Managing risk from increased whiplash—Hydroclimate and beyond

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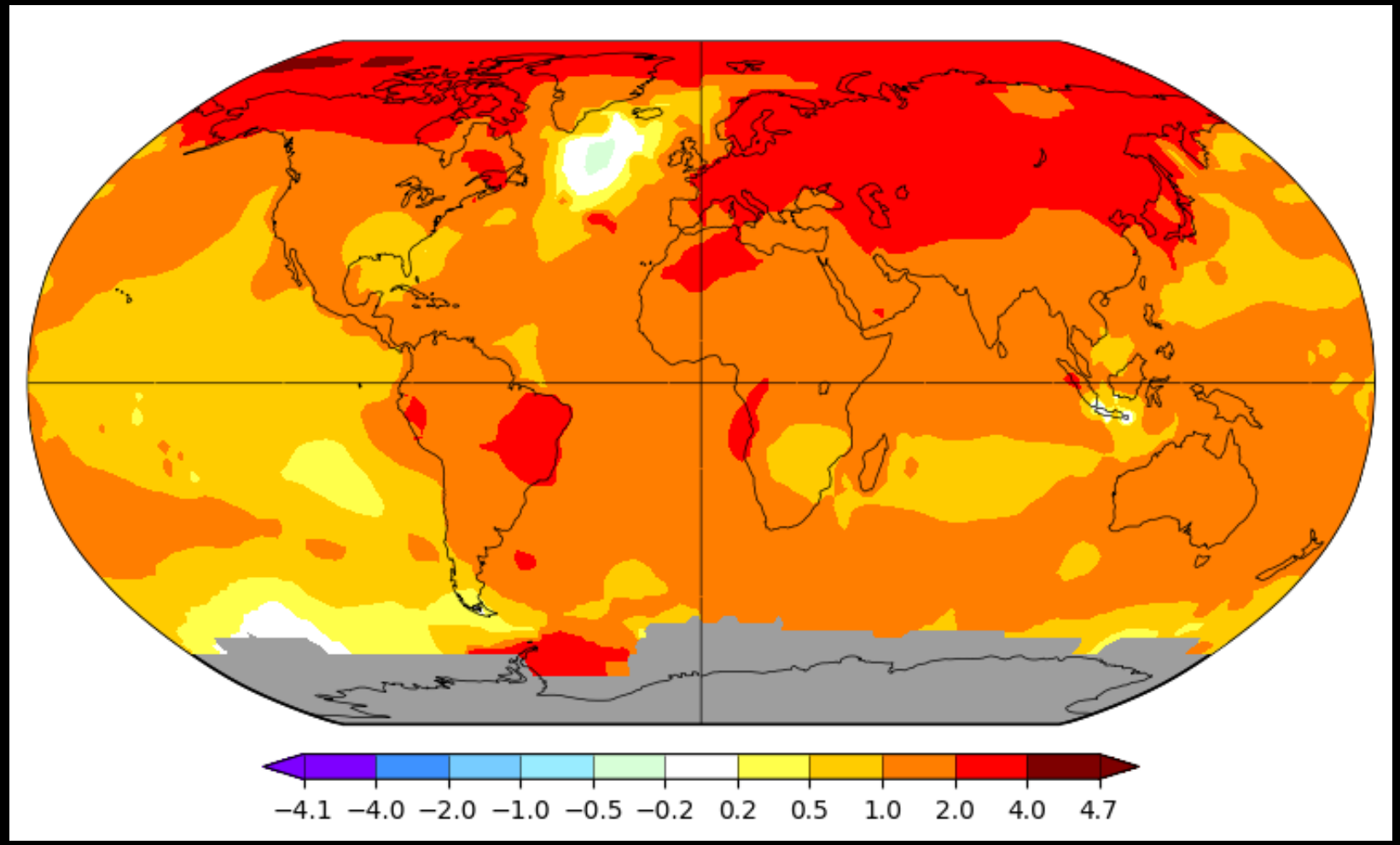
Global climate change: Where we are now?

Change in average annual temperature, 1900-2025



NASA GISS (2026)

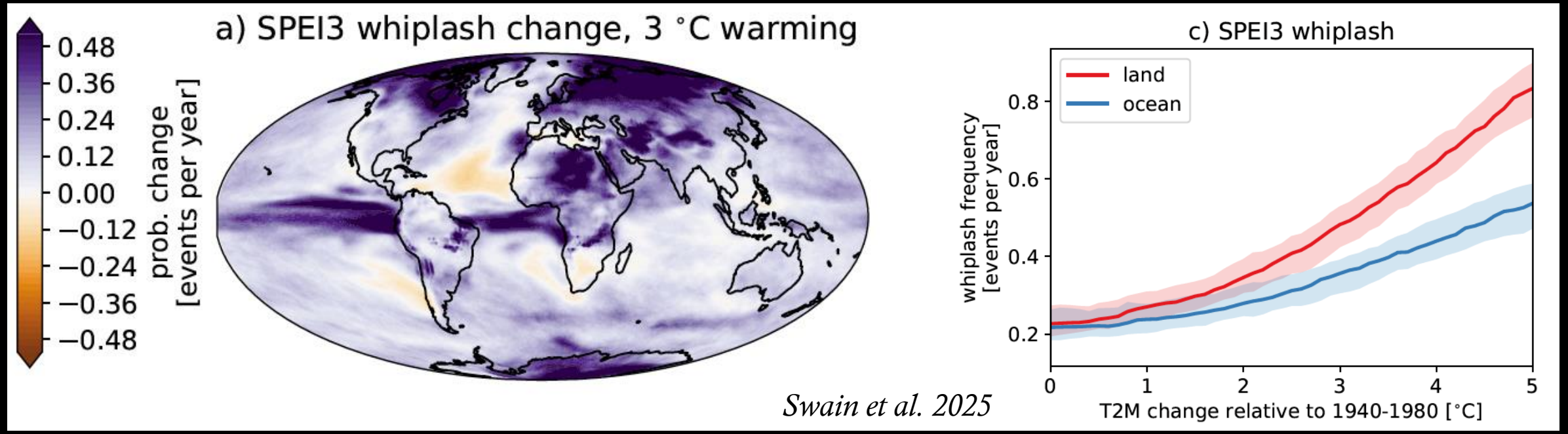
- The Earth had warmed ~1.3°C (2.5°F) as of 2022, but ≥ 1.5°C in 2023/2024!
- Spatial pattern of warming is not uniform: much faster warming over land vs sea (1.5-2x) and in Arctic (3-4x)
- But to understand impacts, we must look beyond global mean temperature!

The “expanding atmospheric sponge effect”

The figurative “atmospheric sponge,” which grows ~4% larger per °F of warming

- As temperatures rise, the water vapor holding capacity of air rises rapidly—like an expanding sponge
- ↑ Potential maximum intensity of both precipitation and evaporation
- **Net result? Increasing “hydroclimate whiplash” swings between wet & dry**

Increased hydroclimate whiplash with warming



- Nearly universal increases in hydroclimate whiplash over land with warming
- Projected acceleration of whiplash trends between 1° and 3 °C
- Mainly caused by combination of ↑ precip intensity plus ↑ evaporative demand

Why care about hydroclimate whiplash?

Thomas Fire,
Ventura County
Dec 2017

Debris flows,
S. Barbara County
Jan 2018

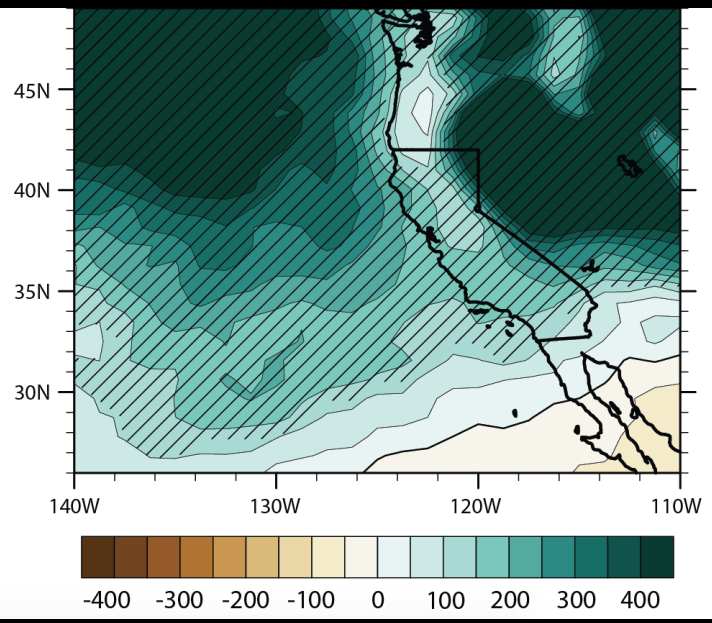
On average, it was mostly sunny and breezy—with below-average precipitation.

If we only consider changes in average climate,

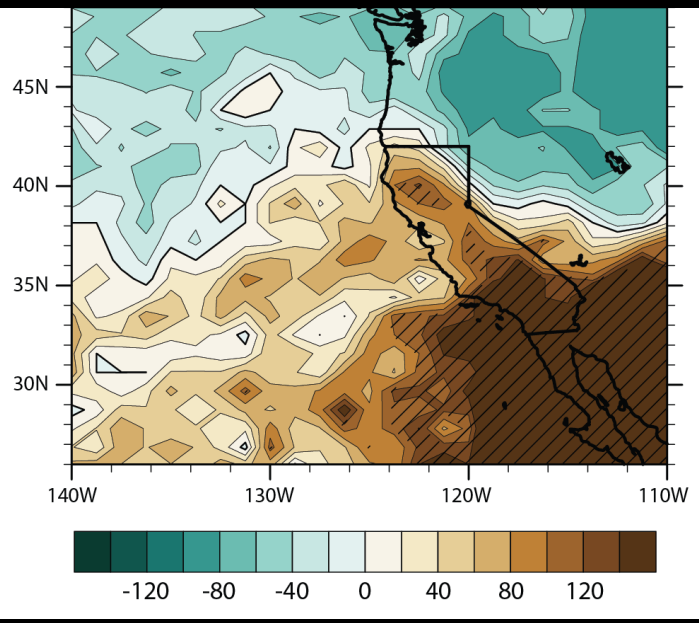
then we're largely missing the point.

Precipitation in CA: A wetter *and* drier future?

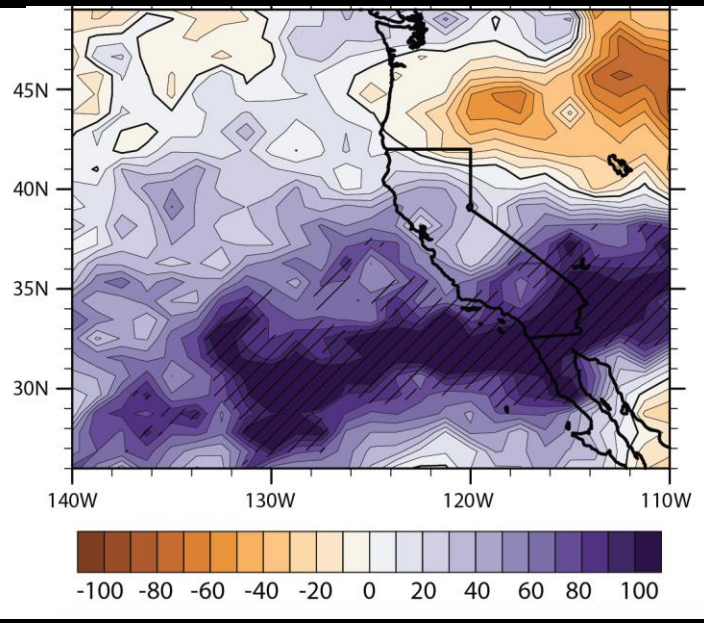
Increase in very wet years



Increase in very dry years



Increase in "whiplash"



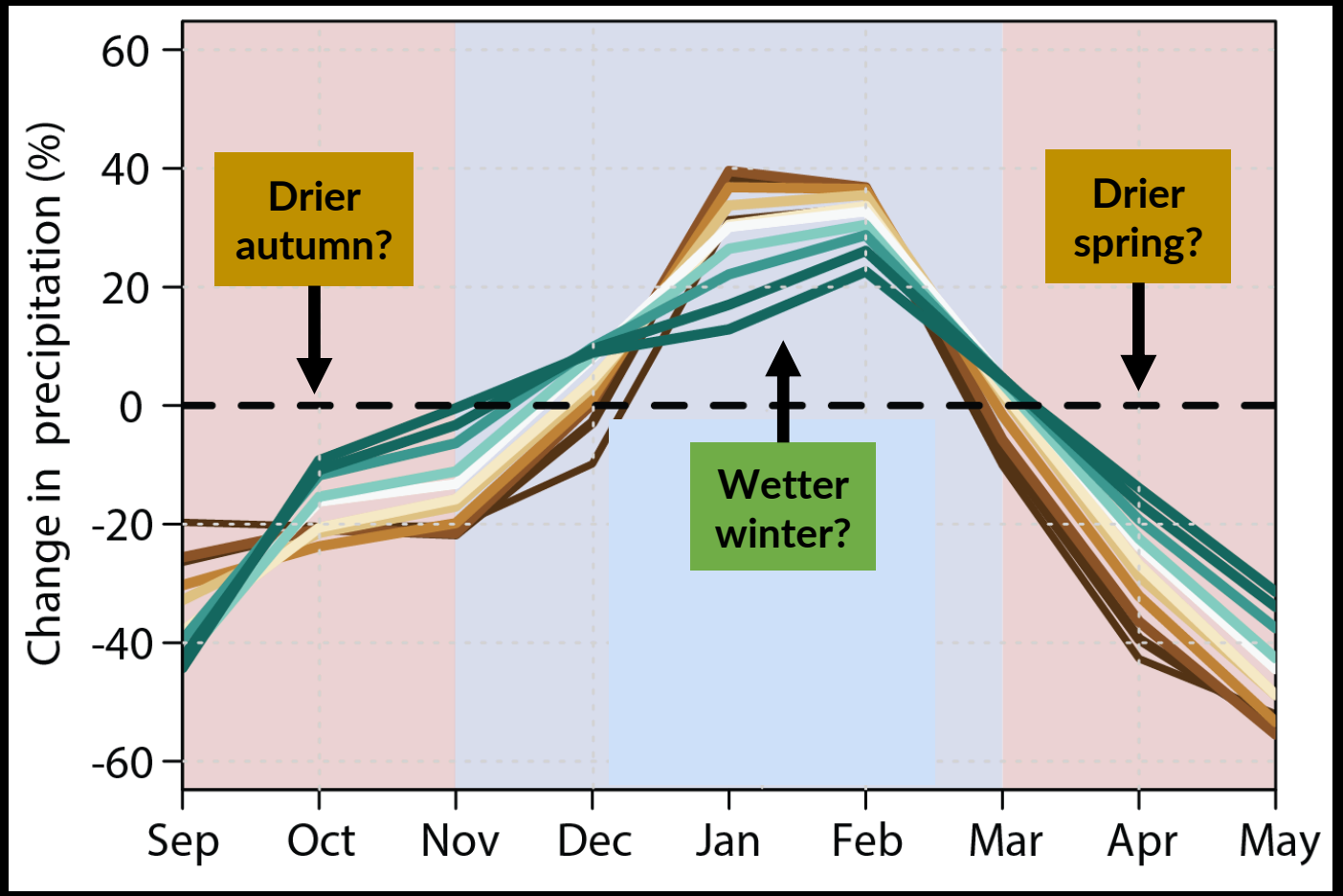
Swain et al. 2018

Large increase in wet extremes
(and, to lesser extent, dry extremes)
despite little and/or uncertain mean precip change!

An (even) shorter, (even) sharper rainy season

- Less precipitation during autumn/spring "shoulder seasons," but more in core winter "rainy season?"
- Net result: Longer dry season, more intense wet season
- Large implications for ecosystems, wildfire, agriculture, water supply

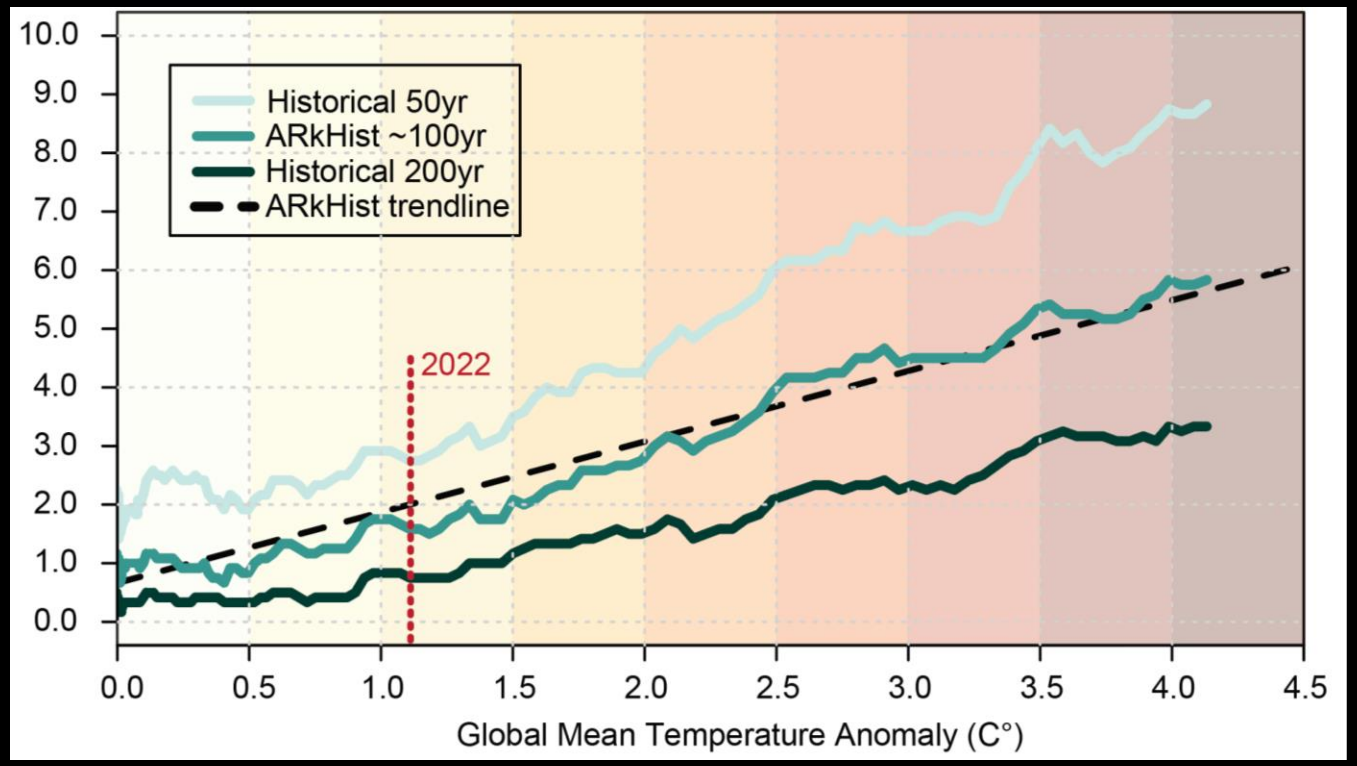
Projected change in "seasonal sharpness" of California precip



Swain et al. 2018

Climate change is increasing the risk of a severe California flood event

Likelihood (%) of a severe statewide flood event

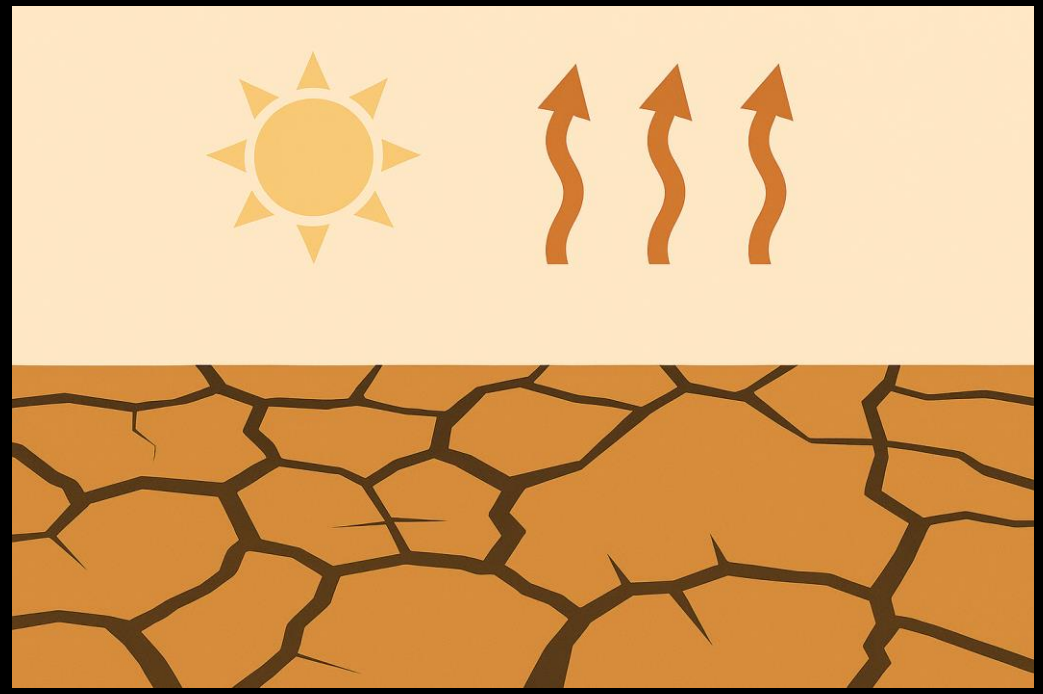


Huang and Swain 2022

- Climate change has already (though quietly) doubled the likelihood of a historically severe statewide flood
- Cumulative risk of severe statewide flood event between 2020-2060? >65%!

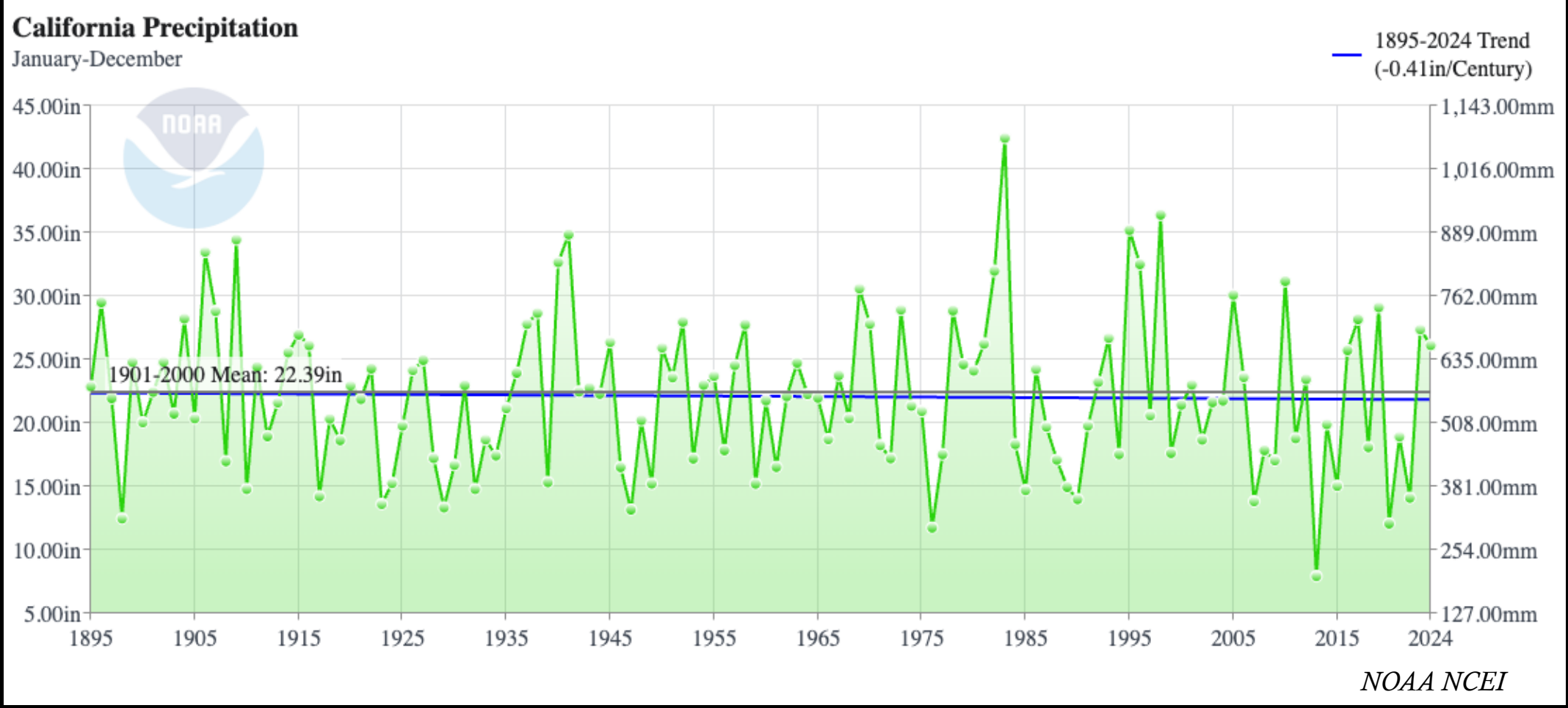
Worsening droughts driven by higher temperatures and increasing evaporative demand

- The same amount of rain/snow simply just doesn't go as far. But why?
  - More dry days overall
  - Faster evaporation during dry periods
  - Less snowpack & shorter snow seasons
- Droughts used to be hot or cold…*but now they're all hot by historical standards.*
- Blame the dry side of the expanding atmospheric sponge!



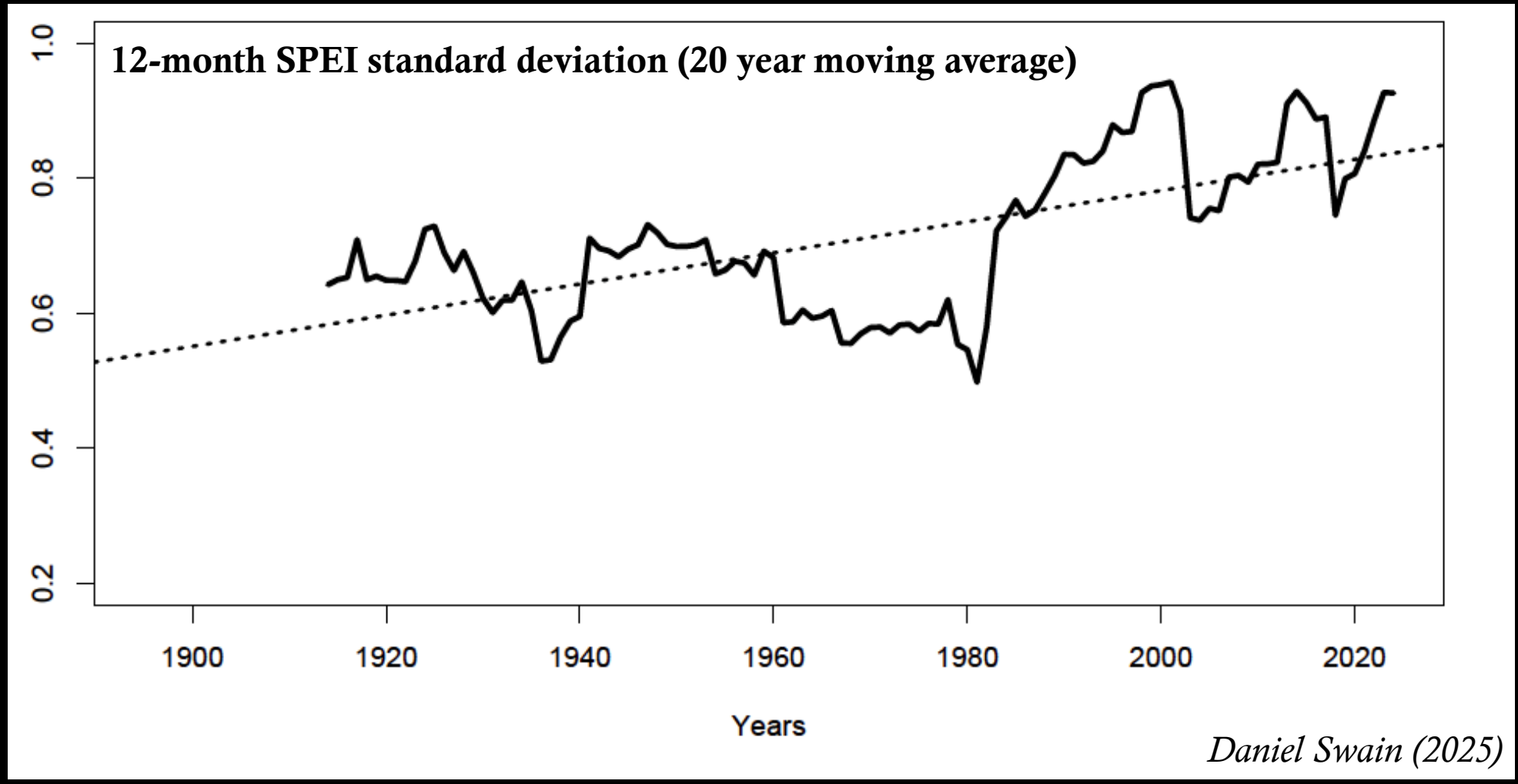
So…What's actually going on in California?

Little trend in annual/winter mean precipitation…



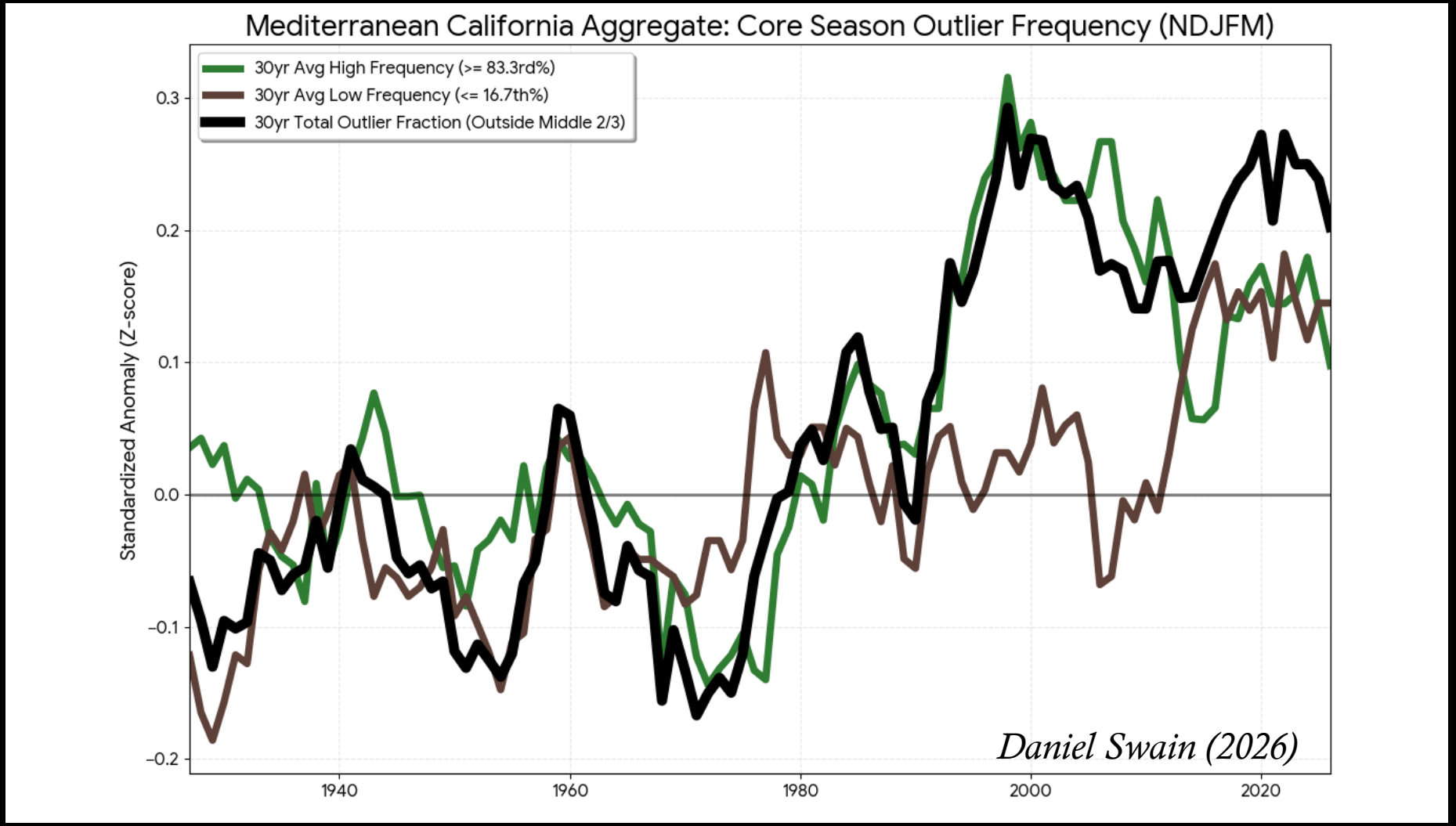
So…What's actually going on in California?

…Amid a substantial increases in moisture *variability!*



So…What's actually going on in California?

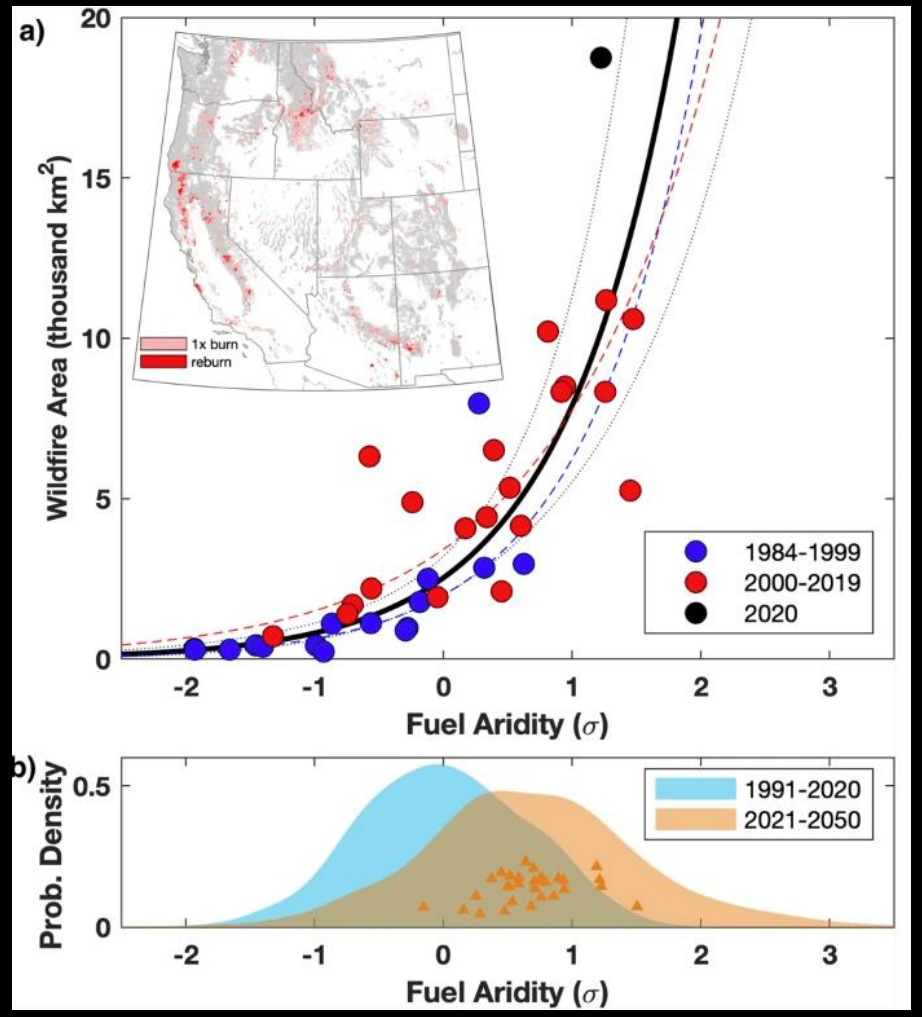
…And a large historical increase in precipitation variability during wet season



Honing in on the evolving dynamics of wildfire risk amid increasing hydroclimate whiplash

Dry side of "expanding atmospheric sponge" is (largely) driving wildfire trends

Relationship between forest fires & vegetation aridity

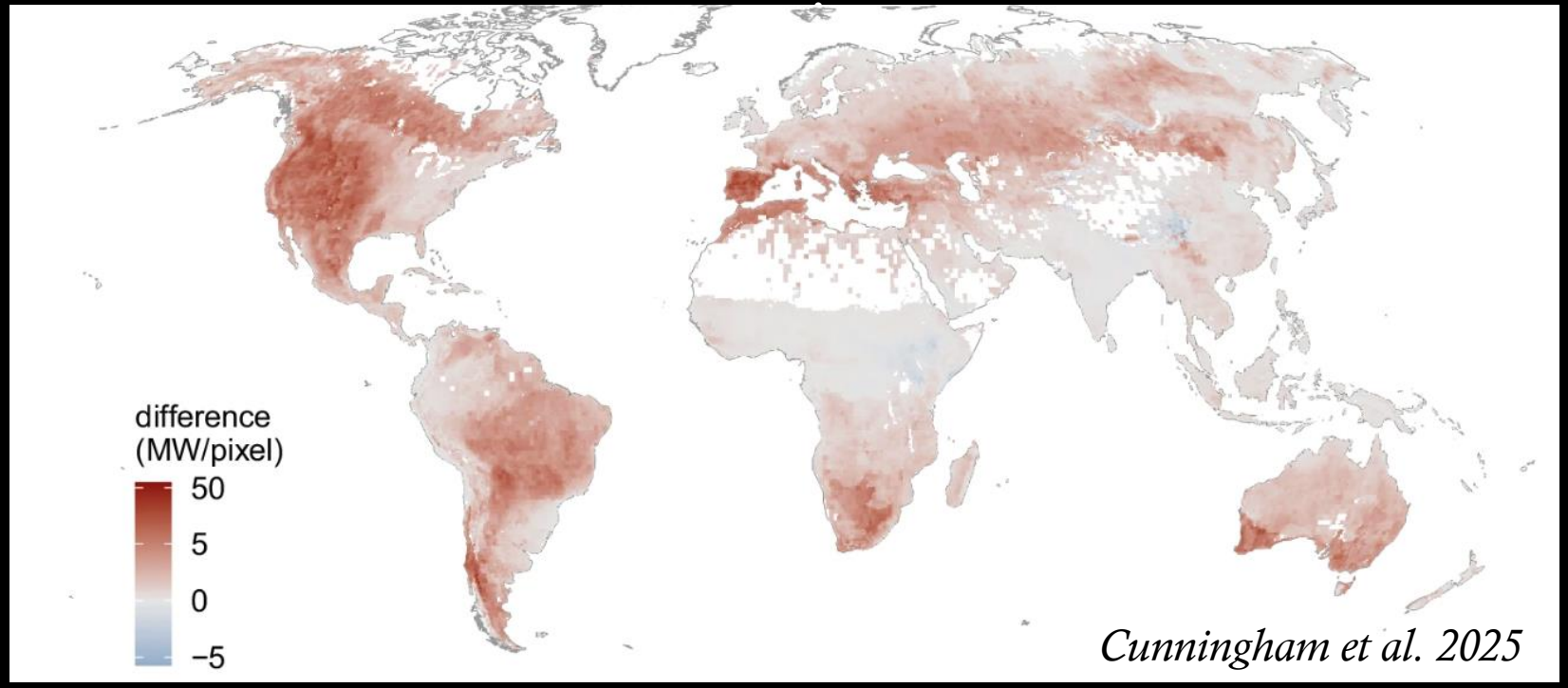


Abatzoglou et al. 2021

- Studies show historical relationship between vegetation dryness and wildfire extent/severity is *exponential* (at least in forests/heavier fuels)
- Many regions have already experienced profound shifts in upper tails of vegetation aridity distribution, largely driven by increasing atmospheric evaporative demand & rising VPD

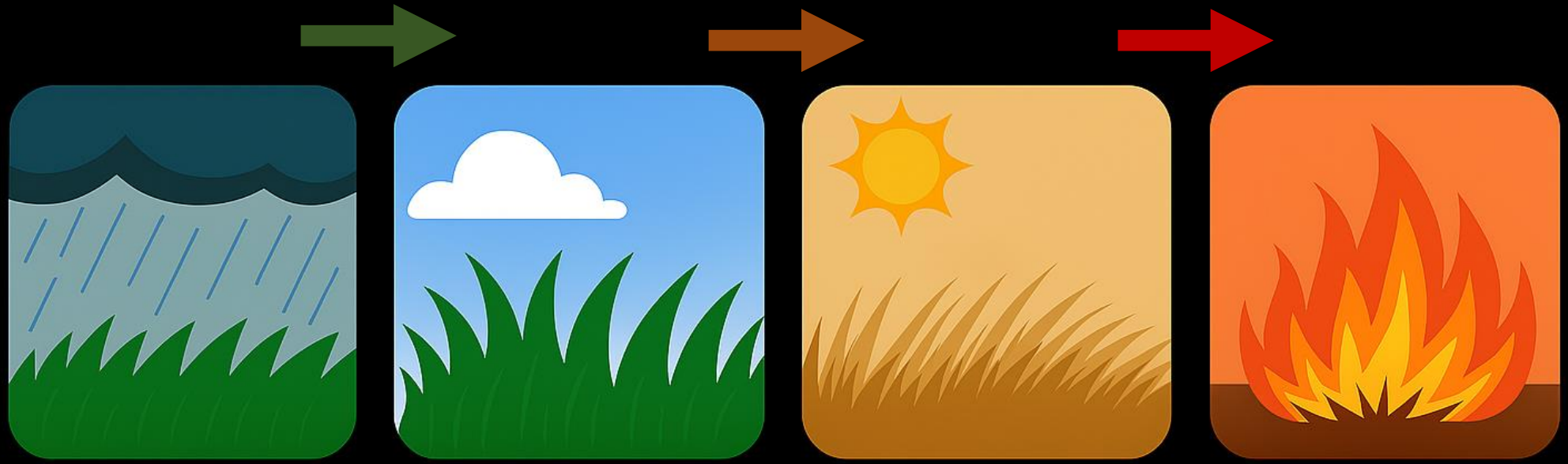
Widespread increases in fire intensity w/warming

Projected increase in wildfire thermal intensity under 2°C of warming



- Even w/modest warming, near-universal global increases in wildfire potential intensity
- Largest/most widespread increases in western U.S./Canada
- Regional hotspots in northern Mediterranean, southern Chile, SW & SE AUS, & S Africa

Increasing “wildfire whiplash” in grassland and shrubland settings



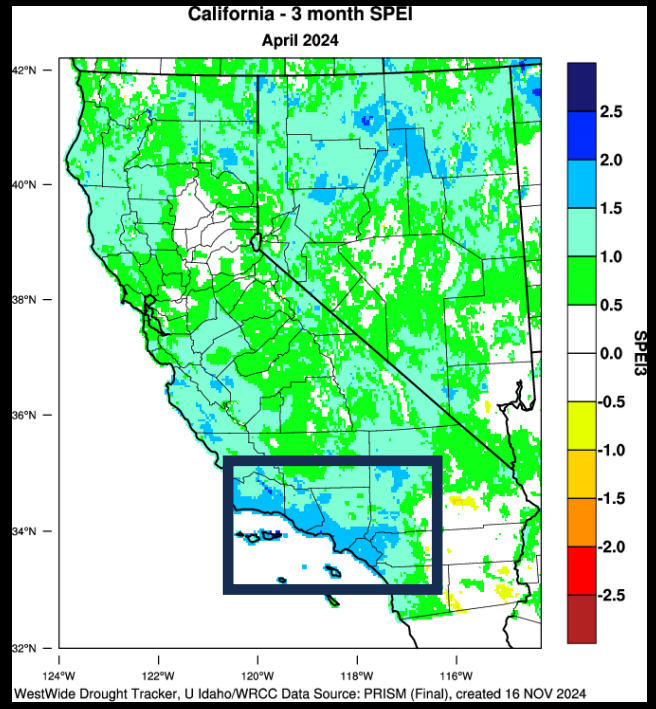
- Fuel accumulation → desiccation cycles are linked to ↑ grass & shrub fire intensity
- This is exactly what we expect to see with ↑ hydroclimate whiplash!
- Forest fire risk follows dryness; grass fire risk follows wet → dry cycles. Both are ↑.

Another consequence of hydroclimate whiplash: Devastating Jan. 2025 wildfires in Los Angeles

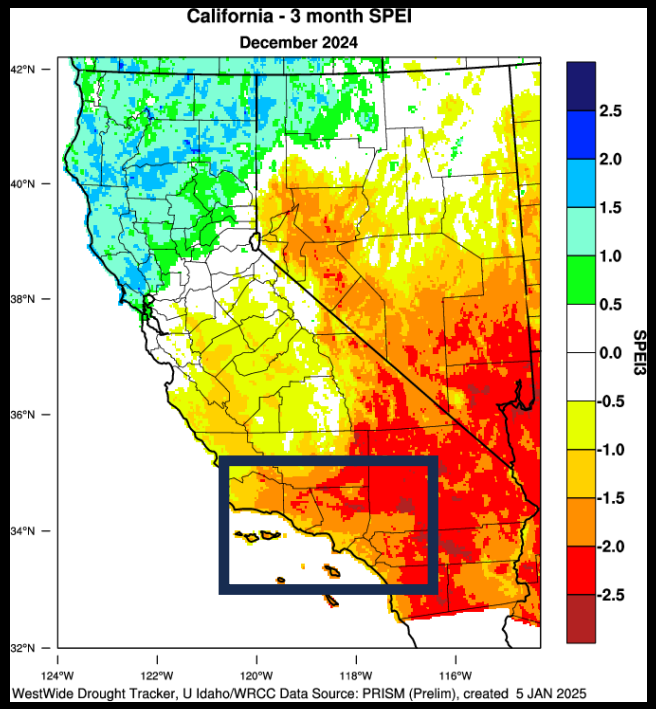
And then, in autumn 2025, back to record wet!

Extreme/near-record wet in winter 2023-2024 → **Record heat & evaporative demand at times summer-autumn 2024** → **Failure of rainy season 2024-2025 through Jan. 2025; record low precip** → **"Extremely critical" fire weather conditions following record wet-dry swing set stage for devastating Jan. 2025 fires in LA**

April 2024: Extremely wet in SoCal



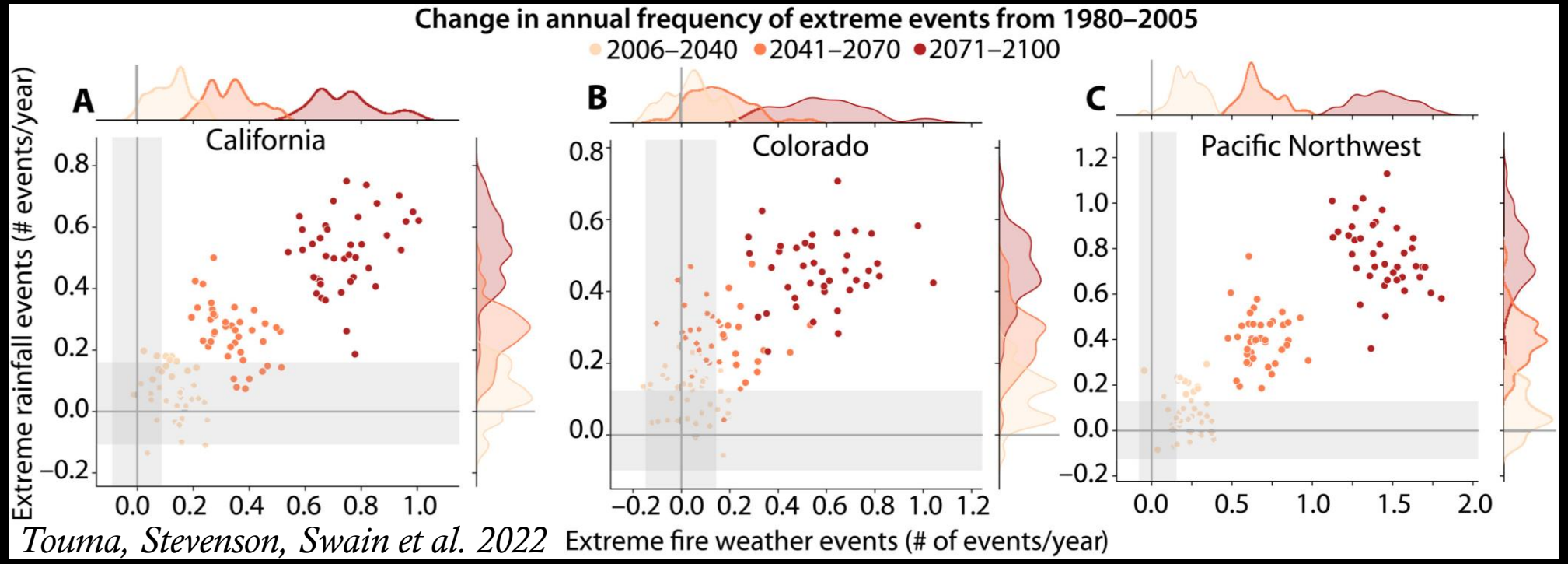
Dec. 2024: Extremely dry in SoCal



Data/plots via Western Regional Climate Center (WRCC); photo from AP/Ethan Swope

Dry-to-wet whiplash also amplifies post-fire hazards

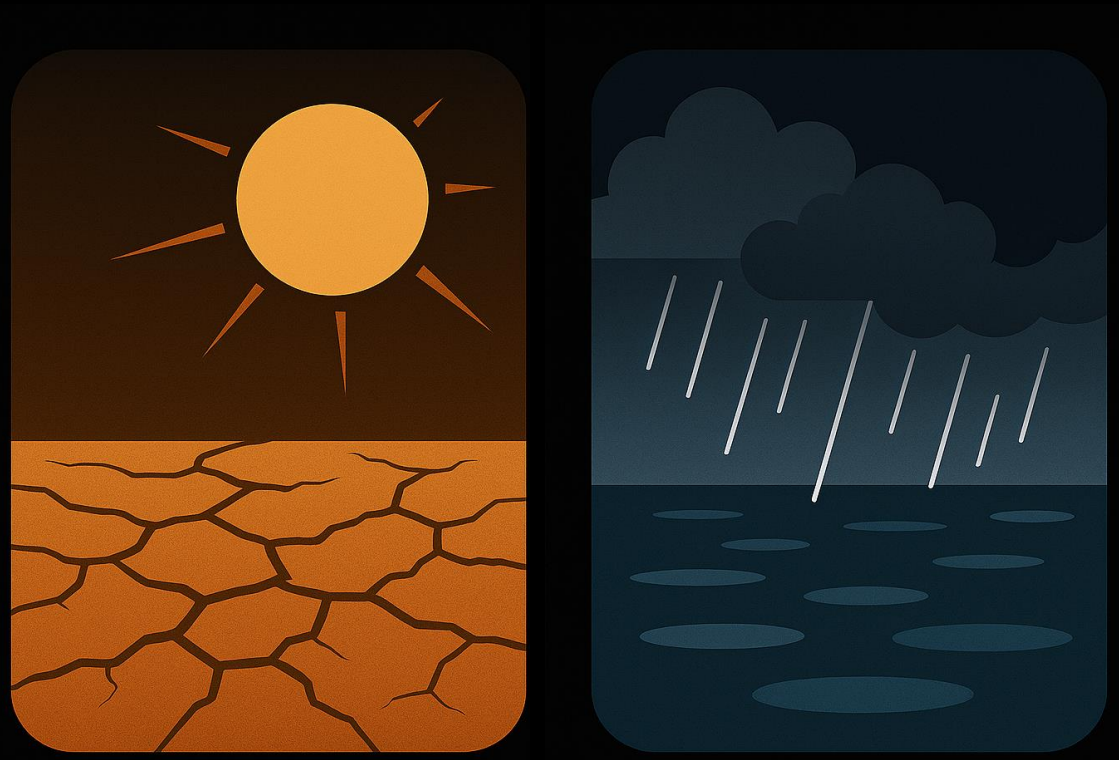
Projected change in extreme fire weather and extreme rain events in high warming scenario



- *Dry-to-wet* whiplash, while not directly implicated in increasing fire risk, can increase post-fire hazards including flash floods, debris flows, and other geophysical "mass wasting" events.
- Increased risk persists for at least months, and sometimes 3-5 years, following large/high-intensity fires

Is there a broader signature of increasing volatility, or “whiplash,” in a warming climate?

Increasing hydrologic whiplash: Drier soils lead to fewer but more intense floods?

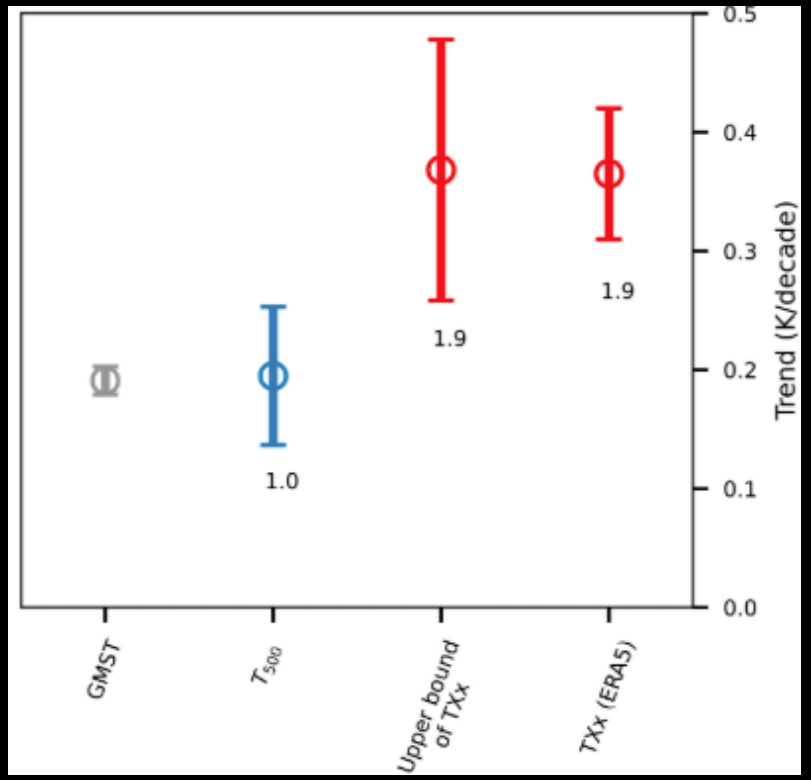


- The very heaviest rainfall increases the most, but light precipitation decreases
- Greater soil drying amid less frequent precipitation events & “thirstier” air
- **Net result: Less frequent, but more severe, floods? This represents a major challenge!**

Heatwave *intensity* whiplash?

- No evidence for *overall* increase in temperature variability
- ***However,* very most extreme continental heatwaves may be warming faster than both mean temp & more moderate events.**
- Theoretical upper limit on surface heat extremes scales at ~1.9x rate of local mean warming (but locally higher)
- Linking it back to dry & moist thermodynamics:
  - Soil moisture depletion = increased sensible (vs latent) heat fluxes locally
  - Upstream latent heat release = increased downstream airmass MSE
  - Both processes may increasingly contribute to heatwaves amid warming—even in same event (e.g., June 2021 record-shattering PacNW event)
  - Notably, this represents both "wet" and "dry" side thermodynamic effects!

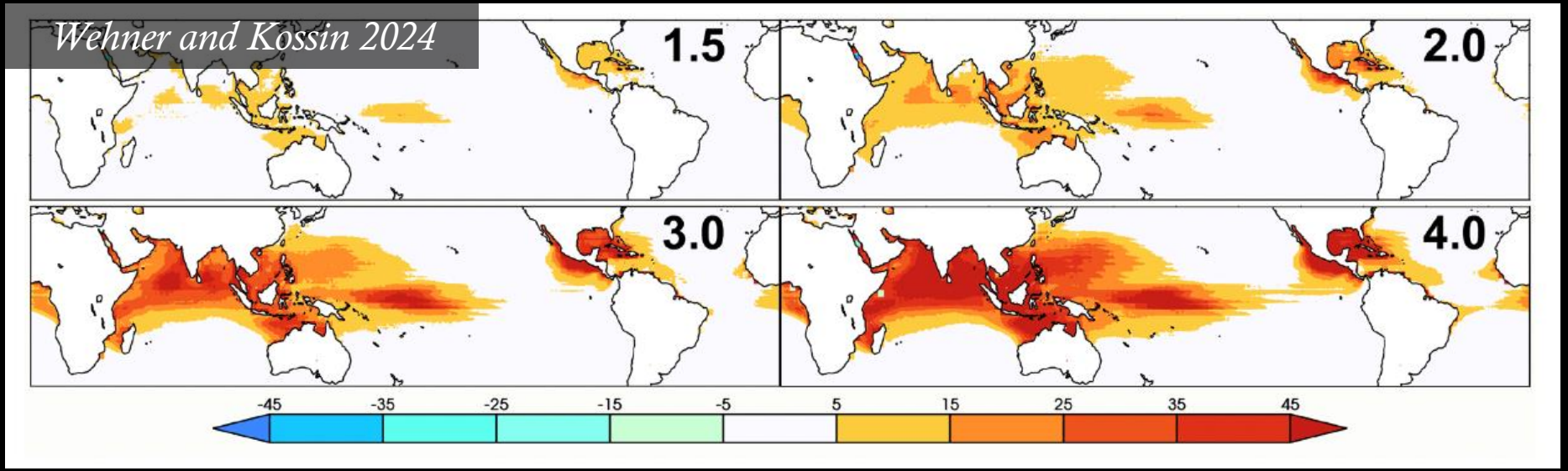
Observed rate of mean vs extreme hot day warming (& theory)



Zhang and Boos 2023

Increasing tropical cyclone *intensity* whiplash?

Change in occurrence of TC max intensity supporting above scale/"Category 6" TCs

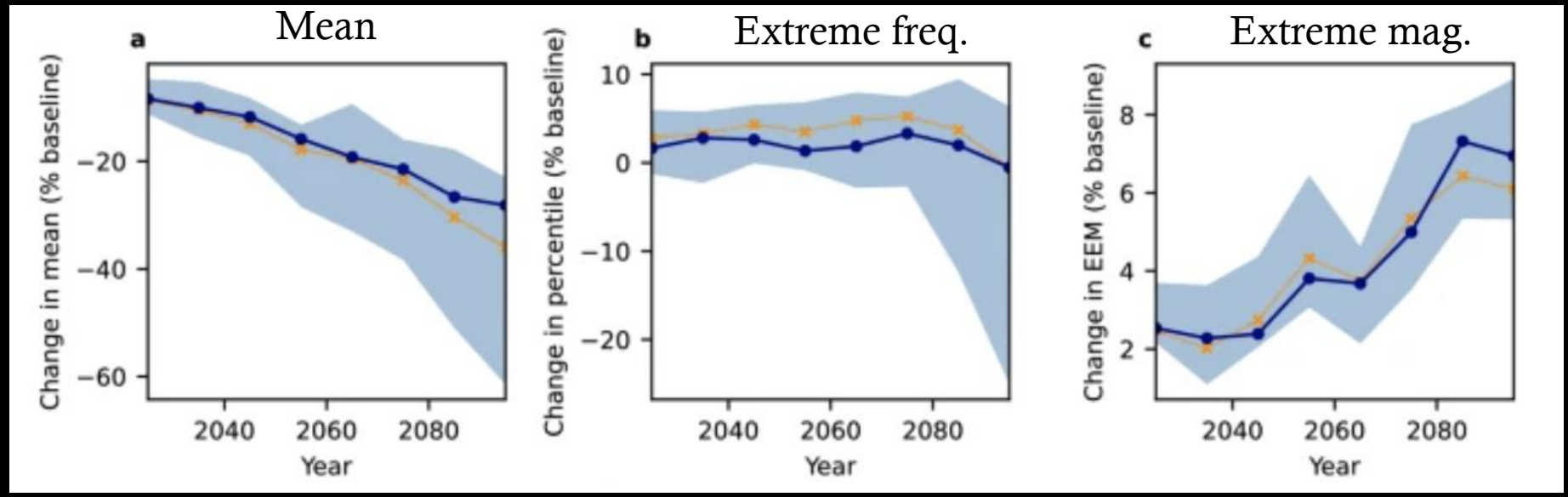


- Still unclear whether CC will cause increase or decrease in # of TCs
- But growing evidence that both proportion and total number of "major hurricanes" (Cat 3-5 storms) is increasing in real world
- Theoretical maximum TC intensity scales with local SST & upper TT
- ***TC intensity whiplash ↑ via potentially fewer, but wetter and stronger hurricanes with warming?***

Increasing "snowfall whiplash?"

Projected increase in extreme snowfalls along U.S. Eastern Seaboard

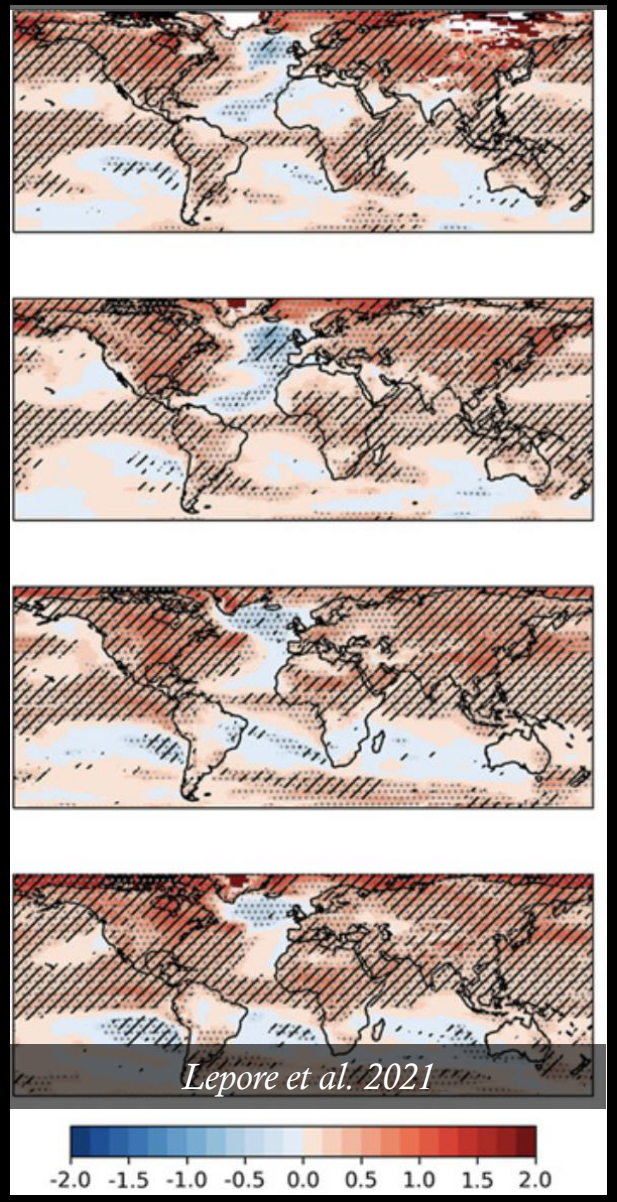
Quante et al. 2021



- Thermodynamics: warmer = thermal profile generally less conducive to frozen p-type, but more intense precip if/when conditions favorable (due to increased moisture)
- **Upshot: extreme snowfalls will still occur in warmer climate, and may become even more disruptive as gap between mean and extremes widens.**

Increasing severe convective whiplash?

Change in CAPE, +2C warmer world (σ)



Lepore et al. 2021

- Generally low scientific confidence in details!
- Overall, a more unstable atmosphere across broader region (increased CAPE; stronger updrafts)
- But…decreased vertical wind shear in many areas, though with complex regional/seasonal signal
- Opportunities for *more intense* severe thunderstorms, but fewer days on which factors align? ↑ variability?
- ***Plausible: increased potential for "weird" events, including outbreaks in unusual locations/seasons, wider variability***

Closing thoughts

- There is now clear evidence for increased volatility, observed and projected, in the global hydroclimate system with warming
- There are also plausible mechanistic linkages between *many other types* of extremes intensified by increases in specific humidity, evaporative demand, vapor pressure deficit, or changes in spatiotemporal gradients of moisture.
- Two key reasons why this matters:
  1. Effects of increases volatility often different from, or additive to, isolated extremes
  2. Higher predictive confidence in thermodynamic processes (inc. whiplash)
- How to best integrate whiplash-aware metrics & methods into research?
- Lessons for planning and adaptation:
  - Need to look beyond isolated extremes & consider event transitions/sequencing
  - Adaptations must be flexible & multi-hazard capable; learn to “roll w/punches”

Thank you!

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Link to UC survey