Quantifying heat extremes in a changing climate:

Some thoughts on how, and why it matters

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2025 US CLIVAR summit

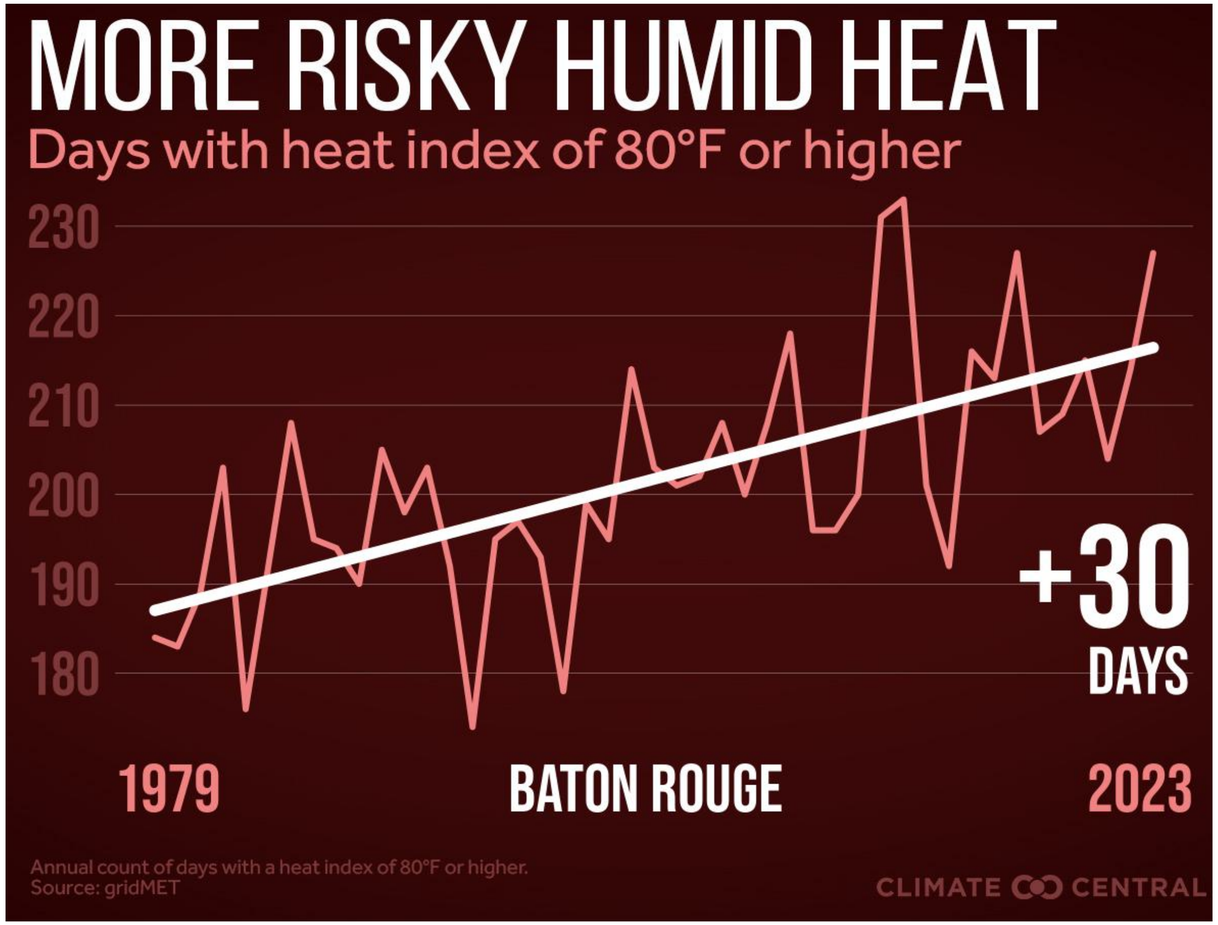
Extremes: a definitional challenge

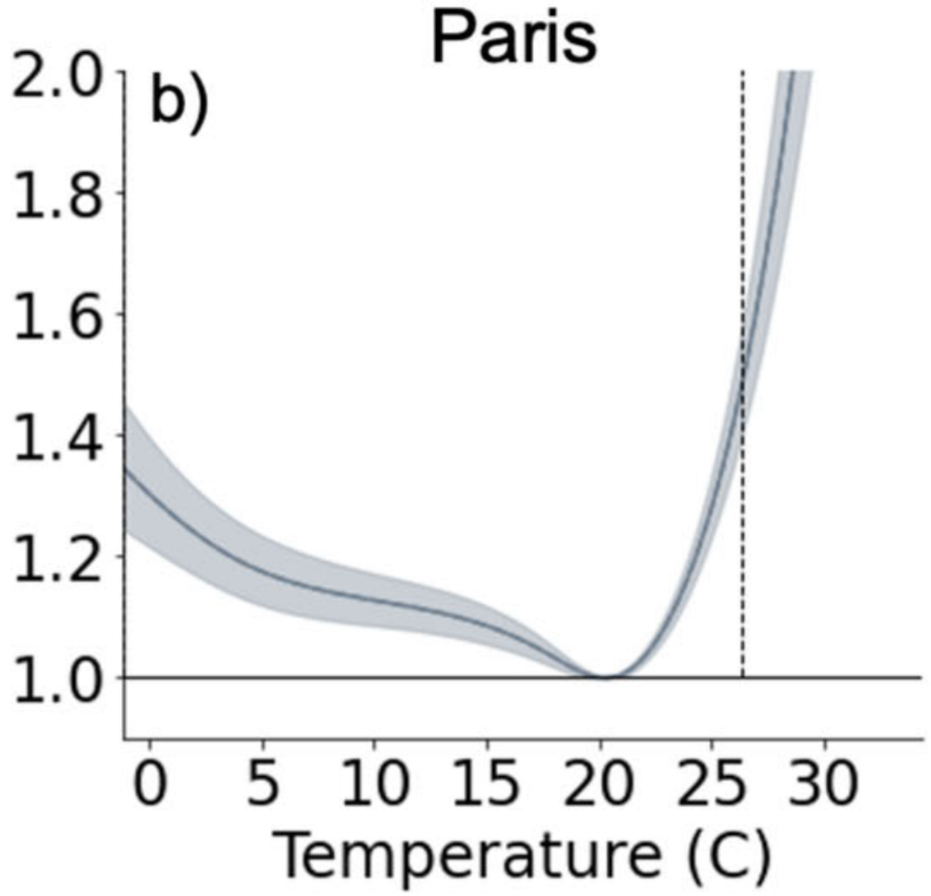
Absolute extremes	Relative extremes
A temperature over a threshold (e.g. 95 degrees F)	A temperature over a percentile (e.g. 95th percentile)
Other considerations are often shared, for example definitions for length, compound extremes	
Impact motivated (health, biosphere, infrastructure…)	Generally (but not always) impact agnostic
Strong spatial structure due to climatology: some places may have extremes all the time, some may never have them	Probability is spatially-uniform by design
Strong seasonality	Seasonality often removed through choosing a day-of-year varying percentile
Baseline is irrelevant	Affected by choice of baseline
Should the threshold change with climate change?	Should the baseline change with climate change?

What factors should be taken into consideration when identifying an extreme in a changing climate?

The baseline matters — and its choice depends
on why we care about a particular extreme

Impacts-motivated extremes: the choice of threshold depends on the impact, and may or may not be changing with time (is there adaptation?)



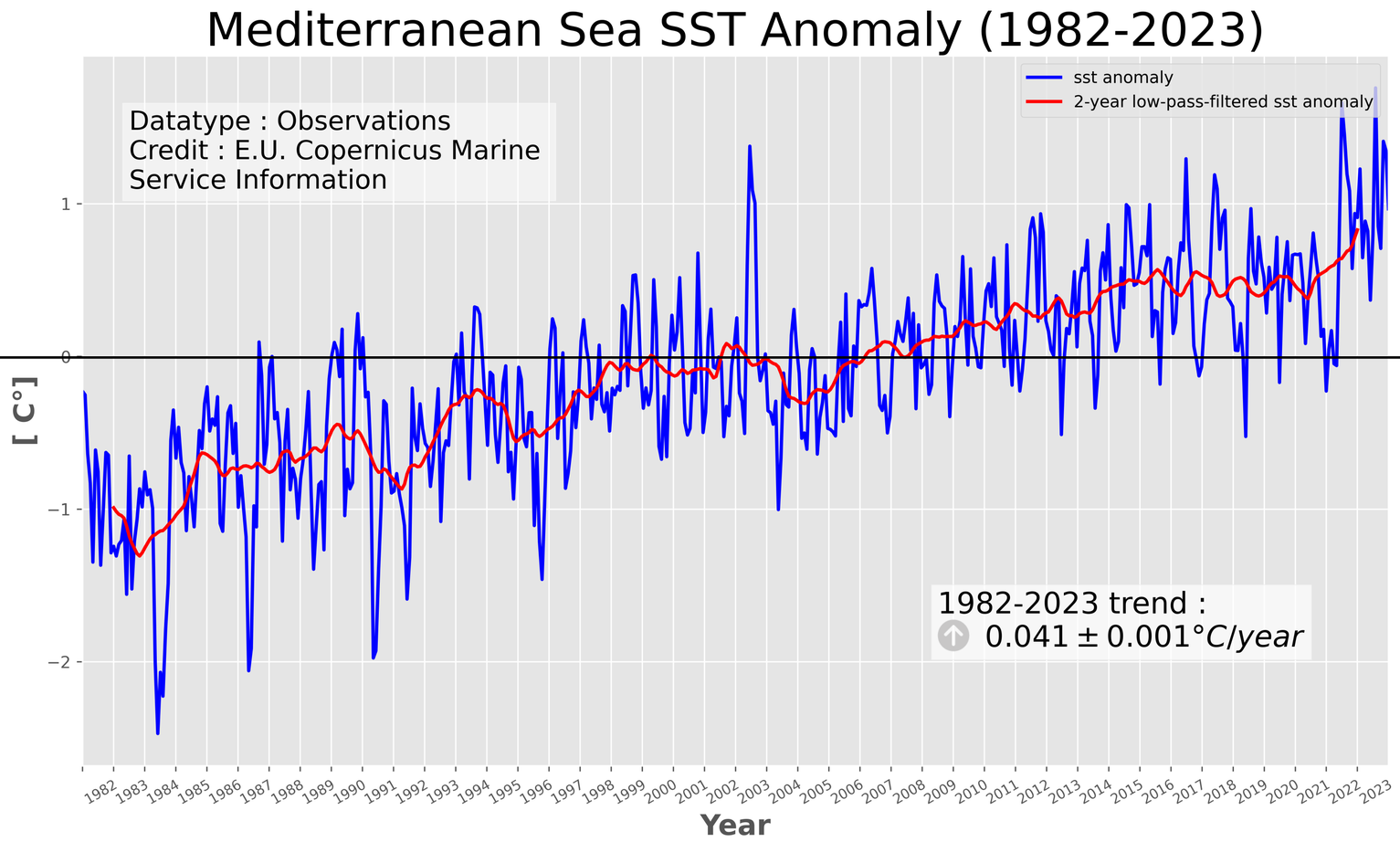


Lüthi et al., 2023, *Nature Communications*

Percentile-based extremes: fixed baselines can cause challenges in a rapidly warming climate

Extreme high temperatures

Extreme low temperatures



A proposal for baselines: A hierarchy of controls on the change in extremes, as measured by a percentile

Global mean temperature

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Global land temperature

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Summer versus annual-mean temperatures

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Summer versus annual-mean temperatures

Local summer average temperature

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The pace of change of summertime temperature extremes

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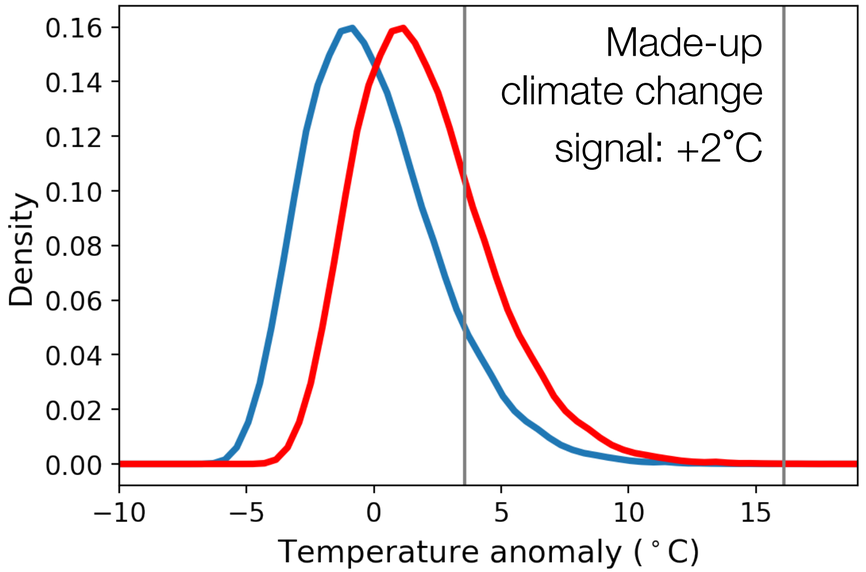
Affiliations are included on p. 9.

Edited by Kerry Emanuel, Massachusetts Institute of Technology, New Harbor, ME; received March 25, 2024; accepted August 30, 2024

Here, we show that, in both observations and historical climate model simulations, the hottest summer days have warmed at the same pace as the median globally, in each hemisphere, and in the tropics from 1959 to 2023.

"simple shift" mode



How can we integrate different techniques (dynamical, empirical) to better inform the evolving risk of extremes over time?

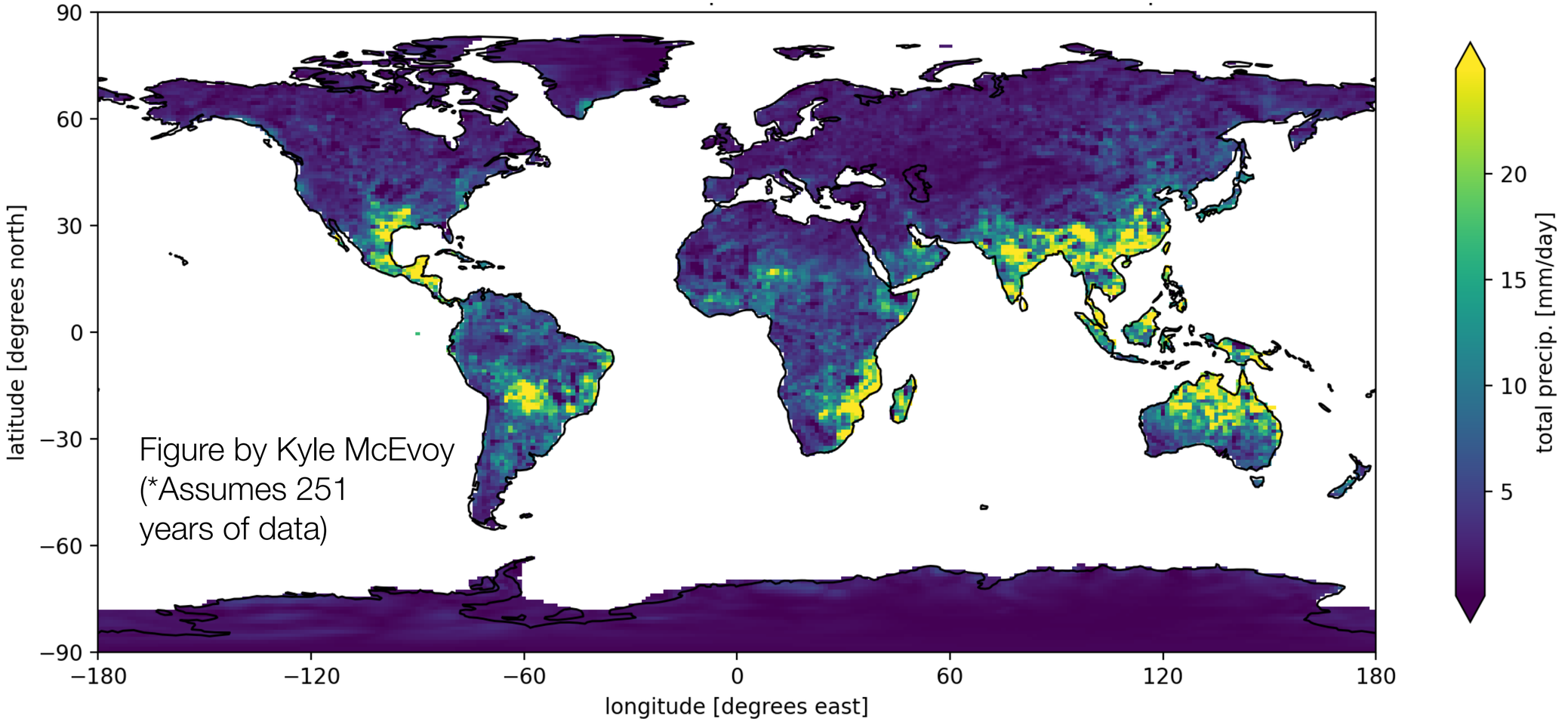
The challenge: extremes are by definition rare — in some cases, very rare!

Two interrelated questions:

1. What is the probability of a given extreme in a “baseline” climate?

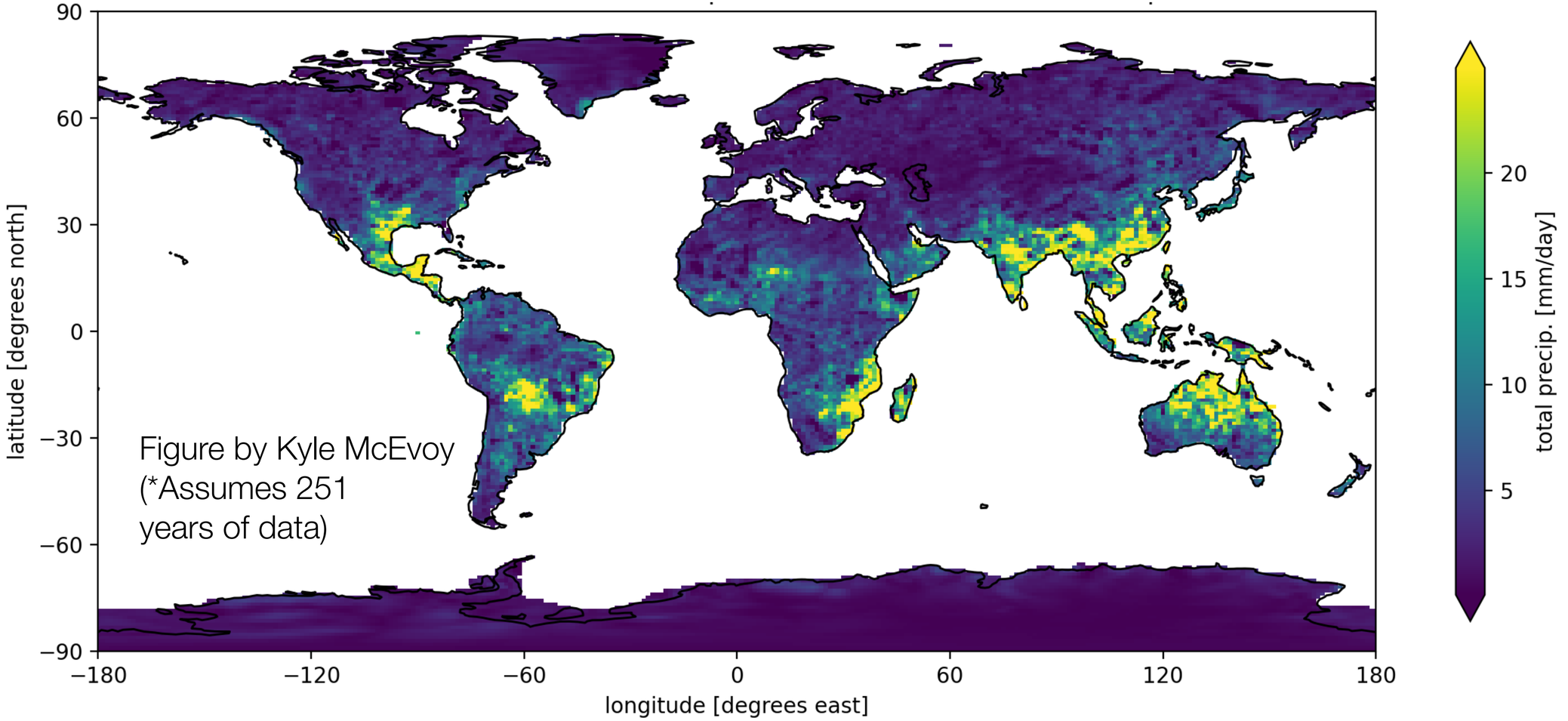
2. (How) is that probability changing with climate change?

One important (philosophical) tool: large ensembles



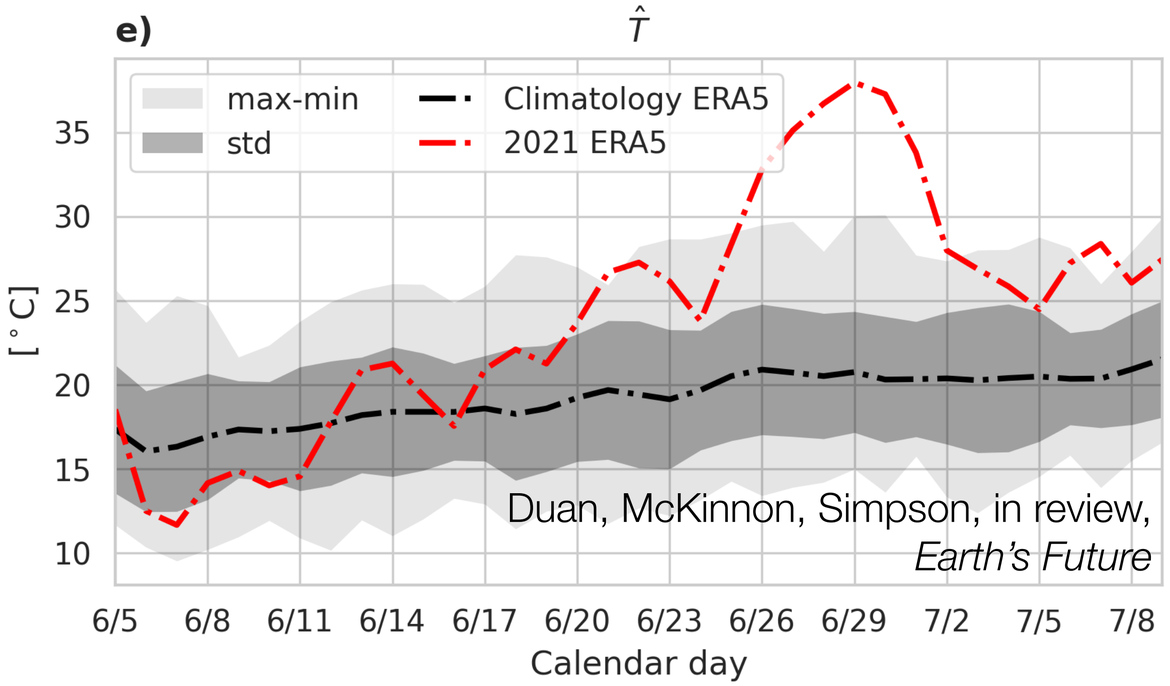
Example: what is the difference between the largest monthly-average precipitation over 50 ensemble members compared to what we might observe in one record?

One important (philosophical) tool: large ensembles



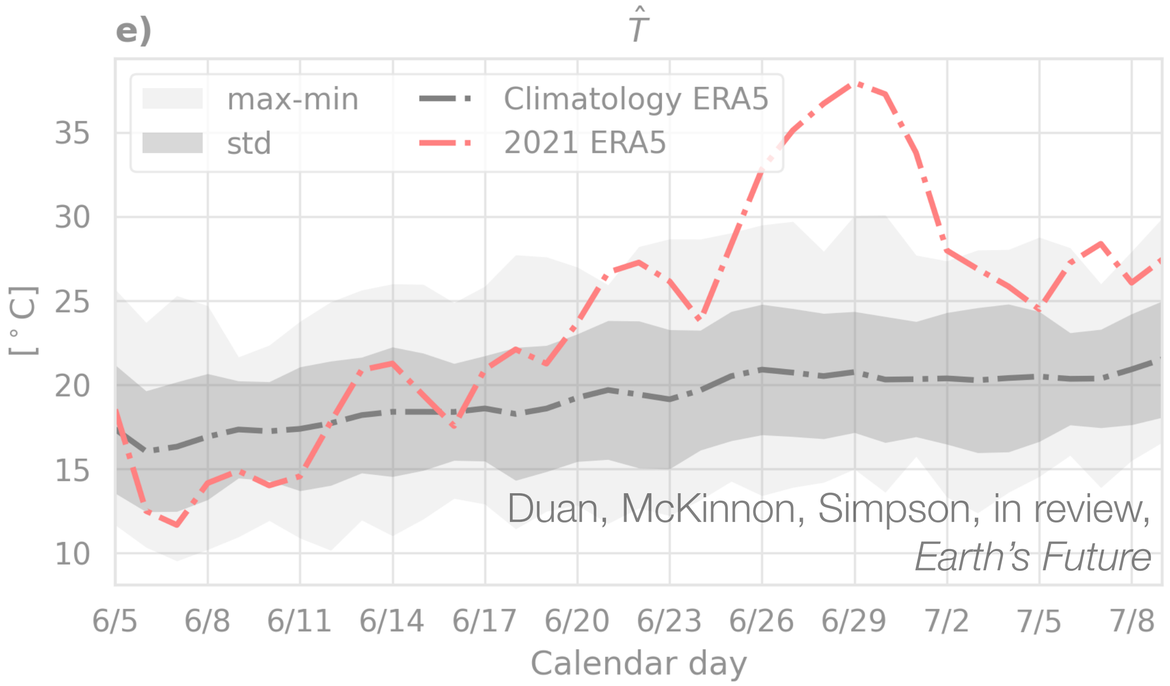
Or… how much more extreme could a precipitation event be than what we've seen?

Many extremes share characteristics: Can we share across time and space?

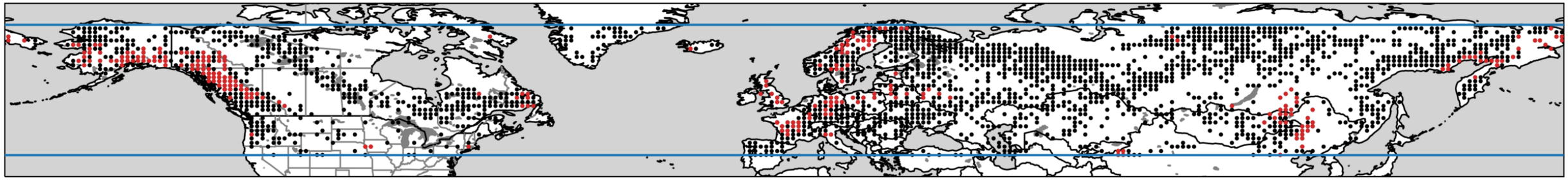


The 2021 Pacific Northwest heat wave was a ~4σ event: rare in one location, but much less rare across many locations.

Many extremes share characteristics: Can we share across time and space?

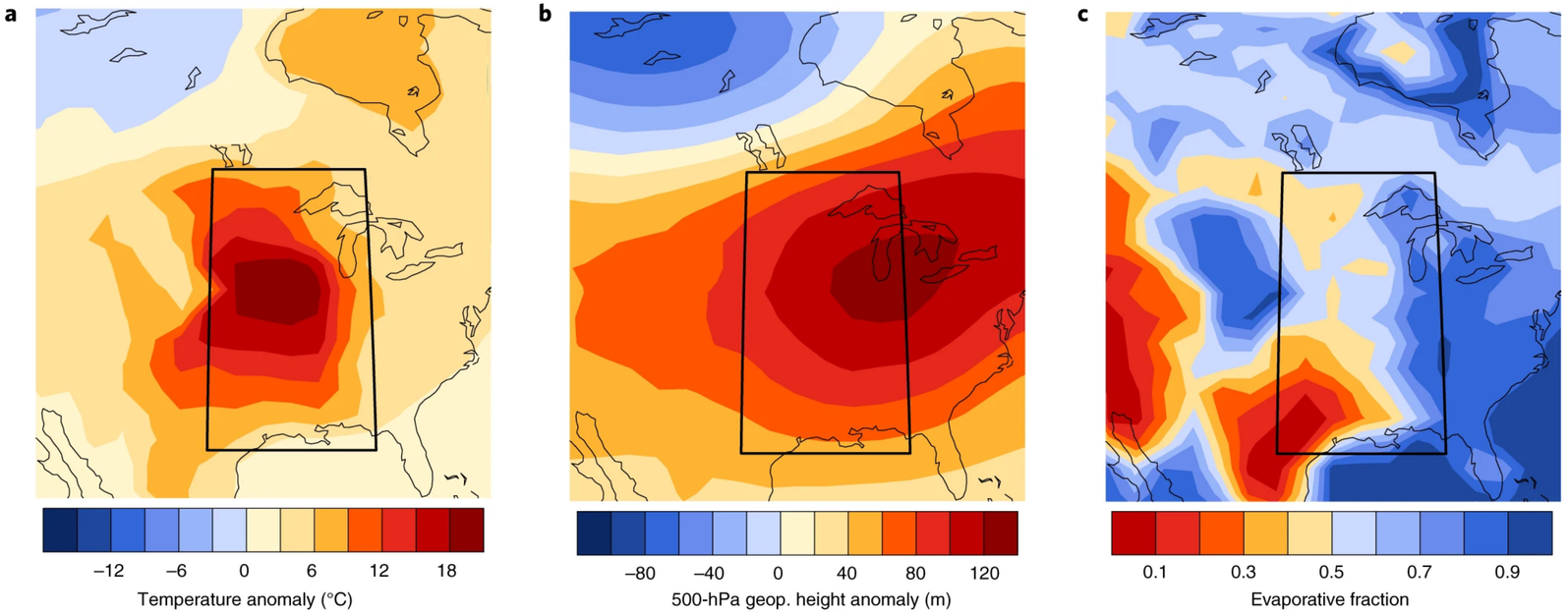


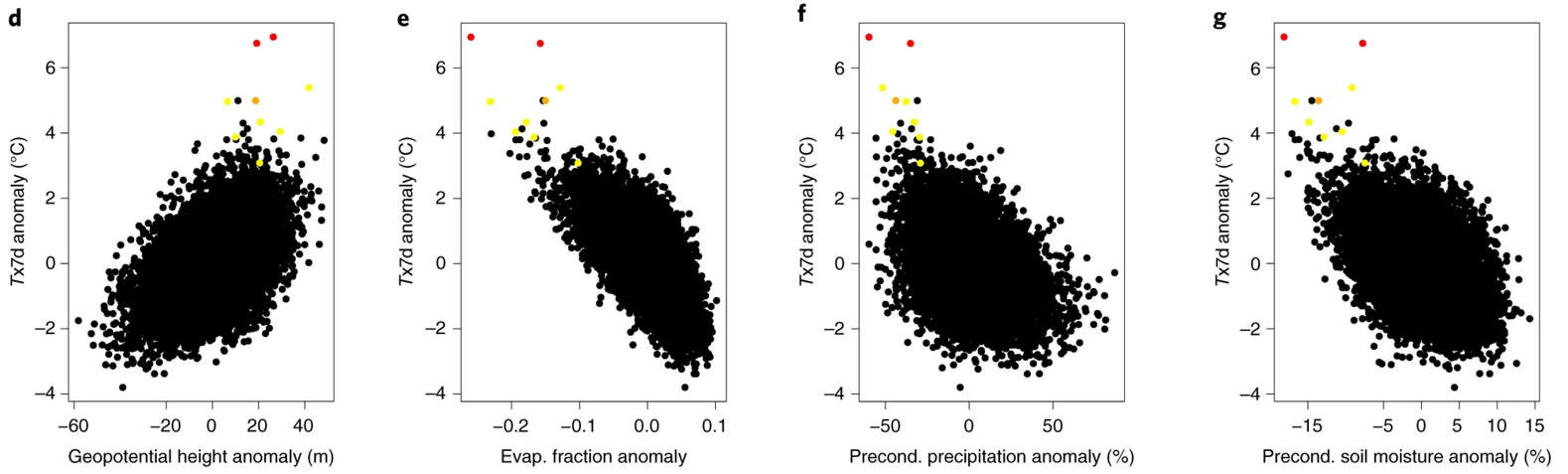
In CESM2, we identified "analog" midlatitude locations (black) that shared the same climatological skewness and kurtosis, many of which had major ($> 4\sigma$) heat waves in a historical simulation.



McKinnon and Simpson, 2022, *GRL*

Learning from analogs, extrapolating from other events, and using climate models all require understanding mechanisms





Are the physics of the most extreme events just an extrapolation of more typical events?

Fischer et al., 2021, *Nature Climate Change*

What are the implications of different techniques for identifying extremes over time?

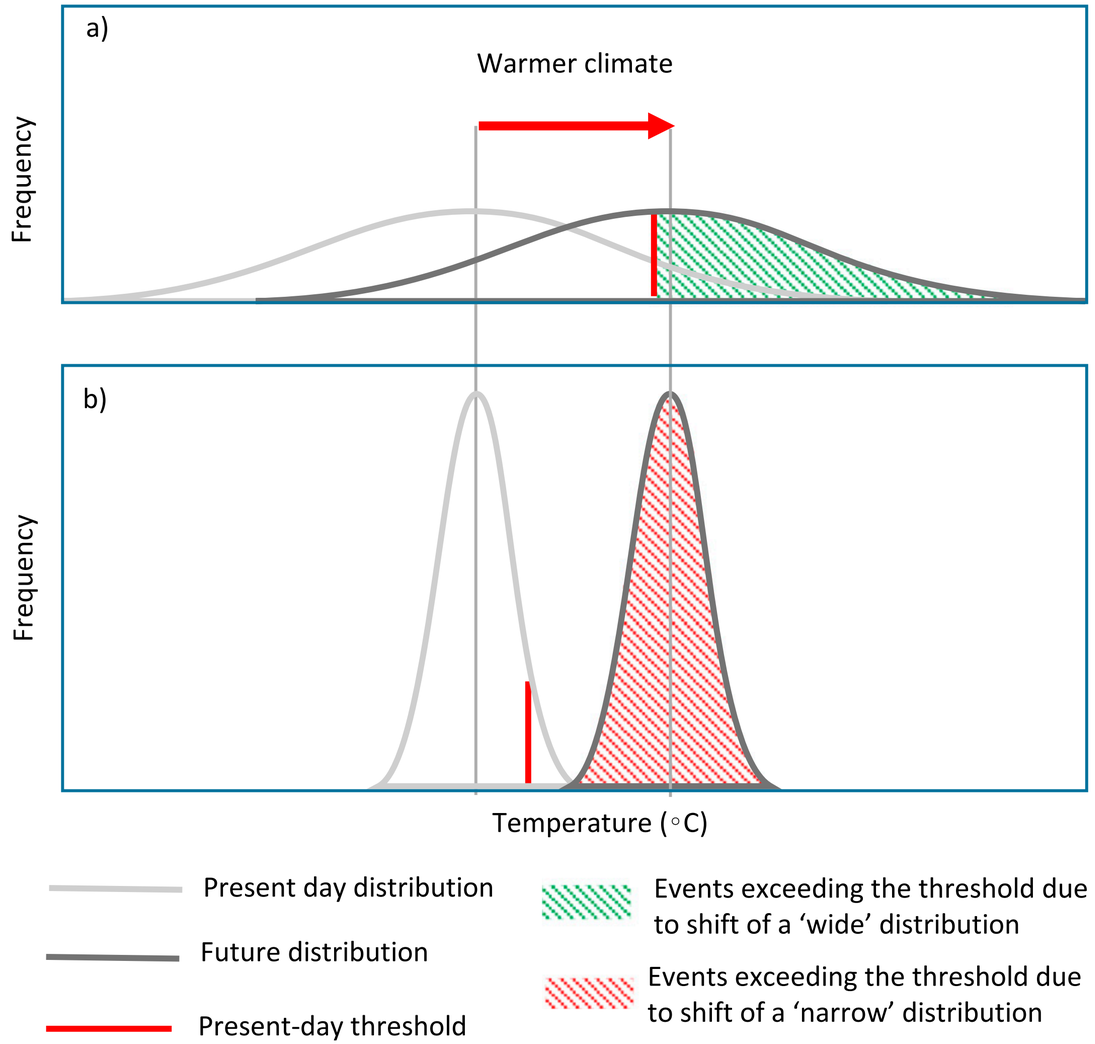
What are the implications of different techniques for identifying extremes over time?

Many metrics of changes in extremes are a strong function of the mean state.

Three examples.

In all cases, the true climate change signal is a uniform warming across summertime temperatures.

The change of the number of days beyond a threshold depends on the width of the distribution: greater increases for narrow distributions

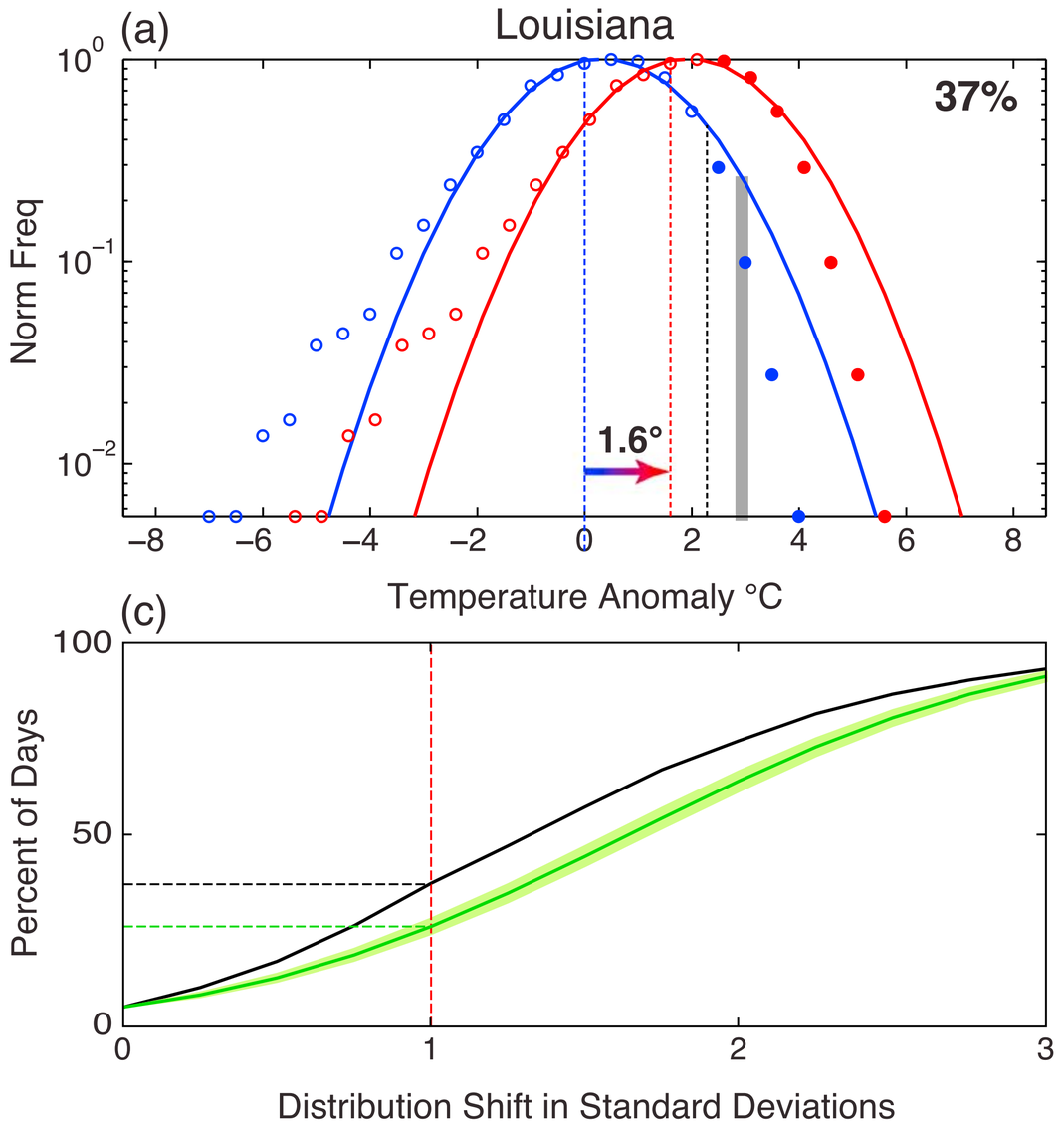


Borodina et al (2017) *JClim*

The change of the number of days beyond a threshold depends on the symmetry of the distribution: greater increases for short upper tails

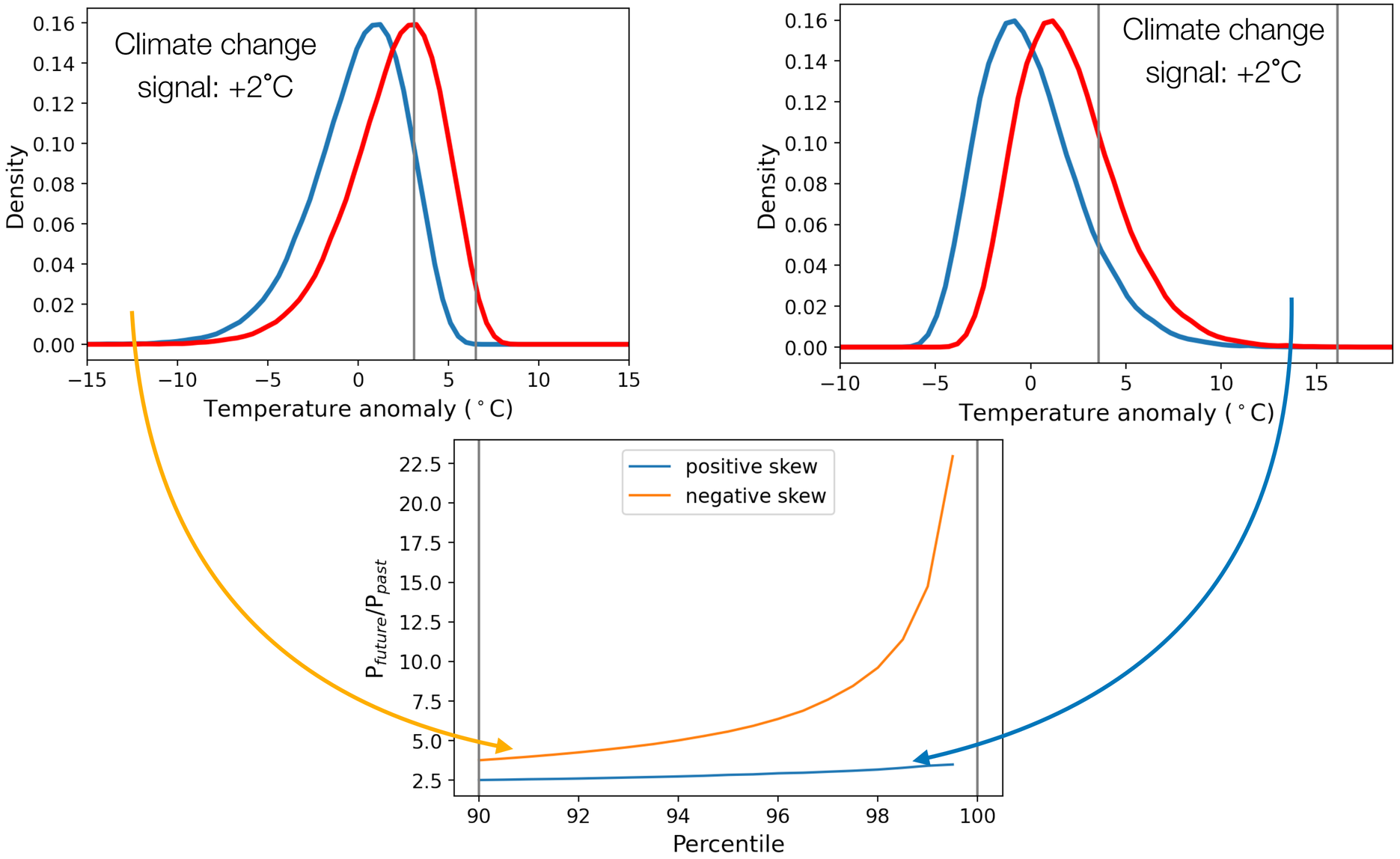
actual distribution

normal distribution



Loikith and Neelin (2015) *GRL*

The change in the probability of an event depends *non-linearly* on the threshold and the underlying distribution



In our papers, should we…

measure changes in extremes as the change in temperature for a given percentile (max = 100th percentile)?

…or…

provide metrics such as heat wave days?

Who is our audience?

Thank you!

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