Record-breaking extremes in a warming climate

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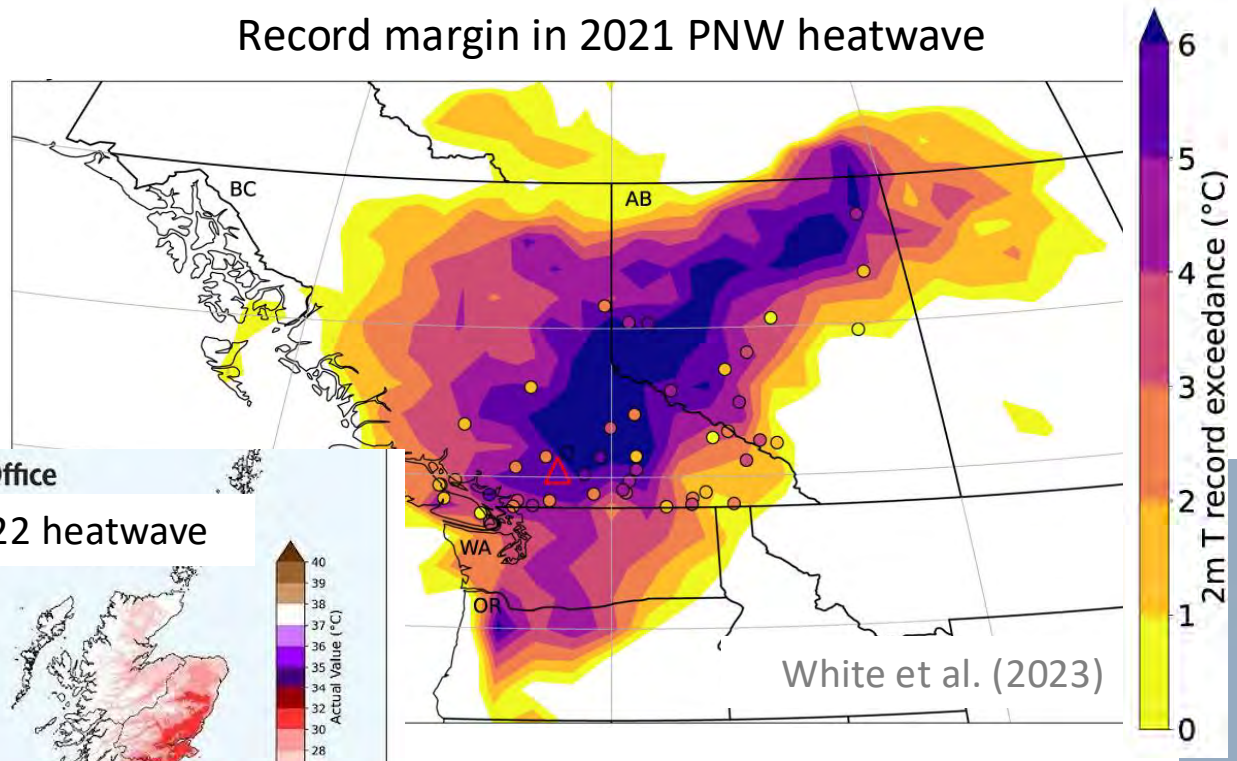
Thanks to Samuel Lüthi, Lizzie Kendon, Yurong Gao, Yixuan Guo, Ana Vicedo-Cabrera, Margot Bador, Alex Robinson, Raphael Huser, Sebastian Sippel, Reto Knutti

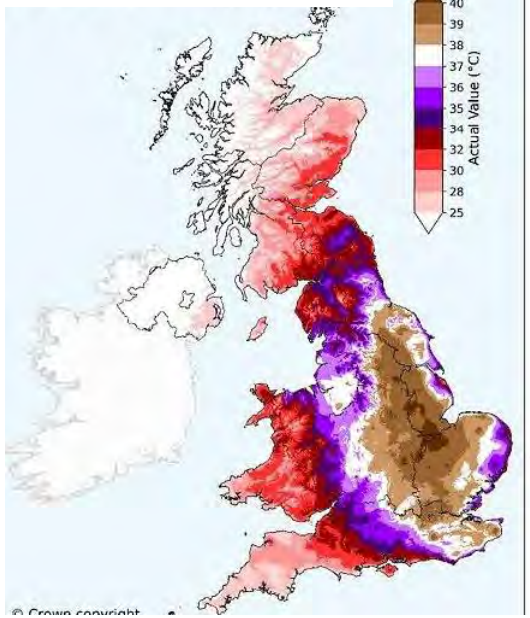
Many recent heatwaves were record-breaking

Record margin in 2021 PNW heatwave

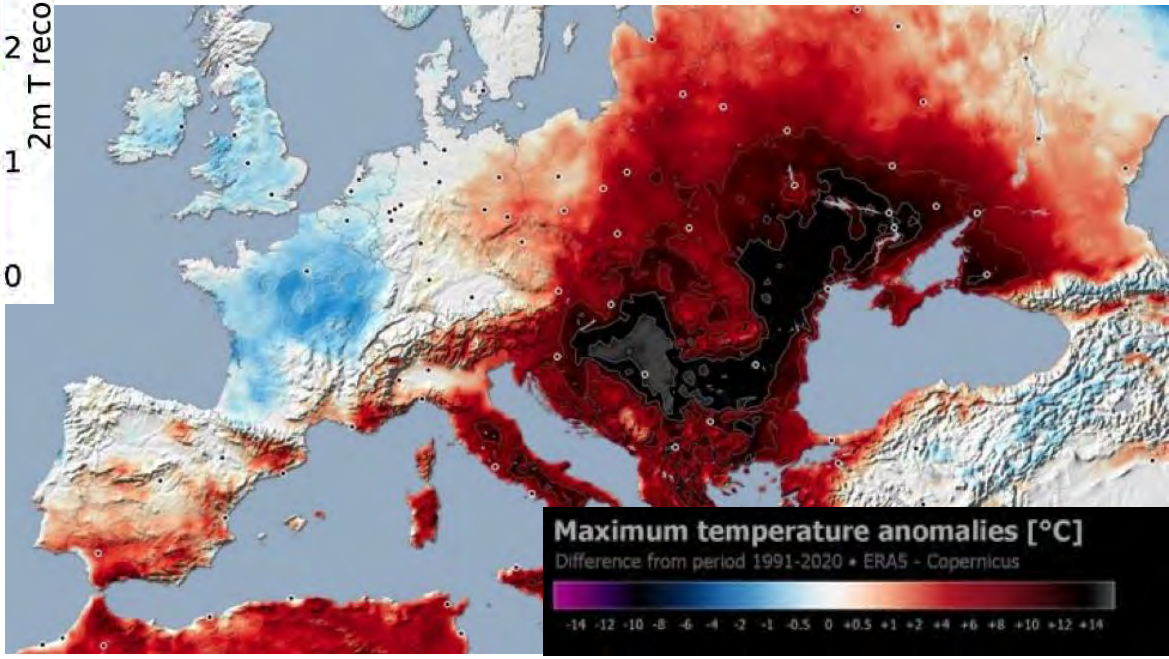


Met Office

UK 2022 heatwave

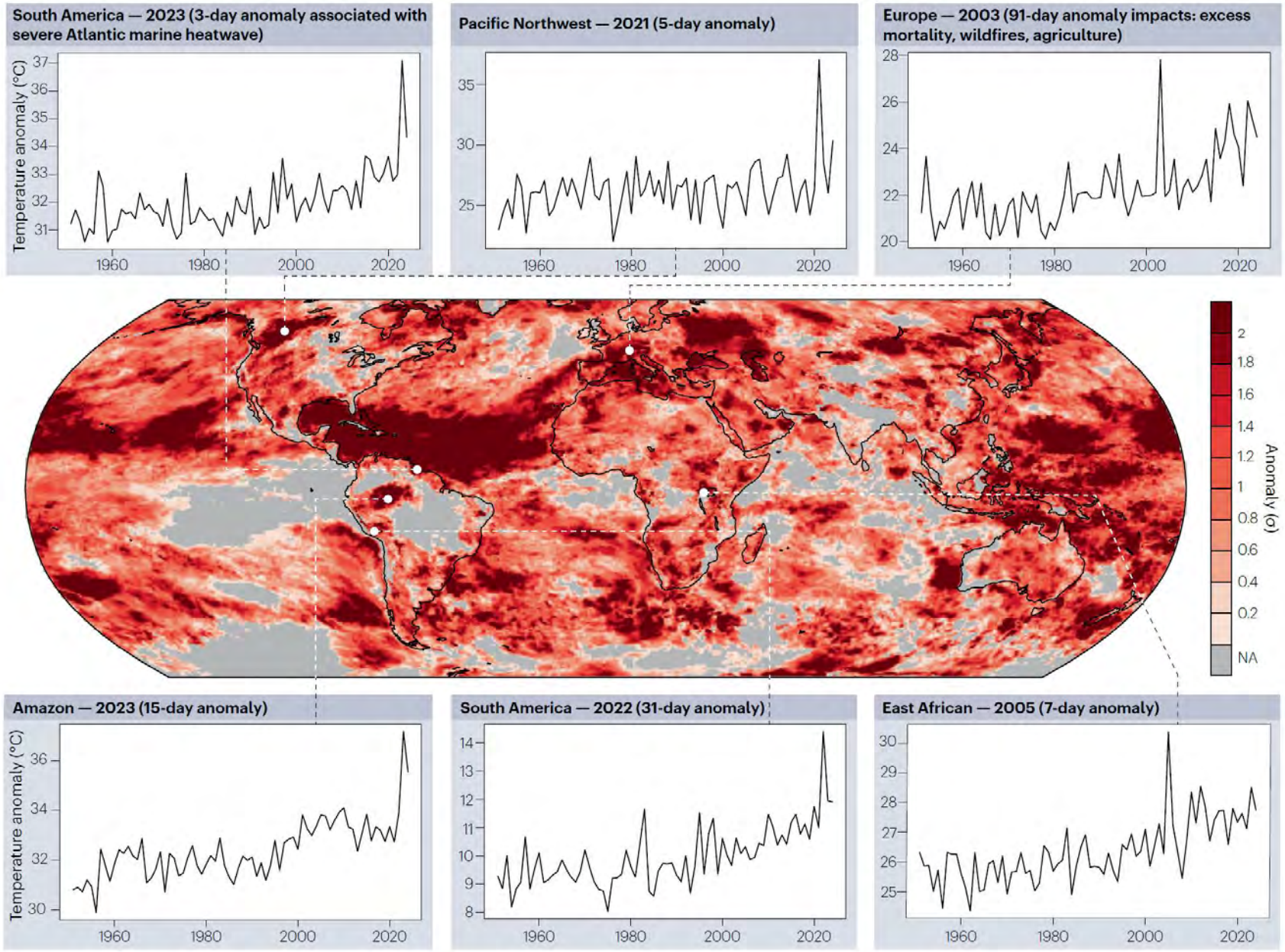


Record breaking 2024 Eastern European heatwave



Record-shattering heat across the globe

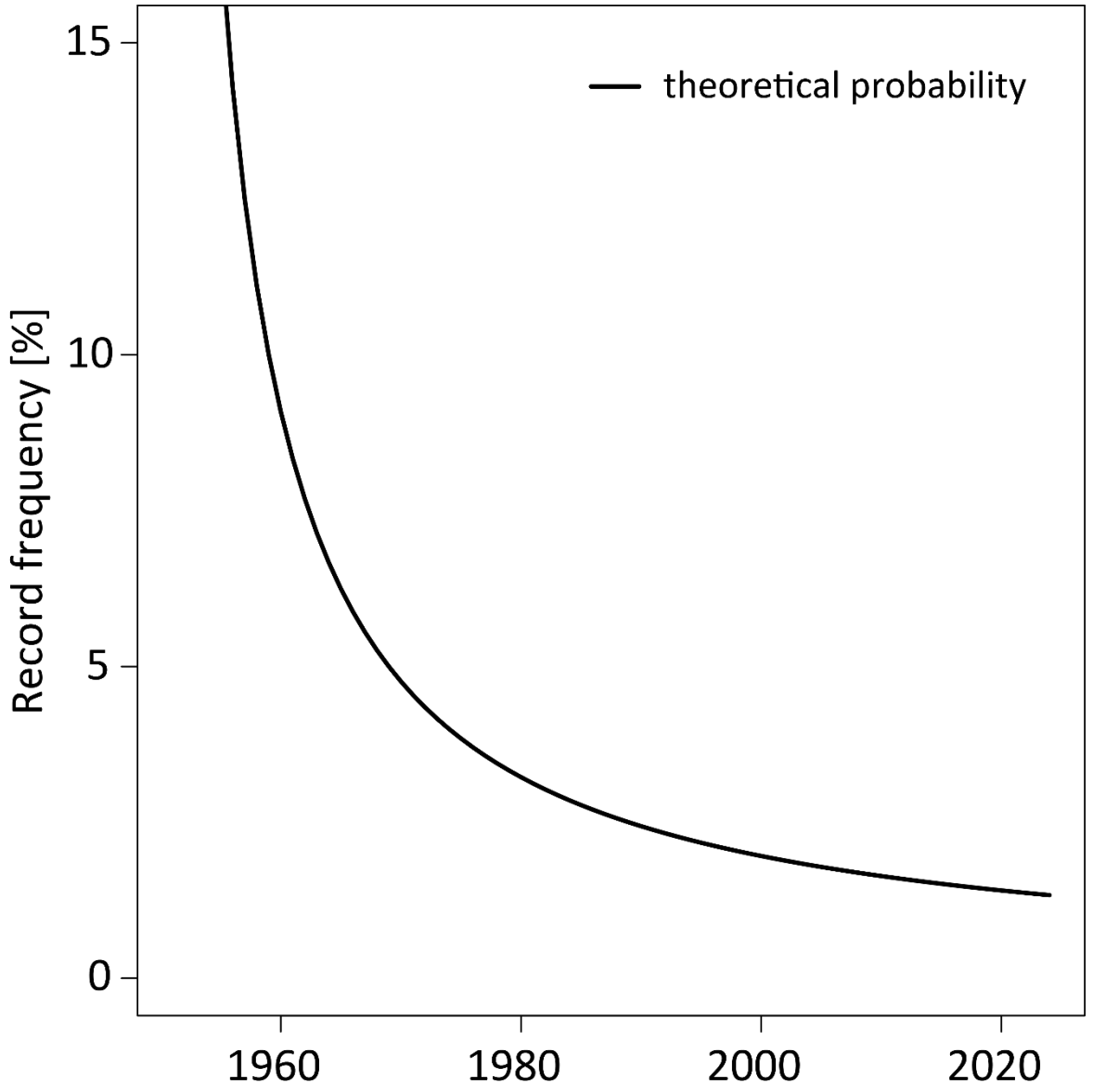
Biggest local record margin since 2000 in ERA5



Fischer, E.M., M. Bador, R. Huser, E.J. Kendon, A. Robinson, and S. Sippel (2025) *Nature Review Earth & Environ*

Records should become rarer…

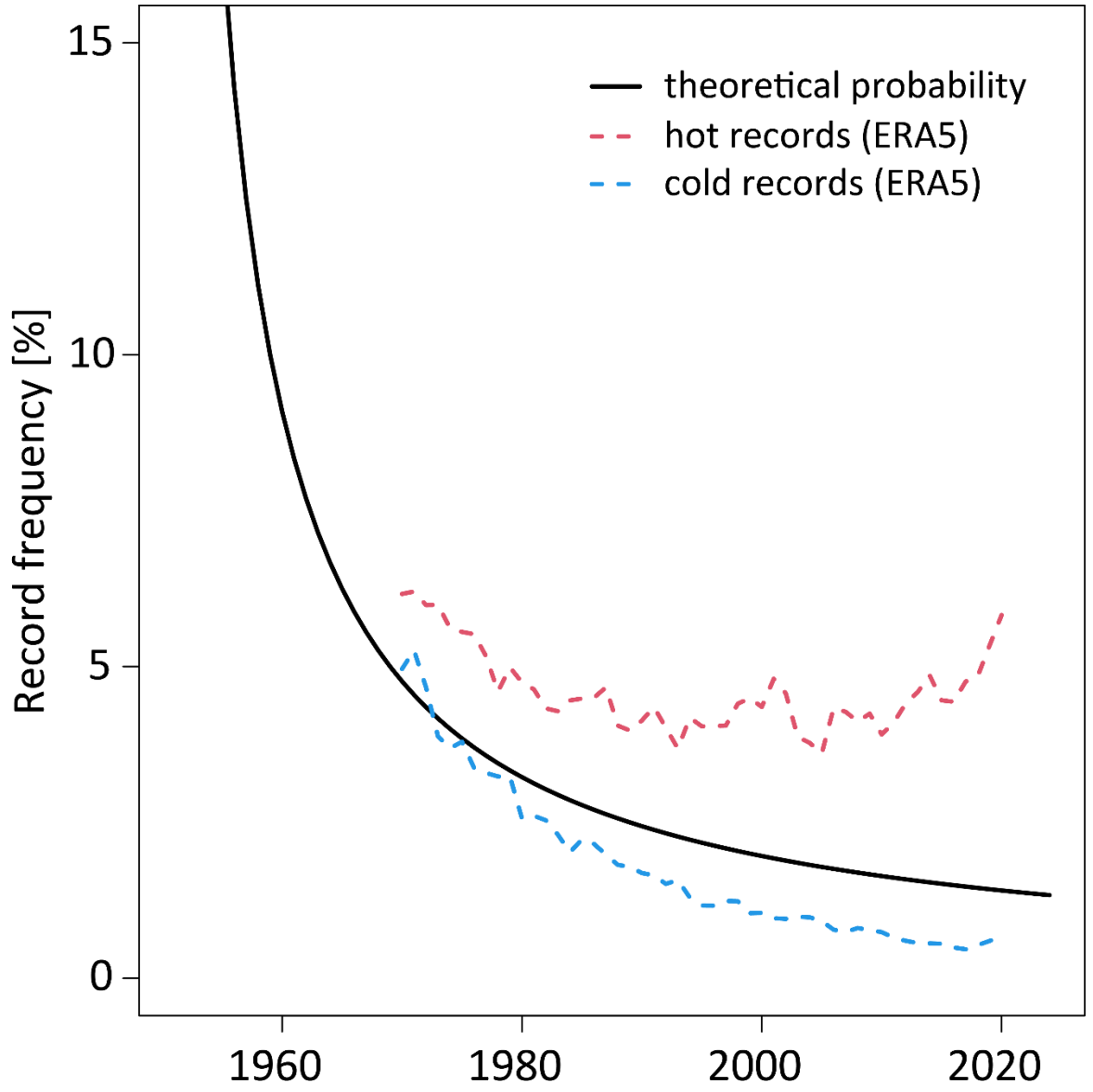
$$\Pr(\text{record}) = \Pr\{X_n > \max(X_1, \ldots, X_{n-1})\} = 1/n$$



… but all-time heat records are on the rise

Hot record become more frequent

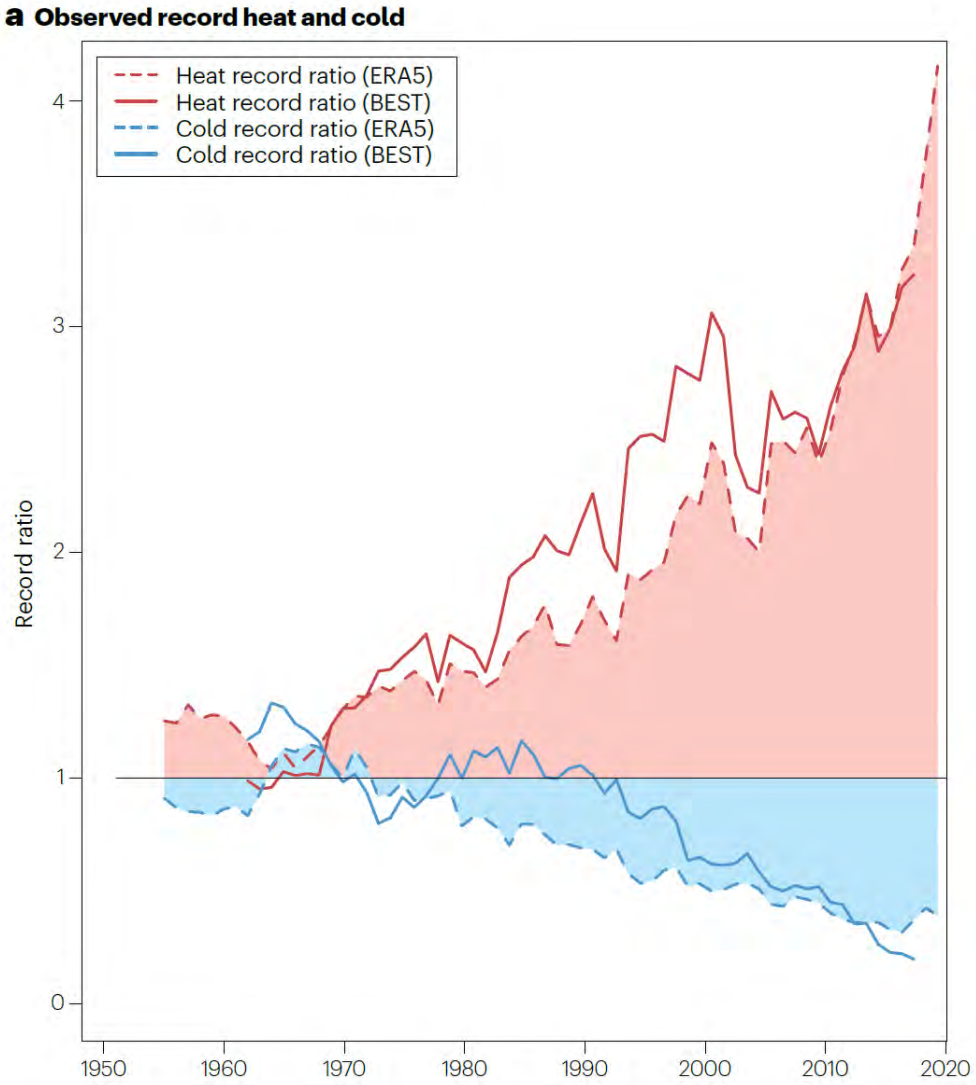
Cold records decline rapidly



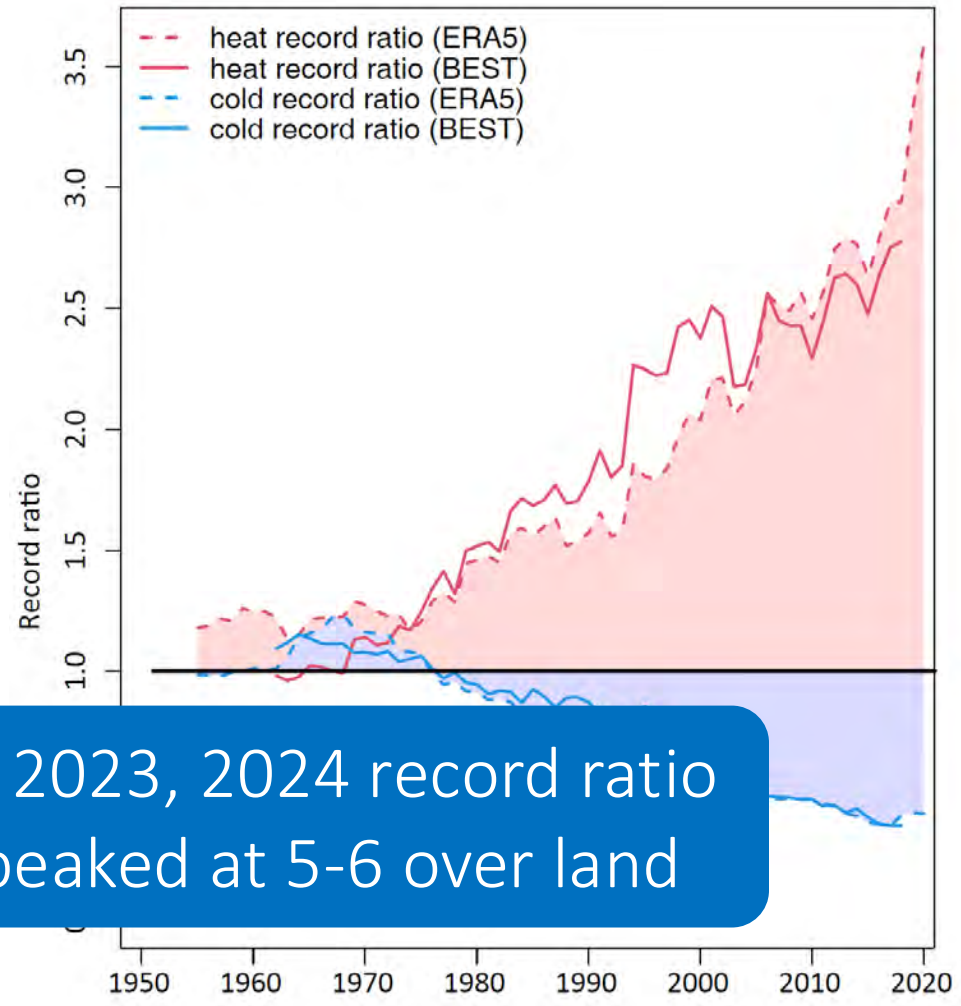
Fischer, E.M., M. Bador, R. Huser, E.J. Kendon, A. Robinson, and S. Sippel (2025)
Nature Review Earth & Environ

3-4 times more hot records – less than half cold records

Daily all-time records



Daily record for corresponding month



In 2023, 2024 record ratio peaked at 5-6 over land

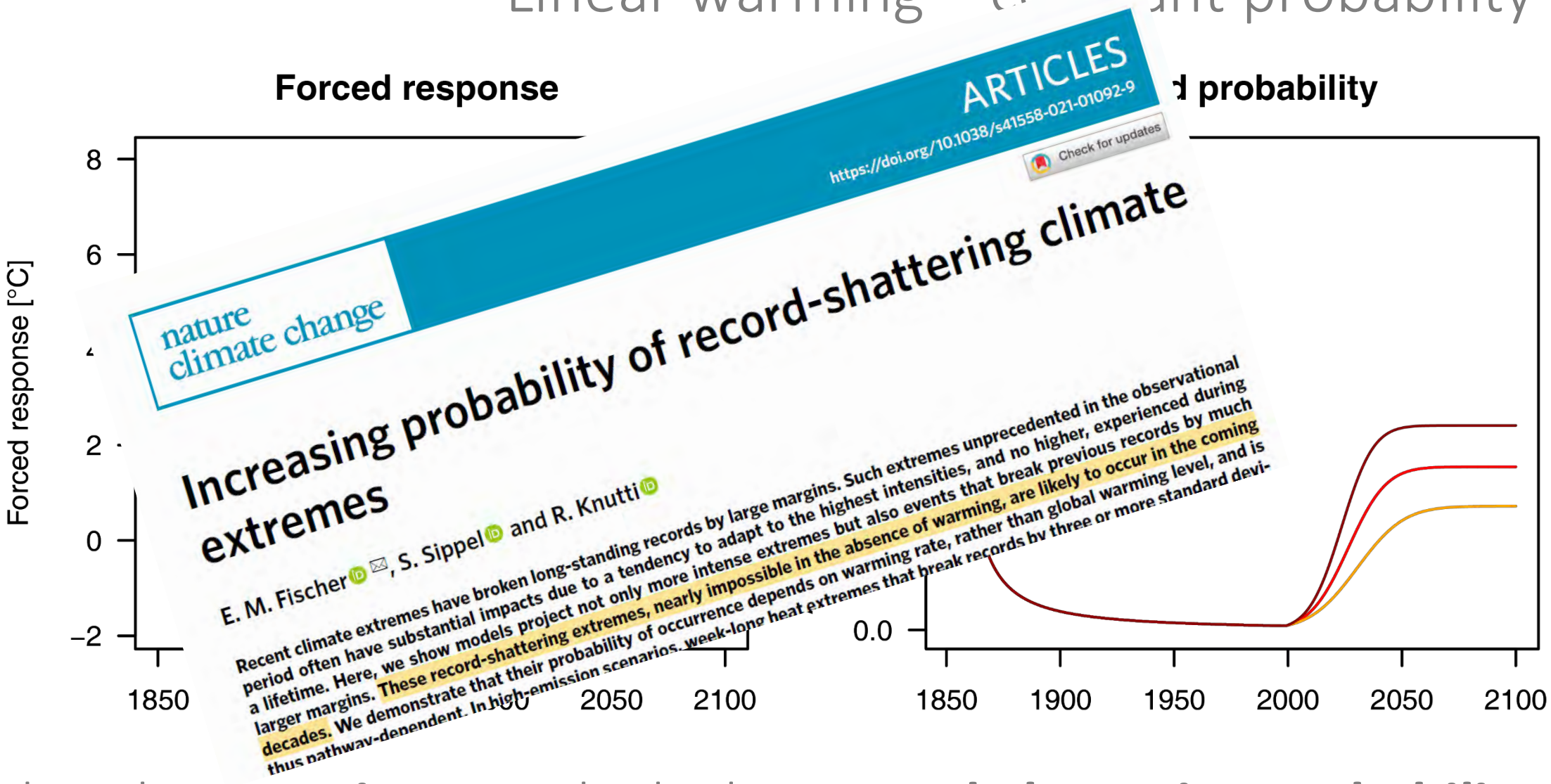
Fischer et al. (2025) *Nature Review Earth & Environ*

Climate change **signal in temperature records** is very distinct

Why such large record margins?

Record margins should become smaller

Linear warming – constant probability



ARTICLES
https://doi.org/10.1038/s41558-021-01092-9
Check for updates
nature climate change

Increasing probability of record-shattering climate extremes

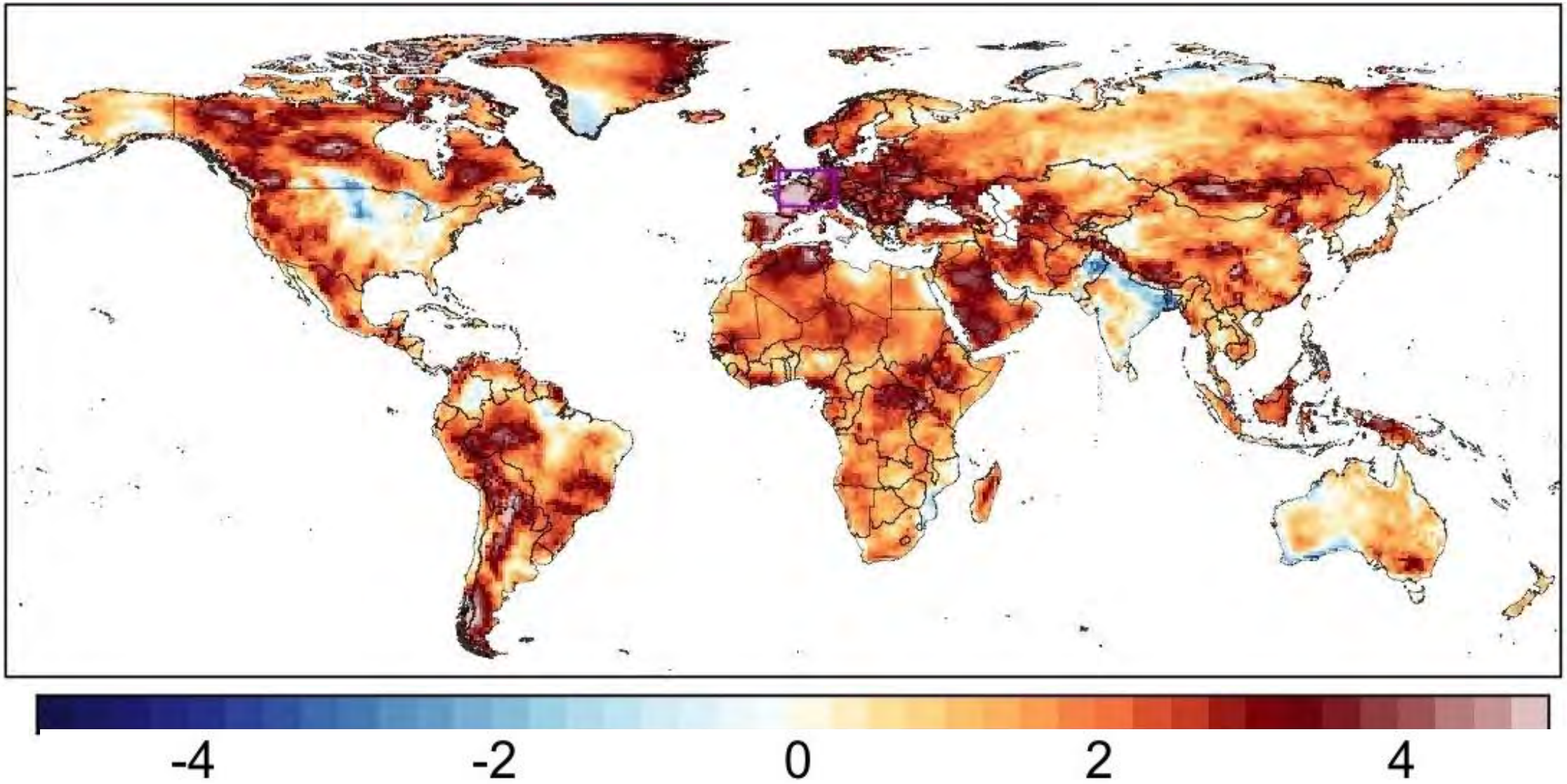
E. M. Fischer ✉, S. Sippel and R. Knutti

Recent climate extremes have broken long-standing records by large margins. Such extremes unprecedented in the observational period often have substantial impacts due to a tendency to adapt to the highest intensities, and no higher, experienced during a lifetime. Here, we show models project not only more intense extremes but also events that break previous records by much larger margins. These record-shattering extremes, nearly impossible in the absence of warming, are likely to occur in the coming decades. We demonstrate that their probability of occurrence depends on warming rate, rather than global warming level, and is thus pathway-dependent. In high-emission scenarios, week-long heat extremes that break records by three or more standard devi-

The higher the **warming rate** the higher **record-shattering probability**

Fischer et al. (2021), *Nature Clim. Change*
Fischer et al. (2025) *Nature Review Earth & Environ*

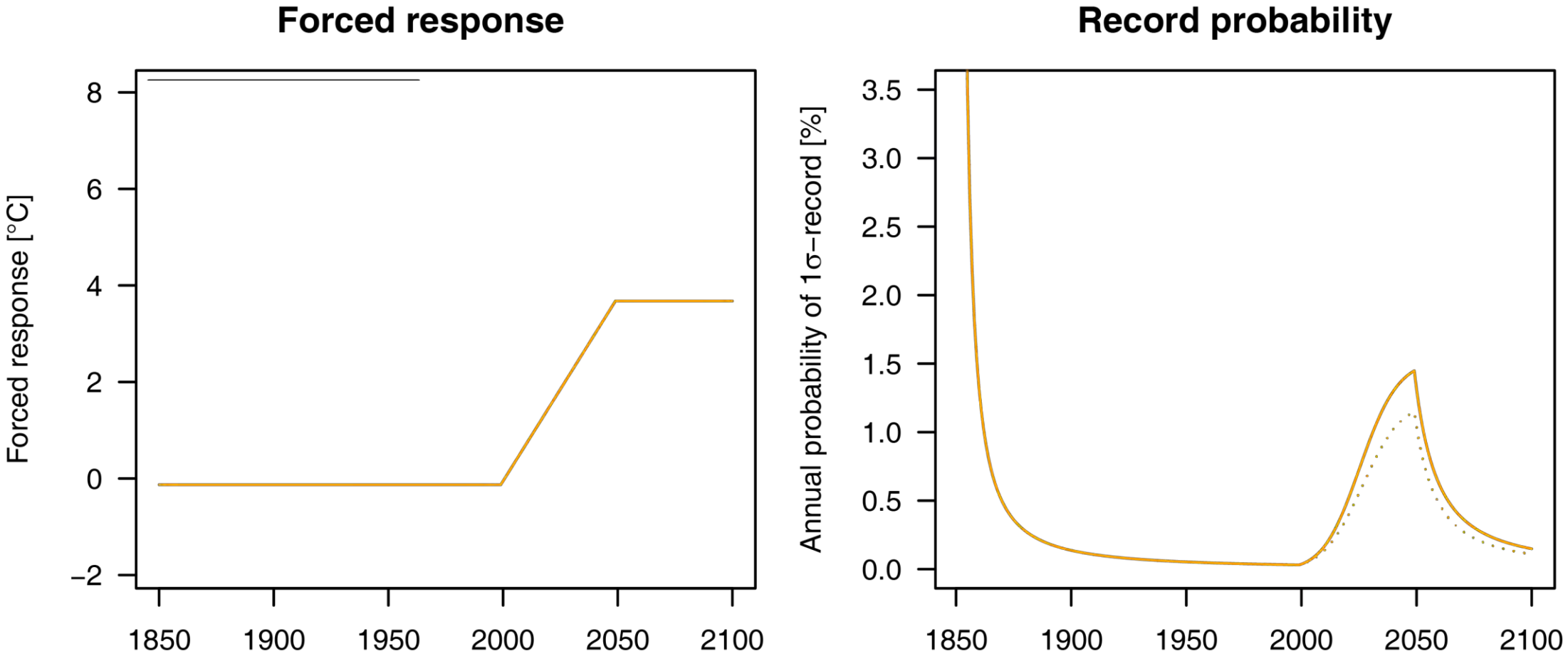
Quantifying the forced warming response is crucial



Warming trend of annual 5-day maximum temperature (°C)
1950-2024 (ERA 5)

Update of Singh et al., 2023, *Nature Comms*

Stabilizing temperature – declining probability

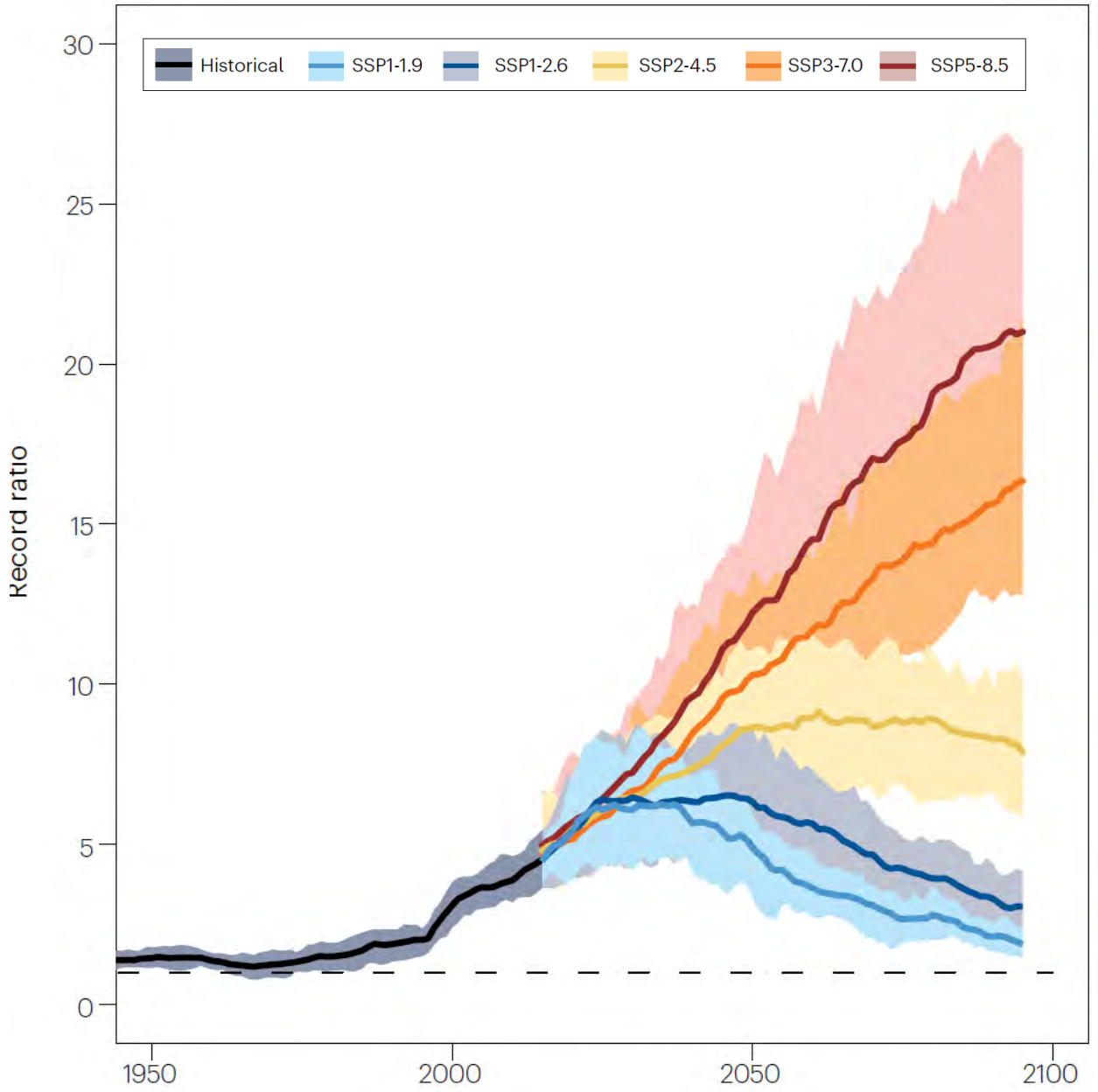


Stabilized temperatures -> **lower** record-shattering **probability**

Fischer et al. *Nature Review Earth & Environ*

Early benefits of mitigation

Slowing down warming **reduces the probability** of record-shattering extremes



Fischer et al. (2025) *Nature Review Earth & Environ*

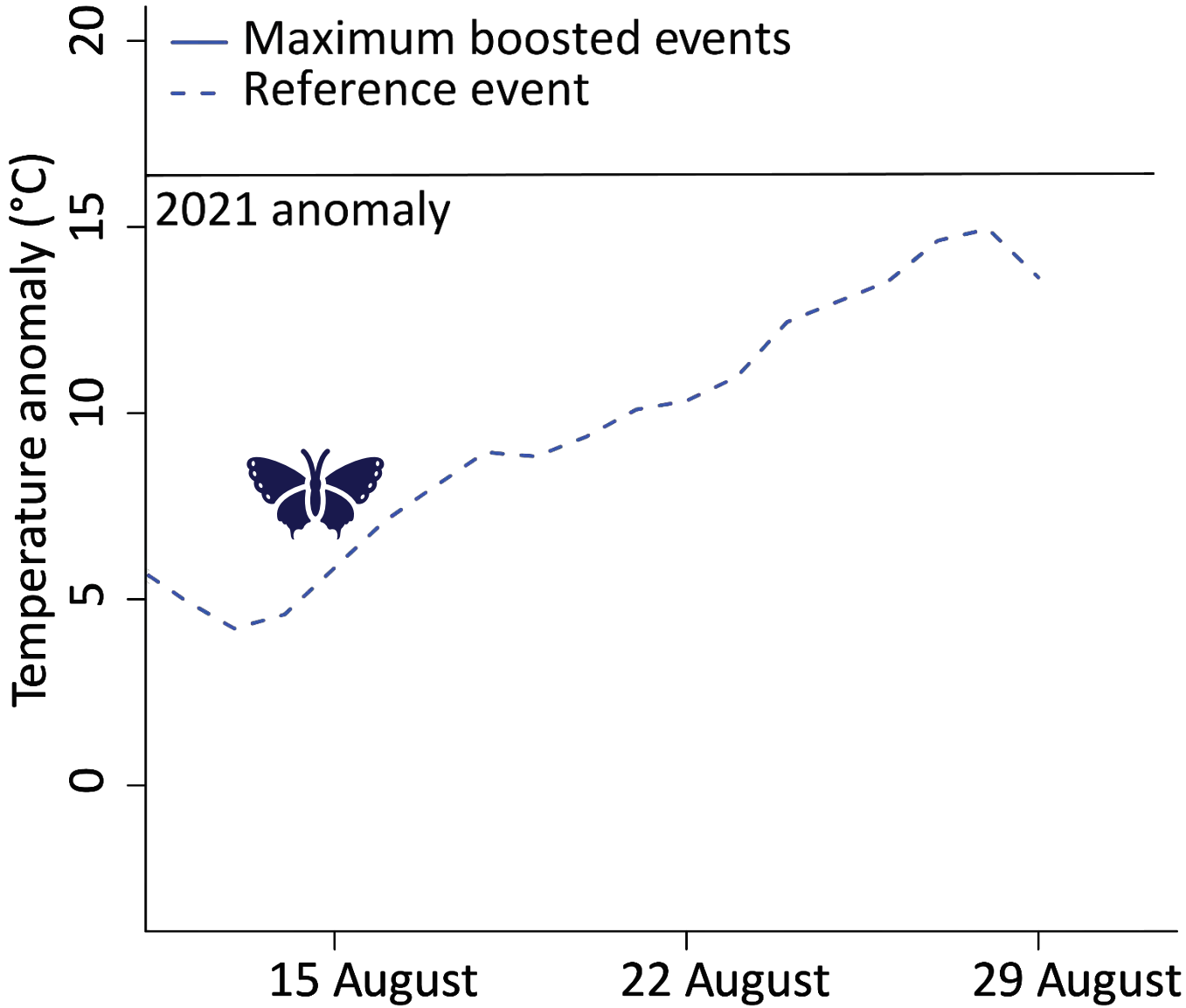
The warming rate controls the
record probability

How hot could it get?

Towards quantifying an upper limit

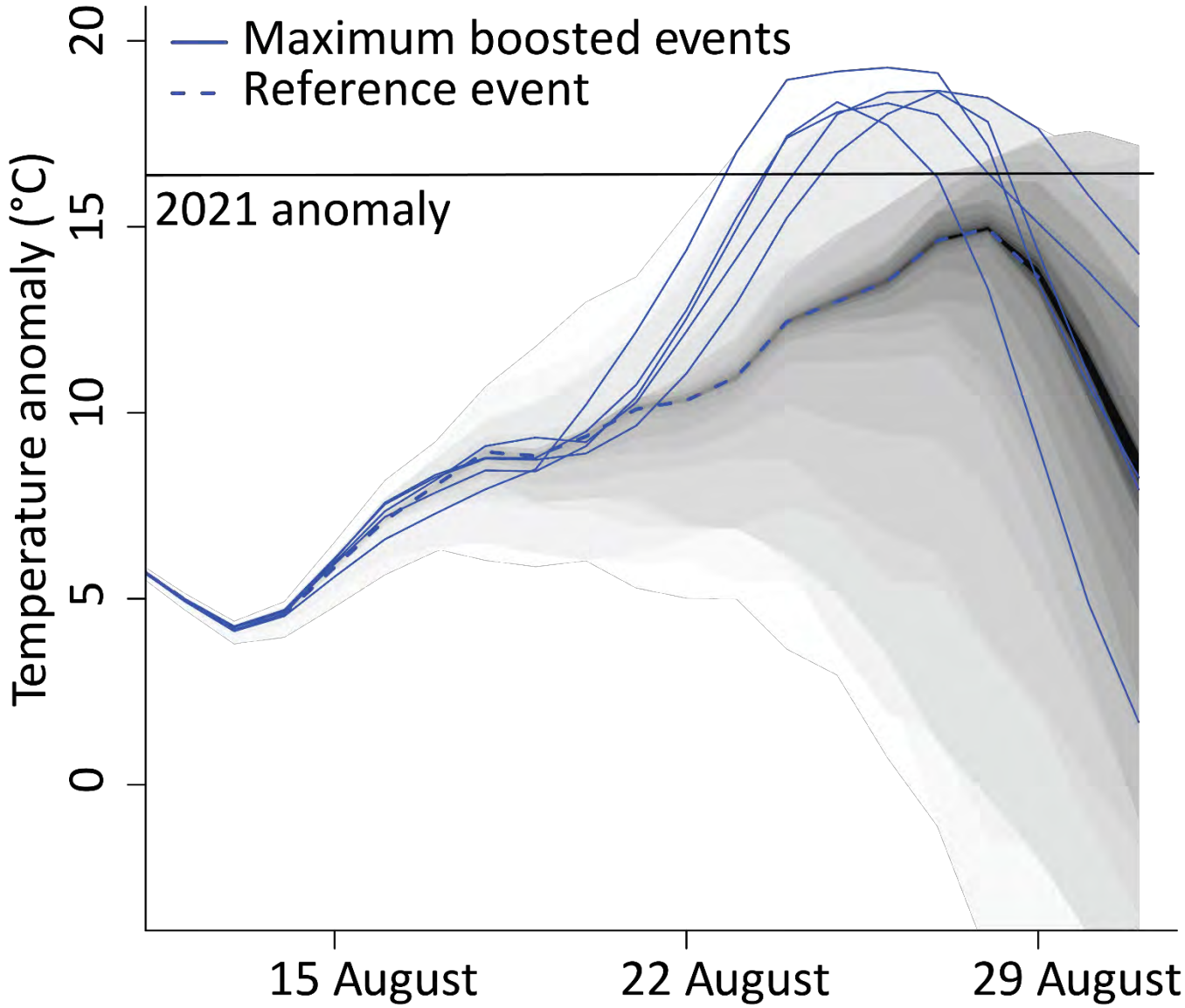
Figure credit: Michael Boettinger (DKRZ) and Jochem Marotzke (MPI-M)

«Ensemble boosting» for very rare storylines



Fischer et al. (2023) *Nature Comms*

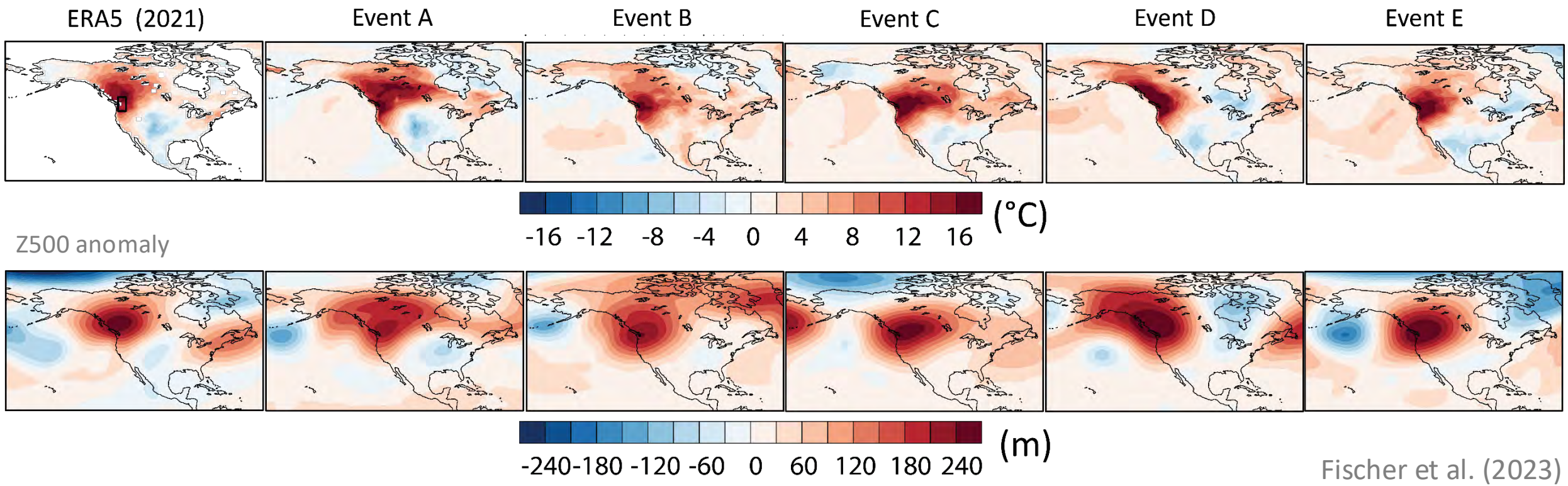
How do very extreme differ from more moderate heatwaves?



Fischer et al. (2023) *Nature Comms*

Ensemble boosting allows to evaluate processes

Temperature anomaly



Fischer et al. (2023)
Nature Comm.

Consistent drivers despite event only being selected based on PNW temperature anomaly

Ensemble boosting allows to disentangle processes

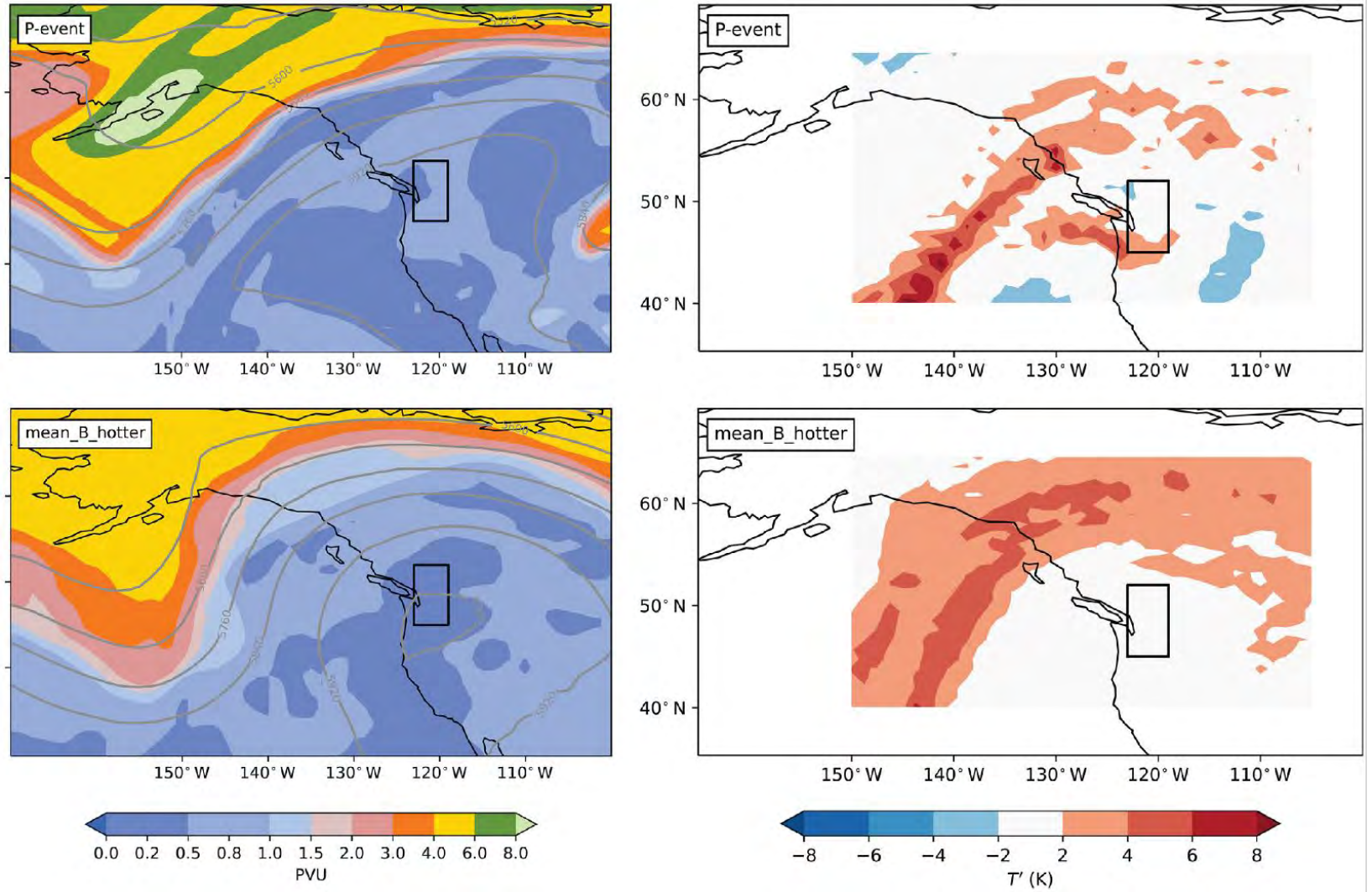
Diabatic heating (condensation) upstream of blocking plays crucial role

Most extreme boosted case

Ridge amplification and enhanced subsidence

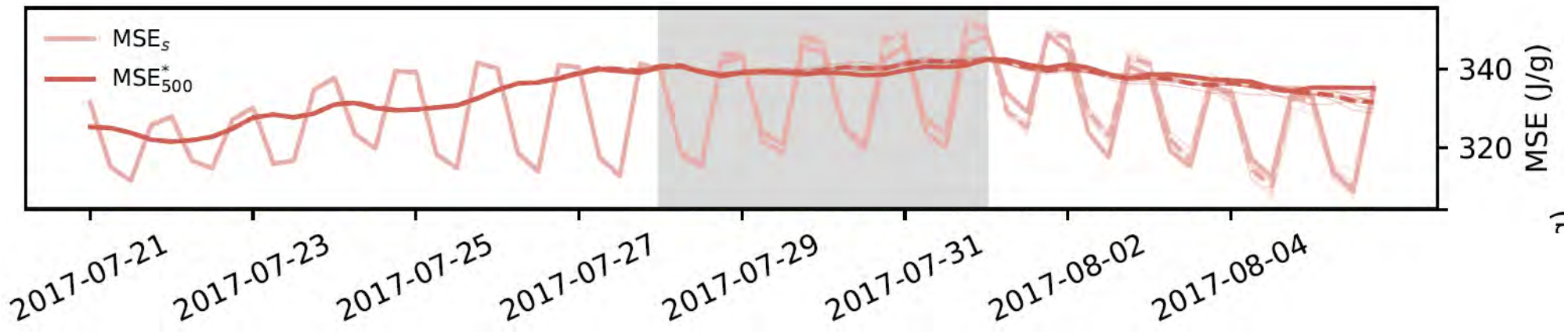
PV at 330K & Z500 at 12 UTC 28 August

5-day averaged diabatic T' at 330K

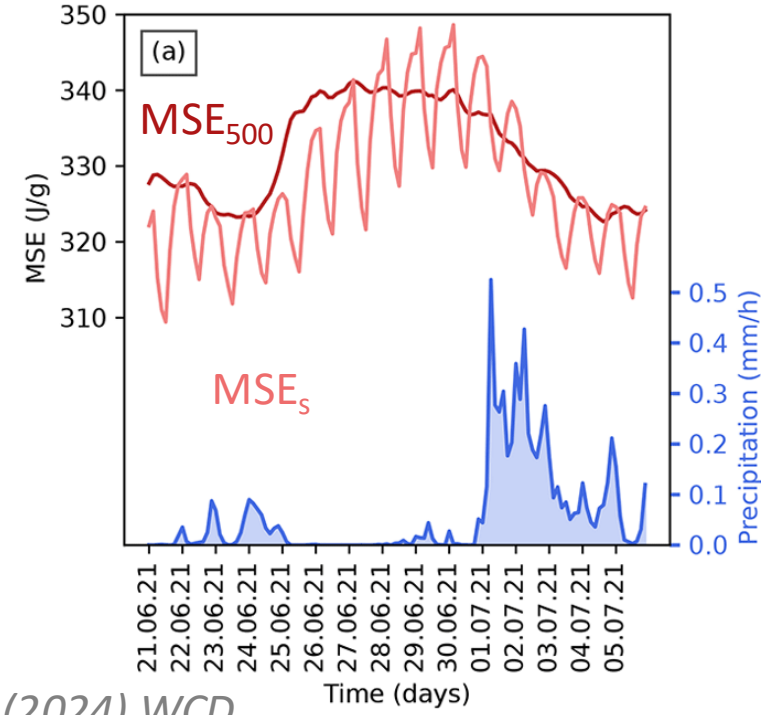


Yurong Gao, MSc thesis, ETH Zurich

Violating the «physical constraint» on the upper bound?



Yurong Gao, MSc thesis, ETH Zurich



Hotz, Papritz, Roethlisberger *(2024) WCD*

MSE$_{500}$ constraint did not hold up in ERA5 during PNW

Lower tropospheric inversion can further stabilize troposphere

Atmospheric stability sets maximum moist heat and convection in the midlatitudes

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[a]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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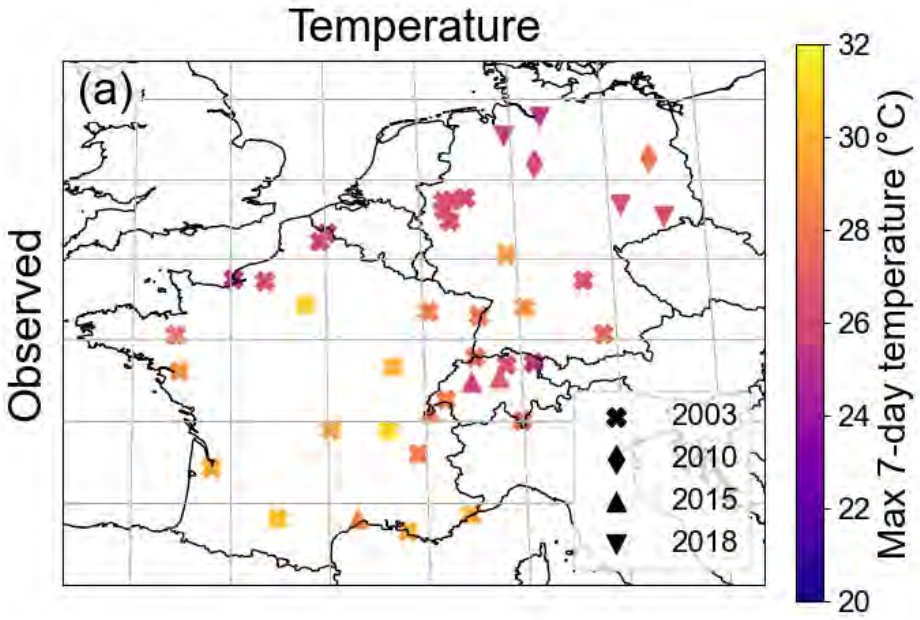
Extreme moist heatwaves pose a serious threat to society and human health. To manage heat-related risks, it is crucial to improve our understanding of what limits the maximum near-surface moist heat. This question has been extensively studied for moist heat in the tropics

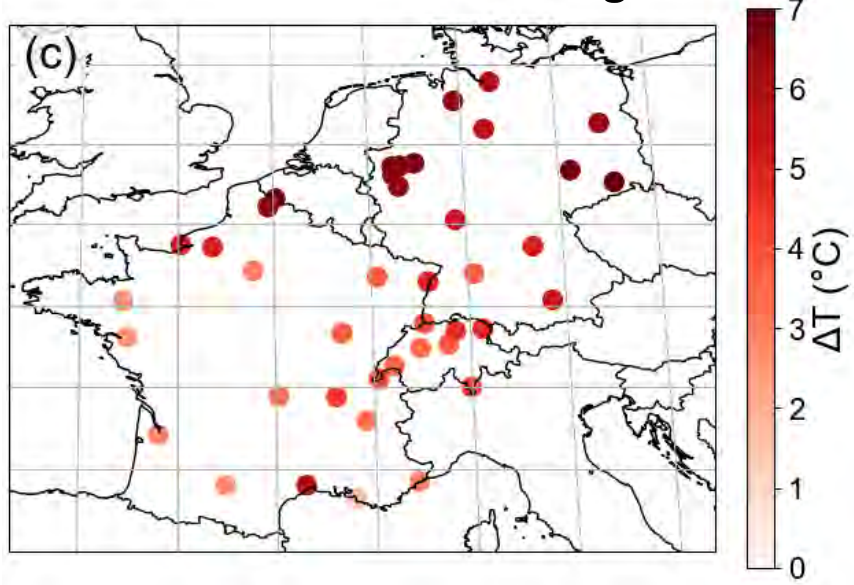
Temperature anomalies during the events

Most intense 7-day event

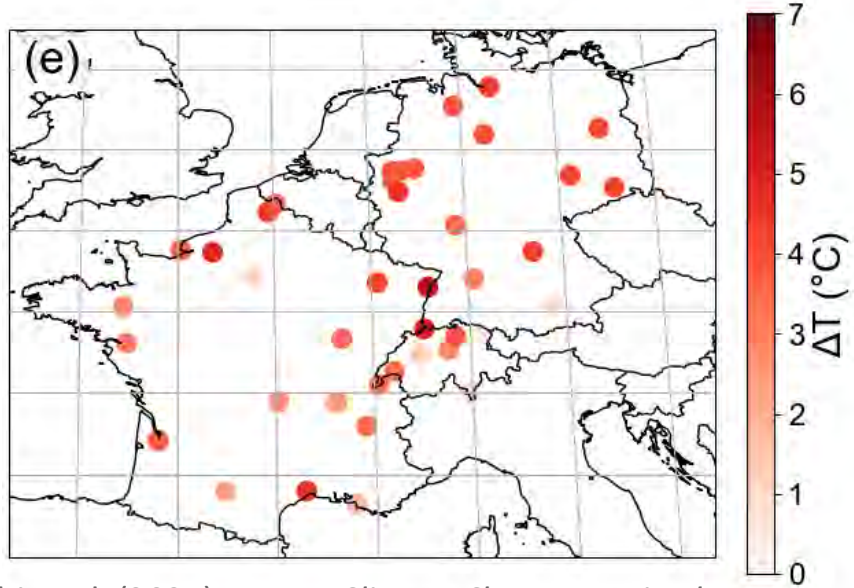


How much hotter could get?

Ensemble boosting



UNSEEN approach

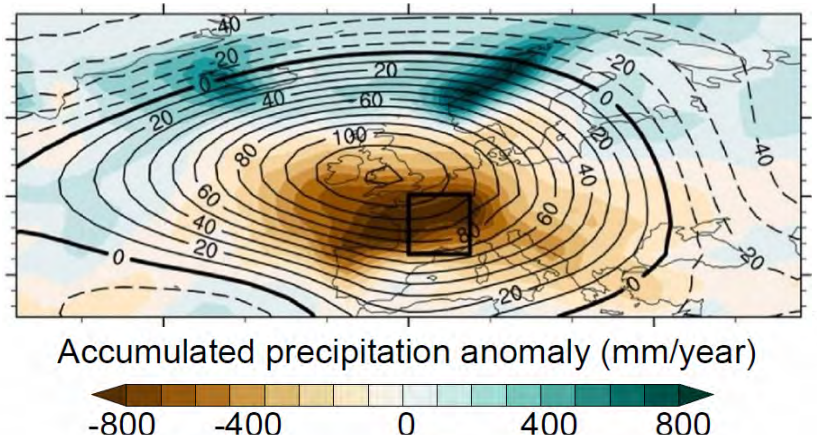


All lines of evidence agree that events of much greater intensity than observed are possible (particularly over Germany!)

Lüthi et al. (2025) *Nature Climate Change, revised*

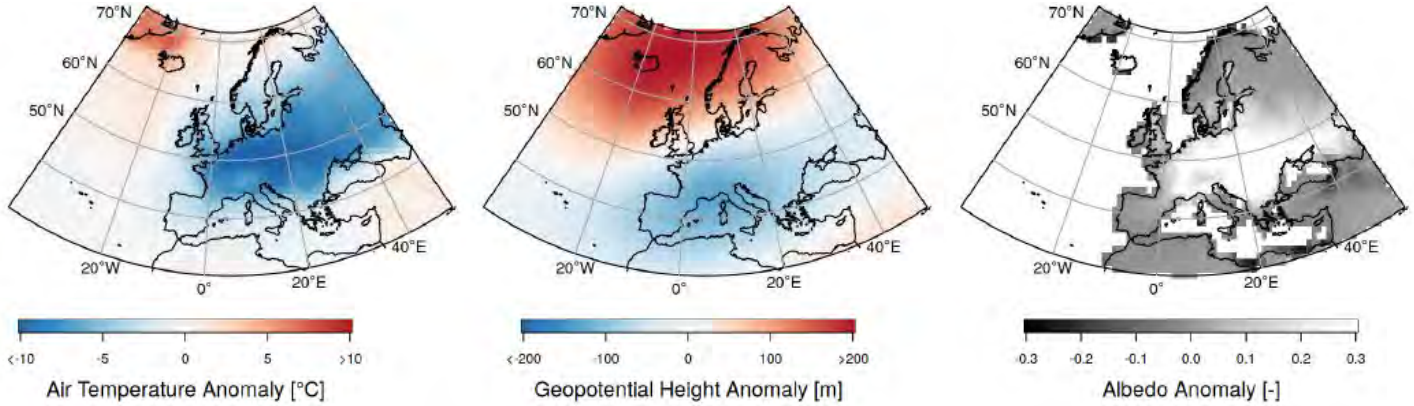
Using worst-case storylines for other impacts

Worst-case multi-year drought for biodiversity, carbon cycle and agriculture



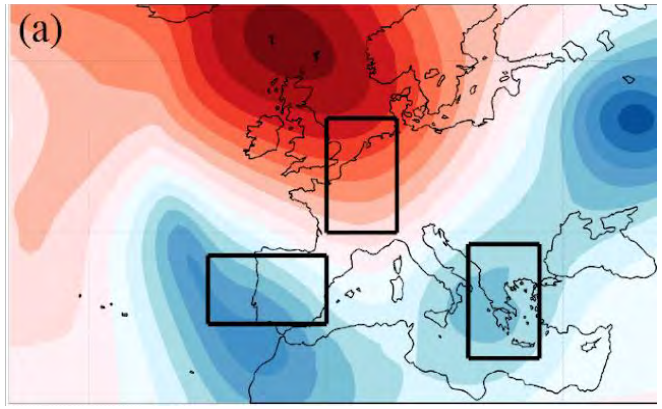
Gessner, Fischer, Beyerle and Knutti (2022) *Weather and Climate Extremes* and Noyelle et al. (2025) in prep.

Worst-case winter in 2030s to test resilience of (renewable) energy systems



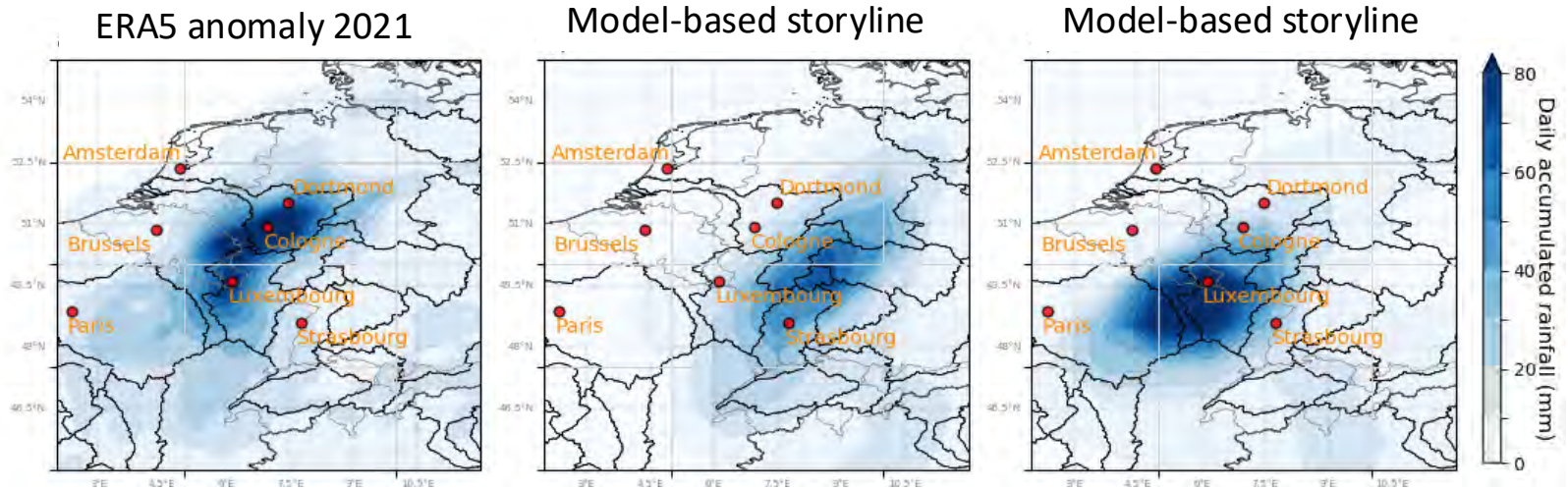
Sippel et al. (2024) *Weather and Climate Dynamics*

Compound flood-heat-flood



Guo et al. (2025), *Comm. Earth Environ.*

Large-scale precipitation for flooding in urban areas



Thompson et al. (2025), *Comm. Earth & Environ*

Conclusions

- There is a distinct climate change **signal** in record frequencies
- We need to **prepare** for extremes of **unprecedented** intensity, duration, and extent as a result of the very high **warming rate**
- Multiple **lines of evidence** suggest that also in **heat records** of much higher temperatures are **possible** today

References

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