Simulation et compréhension physique de la dynamique des événements de chaleur extrême dans un contexte de changement climatique

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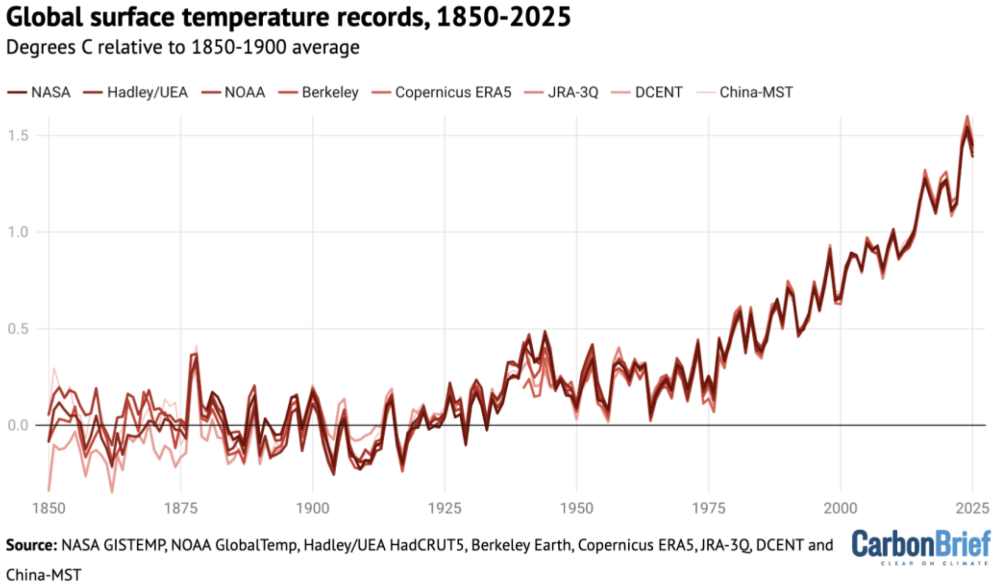
Our climate is warming, impacting extreme events



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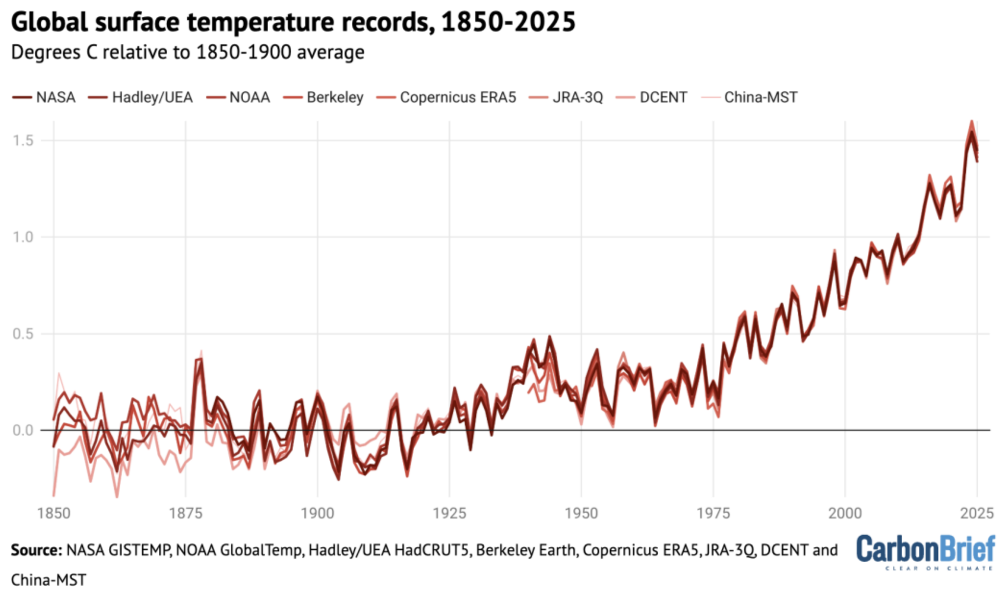
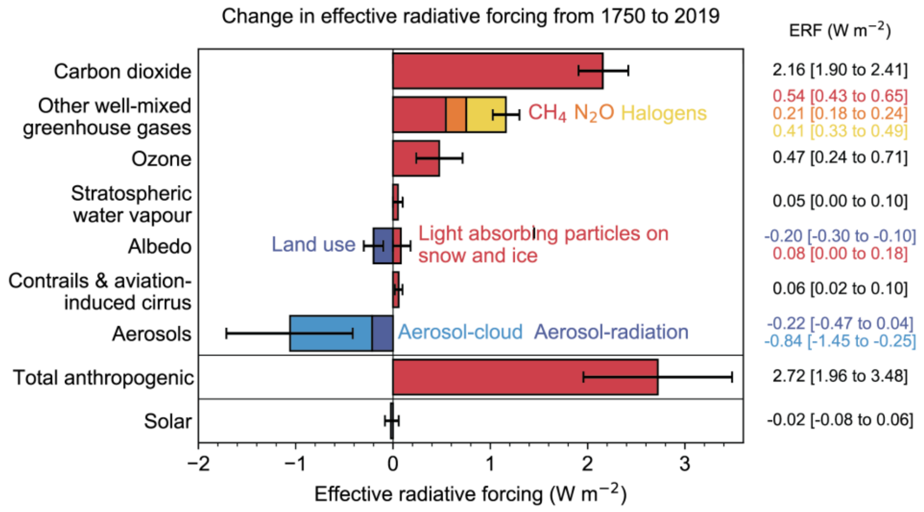


IPCC (2021)



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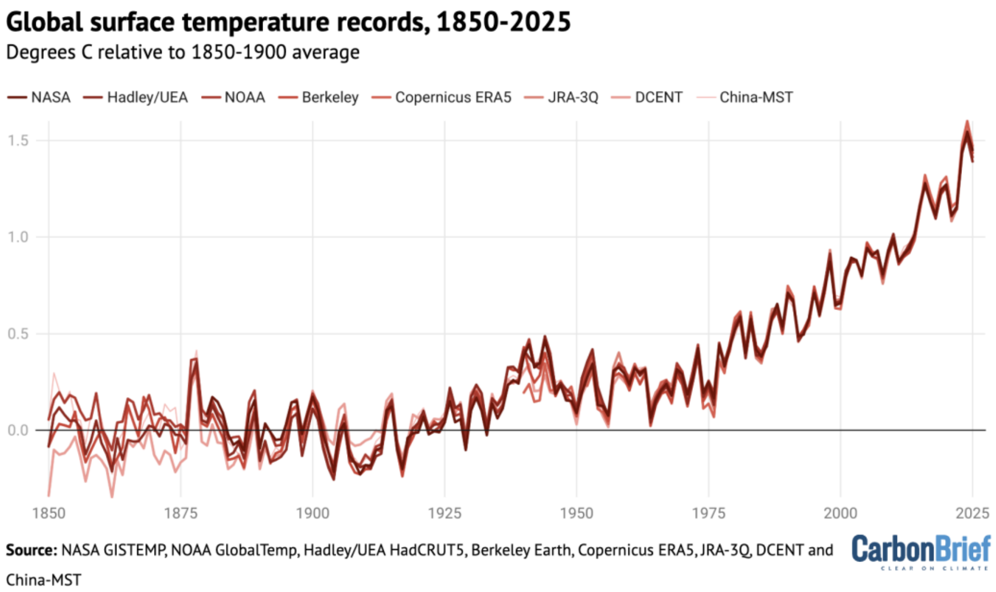
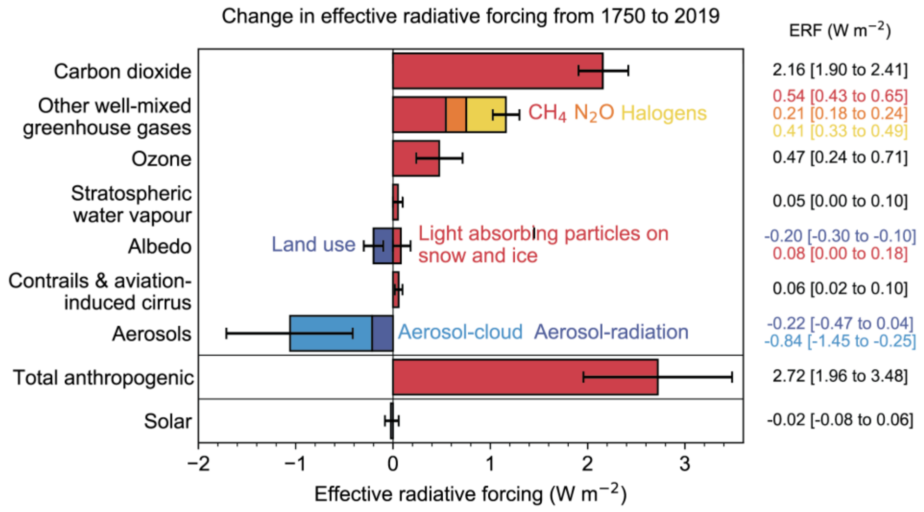
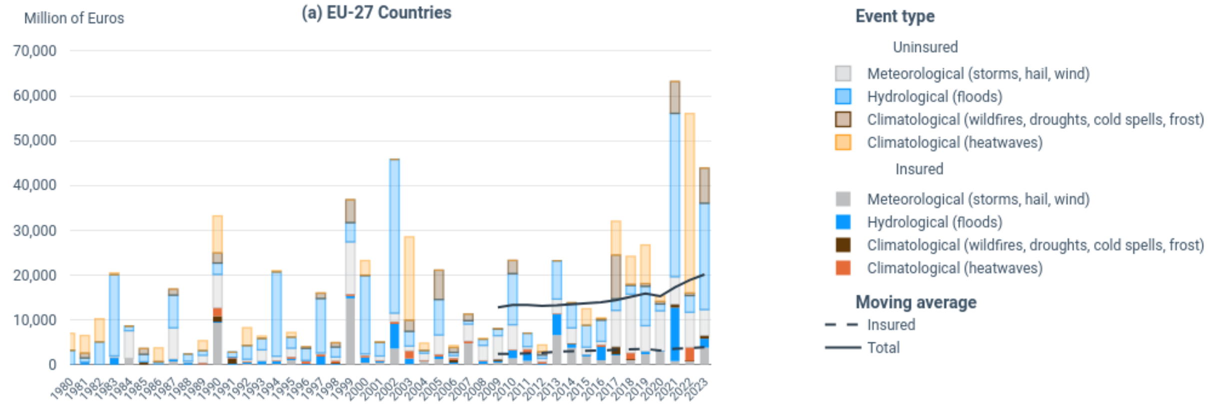
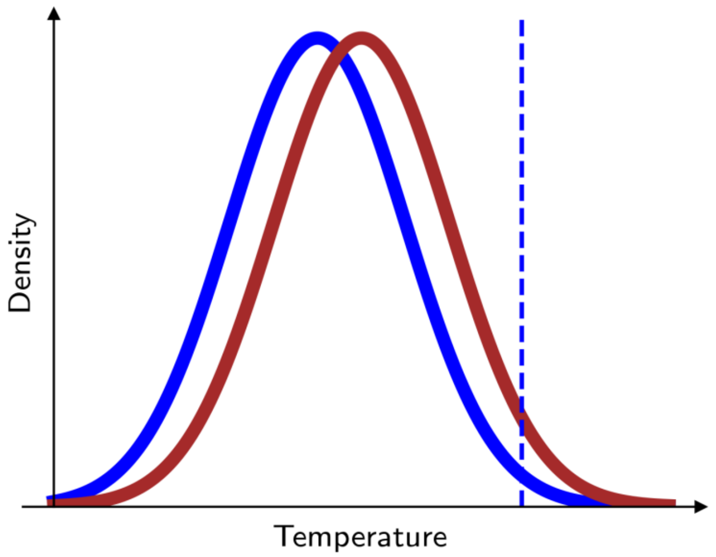






EEA

Climate science, climate change and the importance of rare and extreme events



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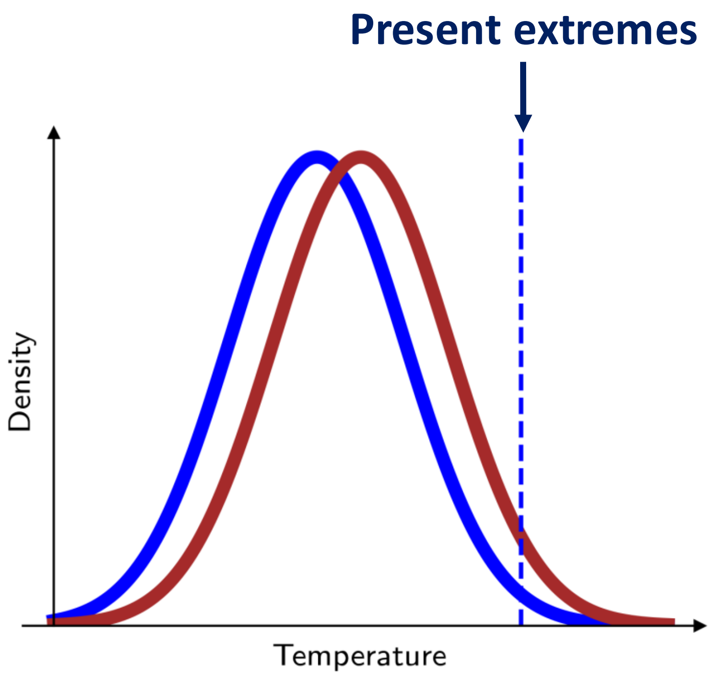
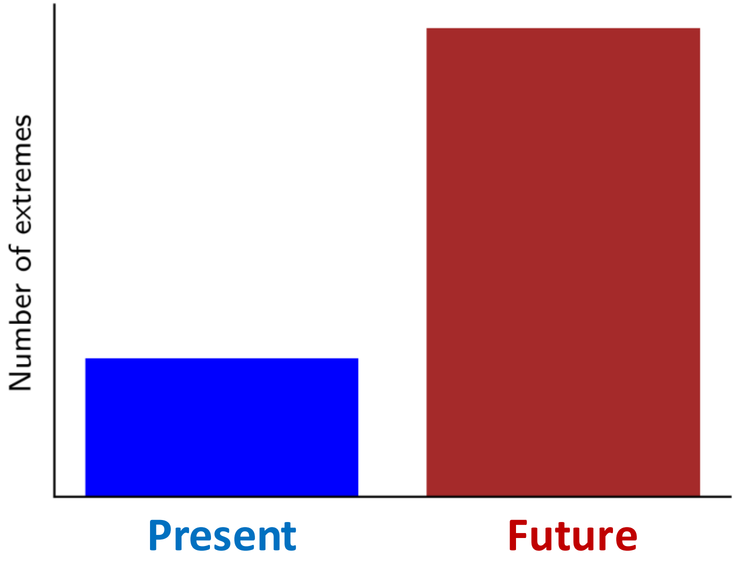
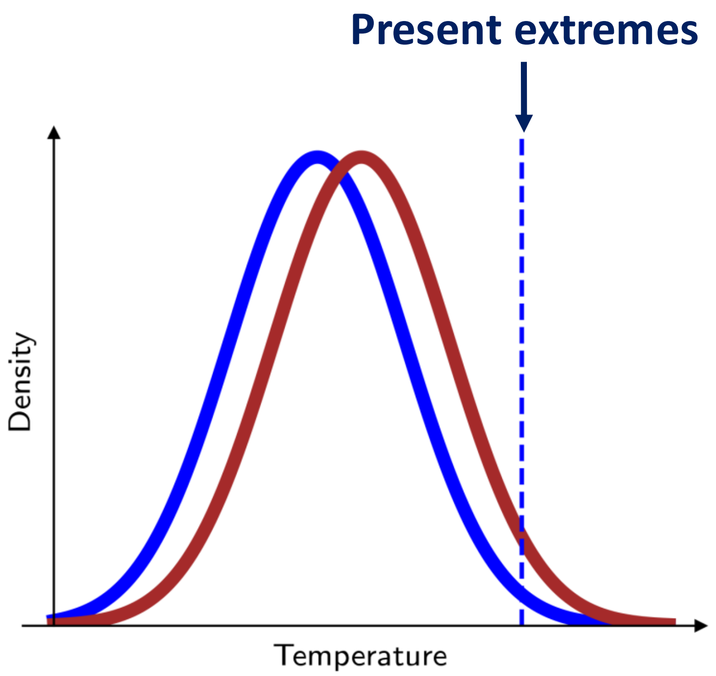
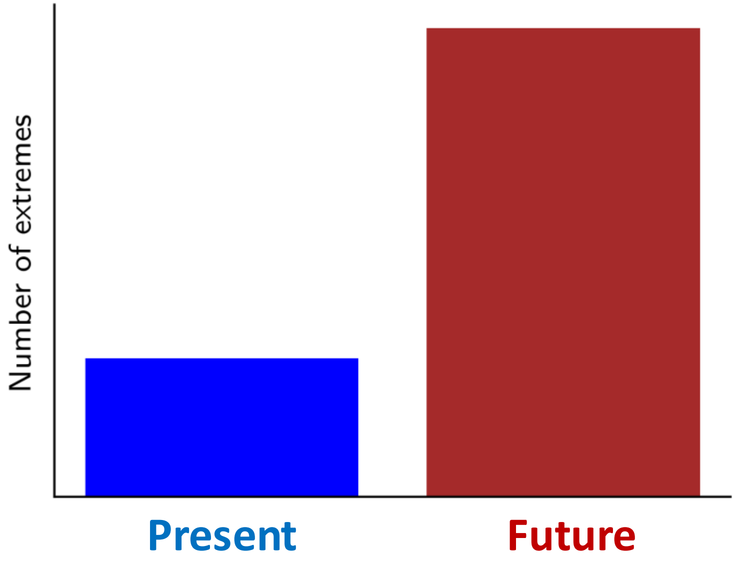




For this example: 250% increase in extremes (and related impacts)

Climate science, climate change and the importance of rare and extreme events





For this example: 250% increase in extremes (and related impacts)

First IPCC report (1990) : "changes in the variability of weather and the frequency of extremes will generally have more impact than changes in the mean climate at a particular location"

Key issues for the research on extreme events

General scientific question: What is the response of extreme weather and climate events to anthropogenic forcings?

- How to distinguish forced from unforced variability?
- What are the physical mechanisms explaining the response?
- Are climate models getting the response right (and for the right reasons)?
- ...

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Key issues when addressing extreme weather and climate events:

1. **Few minimal theoretical models** exist to explain extreme events dynamics
2. Extreme events are **imperfectly represented by numerical models**
3. **Extreme events are <u>undersampled</u>** in observations and simulations

Undersampling problem: why studying extreme events is challenging

Let's play a game: one flips an **unbalanced** coin, what is the probability p to land on heads ?

But: the coin is very unbalanced and the (unknown) probability is p = 1/100

We have only ***N* = 100 samples**, can we compute an estimator for $\tilde{p}$? **Easiest way: count the frequency of heads**

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Number of heads k	0	1	2	3
$P(N\tilde{p} = k)$	37%	37%	18%	6%
Relative error	**100%**	**0%**	**100%**	**200%**

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Burden of rareness: there are too few extreme events in small samples and the estimations of their properties are unprecise

$$RE \simeq \frac{\sqrt{\mathbb{V}[\hat{p}]}}{\mathbb{E}[\hat{p}]} \simeq \frac{1}{\sqrt{pN}}$$

To have *RE* **small** (10%), one needs **a large sample** size *N*:

For $p = 10^{-2}, N = 10^4$

How to overcome the undersampling problem

Brute force

Idea: use large data sets (e.g. long control run and/or large ensembles)

Mathematical theory

Idea: parametric hypotheses on the distribution of extremes (EVT, LDT)

Rare events algorithms

Idea: resampling to « force » a physical model to simulate more extreme events

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Noyelle, R., Yiou, P., & Faranda, D. (2023). Investigating the typicality of the dynamics leading to extreme temperatures in the IPSL-CM6A-LR model. *Climate Dynamics*

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Noyelle, R., Zhang, Y., Yiou, P., & Faranda, D. (2023). Maximal reachable temperatures for Western Europe in current climate. *Environmental Research Letters*

Noyelle, R., Robin, Y., Naveau, P., Yiou, P., & Faranda, D. (2026). Integration of physical bound constraints to alleviate shortcomings of statistical models for extreme temperatures. *Journal of Climate.*

Rare events algorithms

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Noyelle, R., Caubel, A., Meurdesoif, Y., Faranda, D., & Yiou, P. (2025). Evolution of the dynamics of centennial hot summers in Western Europe with climate change. *Geophysical Research Letters*.

Evolution of the dynamics of extremely hot summers in Western Europe in response to climate change

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A very simple schematic of heatwaves physical mechanisms

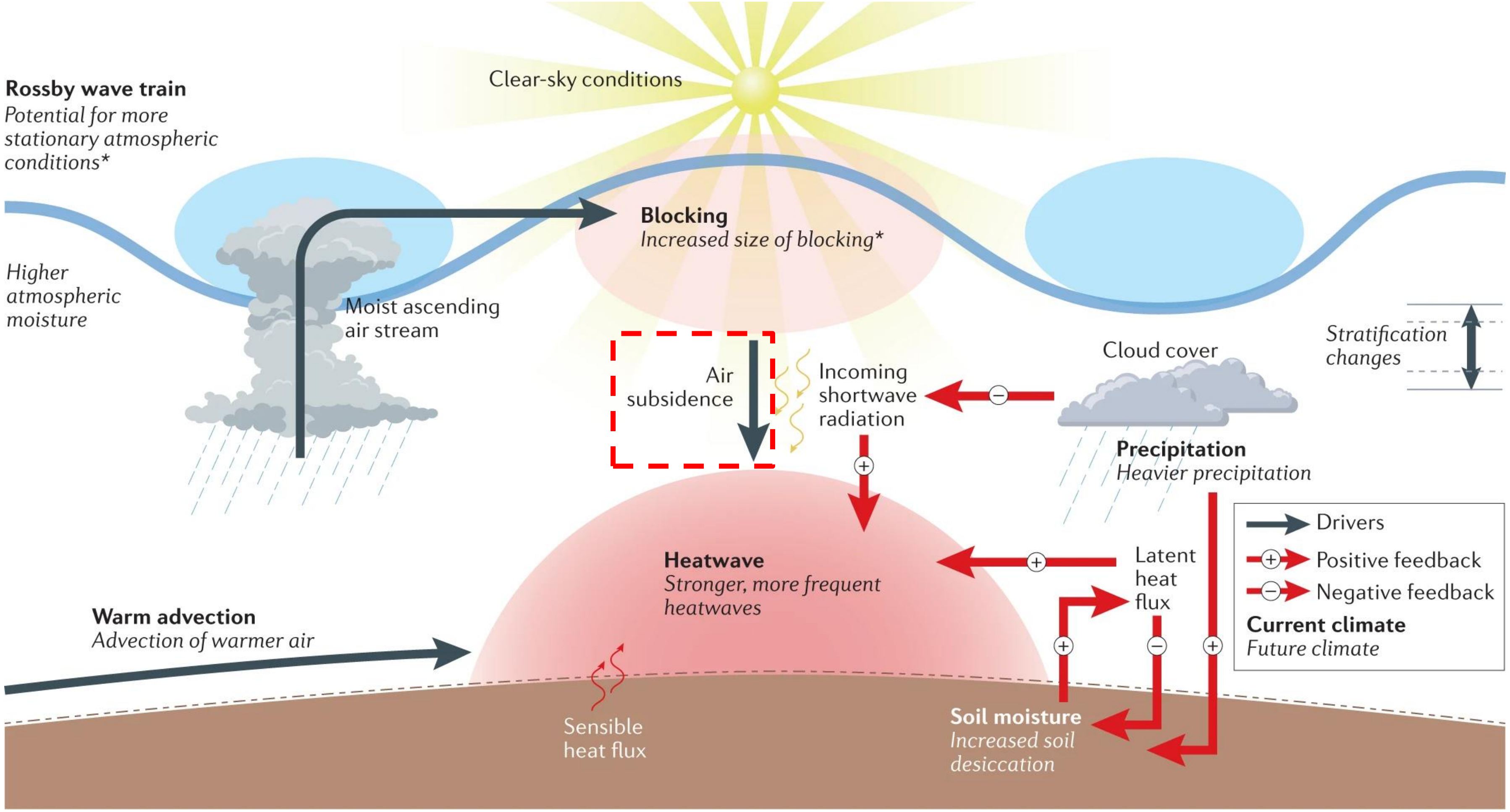
heatwave = anticyclone + « drought »

Prolonged period with unusually high temperatures (e.g. at least 3 days above the 90th quantile)

Extended zone of **high pressure** (or geopotential height) in the mid- to high-troposphere

Extended zone with **low soil moisture**

Heatwaves physical mechanisms



Three sources of heat (% for Europe):

1. **Adiabatic warming by subsidence (~50%)**
2. Diabatic warming (shortwave radiation, sensible + latent heat fluxes, ~30%)
3. Advection from neighbouring regions (~20%)

Domeisen et al. (2023), Röthlisberger and Papritz (2023)

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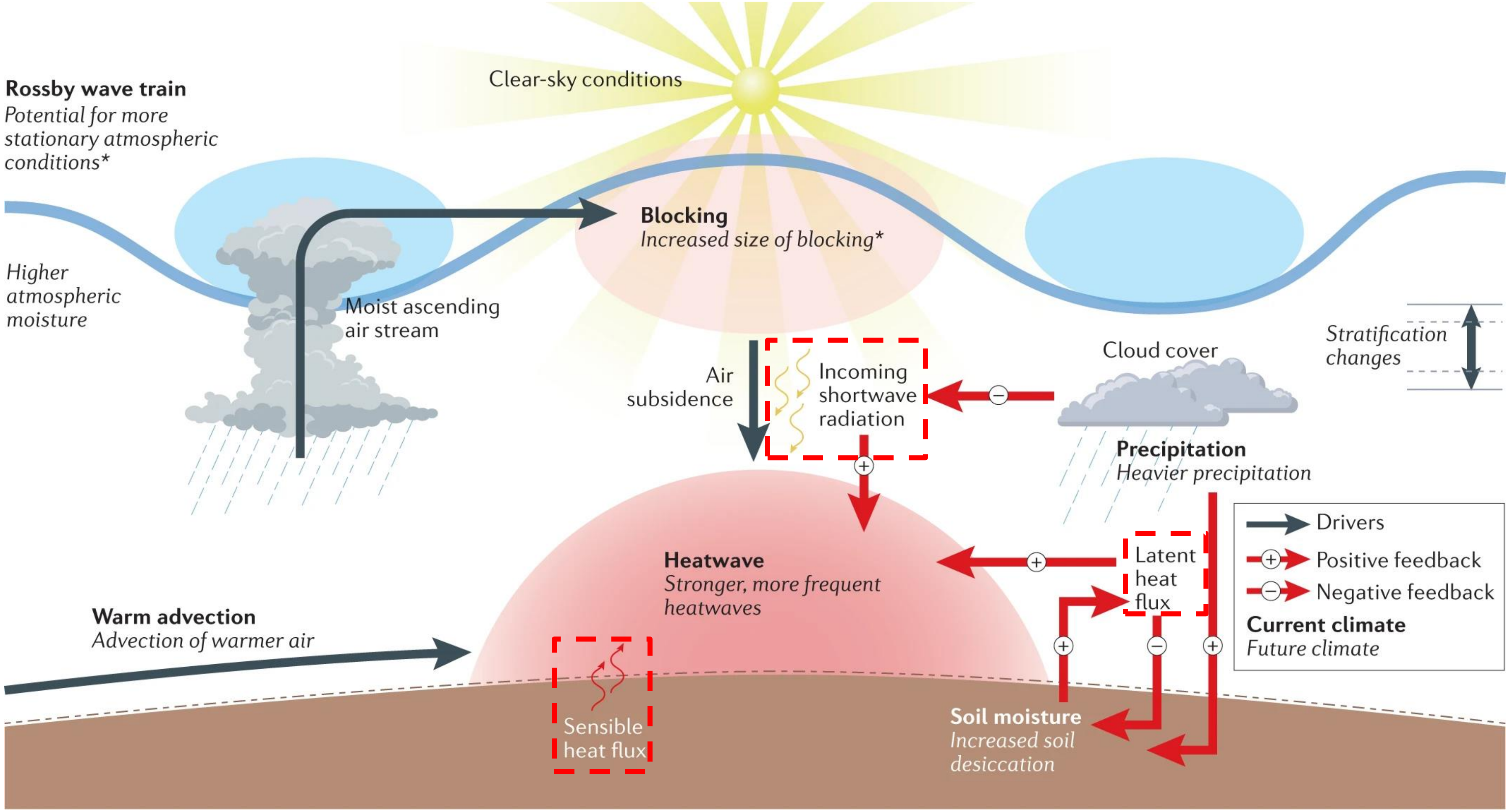

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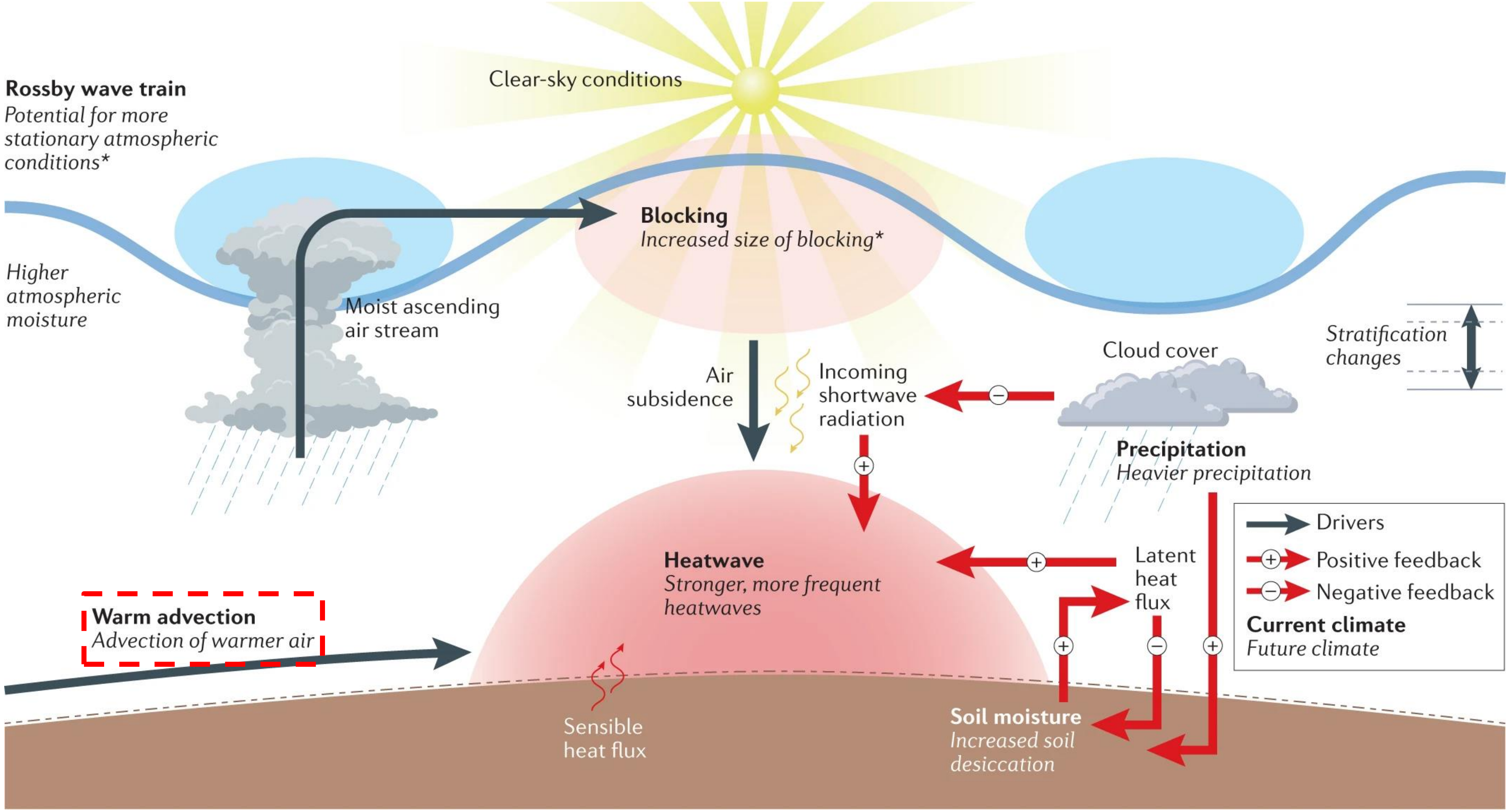

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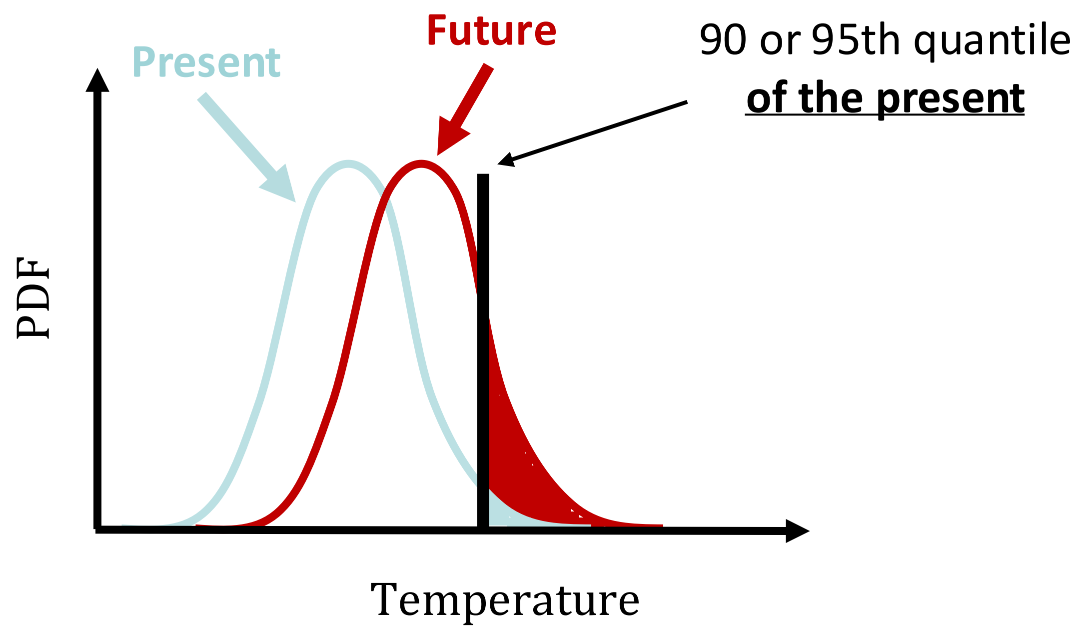
Is there a change in the dynamics of extremely hot events with climate change?

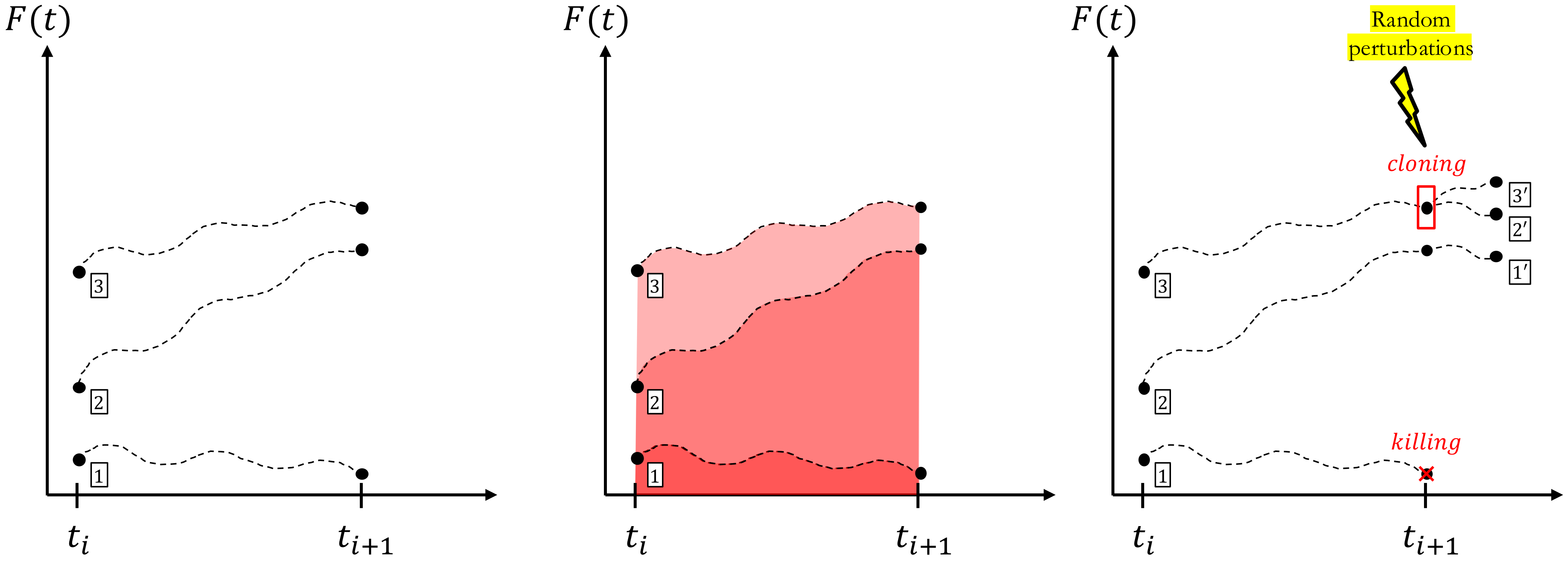
What we understand well: the intensity and frequency of hot events increase with global warming because of the **thermodynamical effect** of climate change



When we condition on equally rare events in the present and the future, are the physical mechanisms of extreme hot events similar?

Issue: extreme hot events are rare and therefore isolating their response is challenging

Solving the sampling issue of rare events: the GKTL algorithm



F = « score function » to be maximized

Giardina et al. (2006)
Tailleur and Kurchan (2007)
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Ragone et al. (2018)

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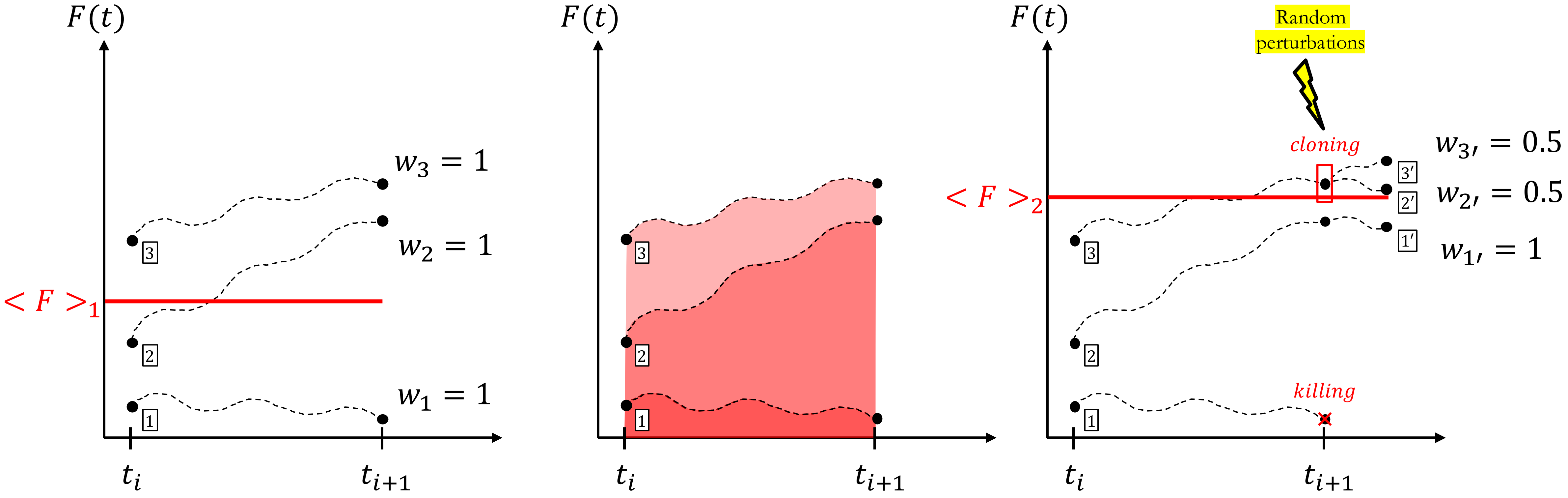

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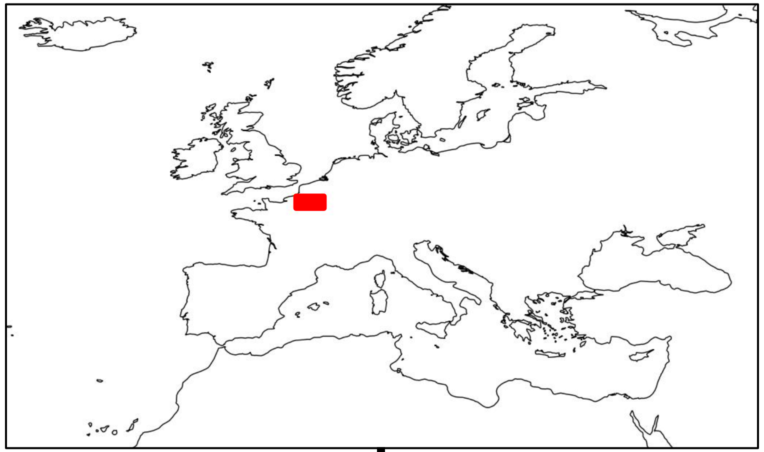
Simulations with the IPSL model (atmosphere+land)



« Local » score function: temperature at one grid point in Western Europe

Control
(no score function)

High temperature (T2M)

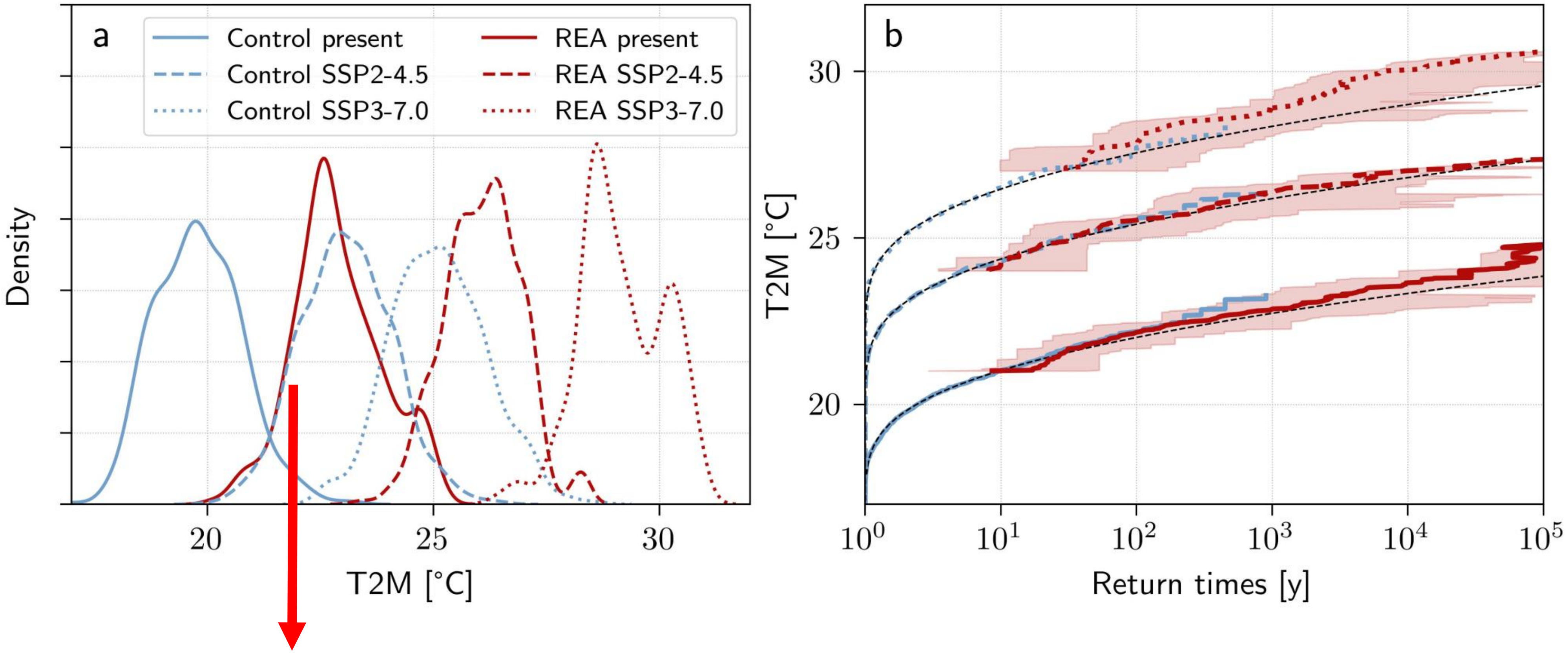
100 members x 9 simulations

<u>Present</u> (2015-2025) + <u>SSP2-4.5</u> and <u>SSP3-7.0</u> (2090-2100)

5400 summers simulated

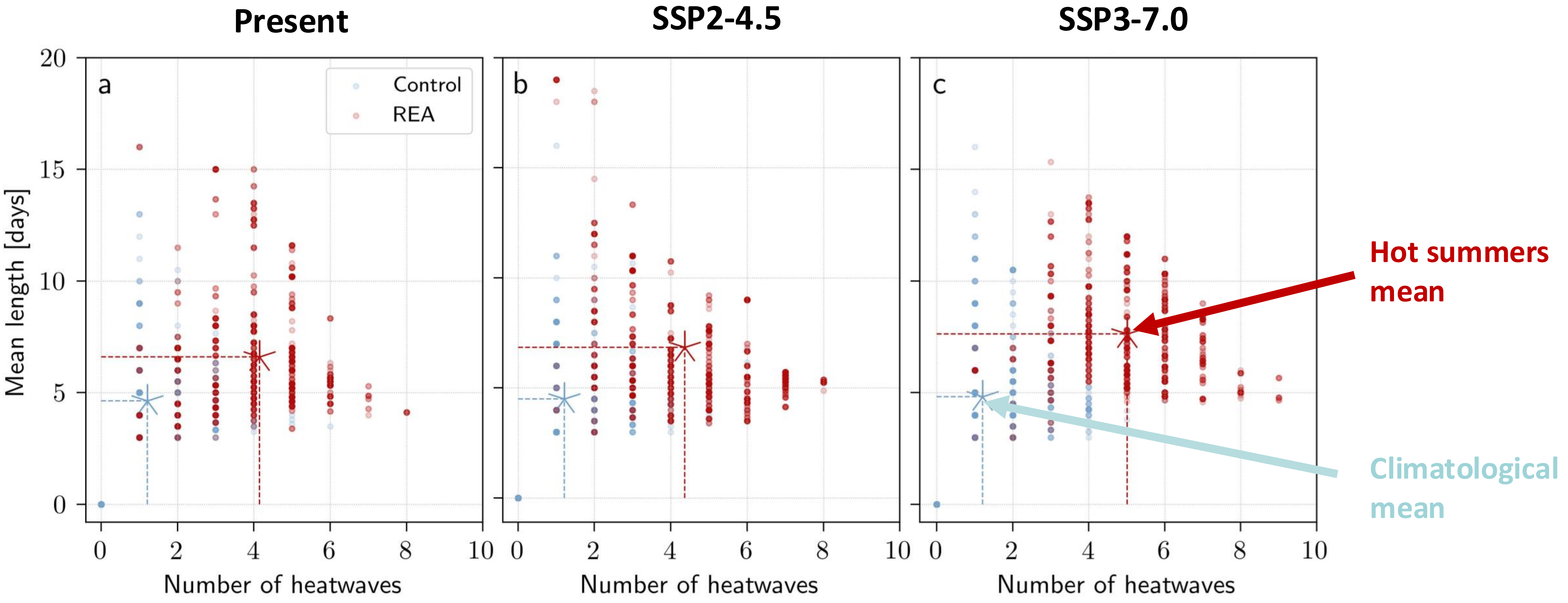
+ pre-industrial simulations giving similar results (not shown)

The algorithm samples a large number of extremely hot summers in all periods



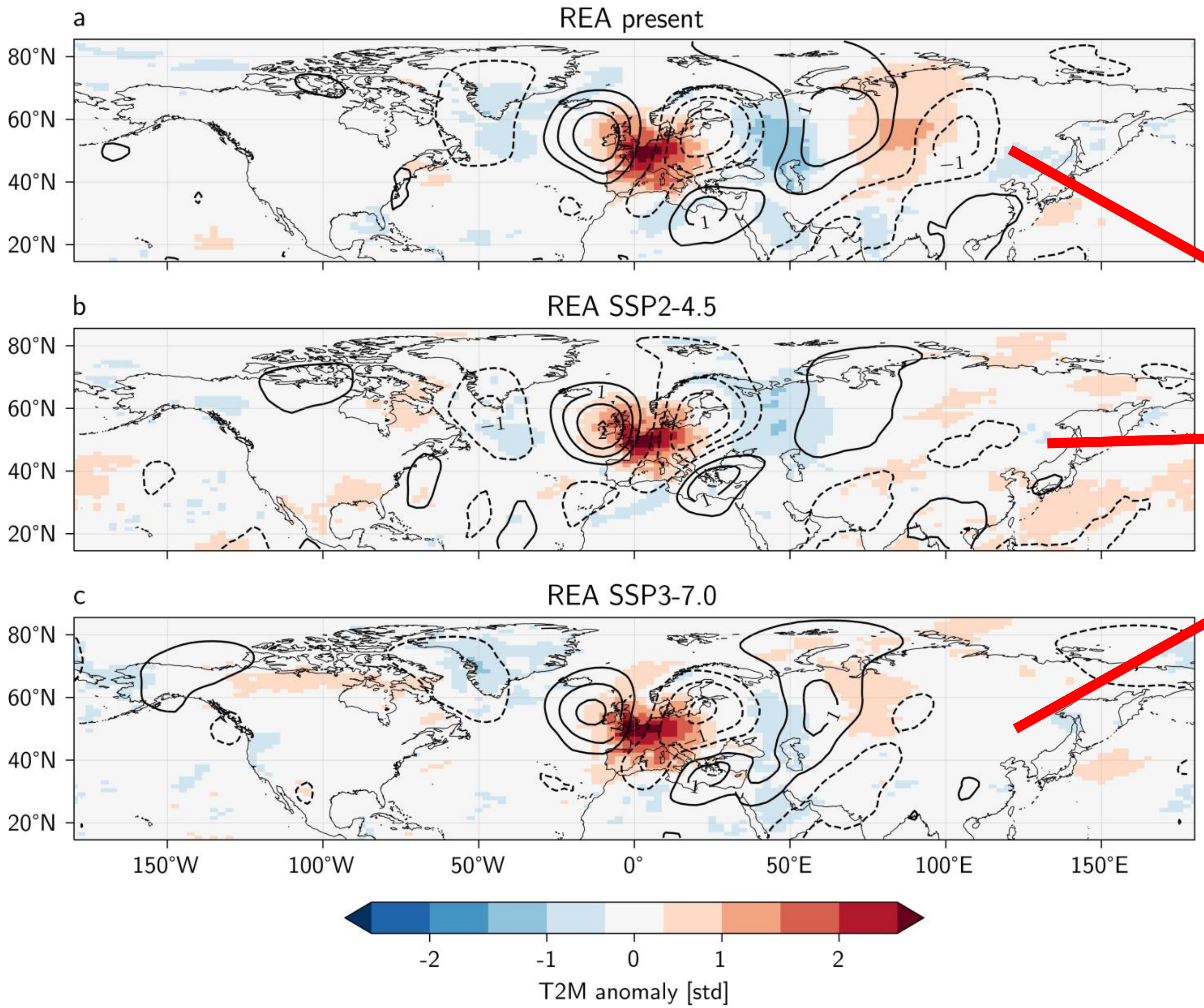
Why are these summers hot ?

What is the substructure of the hot summers?



These extreme hot summers arise through the **succession of several moderately intense heatwaves**

Similar summer-mean dynamics for centennial hot summers in the three periods?

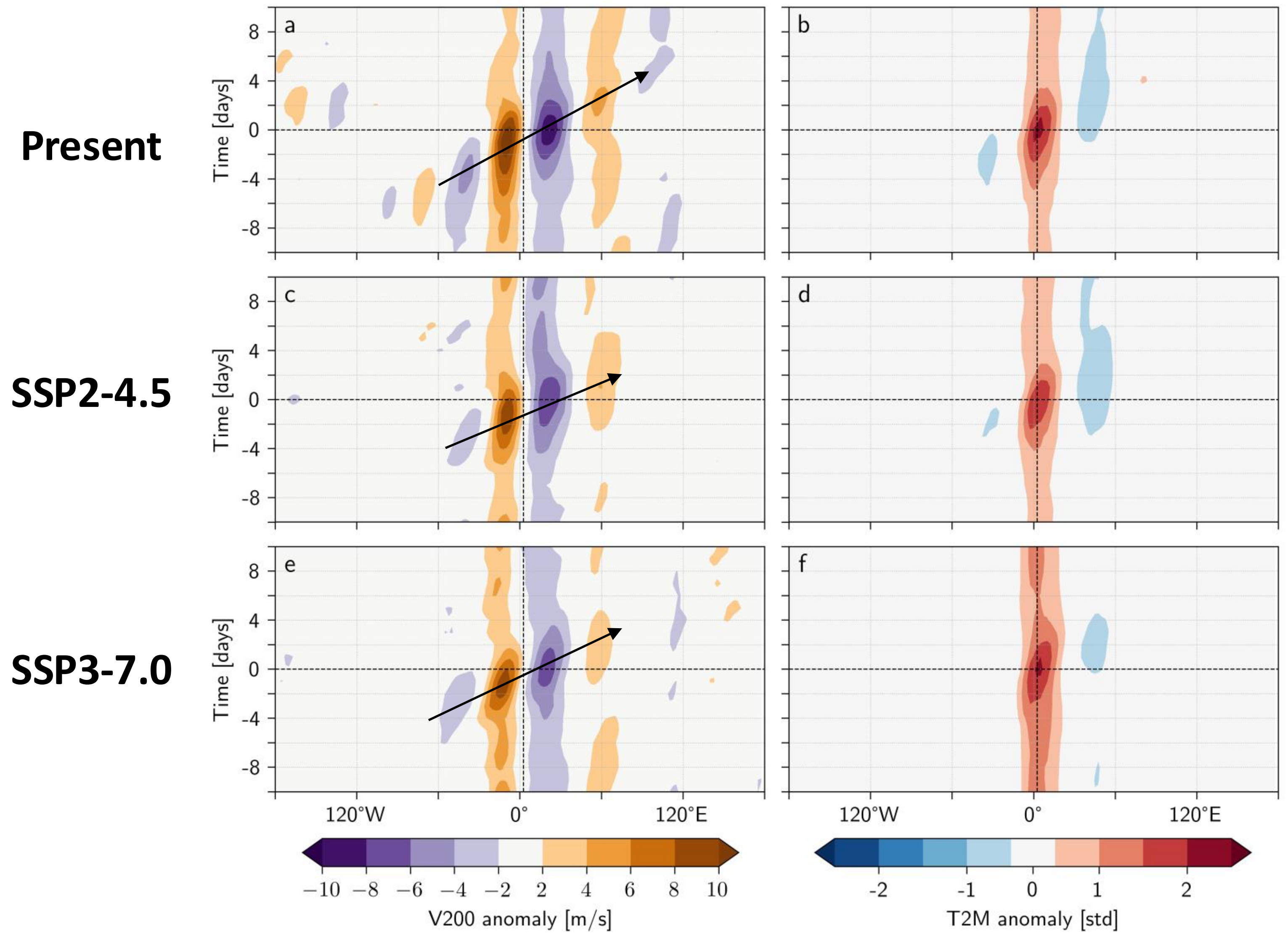


In all periods this summer-mean pattern arises because of the **recurrence of synoptic-scale Rossby wave packets**

Contours: summer mean anomalies of 200hPa meridional wind

Colors: summer mean anomalies of 2-m air temperature

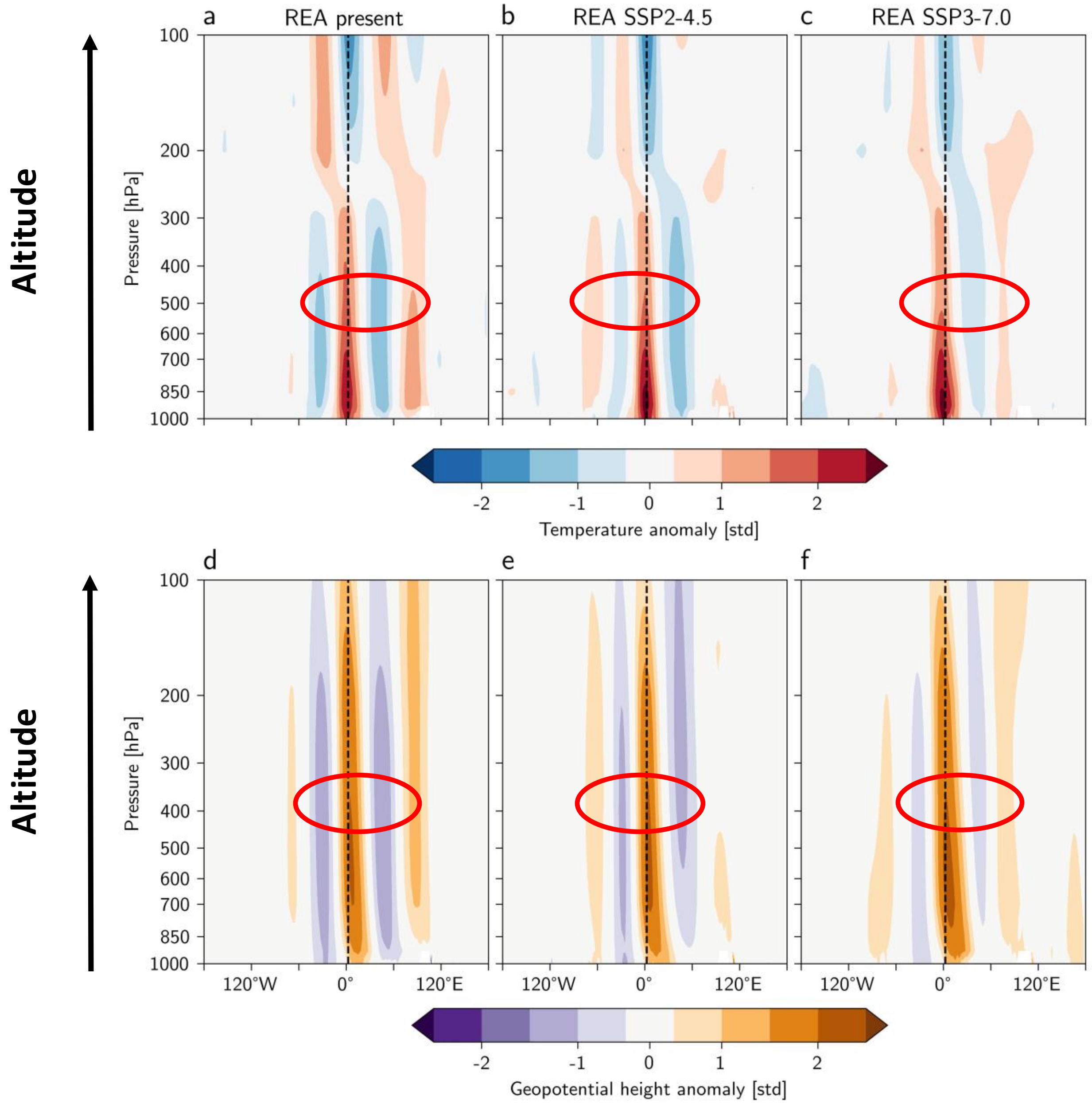
Centering on the dynamics of individual heatwaves



Reduced extension and intensity of the Rossby wave packets with more global warming

Composite Hovmoeller plot over the latitude band 40-70N

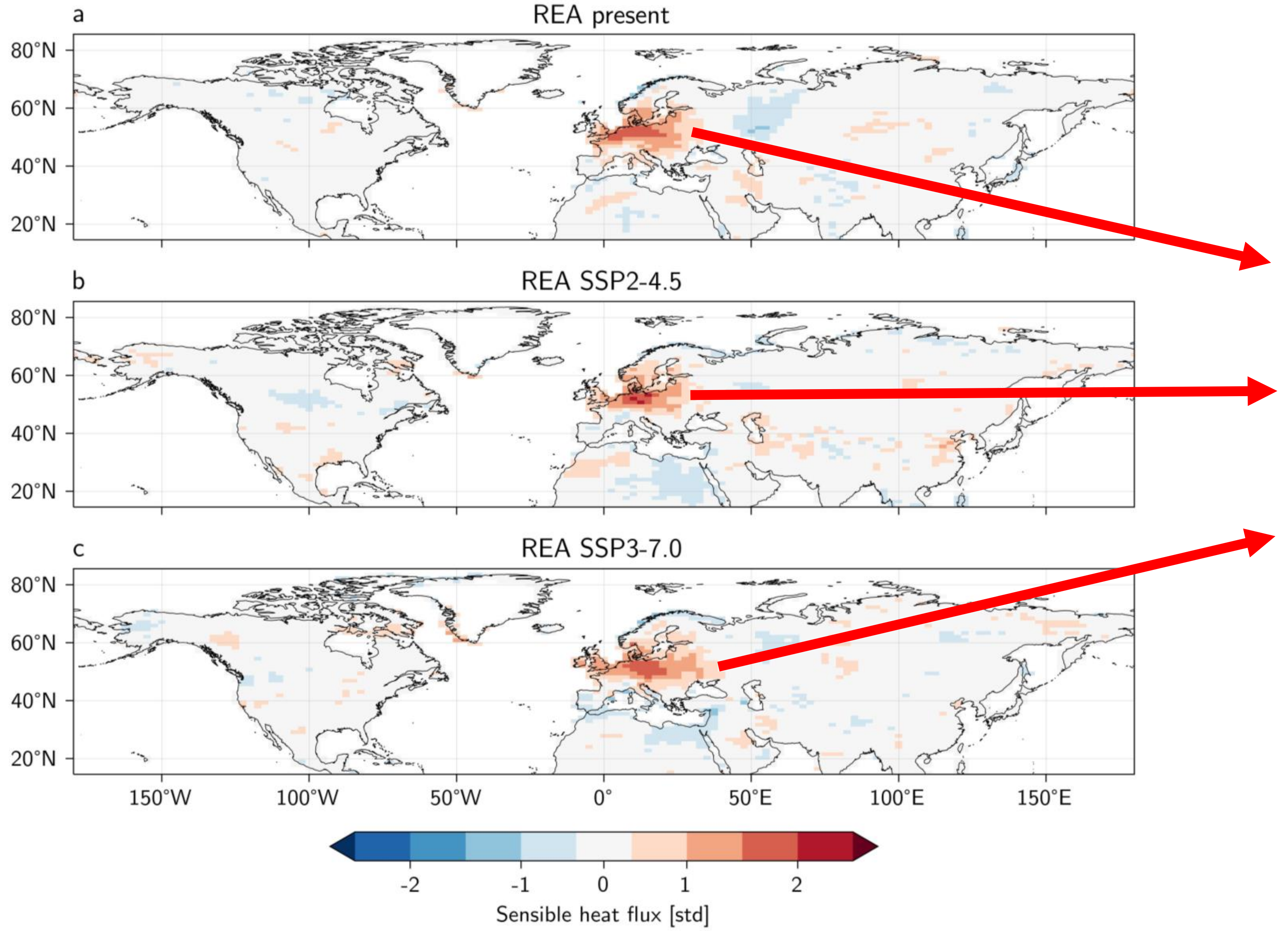
Reduced large-scale organization in the atmosphere during hot summers in the future



Future hot summers tend to be more "local": less driven by the atmospheric circulation and more by interactions with the land

Vertical cross-section over the latitude band 40-70N of the summer-mean anomalies

Soil moisture and surface sensible heat fluxes: similar anomalies but change in the climatology



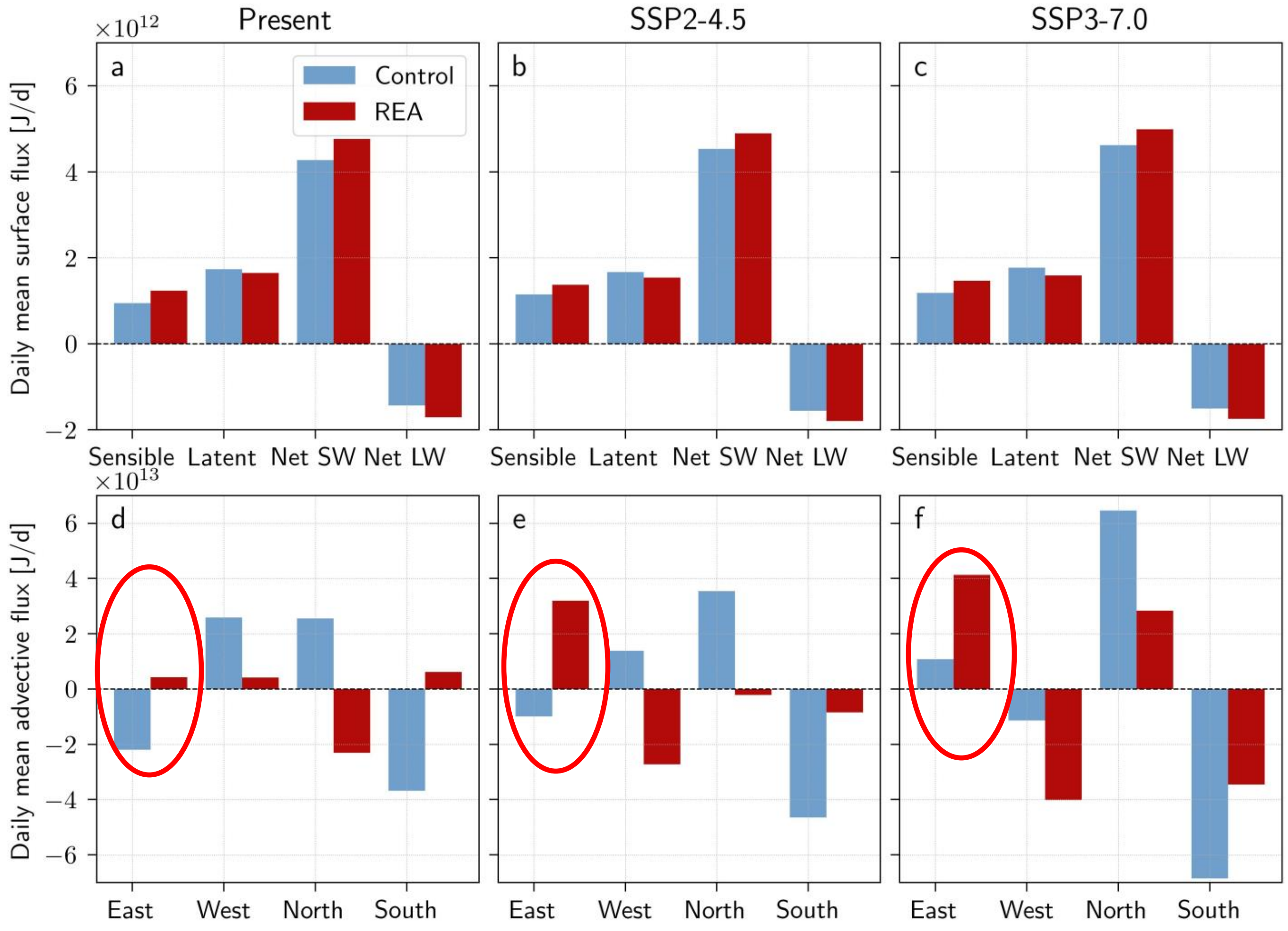
Dryer soils in the future lead to **increased mean sensible heat fluxes** via westward lower-layers advection but **no change in the anomaly** for centennial hot summers

Colors: summer mean anomalies of sensible heat flux

Energy fluxes: a major increase in heat advection from the East

Surface energy fluxes

Heat advection in the boundary layer



Summary, conclusions and future work

- The study of extreme events is impaired by a strong **under-sampling problem:** in numerical simulations this can be alleviated by the use of **rare events algorithms targeting long and short events** (e.g. Bloin-Wibe et al., 2025)

- I showed an example of the use of a rare event algorithm with the **IPSL climate model** to study the dynamical evolution of **hot summers** that **become dynamically local with global warming**

- On-going work on the simulation of **multi-year droughts** in the CESM2 model