



A Large-Deviation View on Persistent Extremes

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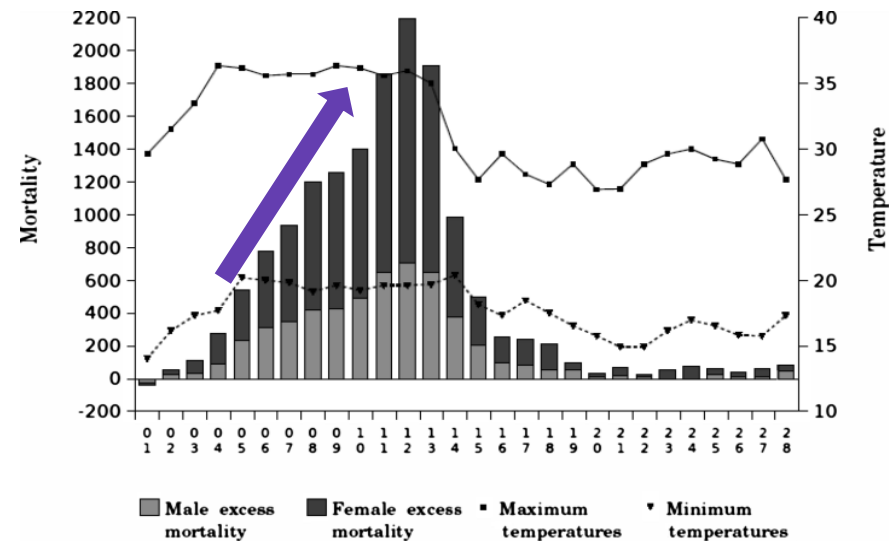
Collaborators: Valerio Lucarini, Gabriele Messori, Jacopo Riboldi

Learning spatio-temporal climate extremes, UCLouvain, 27.5.2026

Persistent extreme events can lead to societal impacts not only through intensity, but also through...

Duration: the impact caused during a persistent extreme event is usually nonlinear.

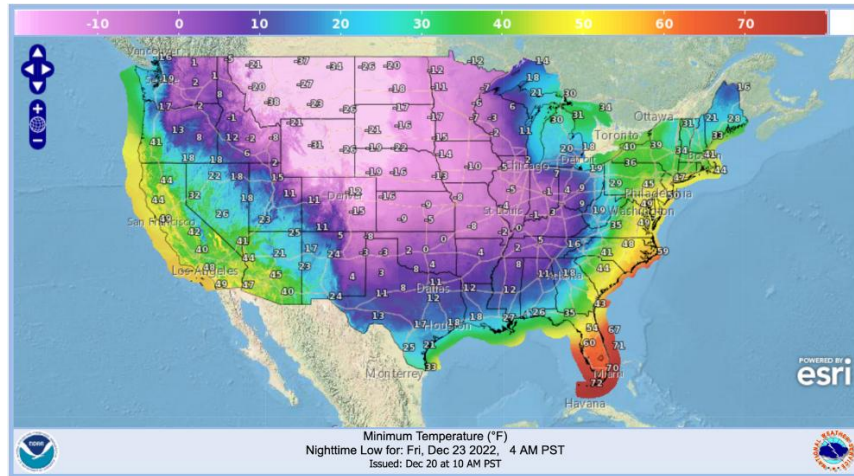
Excess death in summer 2003 in France. Poumadere (2005).



Persistent extreme events can lead to societal impacts not only through intensity, but also through...

Spatial extent:

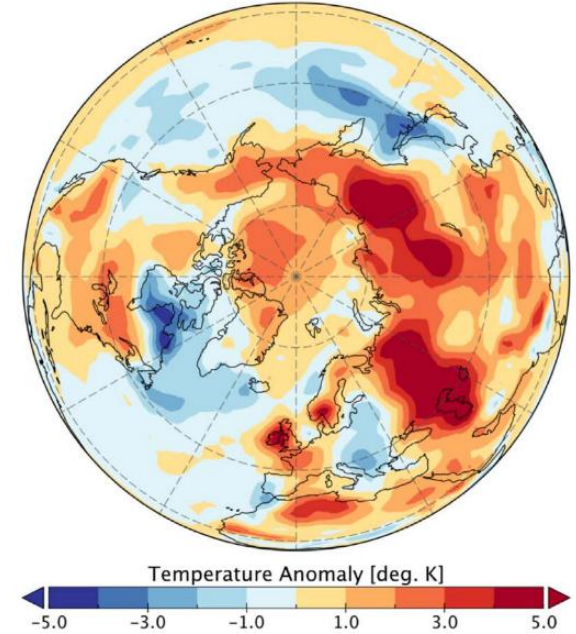
e.g. many people affected by cold spells / heatwave



©NOAA

Co-occurrence:

e.g. simultaneous heatwaves affecting breadbasket regions can be a threat for food security



Kornhuber et al., 2019

Cascading effects:

e.g. heatwaves can lead to or intensify droughts, which then lead to wildfires

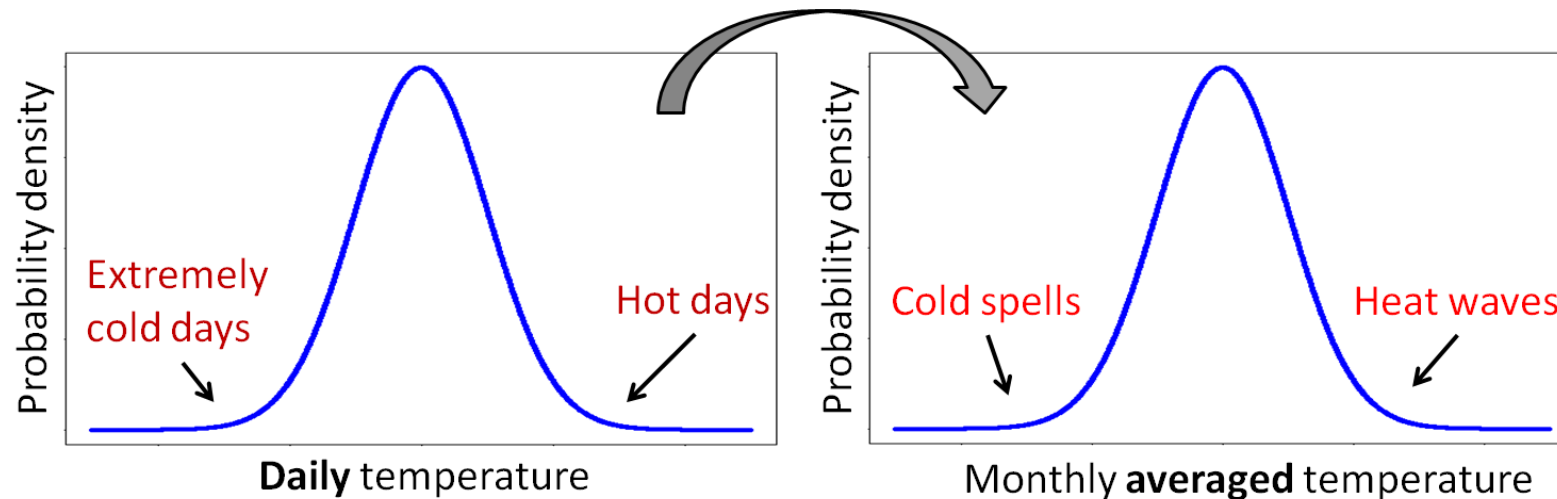


How to study persistent climate events?

Extreme indices - IPCC: events above a fixed threshold, e.g. 95% percentile, with a certain duration, e.g. 3 days.

Extreme Value Theory: limit laws for probabilities of extreme events.
Problem in case of persistent events: extremes are correlated.

Large Deviation Theory (LDT): limit law for probabilities of sample averages.
Persistent events can be identified based on extremes of averages.



Large deviation theory: limit law for sample averages.

Random variables X_1, X_2, \dots

→ averages over blocks of length n , $A_n = \sum_{i=1}^n X_i$

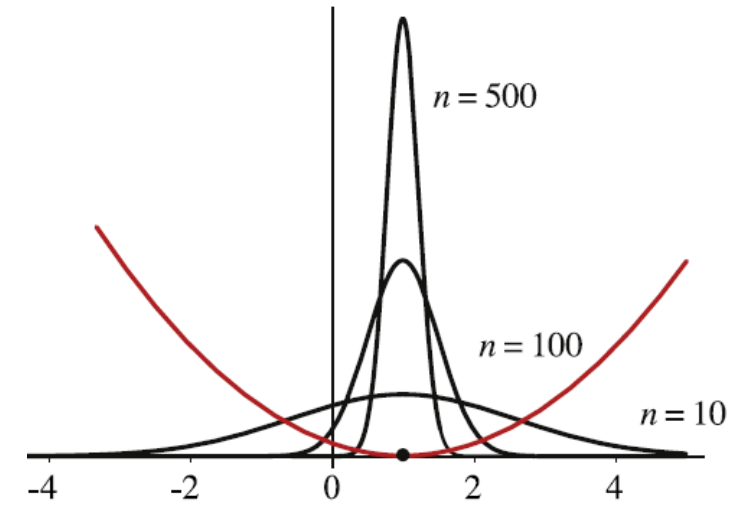
Large deviation principle: [1,2]

for $n \rightarrow \infty$

the probability of A_n decays exponentially with n

$$P(A_n \geq a) \asymp \exp(-nI(a))$$

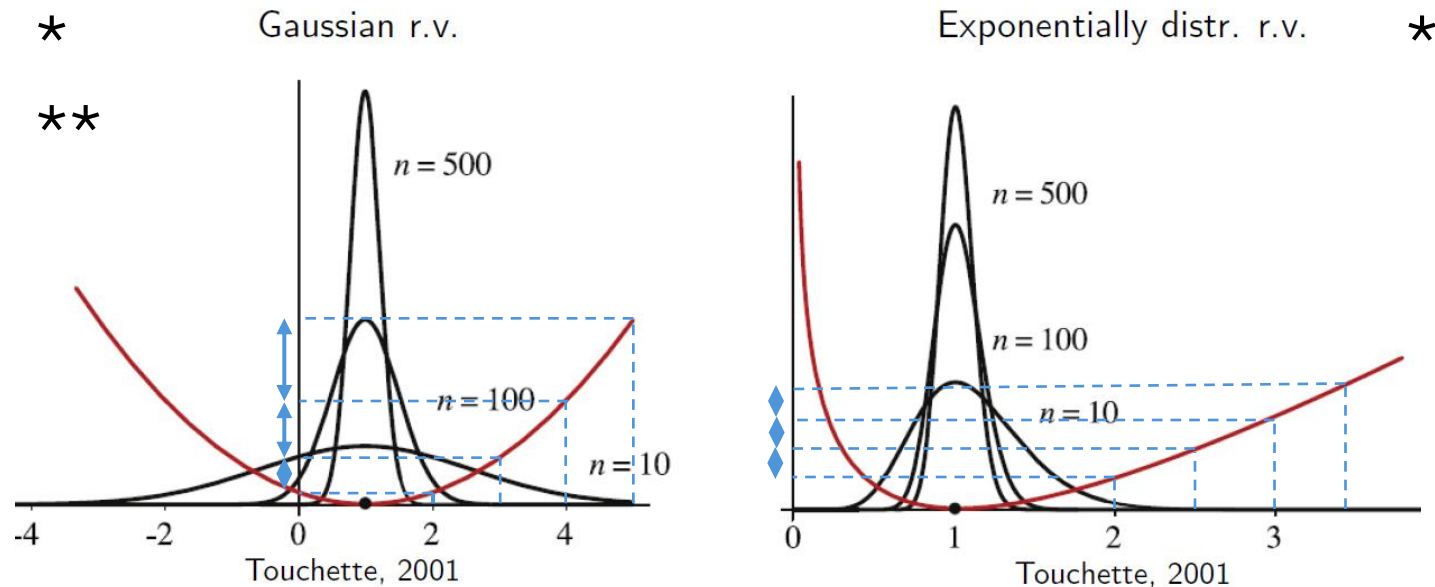
Rate function: speed of decay



[3]

LDT is an extension of the central limit theorem.

Large deviations can be different from small deviations.



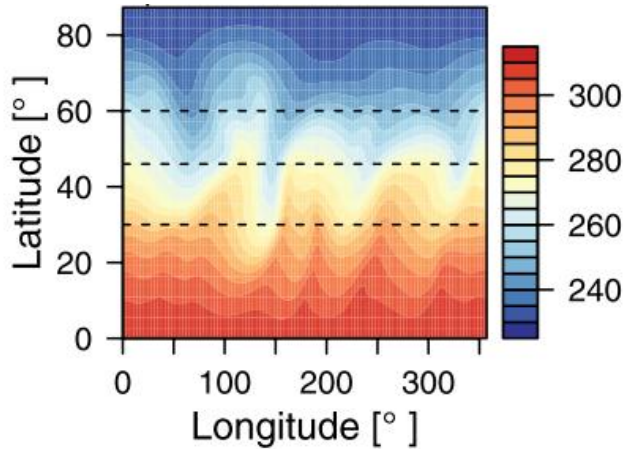
If LDP applies:

- 1) Large values don't dominate the mean. *
- 2) The more extreme, the more similar (if RF nonlinear). **

LDP applies when the most likely of all the unlikely events dominate.

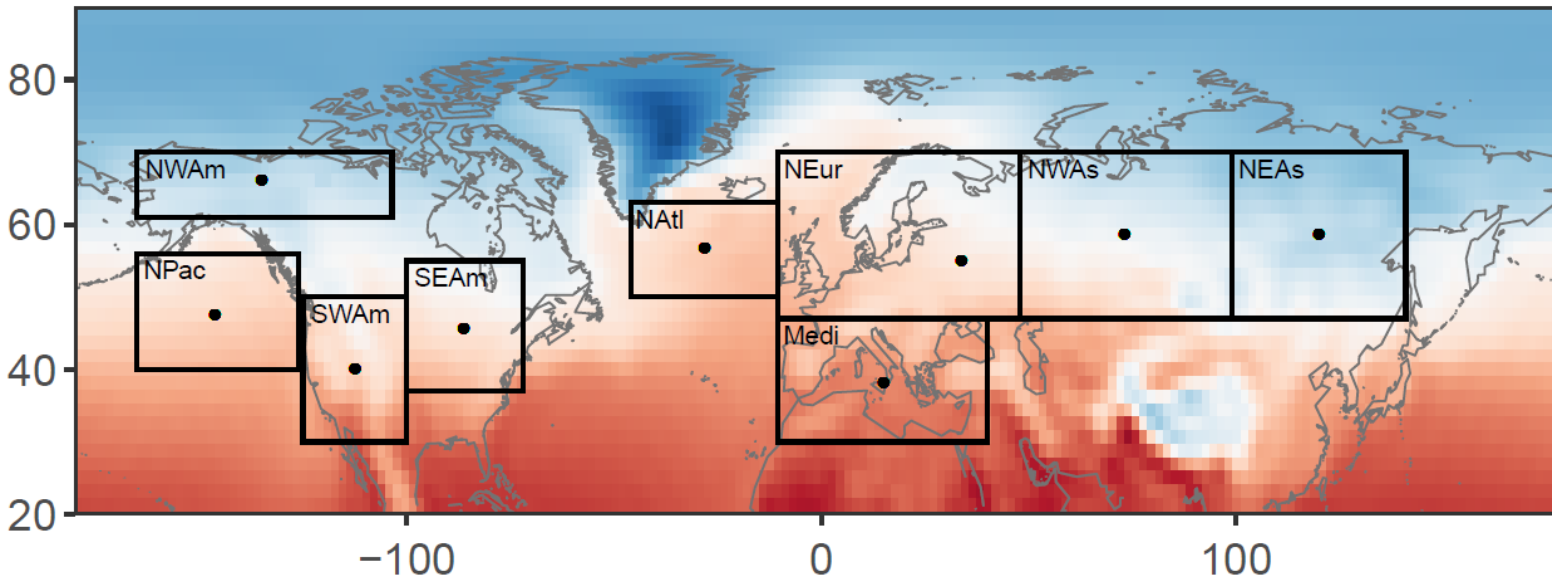
We estimate rate functions of temperature averages from long model simulations.

$$I(T_n) = -\frac{1}{n/\tau} \ln(p(T_n))$$



Atmospheric GCM PUMA:
10.000 years with stationary forcing

Galfi et al., 2019



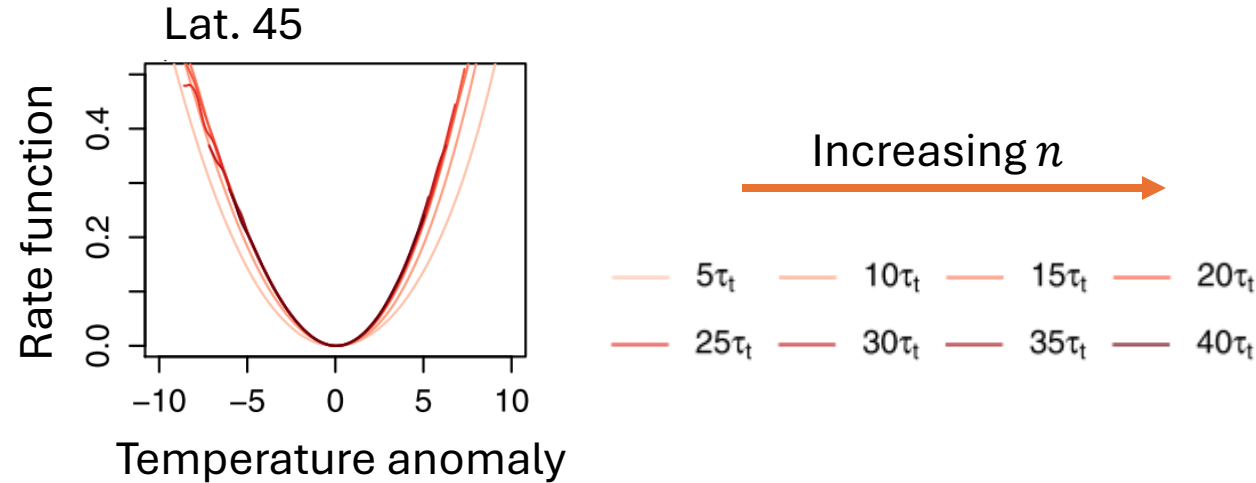
[°C] MPI-ESM-LR model (CMIP6):
1000-year pre-industrial
control run

Galfi and Lucarini, 2021



We estimate rate functions of temperature averages from long model simulations.

$$I(T_n) = -\frac{1}{n/\tau} \ln(p(T_n))$$



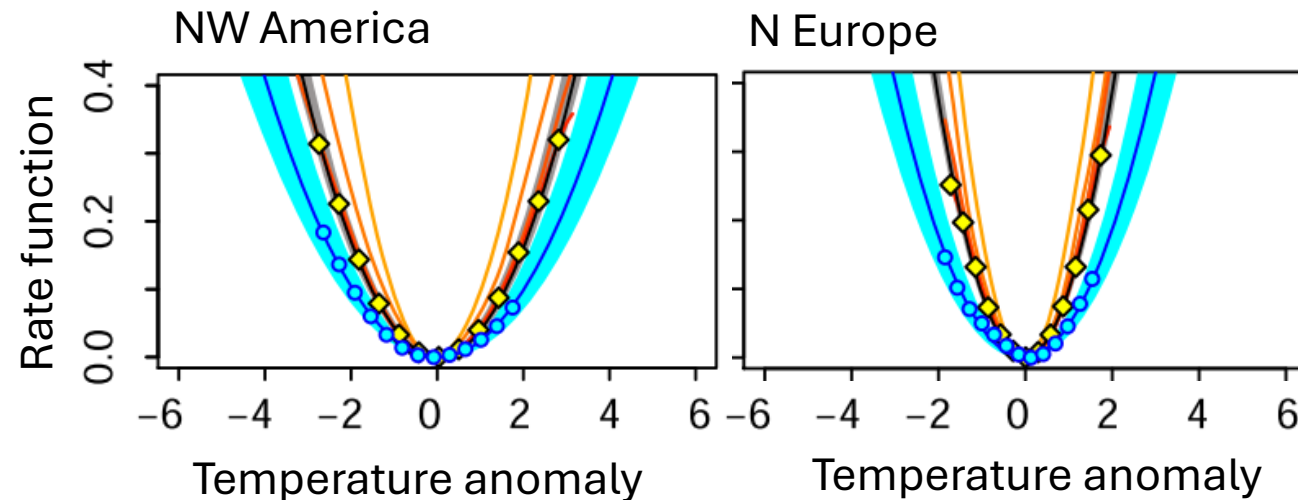
Rate function estimates

- converge at an n of appr. 10-20 τ and
- are appr. quadratic.

The prob. of **more extreme and longer** events can be obtained from the prob. of **less extreme and shorter** events.

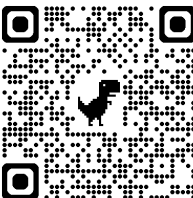
For quadratic rate functions:

$$p(T_{n'} = a') \approx p(T_n = a) \exp\left(\frac{na^2 - n'a'^2}{2\tau\sigma_T^2}\right)$$

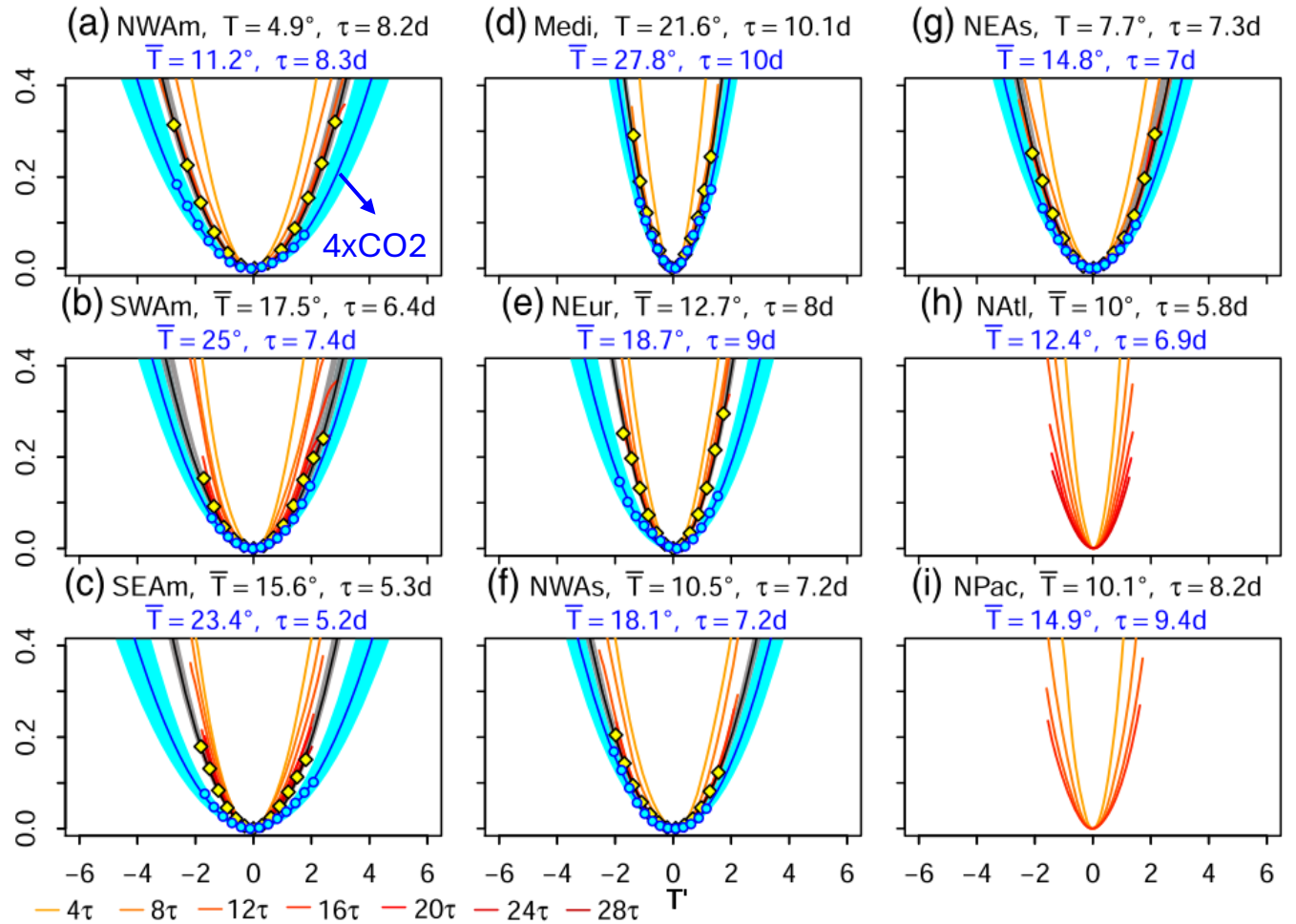


Increasing n

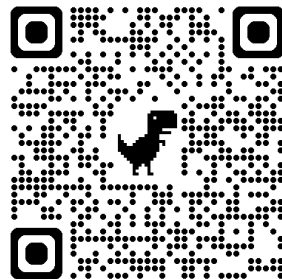
— 4 τ — 8 τ — 12 τ — 16 τ — 20 τ — 24 τ — 28 τ



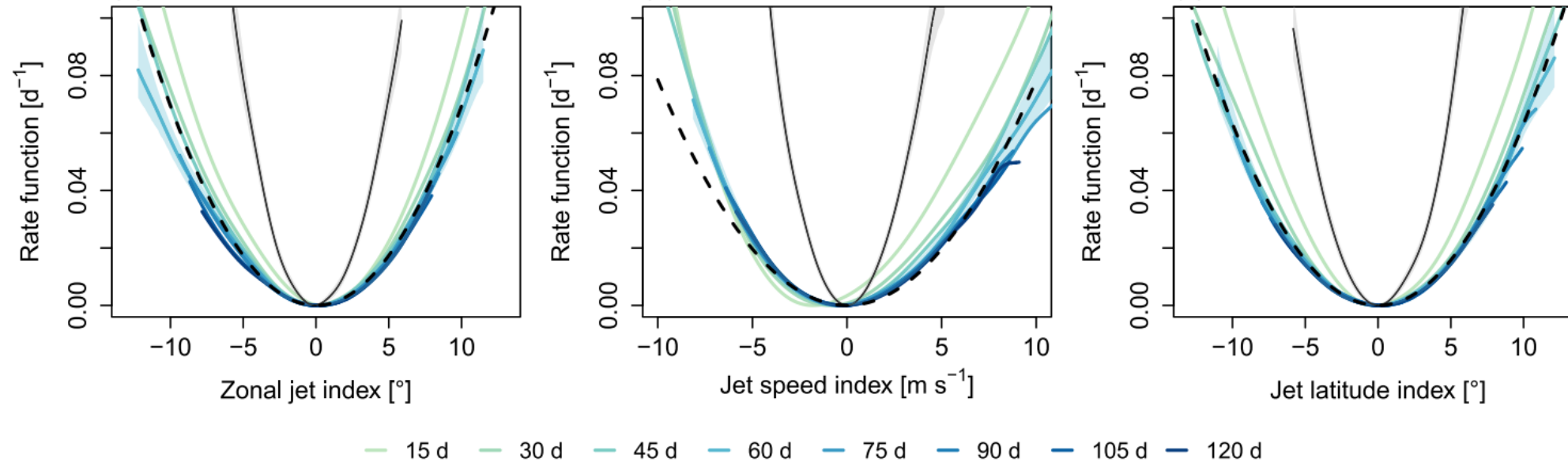
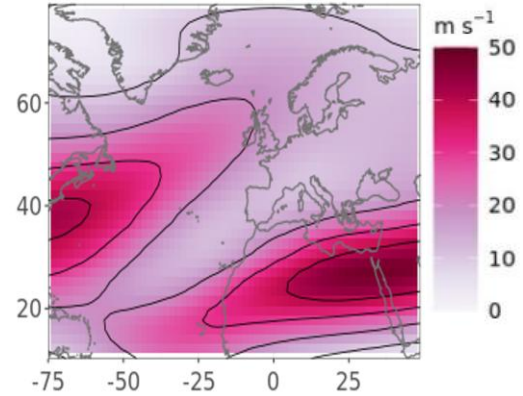
Heatwaves are becoming more frequent and longer lasting with global warming.



No convergence of rate functions over oceanic regions.



A large-deviation view on persistent anomalies of the North Atlantic jet stream based on jet indices.



Rate functions of jet stream indices converge for averaging windows of appr. 2 months.

We obtain LD return level estimates for 4-month averages from 2-month averages.

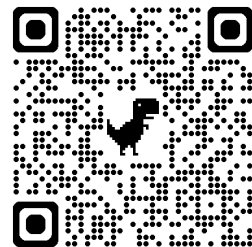
LD return level estimates correspond well with empirical estimates.

In case of EVT, one extrapolates towards longer return periods, i.e. rarer events;

in case of LDT, one extrapolates towards longer averaging times, i.e. more persistent anomalies.

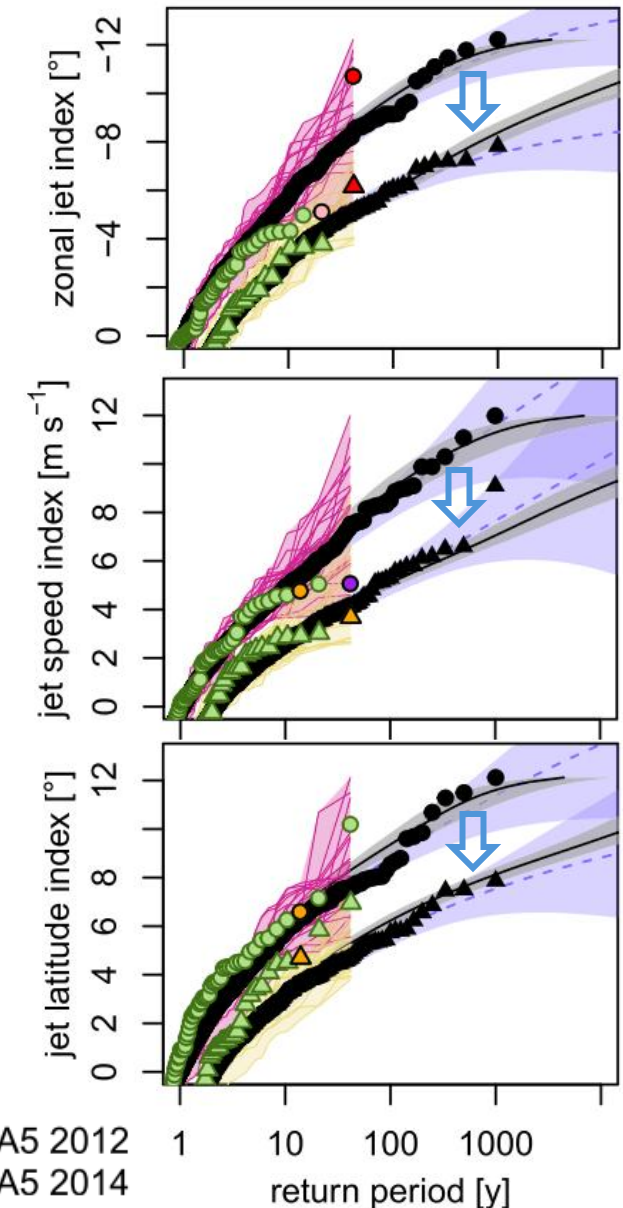
Comparison model – reanalysis:

Some discrepancies can be explained by the shorter length of the reanalysis data (thus larger uncertainty), but not all.



Galfi and Messori, 2023

- MPI-ESM
- ERA5
- ERA5 1985
- ERA5 1992
- ERA5 2006
- ERA5 2010
- ERA5 2012
- ERA5 2014



Rate function estimates of atmospheric variables (temperature, jet indices) **converge** at an n of appr. **1-2 months** and are appr. **quadratic**.



1. Large values don't dominate the mean.
2. The more extreme, the more similar.

Typicality of extreme events

Extreme events are similar among each other in terms of spatial patterns and spatio-temporal evolution – their mean is representative.
This similarity increases with intensity.

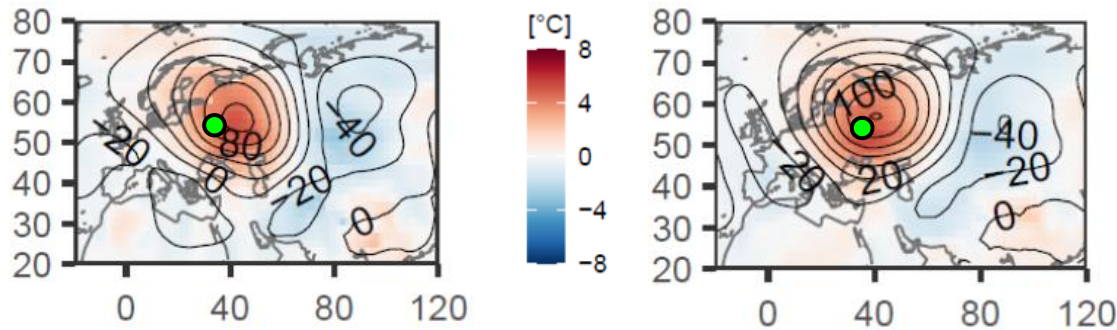


1. Large values don't dominate the mean.
2. The more extreme, the more similar.

Extreme heatwaves are similar among each other.

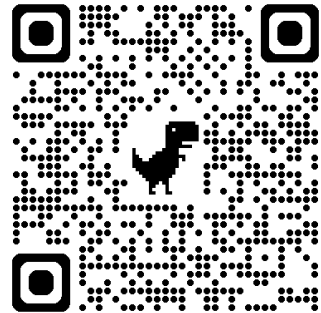
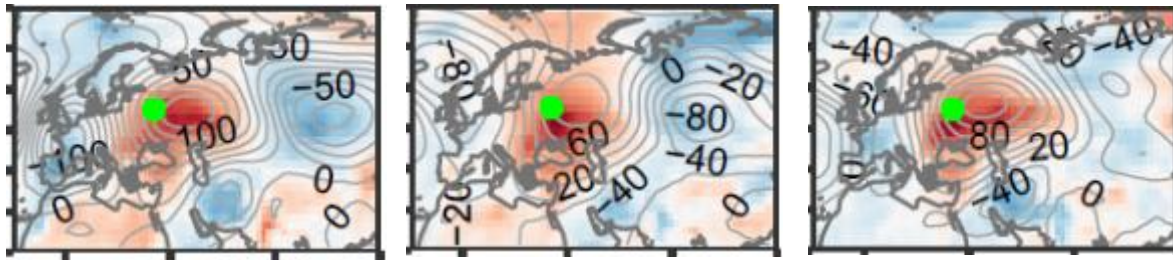
We select the **20 highest temperature anomalies in time** at the location ●

Model, $T' = 4.5 K, n = 30 d$ Model, $T' \geq 4.5 K, n = 30 d$

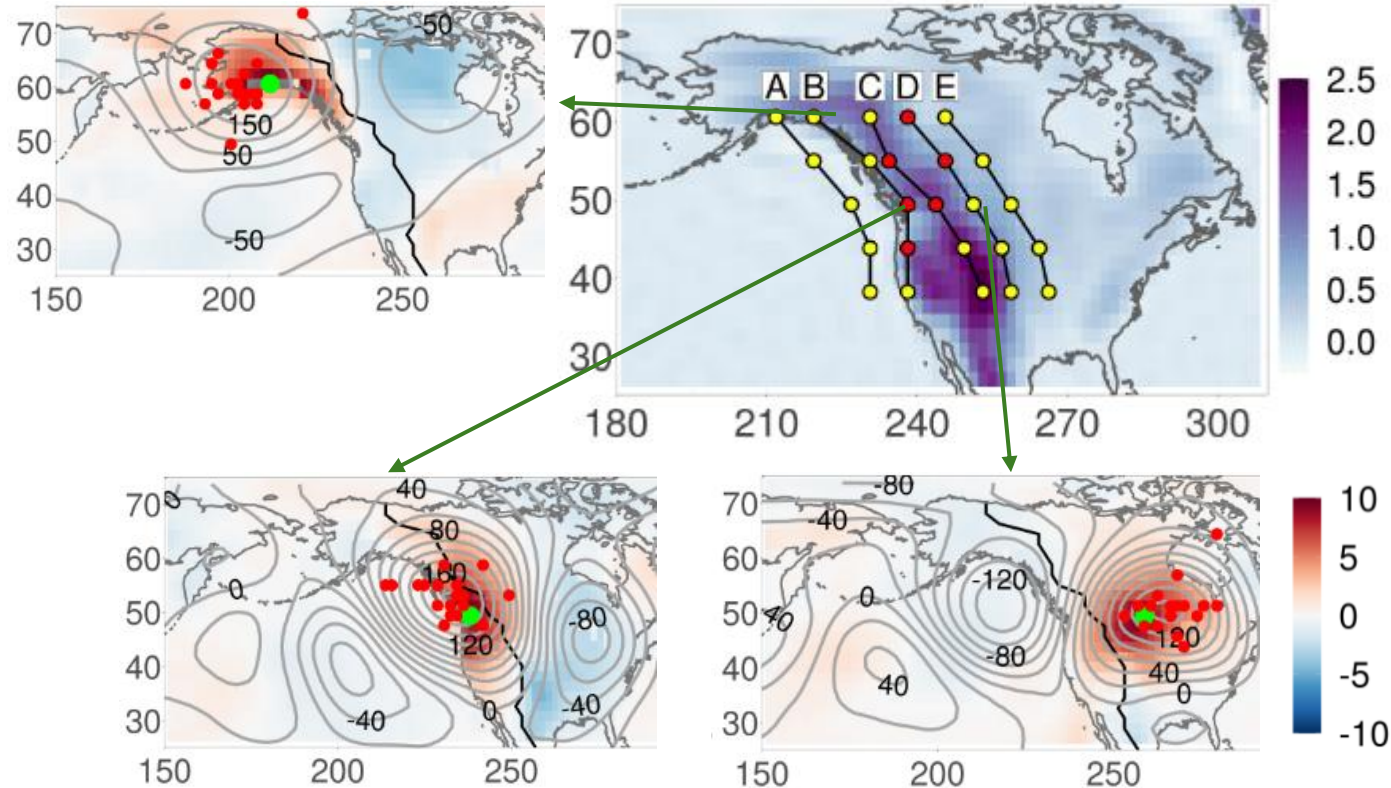


Spatial patterns related to highest anomalies don't dominate the mean pattern.

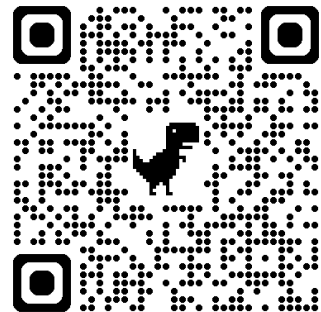
=> Typical spatial pattern



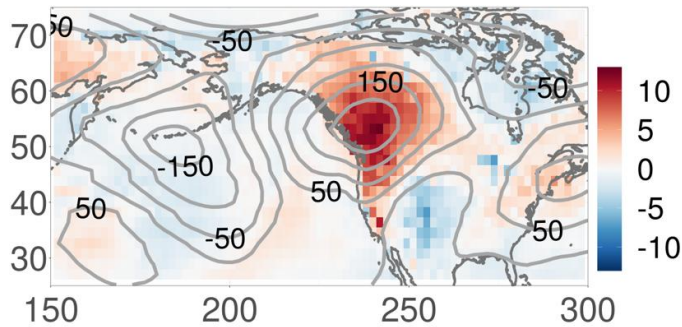
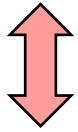
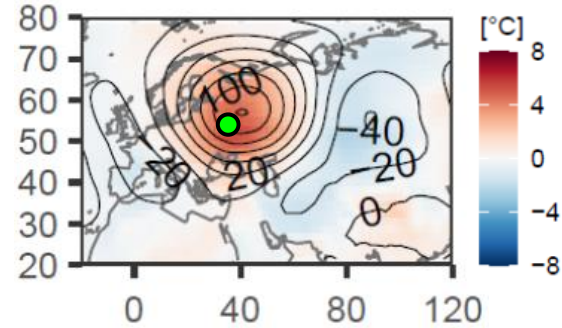
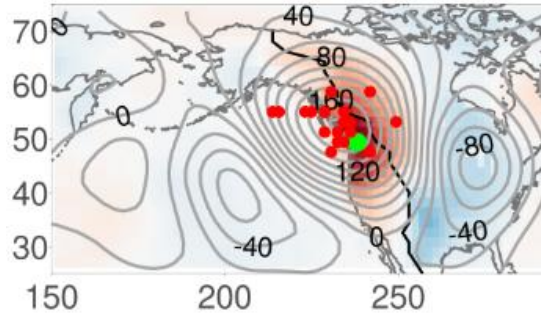
We find typical patterns also in other locations.



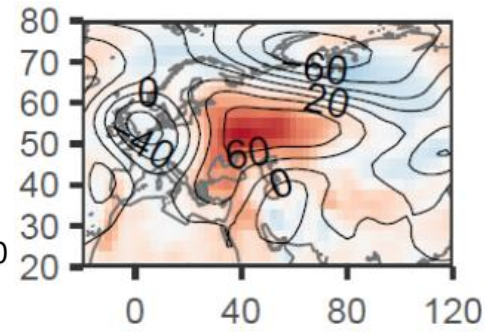
Spatial patterns related to highest anomalies don't dominate the mean pattern.
=> Typical spatial pattern



Are observed record-breaking heatwaves typical?



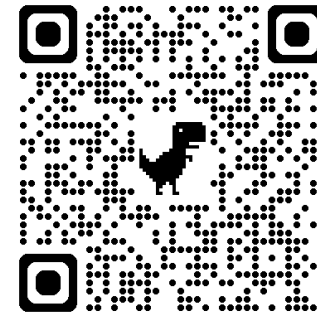
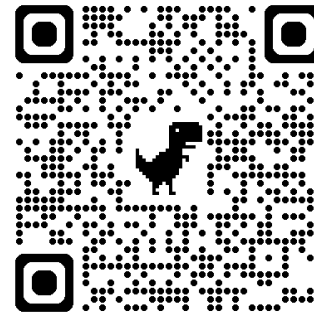
2021 W.N.Am
heatwave




2010 Russian
heatwave

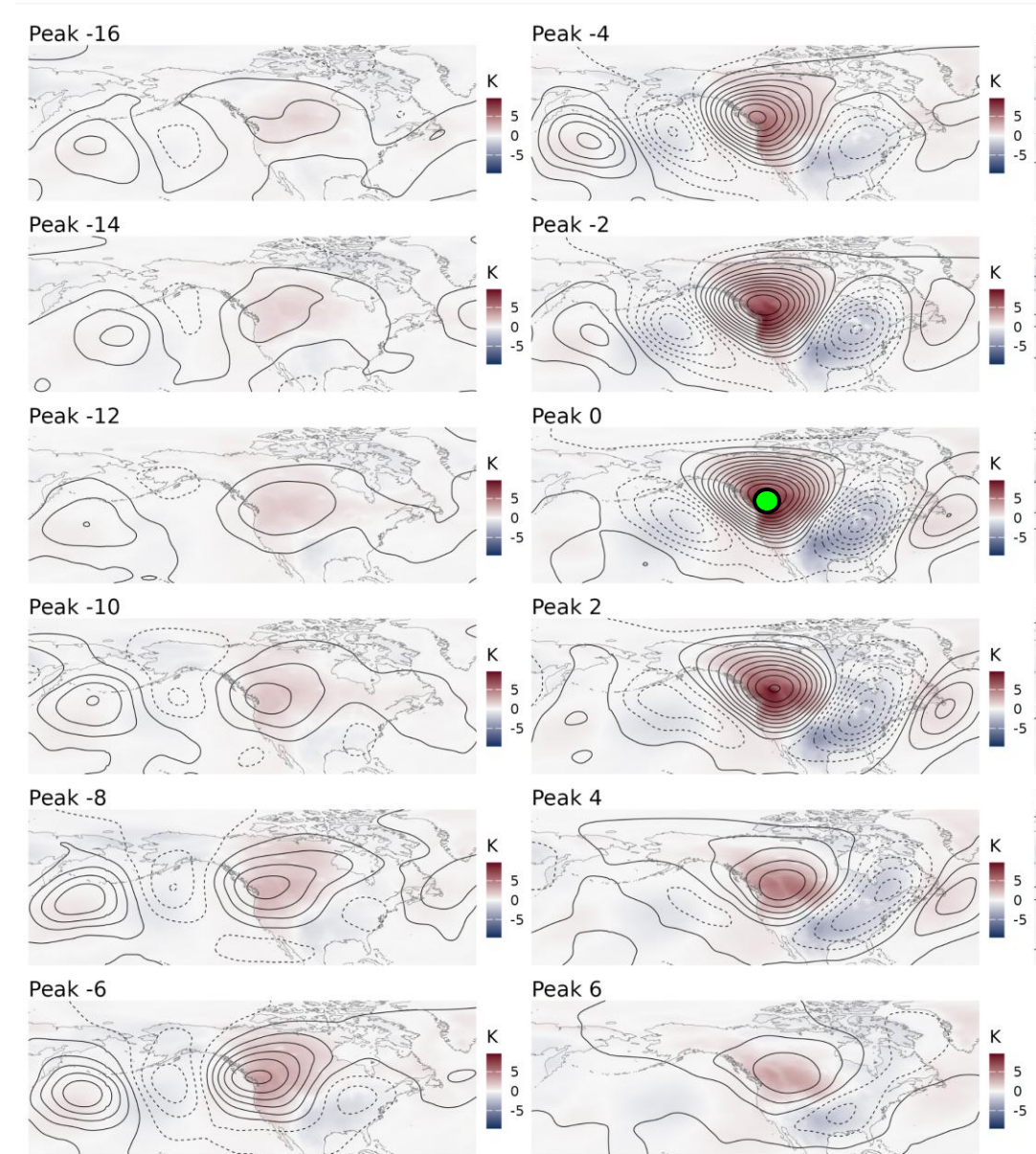
Based on large-scale spatial patterns, the 2010 Russian and the 2021 W.N.Am. heatwaves are typical extreme events.

Still, global warming can make these events more frequent!

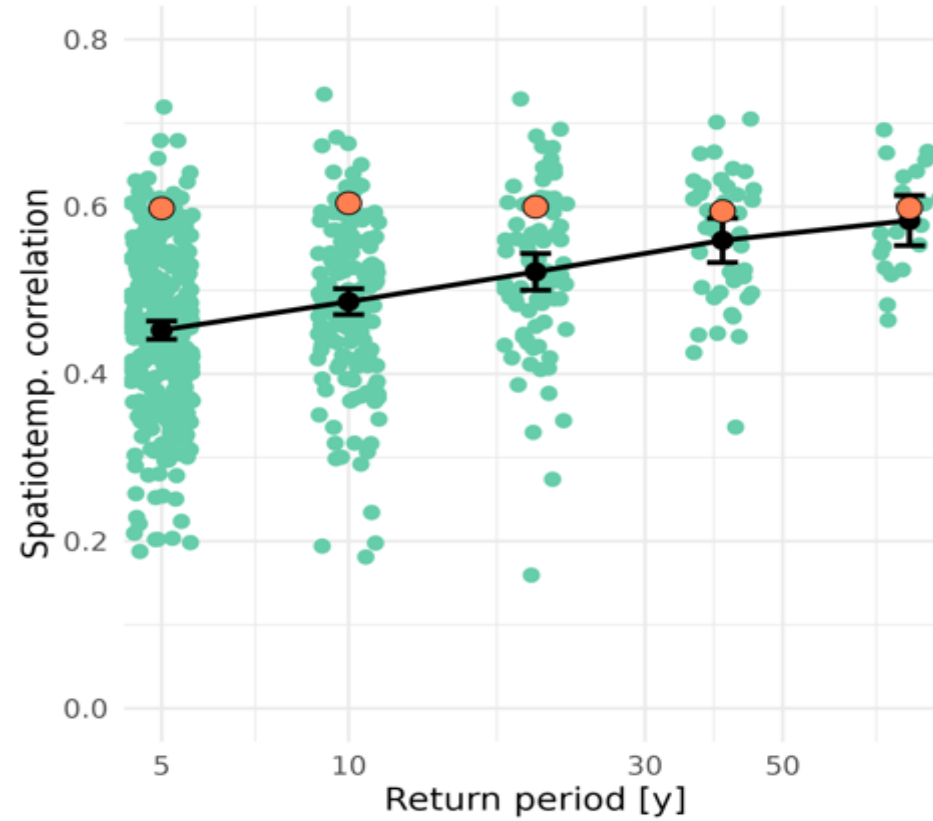


Mean evolution shows a transition from a wave-like pattern through wave breaking to blocking.

Mean spatio-temporal evolution of the warmest 160 events at location 
- from KNMI-Lentis (1600 years with EC-Earth, present day conditions)

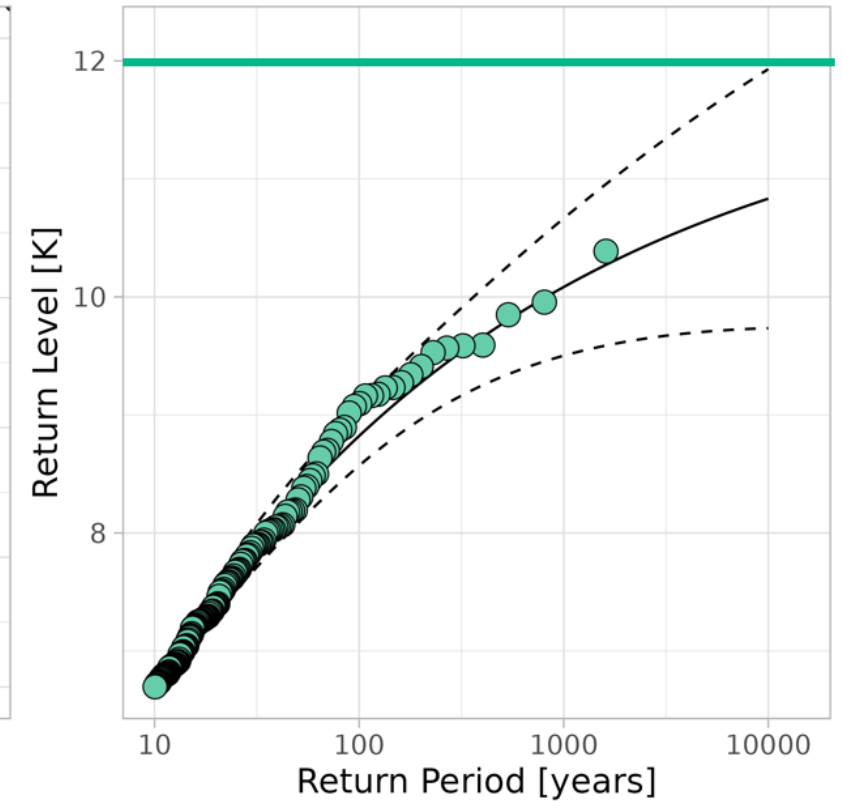
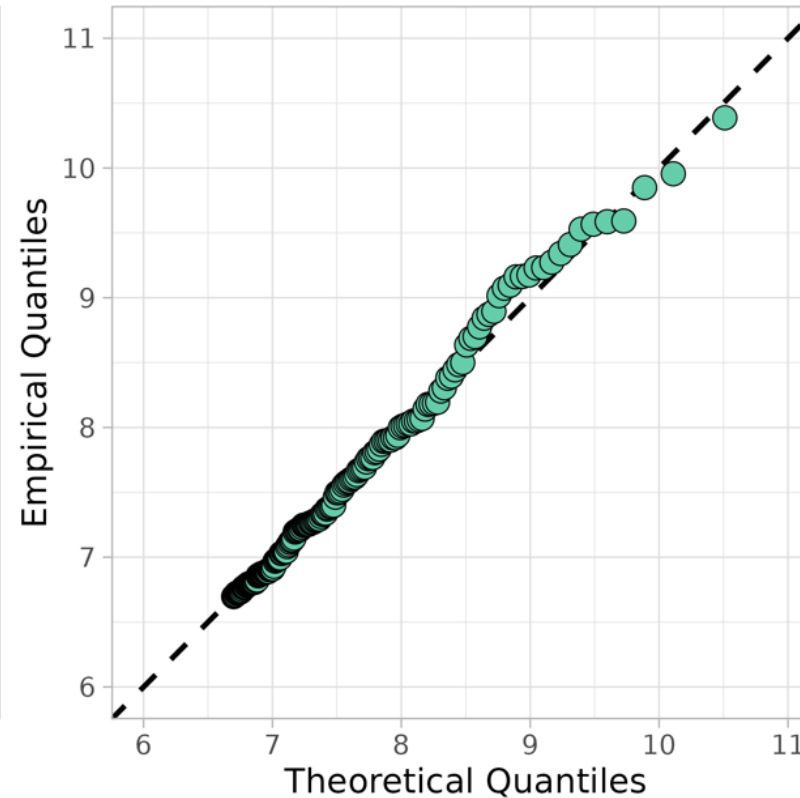
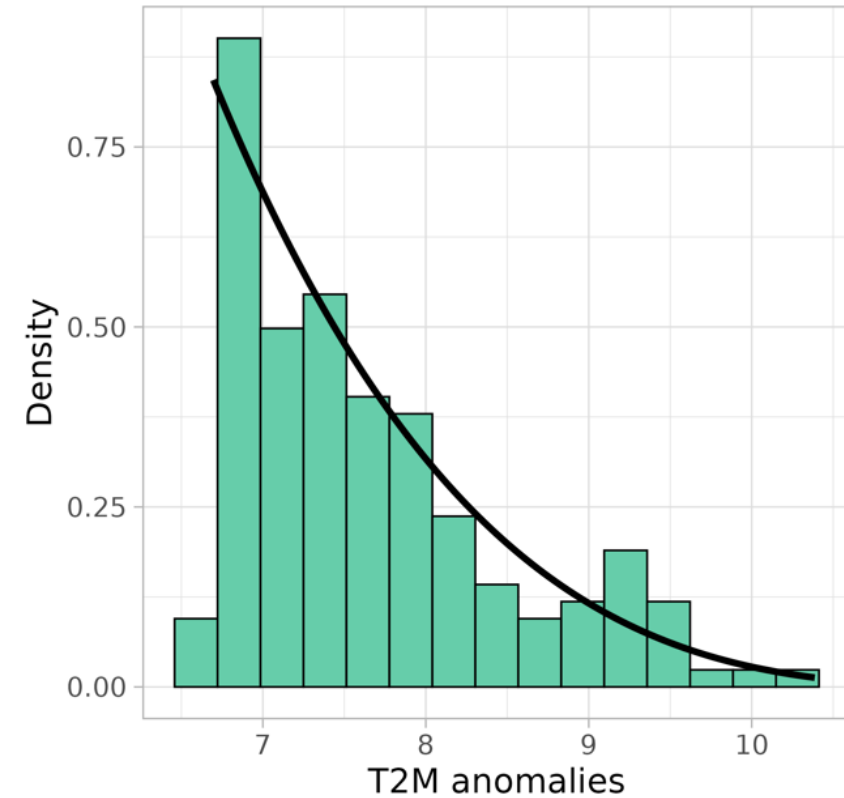


Selecting more and more extreme events, spatio-temporal similarity increases and variability decreases.



A GPD shape parameter below 0 suggests statistical typicality.

Galfi et al., in preparation

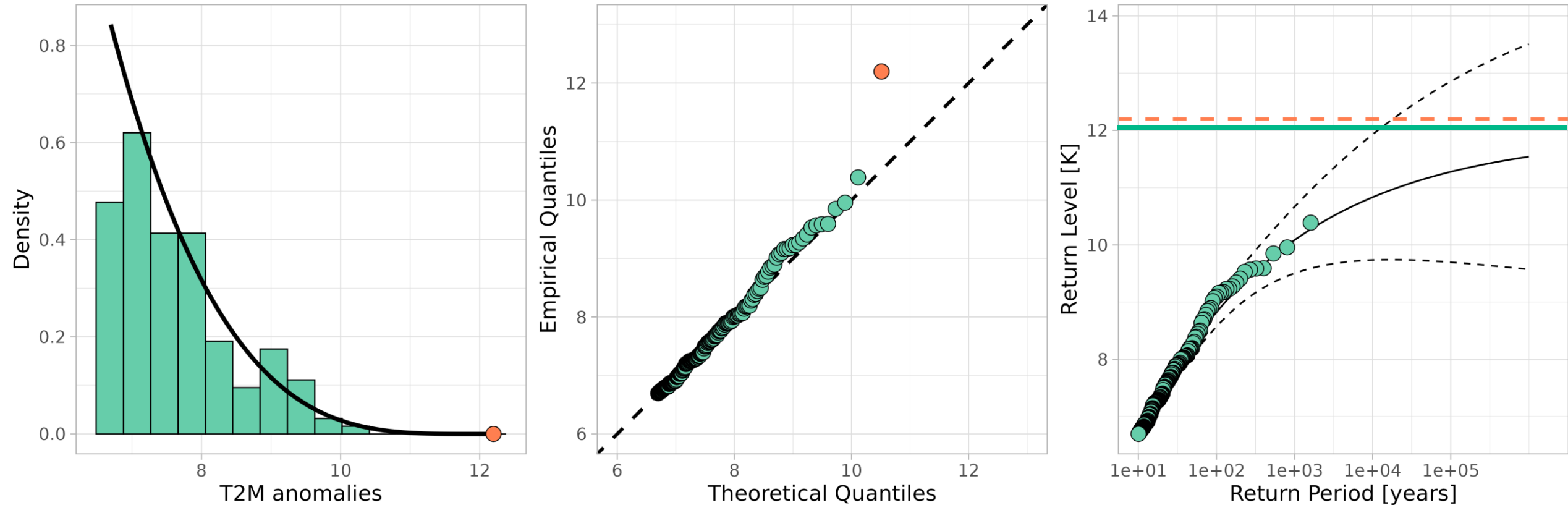


Not even the highest values dominate the mean because their probability is low enough.

Estimated **upper end-point** is **~12 K**.

The **observed value** in **2021** is either atypical or has an extremely low probability. i.e. a very long return period.

Galfi et al., in preparation



Considering the estimation uncertainty for the upper end-point, the **observed value** could still belong to the distribution of **model values**.

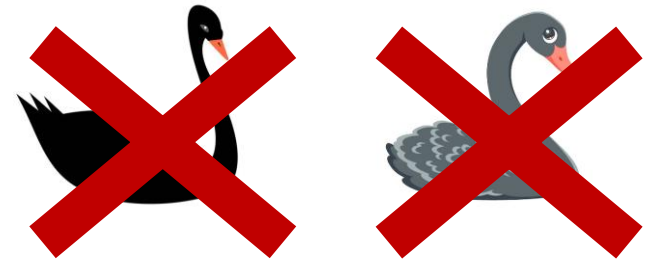
From the perspective of the **large-scale** spatio-temporal evolution, the 2021 WN American heatwave is a **typical** extreme event.

However, **small-scale** processes might have made this event **extraordinary**.

Typicality of extremes: Extreme events are similar among each other in terms of spatial patterns and spatio-temporal evolution – their mean is representative. This similarity increases with intensity.



1. Large values don't dominate the mean.
2. The more extreme, the more similar.



Confirmed by other studies: Noyelle et al., 2023; Hotz et al, 2026.

Implications:

- Are more extreme events better **predictable** than less extreme events?
- Does it have a relevance for **training AI models**?

Questions or comments? Feel free to reach out: v.m.galfi@vu.nl

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