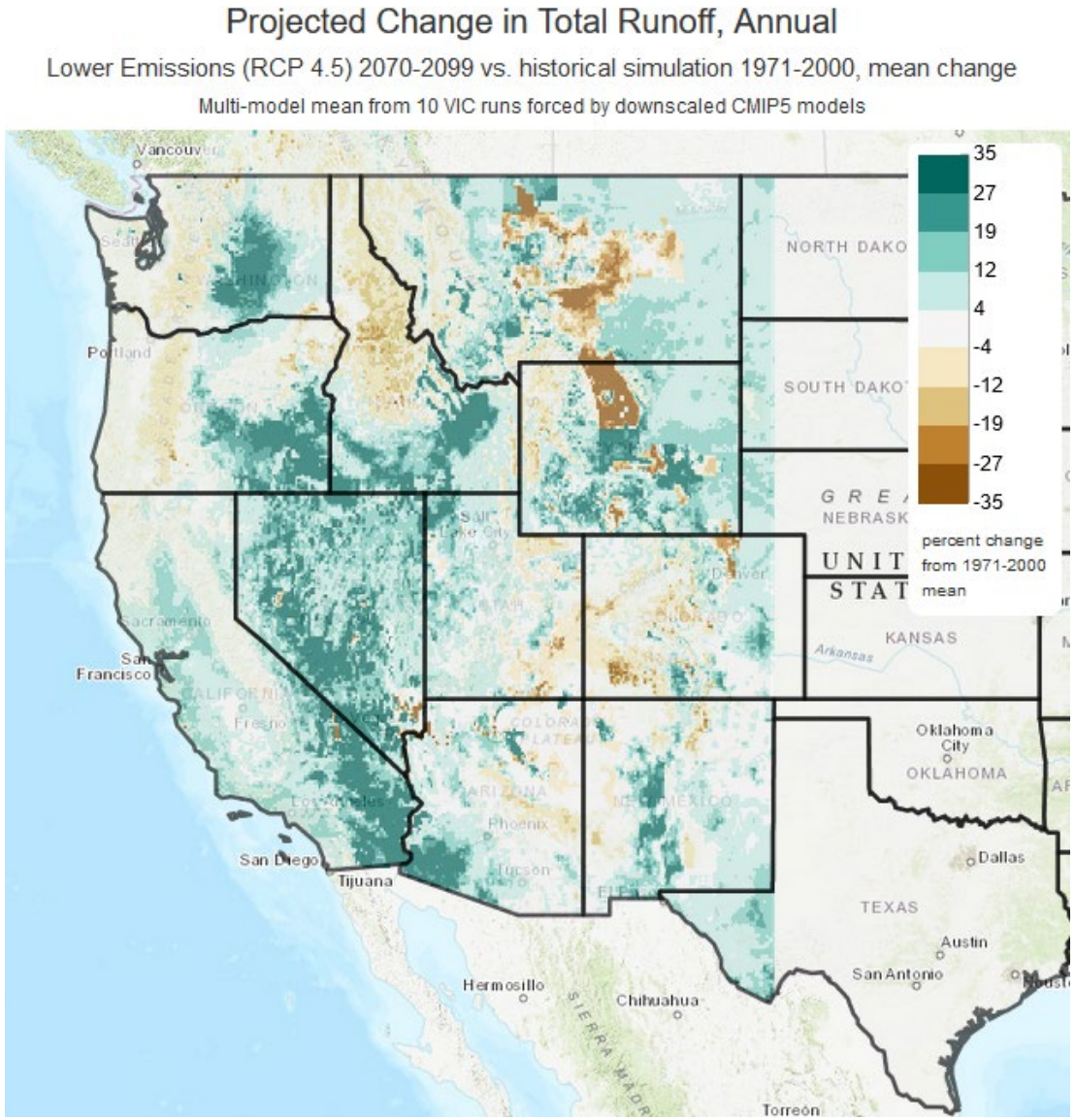
- Driven by warming without compensating increases in precipitation
- The total land area subject to drought will increase and droughts will become more frequent and severe
- Warming will make decades-long megadroughts more common

U.S. EPA Climate Change Indicators https://www.epa.gov/climate-indicators
https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_TS.pdf

Surface water flow trend 1966-2015



USGS Trends Mapper https://iwaas.wim.usgs.gov/sw-flow-trends/

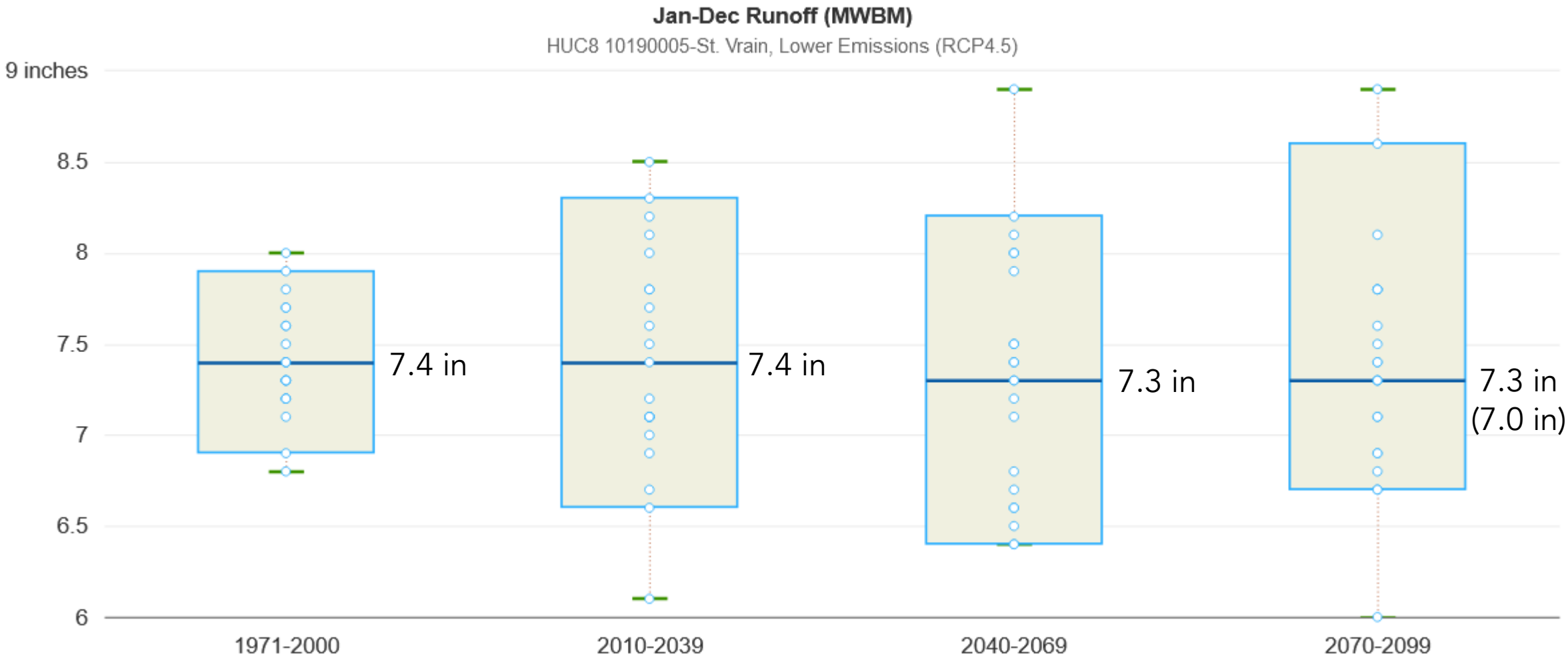


Projected runoff

- Natural runoff—no diversions or storage
- Changes between the historical period (1971-2000) and future period (2070-2099)
- Reductions more pronounced in the Colorado River basin

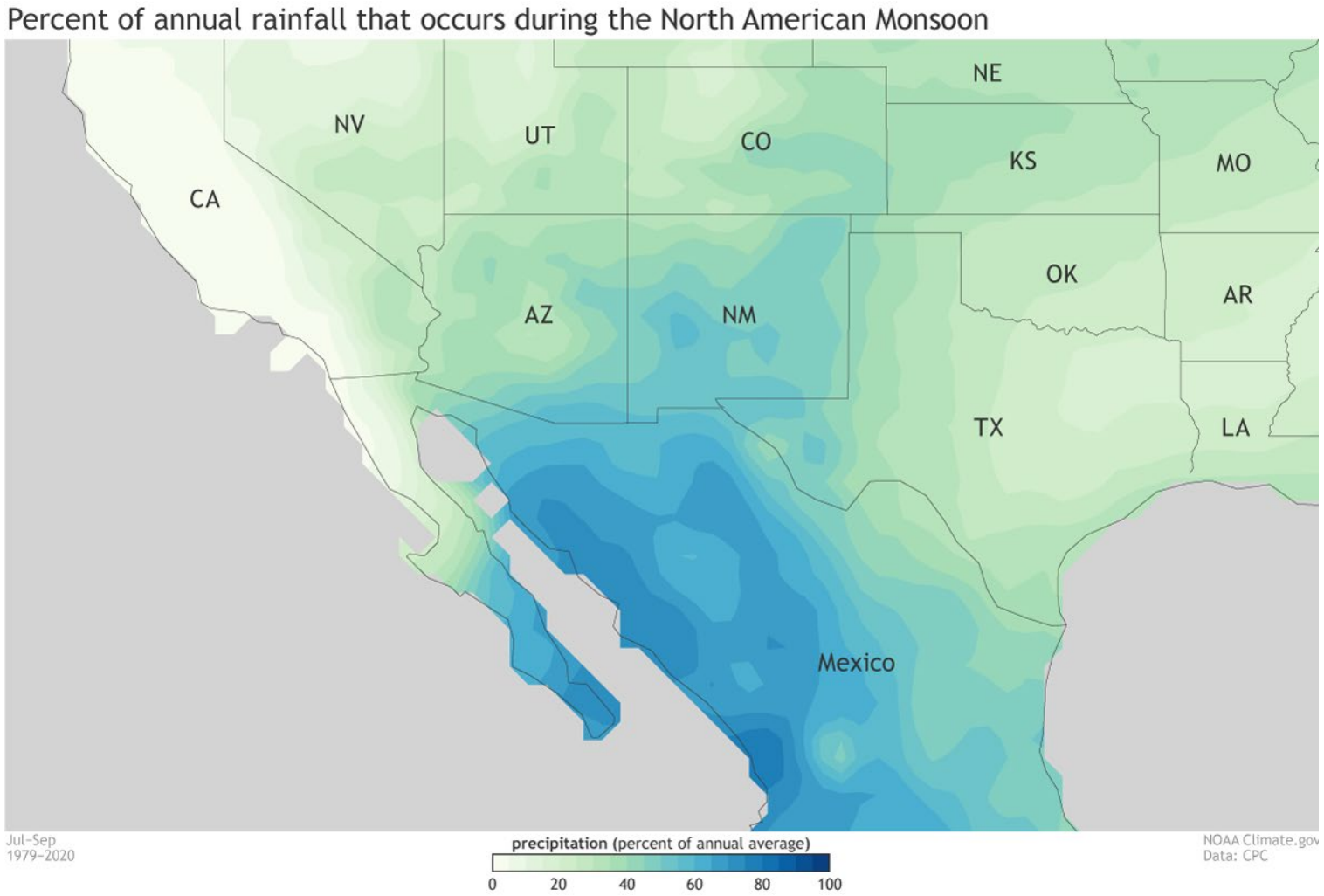
Climate Toolbox: https://climatetoolbox.org/tool/climate-mapper

Projected runoff for the St. Vrain



https://climatetoolbox.org/tool/Future-Boxplots

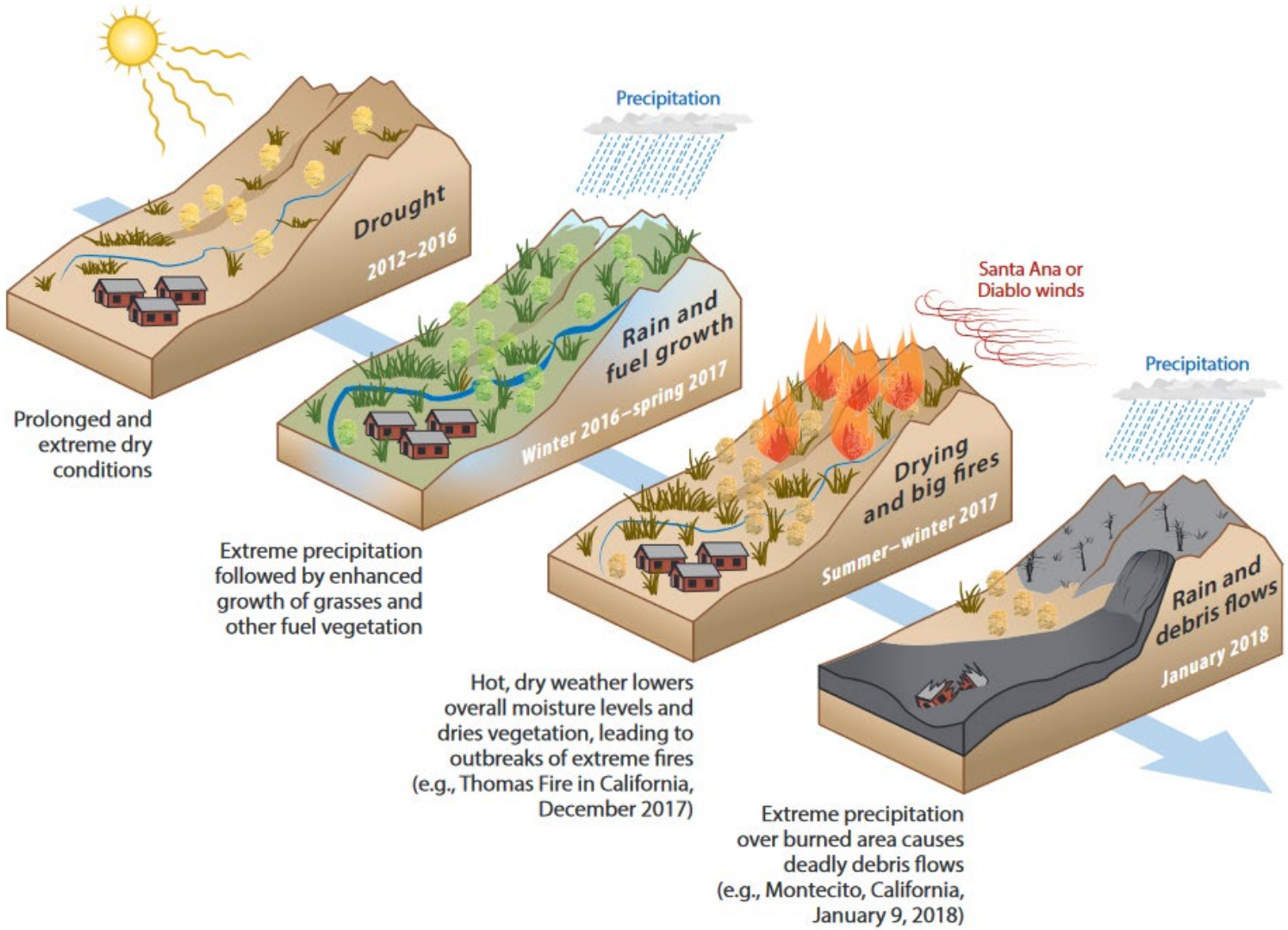
North American Monsoon



- Historically, the monsoon is active from June (in Mexico) to mid-Sep
- Total monsoon rainfall is not expected to change very much
- Monsoon activity is projected to shift later in the year, with lower monsoon precipitation in June-Aug balanced by higher precipitation in Sep-Oct

Figure: https://www.climate.gov/news-features/blogs/enso/north-american-monsoon
Hernandez and Chen (2022) https://doi.org/10.1029/2021JD035911
IPCC Technical Summary: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_TS.pdf

Compound and Cascading Hazards



- Climate change is raising the risk of coincident or consecutive individual hazards that combine to cause greater impacts
- In Florida, this might be sea level rise plus tropical storms.
- In the Midwest, this could be heat plus drought leading to harmful algal blooms
- In Colorado, increasing drought and heavy precipitation events raise the risk of fire followed by dangerous debris flows

AghaKouchak et al. 2020. https://doi.org/10.1146/annurev-earth-071719-055228

Cameron Peak fire and debris flow

July 20, 2021 Black Hollow debris flow

- In August 2020, severe drought, extreme temperatures, strong winds, and high fuel loads contributed to the largest wildfire in Colorado history
- Burned soils tend to have reduced infiltration capacity and are more easily eroded
- Almost a year later, heavy (1-2 in/hr) rain fell across the burn area
- Caused multiple debris flows, tragically resulting in several fatalities

USGS Storymap: https://arcg.is/1qnP4C0
https://drought.extension.colostate.edu/current-conditions/

A washed out bridge shown along the Yellowstone River Wednesday, June 15, 2022, near Gardiner, Mont. Photo: Rick Bowmer/AP NPR

Rain on Snow

- Heavy rainfall combines with snowmelt
- In the Yellowstone event, an atmospheric river from the Pacific coincided with a warm spell that melted the snowpack
- ROS is expected to increase flood risk of 20-200% in western US
- Expected to be less frequent at lower elevations and more frequent at higher elevations

NASA https://earthobservatory.nasa.gov/images/150010/catastrophic-flooding-in-yellowstone
Musselman et al. 2018 https://doi.org/10.1038/s41558-018-0236-4

Takeaways for Boulder County

- Warmer night-time temperatures
- Warmer spring temperatures
- Less snowpack, earlier runoff, and more precipitation falling as rain
- More intense droughts driven by a thirstier atmosphere and soil-atmosphere feedbacks
- Moderate increase in total annual precipitation
- More intense rainfall events driven by increased water holding capacity of the atmosphere and more energetic storms
- Moderate decrease in total annual runoff
- More compound hazard risk
- Watch for the upcoming release of “Climate Change in Colorado”