Worst-Case European Heatwave Storylines generated using Ensemble Boosting

Laura Suarez-Gutierrez [1,2]

1. Wageningen University, the Netherlands

2. ETH Zürich, Switzerland

Collaborators: U. Beyerle, M. Mittermeier, R. Vautard, & E. Fischer

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Unprecedented extremes lead to vast impacts

Past heat extremes that shattered previous records by large margins have lead to immense impacts:

- Thousands of fatalities during 2003 heatwave in Europe
  (Schär et al., 2004; Robine et al. 2008)
- Wildfires, crop and ecosystem damages due to extreme heat and drought in 2018
  (Toreti et al., 2019; Knutzen et al., 2025).

To create sufficient adaptation and preparation strategies, understanding and anticipating the most severe combinations of high-impact extremes is crucial

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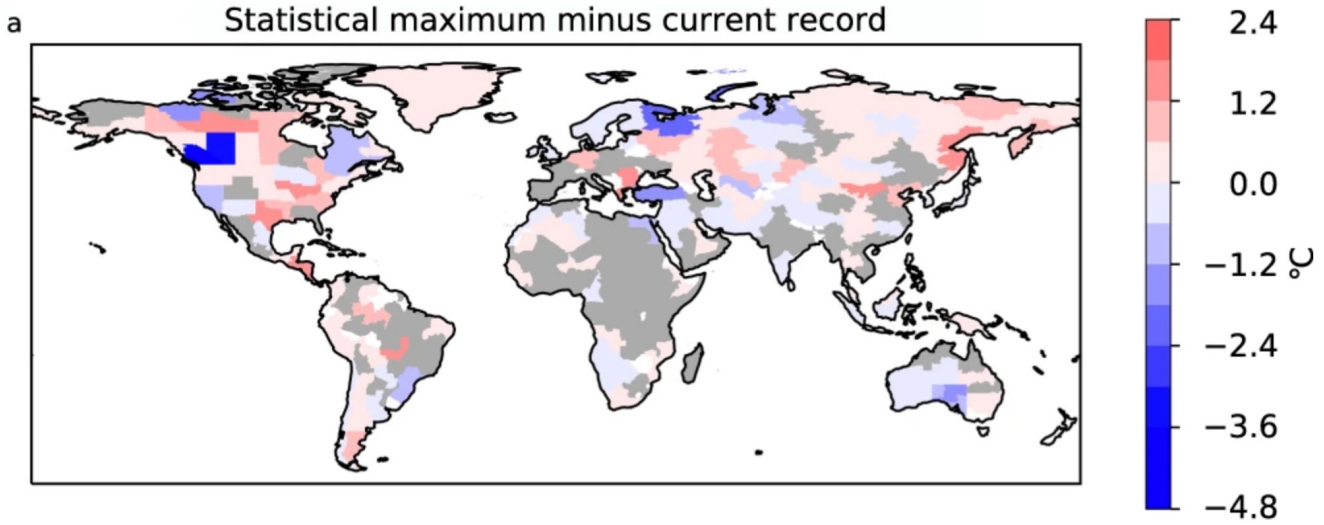
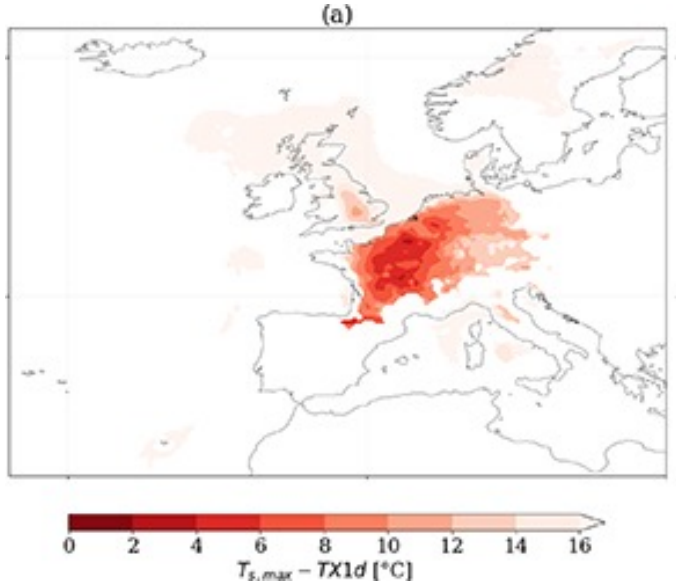
Statistical assessments reveal that higher temperatures as experienced are possible in many areas of the world, particularly in central Europe.



Thompson et al., 2023. Nat Comm.
The most at-risk regions in the world for high-impact heatwaves.



Difference between 2019 heatwave temperature records and maximal reachable temperature

Noyelle et al. 2023 Environ. Res. Lett. **Maximal reachable temperatures for Western Europe in current climate**

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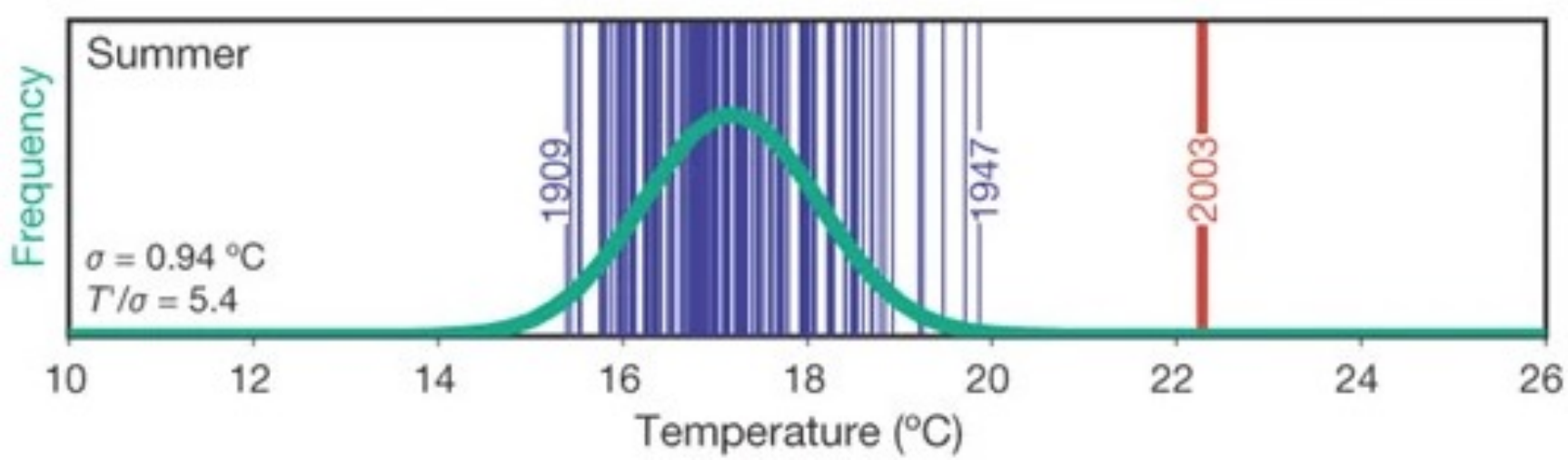
Anticipating unprecedented extremes is crucial

Before happening, these record-breaking events appeared to be extremely unlikely to virtually impossible, based on observational data and traditional modelling approaches

(Schär et al., 2004; Zscheischler et al., 2020; Fischer et al., 2021; 2023).

We need to shift focus away from likely ranges of extremes and toward the limits of plausibility

(Sillmann et al., 2021; Kelder et al. 2025).



Observed summer temperatures in Switzerland for 1864–2003. Schär et al., 2004. Nature

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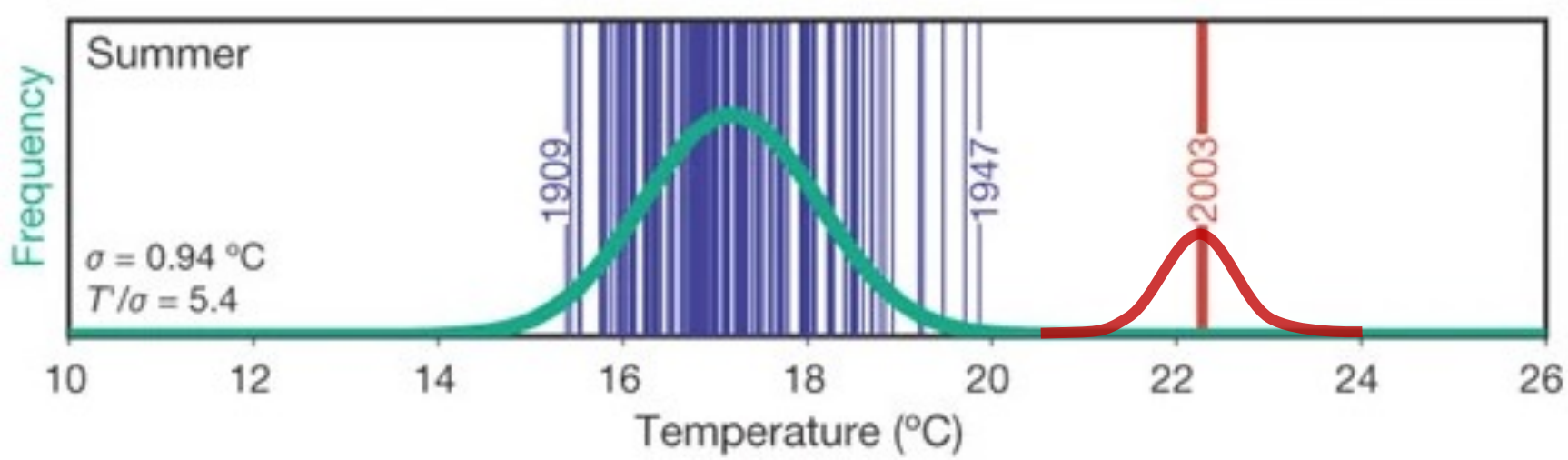
Ensemble Boosting storylines to anticipate worst-case extremes

Storylines: non-probabilistic but plausible event-based narratives exploring the unfolding of extreme conditions (Shepherd et al., 2018; Sillmann et al., 2021; Fischer et al., 2023).

Our method: Ensemble Boosting Storylines

- rerunning simulated extremes, or parents, with a global coupled model (CESM2) after introducing small rounding-error perturbations
- produces large samples of physically-consistent extreme trajectories (Fischer et al., 2023)



Observed summer temperatures in Switzerland for 1864–2003. Schär et al., 2004. Nature

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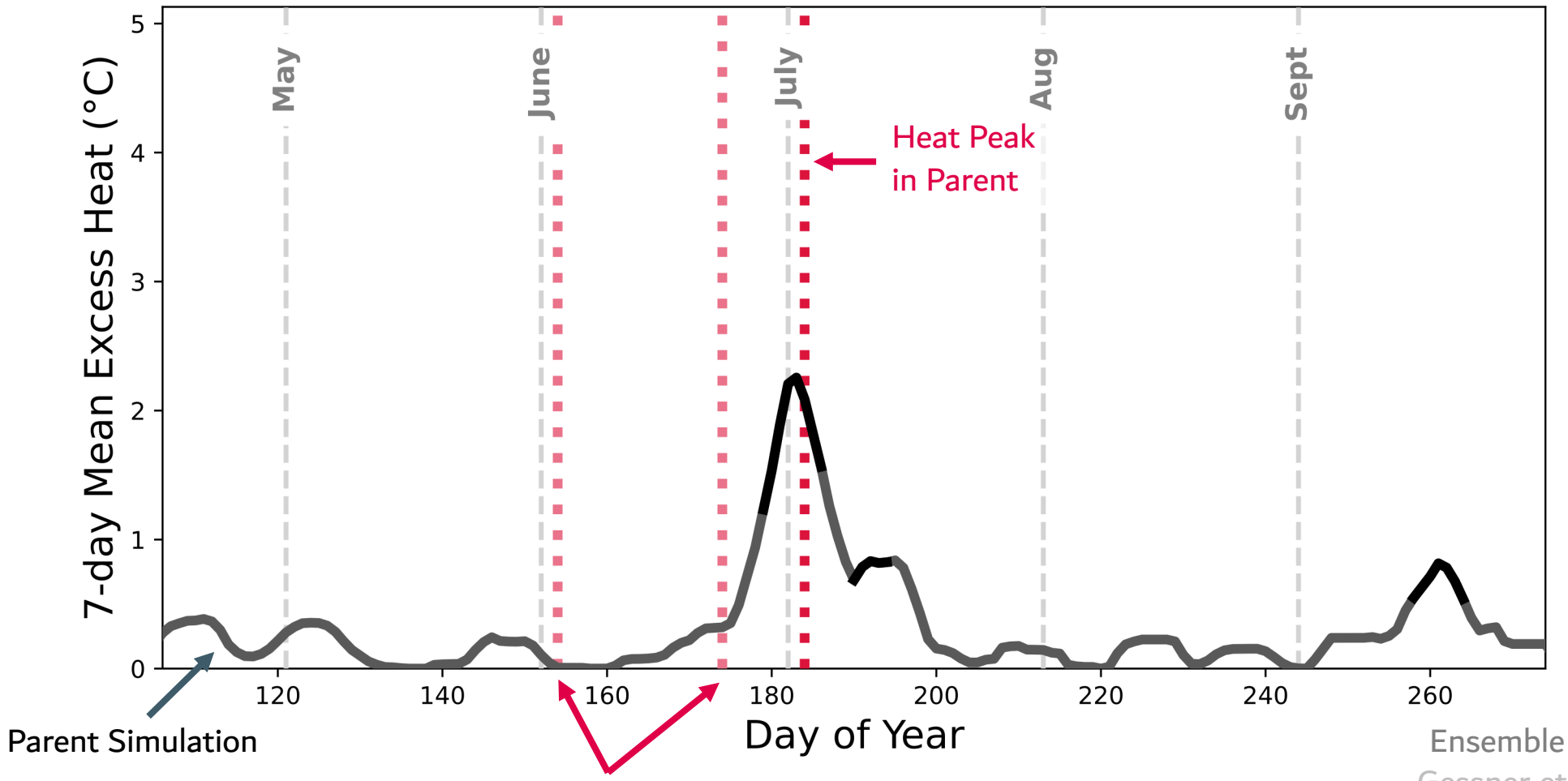
Ensemble boosting to sample chaotic variability



Ensemble Boosting Details:
Gessner et al. 2021 , J. Clim;
Fischer et al., 2023 Nat Comm

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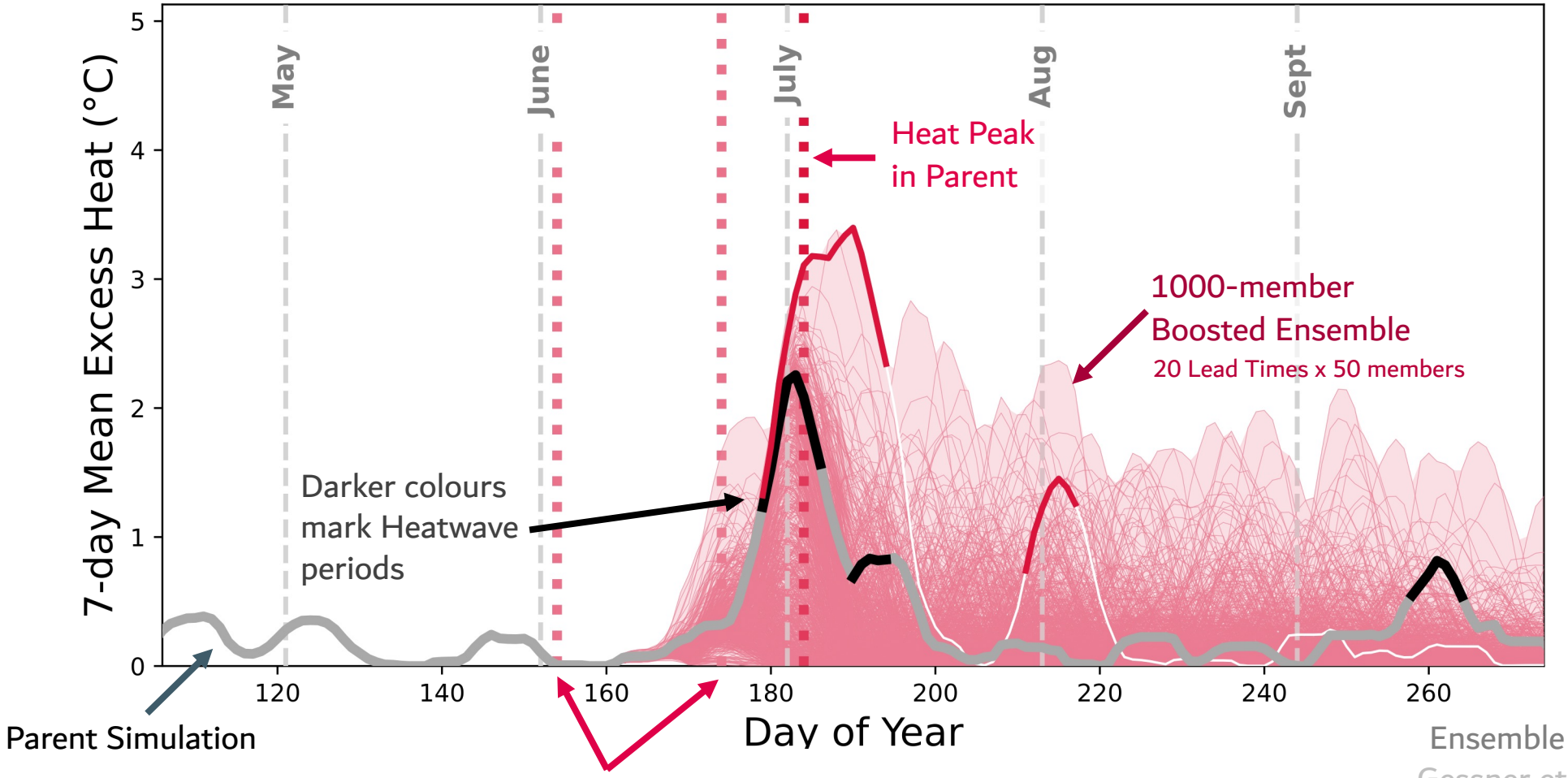

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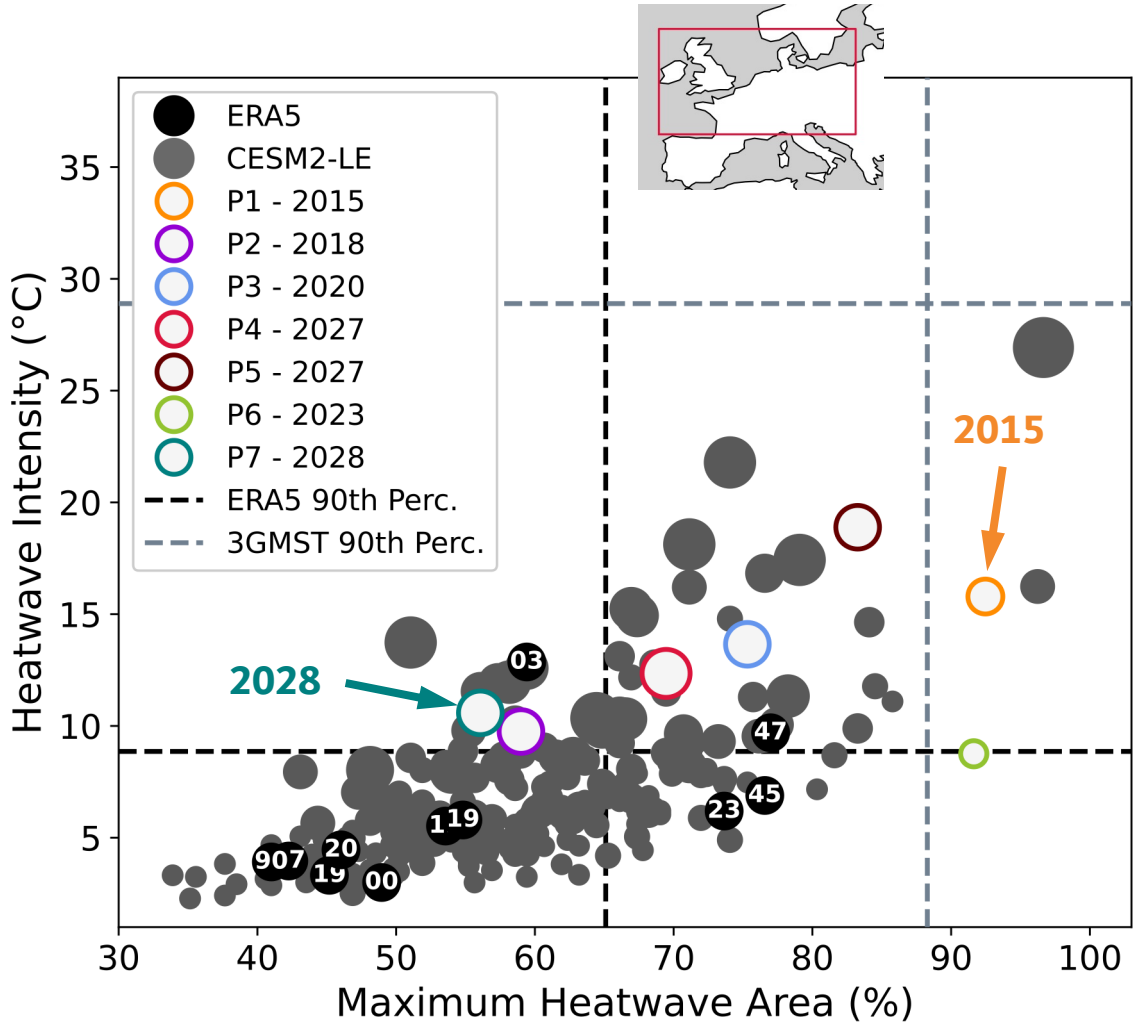
How extreme could Central European Heatwaves become in today's climate?

Heatwave Threshold: 95th percentile over 15-day window for 2005-2023, for each grid cell and day.

Heatwave definition: 5 or more days with daily max temp above threshold, over 30% or more of the grid cells in red box, over extended summer (May to September).

Cumulative Heatwave intensity: Difference between temperature reached minus heatwave threshold. If positive, difference is summer, or accumulated, over all heatwave days, and averaged over region [Perkins-Kirkpatrick and Lewis, 2020, Nat. Comm]



Black Dots: ERA5 Heatwaves (1940 – 2023)
Gray Dots: 35-member CESM2-LE (2010 - 2028)
Dot Size: Proportional to Heatwave length
Colored Circles: Parent simulations

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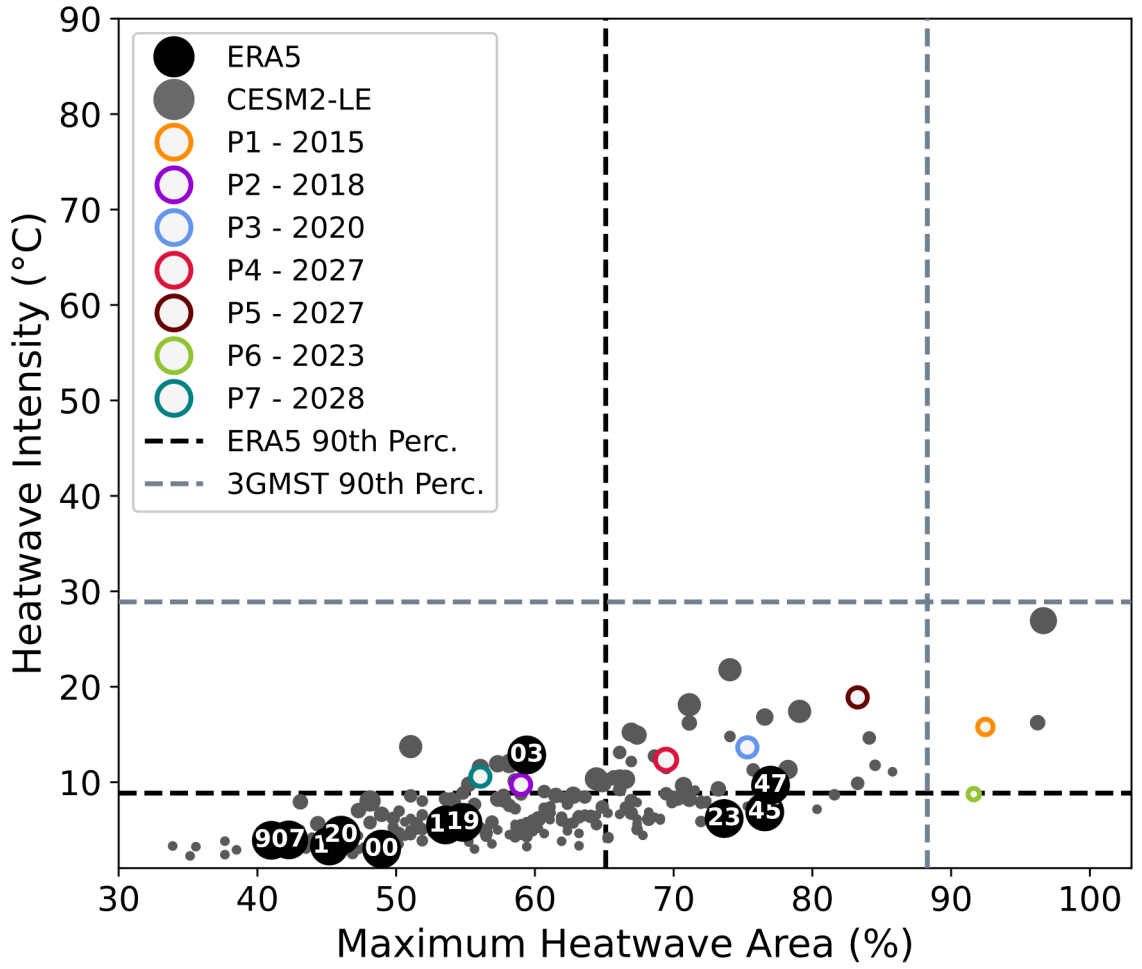

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Boosted heatwaves exceed most extreme heatwaves on record and extreme heatwaves in a 3C world by large margins.

Heatwave Threshold: 95th percentile over 15-day window for 2005-2023, for each grid cell and day.

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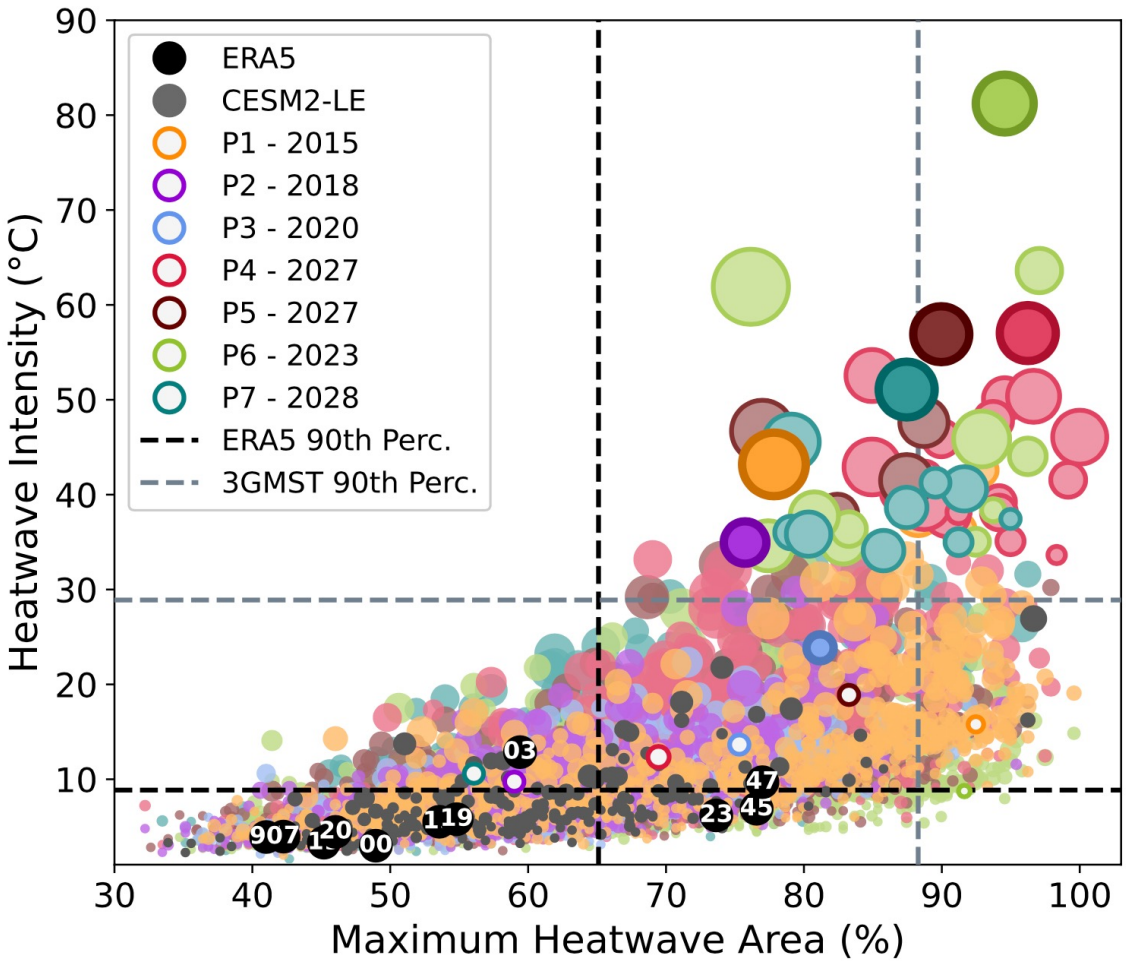

Black Dots: ERA5 Heatwaves (1940 – 2023)
Gray Dots: 35-member CESM2-LE (2010 - 2028)
Dot Size: Proportional to Heatwave length
Colored Dots: Boosted Heatwaves
Bold Colored Dots: TOP50 most extreme Boosted Heataves

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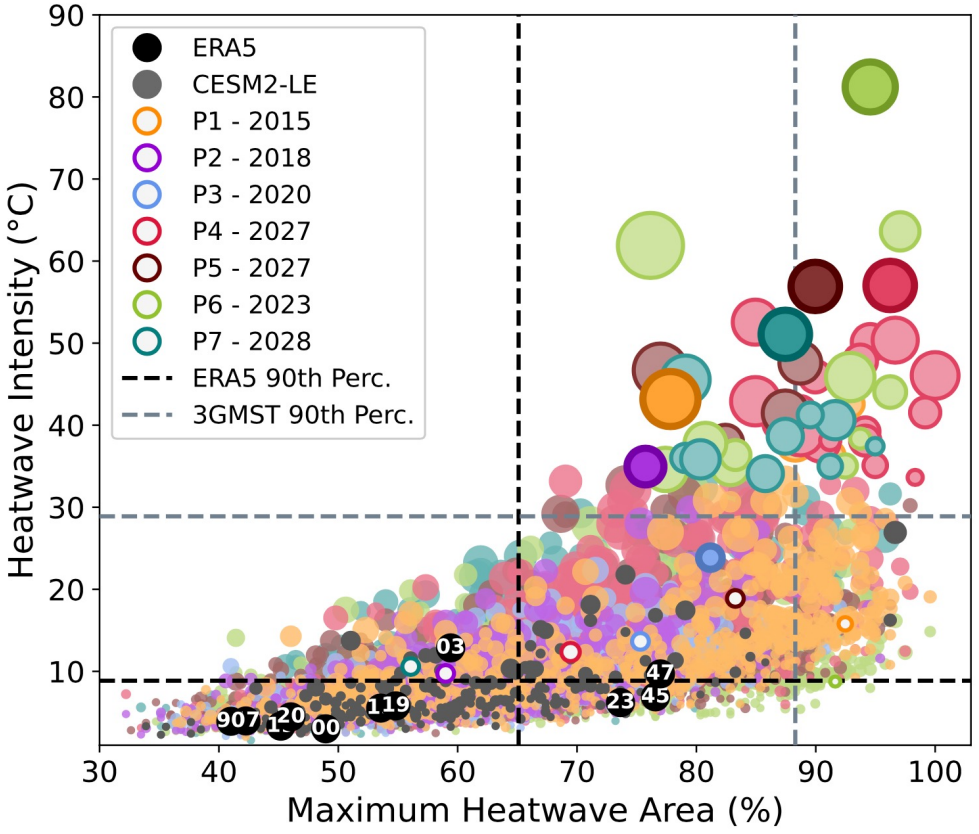
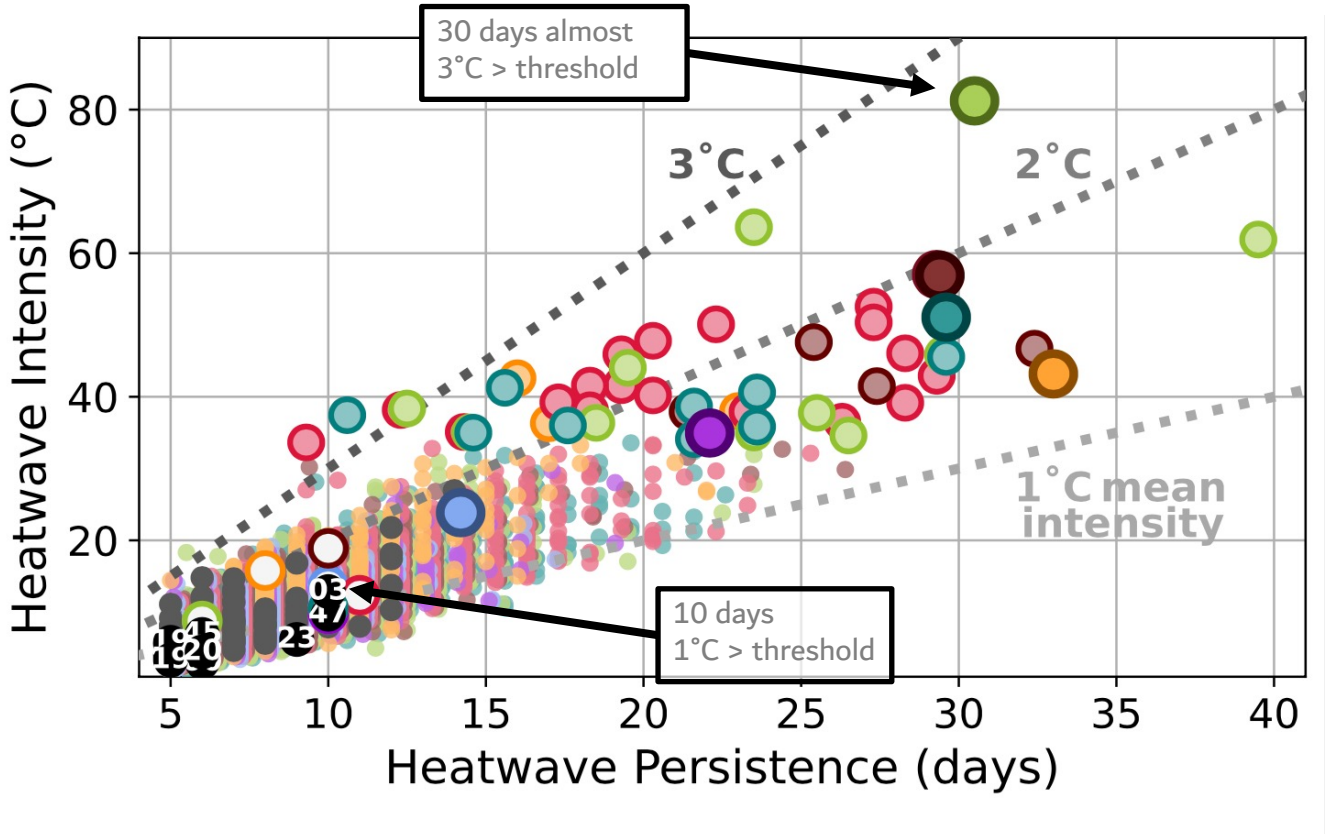
Boosted heatwaves become warmer and last much longer





Black Dots: ERA5 Heatwaves (1940 – 2023)
Gray Dots: 35-member CESM2-LE (2010 - 2028)
Dot Size: Proportional to Heatwave length
Coloured Dots: Boosted HWs from each Parent
Darker Coloured Dots: Top3 most intense Boosted HWs from each Parent

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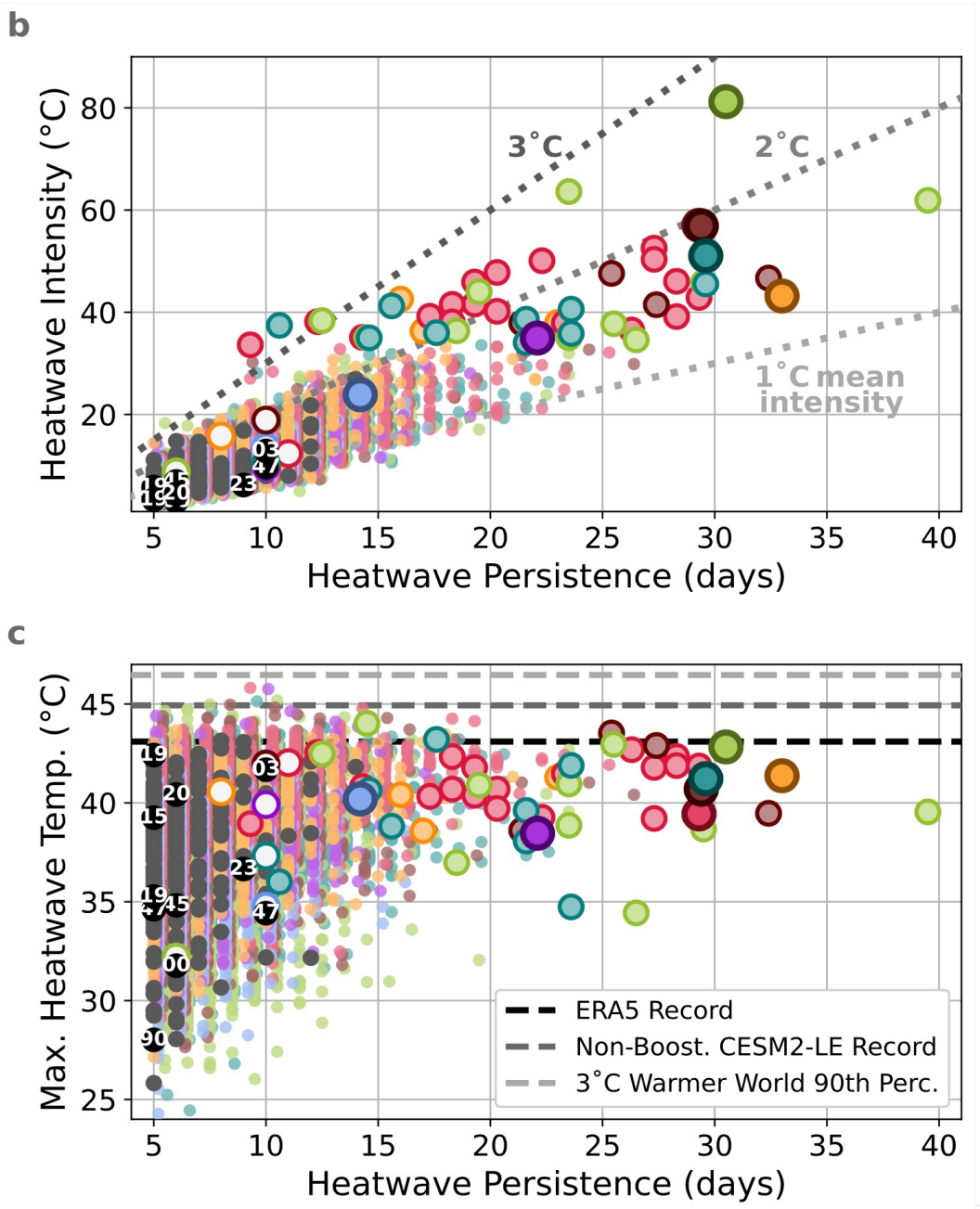
Top most extreme boosted heatwaves reach unprecedented mean intensities and unprecedented persistence, but only marginally higher absolute temperatures



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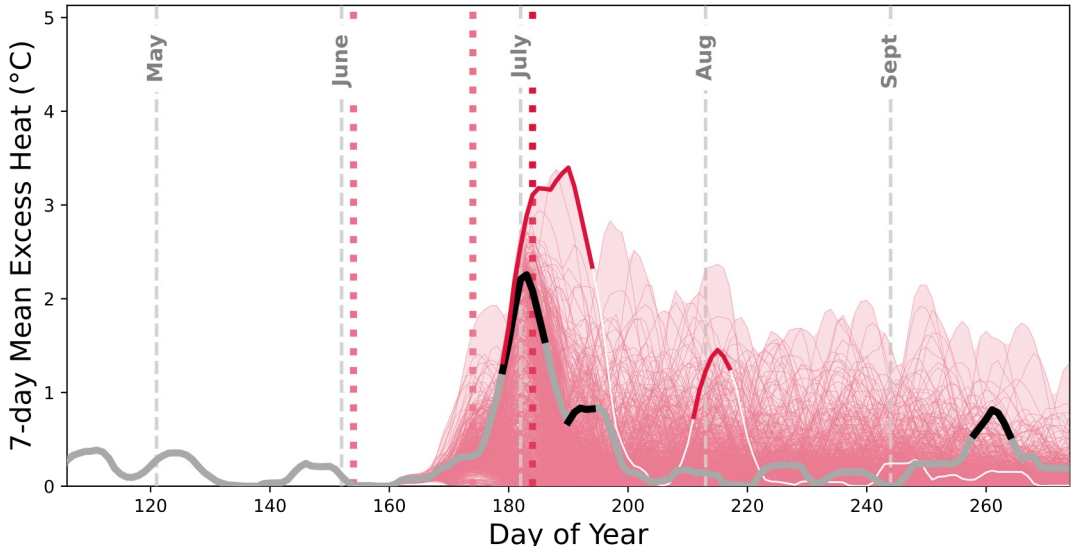
Boosting Heatwave Storylines anticipate another risk:



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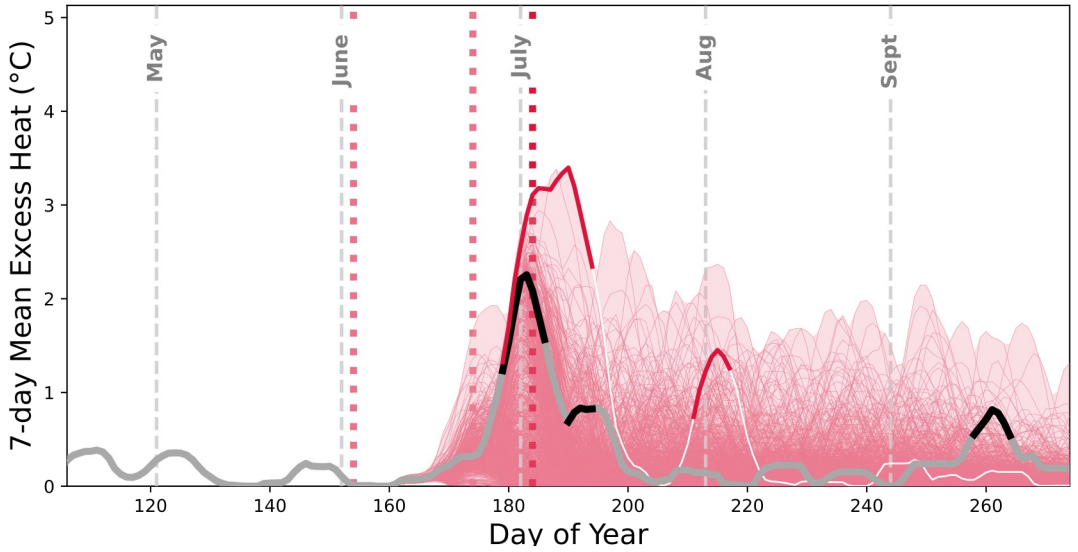
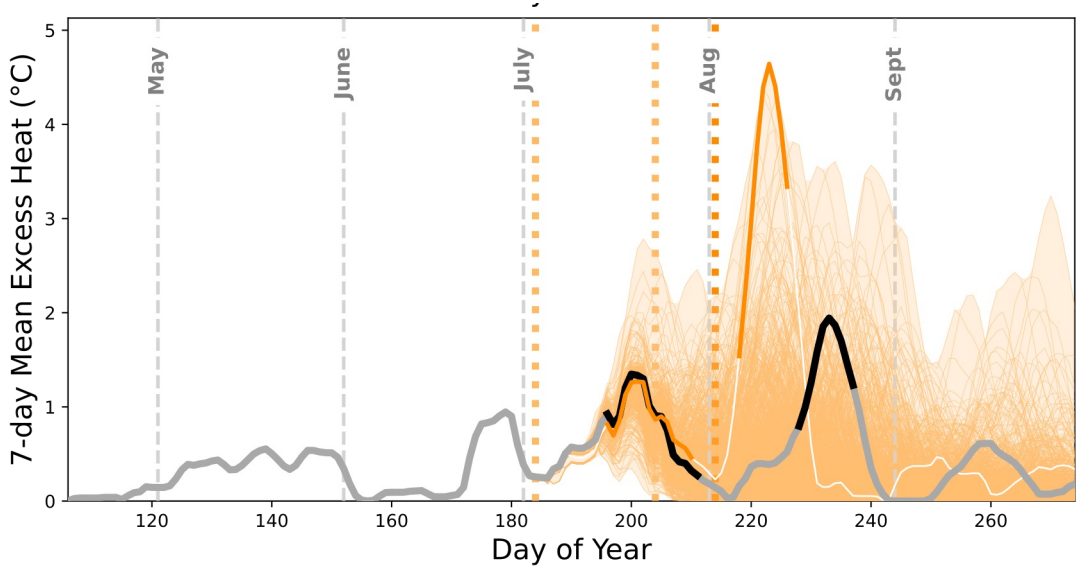
Boosting Heatwave Storylines anticipate another risk:

unprecedented extreme heatwaves occurring successively after another heatwave.





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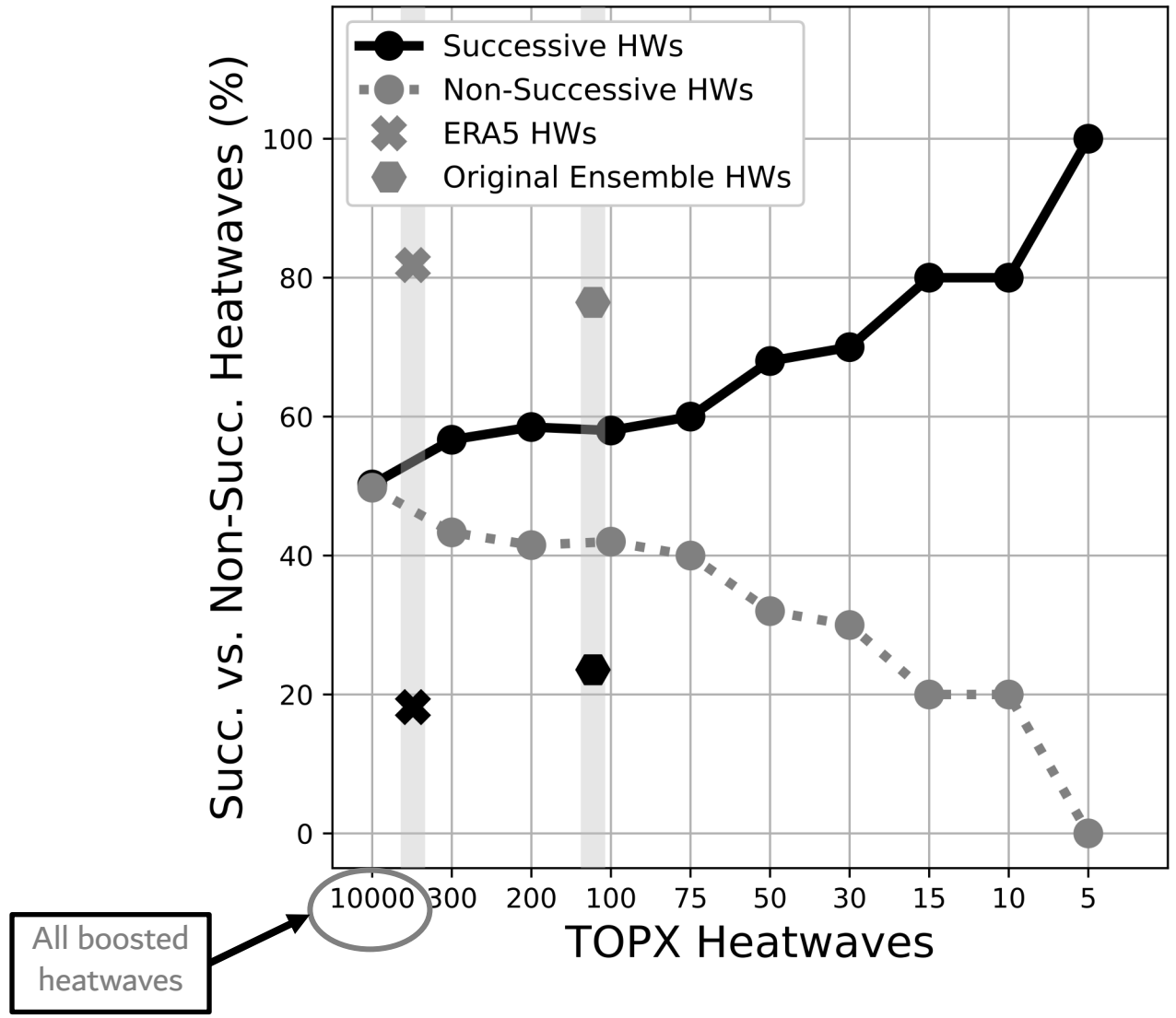
The higher intensity of a boosted heatwave, the likelier it is that it happens successively after another heatwave.



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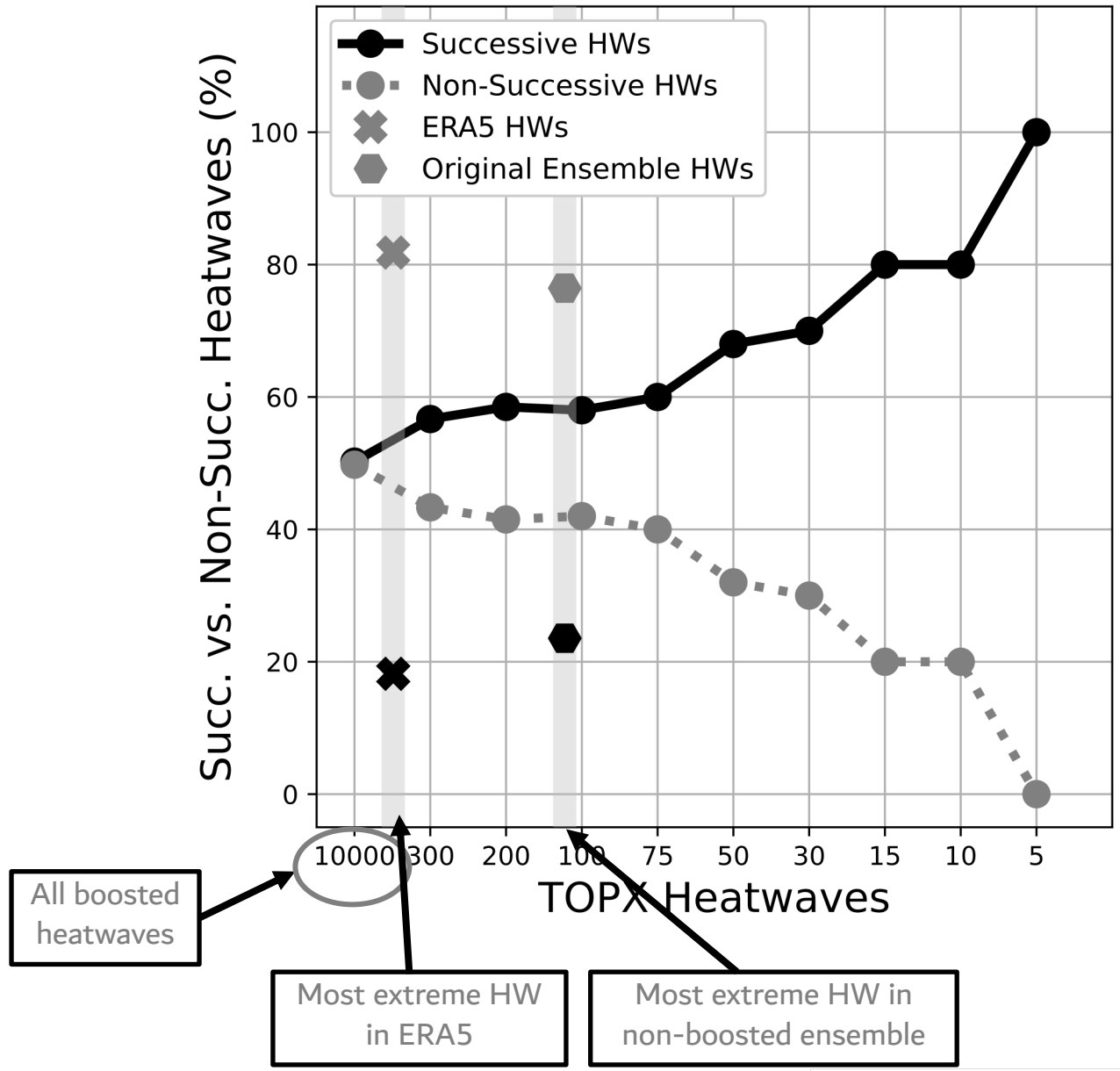

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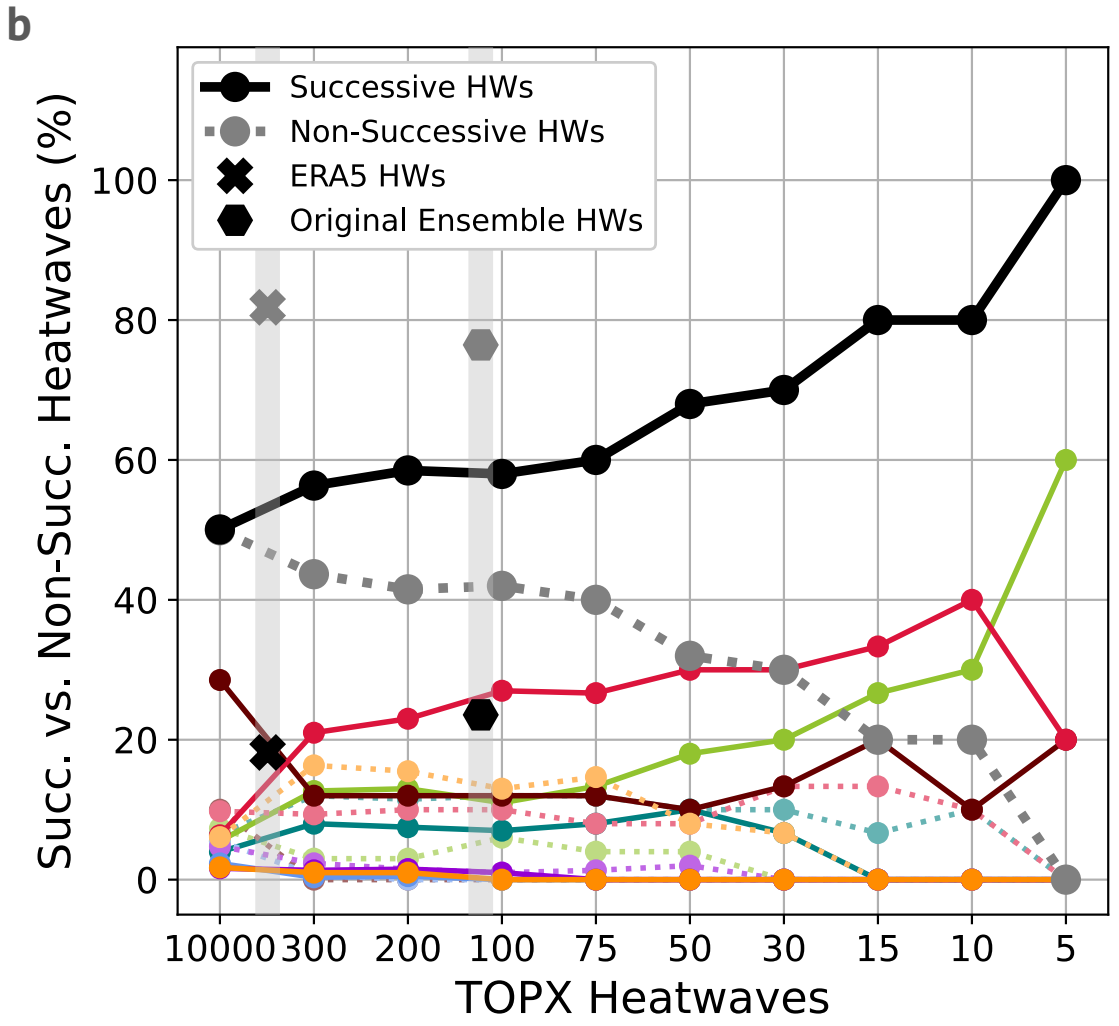
The most extreme boosted heatwaves occur successively after another heatwave



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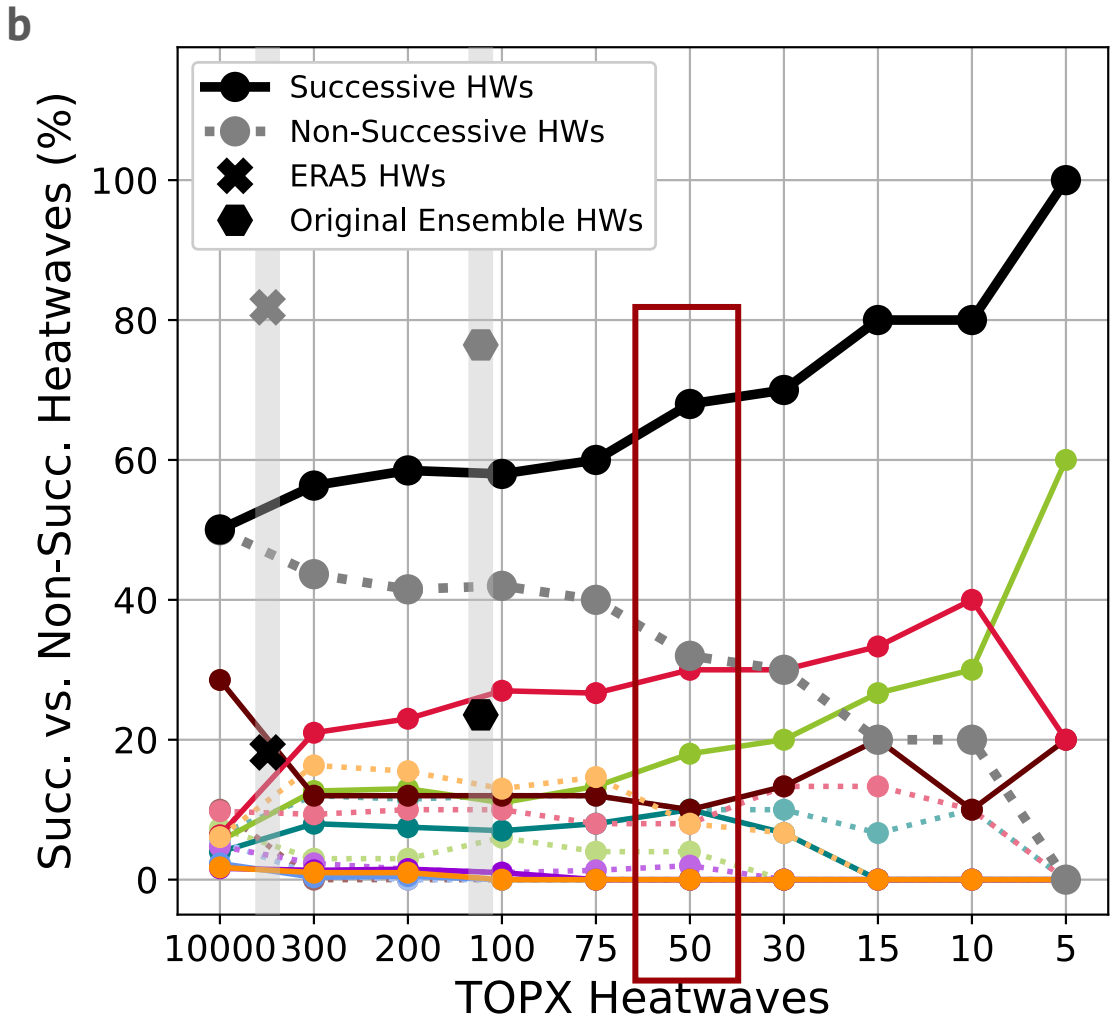
What conditions lead to the most extreme successive vs. non-successive heatwaves?



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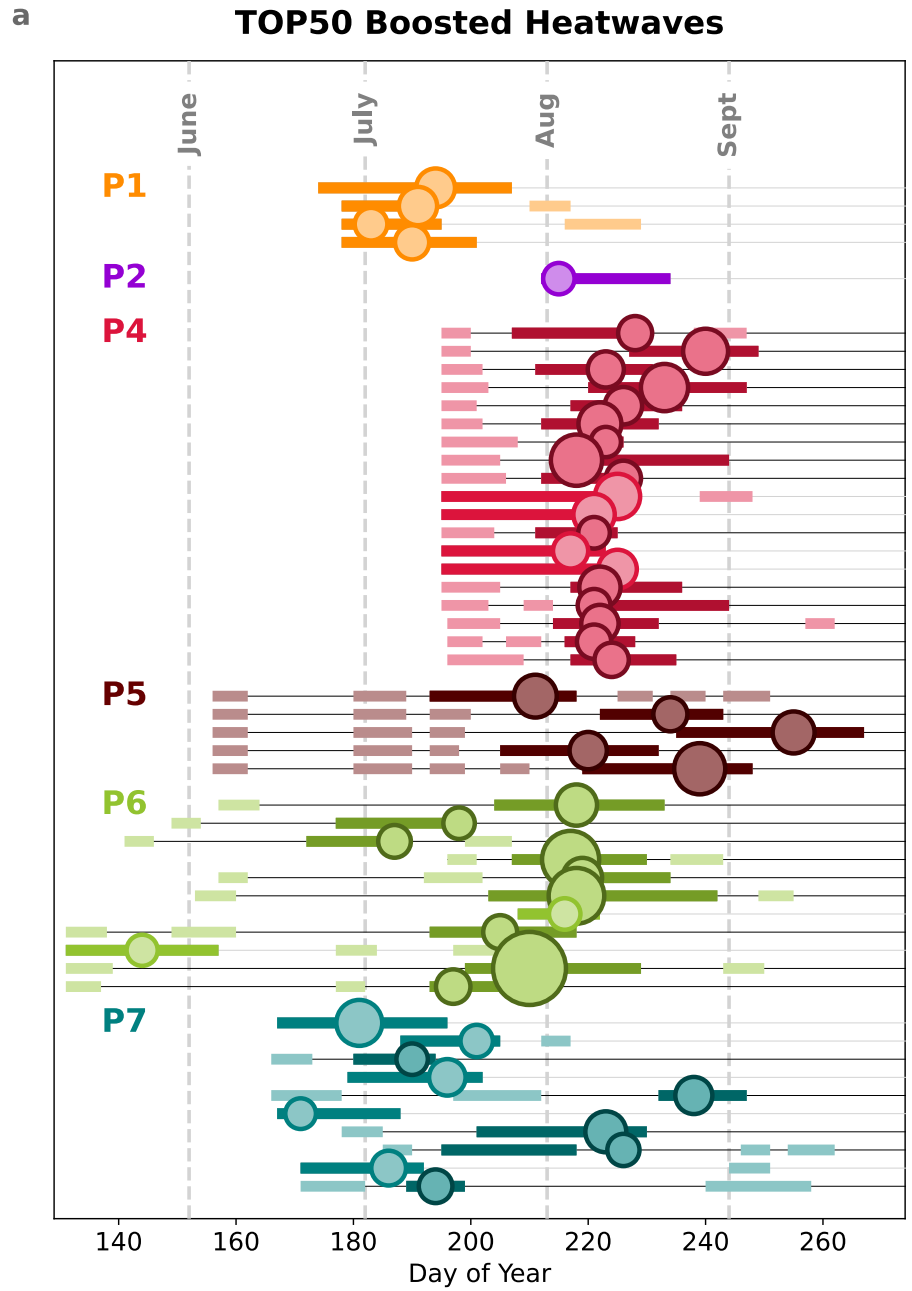

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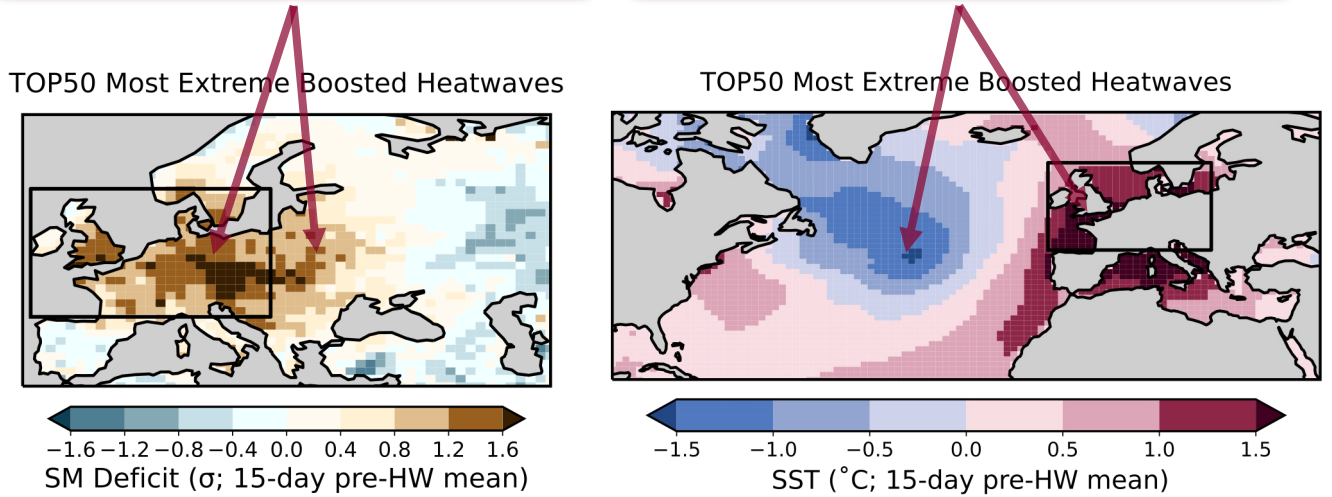
Most Extreme Heatwaves preceded by extreme drought & SST patterns

Preceding Soil Moisture (SM) Deficits Locally & Upstream
[e.g., Schumacher et al., 2019]

Preceding Sea Surface Temperatures (SSTs) Gradients
[e.g., Bischof et al., 2023]



Composites of conditions preceding TOP50 most extreme heatwaves

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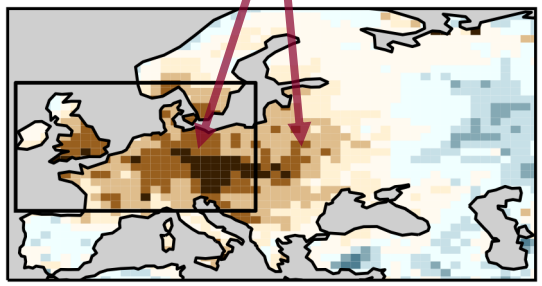
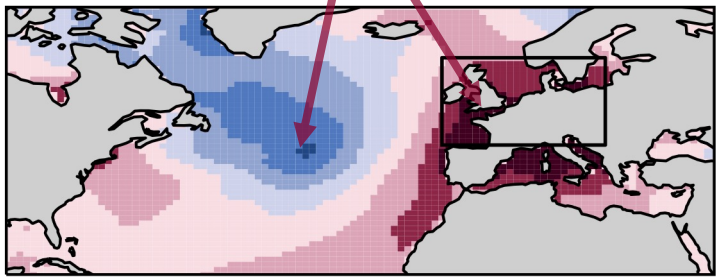
Preceding Sea Surface Temperatures (SSTs) Gradients
[e.g., Bischof et al., 2023]

TOP50 Most Extreme Boosted Heatwaves



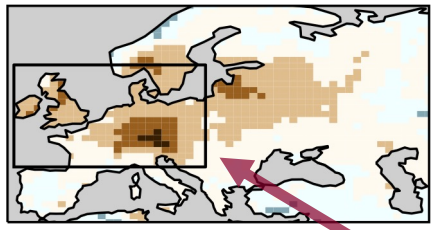
−1.6 −1.2 −0.8 −0.4 0.0 0.4 0.8 1.2 1.6
SM Deficit (σ; 15-day pre-HW mean)

TOP50 Most Extreme Boosted Heatwaves

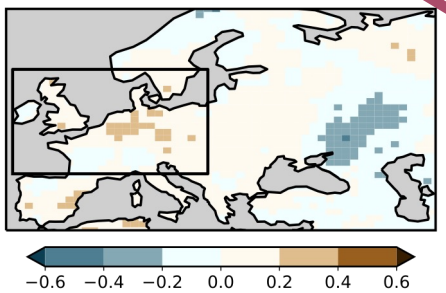


−1.5 −1.0 −0.5 0.0 0.5 1.0 1.5
SST (˚C; 15-day pre-HW mean)

TOP50 Successive (n=34) minus Ensemble Mean



TOP50 Non-Succ. (n=16) minus Ensemble Mean

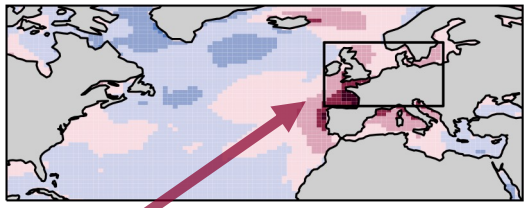


−0.6 −0.4 −0.2 0.0 0.2 0.4 0.6
SM Deficit Diference (σ; 15-day pre-HW mean)

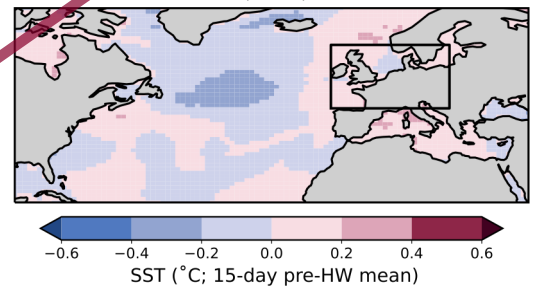
Composites of conditions preceding TOP50 most extreme heatwaves

Successive Heatwaves are preceded by extreme drought, both locally & upstream, and by extreme ocean temperatures in nearby-basins

TOP50 Successive (n=34) minus Ensemble Mean



TOP50 Non Successive (n=16) minus Ensemble Mean



−0.6 −0.4 −0.2 0.0 0.2 0.4 0.6
SST (˚C; 15-day pre-HW mean)

Composites of conditions preceding TOP50 most extreme heatwaves minus ensemble mean conditions in remaining same-parent simulations

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Worst-case European heat storylines generated using ensemble boosting

Suarez-Gutierrez et al. Commun Earth Environ (2026)

Ensemble Boosting is Particularly useful for:

- Assessing **'what if' risks**, e.g., how much more intense or persistent could extremes become.
- **Identifying unforeseen risks,** e.g., successive heatwaves
- **Assessing physically consistent extremes in time, space and variables** in coupled, free-running simulations

But yet limited by:

- **Coarse resolution**, key phenomena may not be correctly captured or simulated
- **Expensive, single-model simulations:** who is interested in running ensemble boosting using other models?

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