Studying extreme heatwaves with rare event simulation techniques

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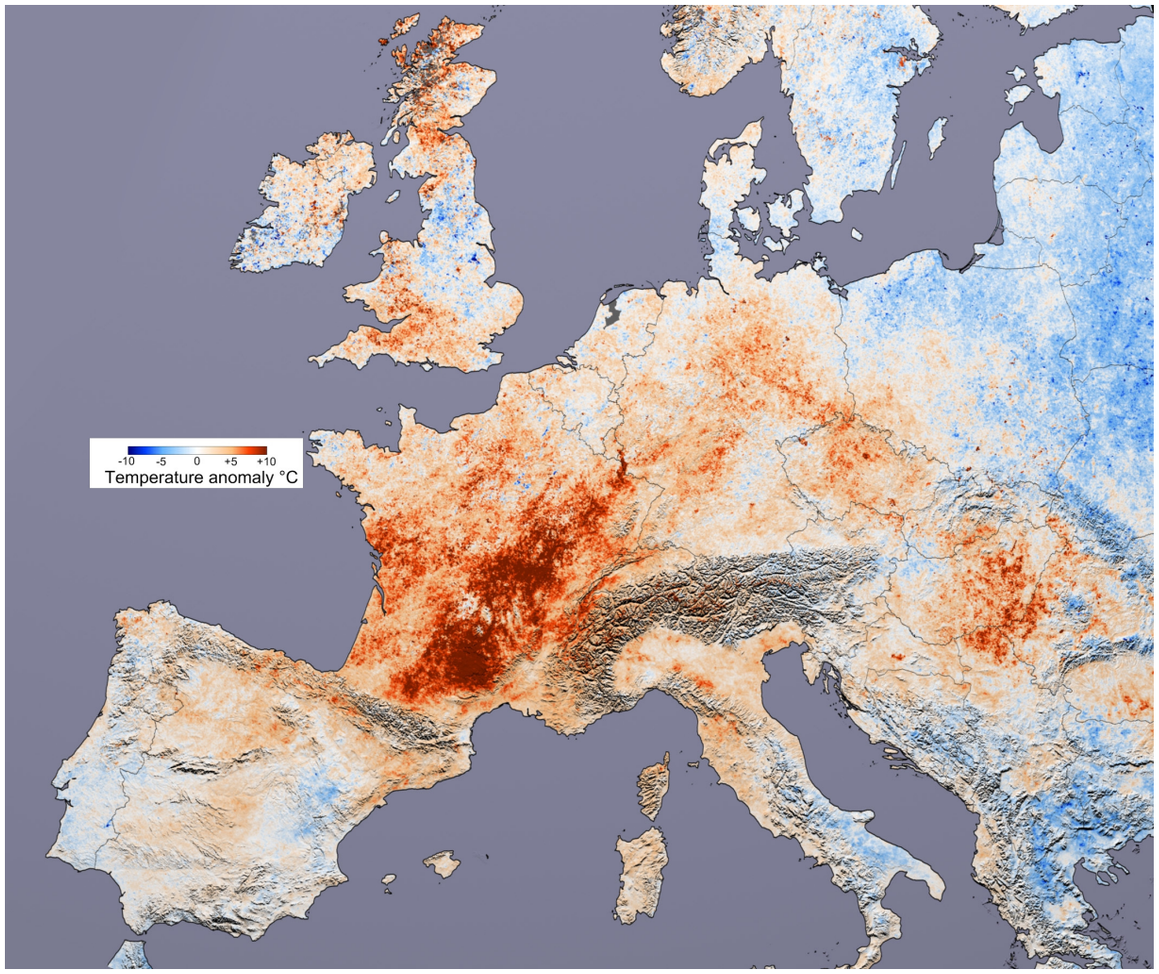
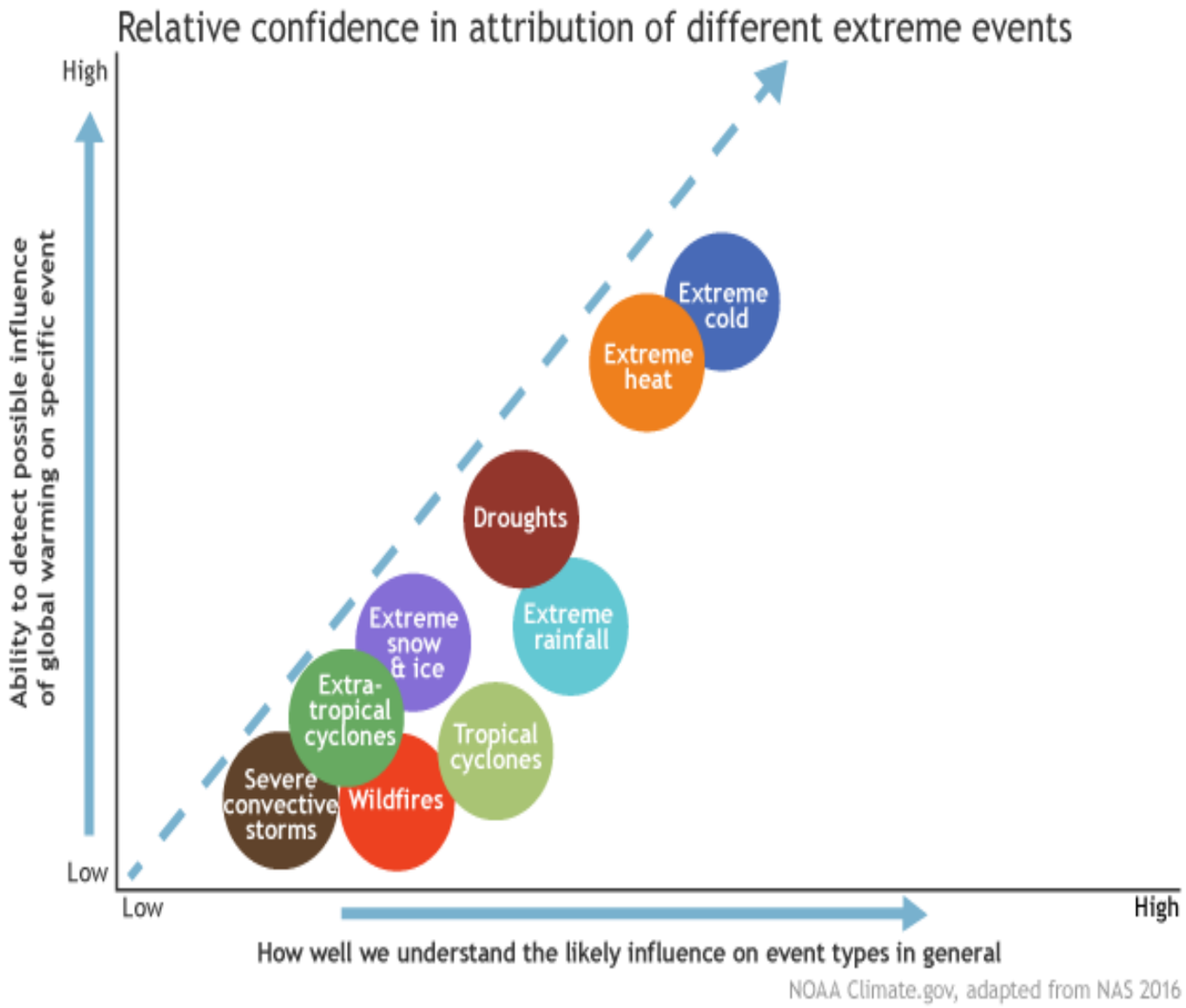
Extreme events in the climate system

Summer 2003 heat wave over France





- Climate extremes: statistical and dynamical studies hindered by three problems

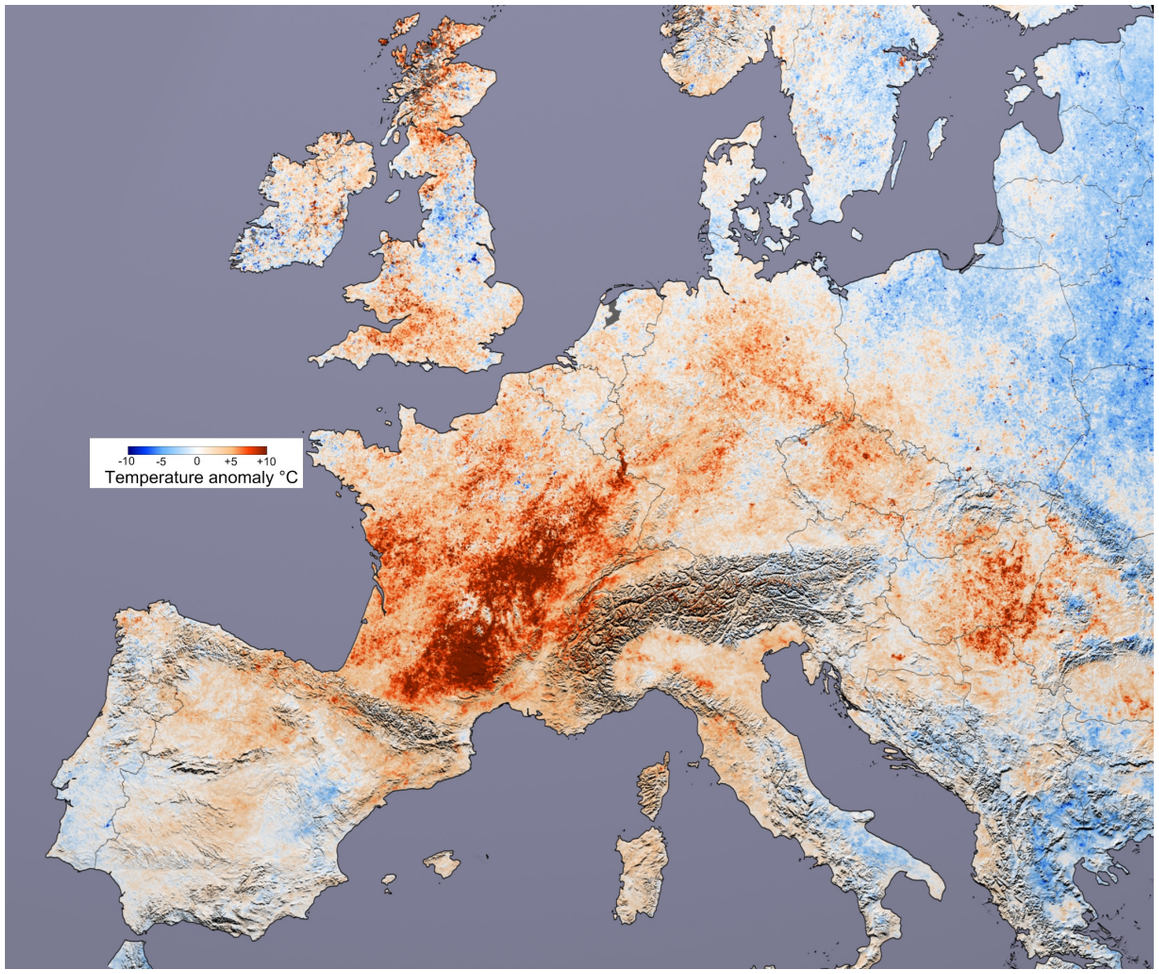
  1) lack of observational data

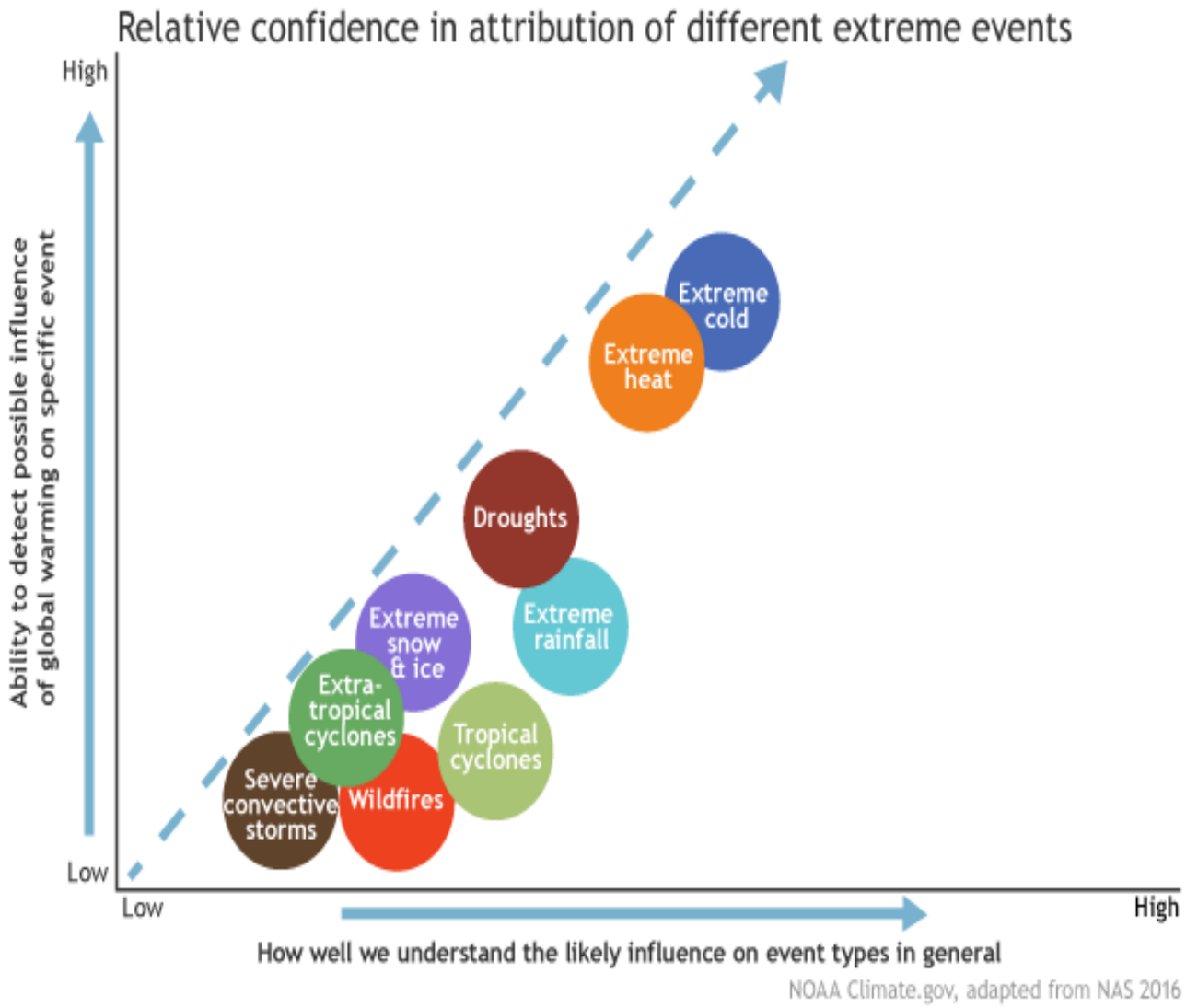
  2) poor sampling with numerical models due to high computational costs

  3) reliability of numerical models

Extreme events in the climate system

Summer 2003 heat wave over France

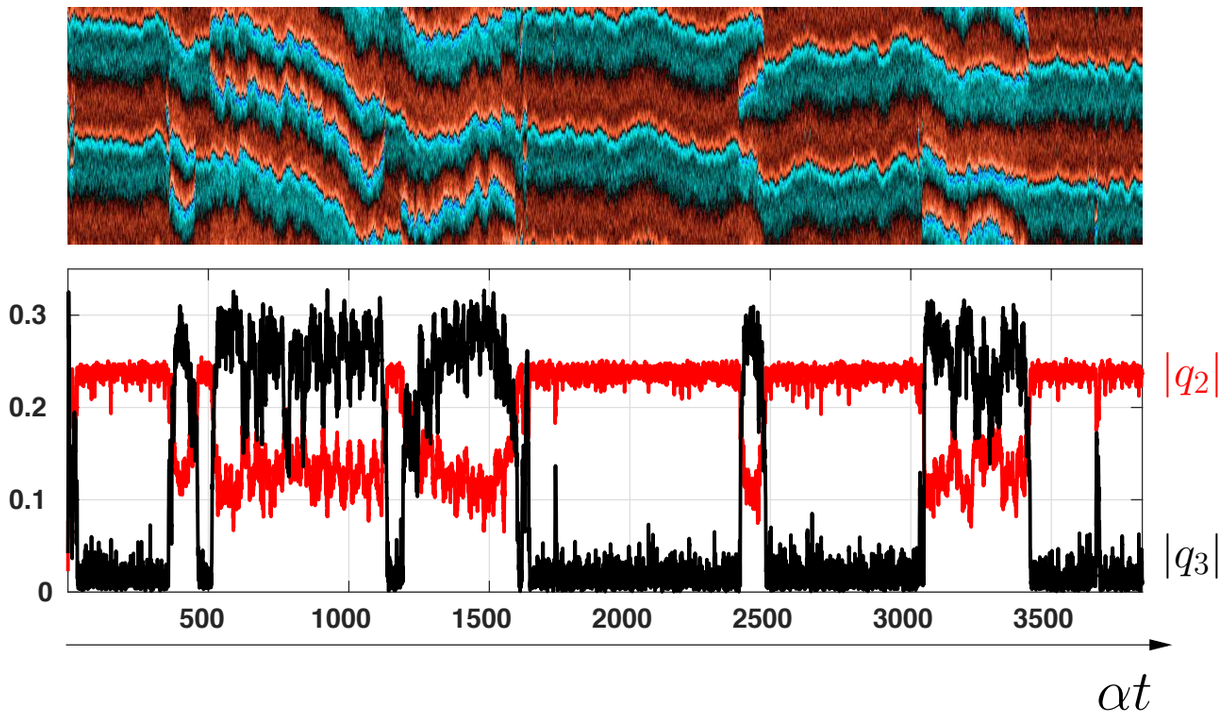


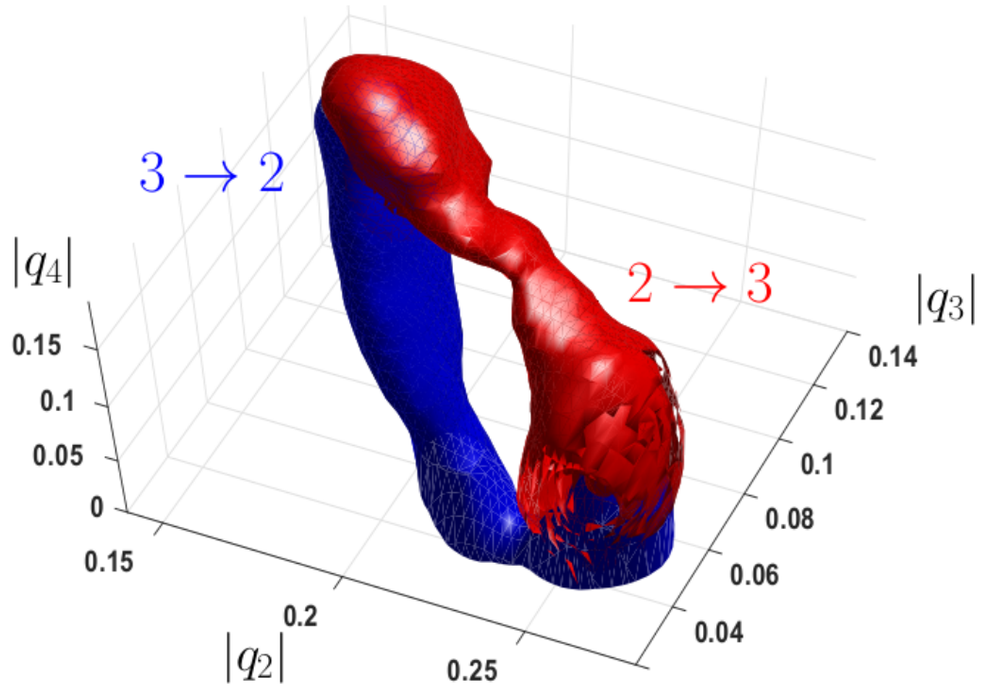


NOAA Climate.gov, adapted from NAS 2016

- Climate extremes: statistical and dynamical studies hindered by three problems
  1) lack of observational data
  2) poor sampling with numerical models due to high computational costs
  3) reliability of numerical models
- Attempt at solving problem 2: improve sampling efficiency with rare event algorithms

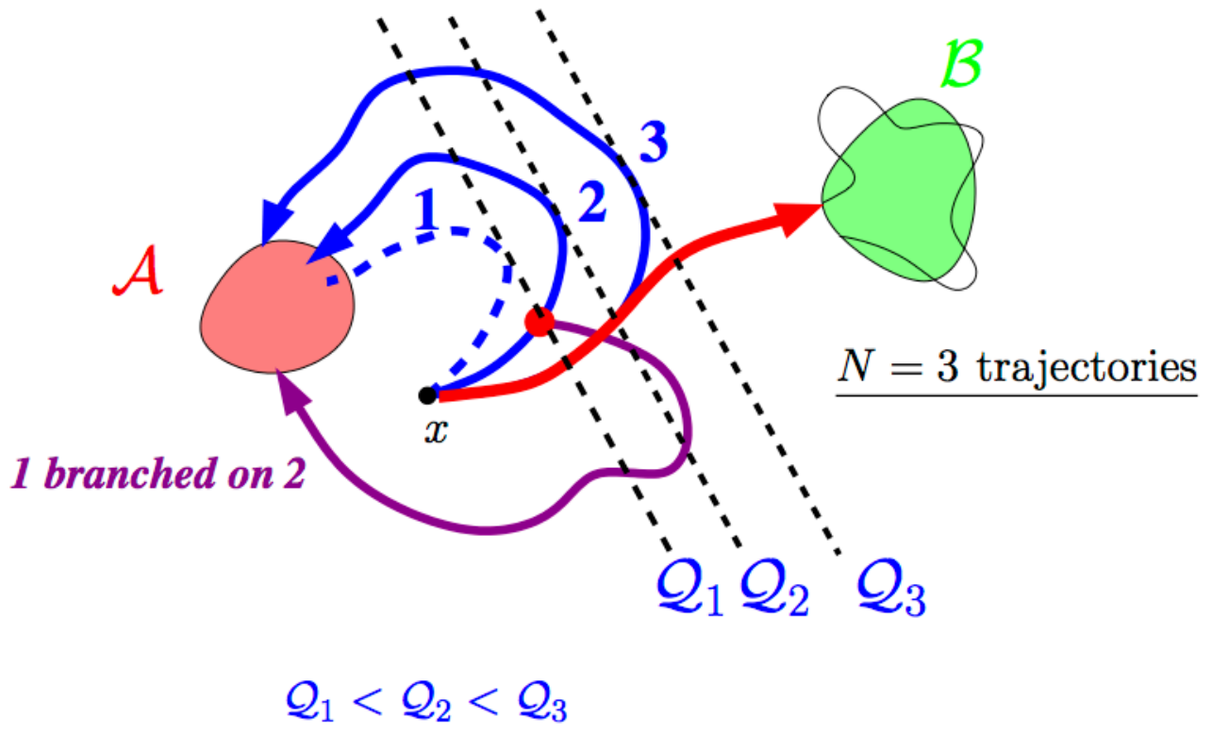
Rare event algorithms



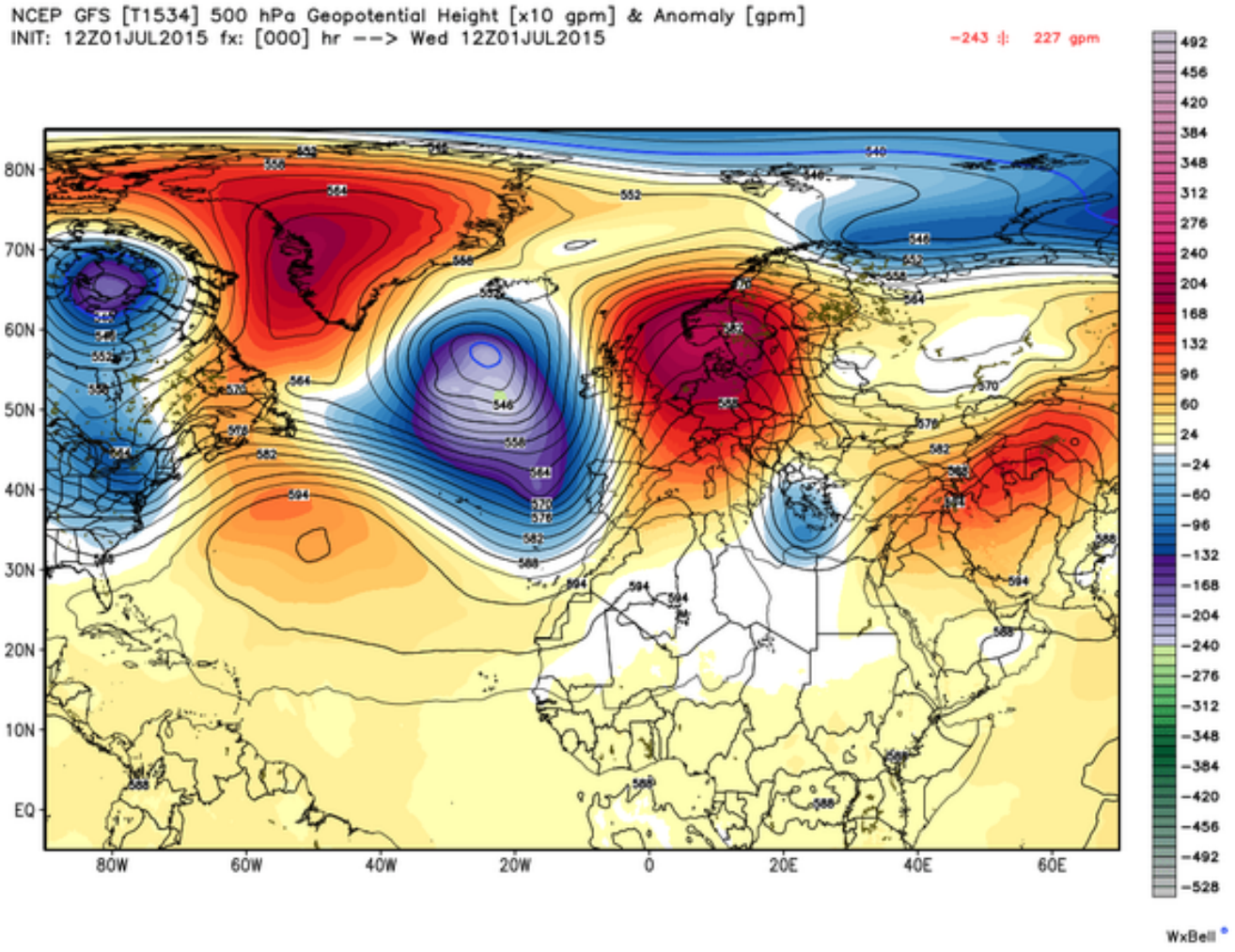


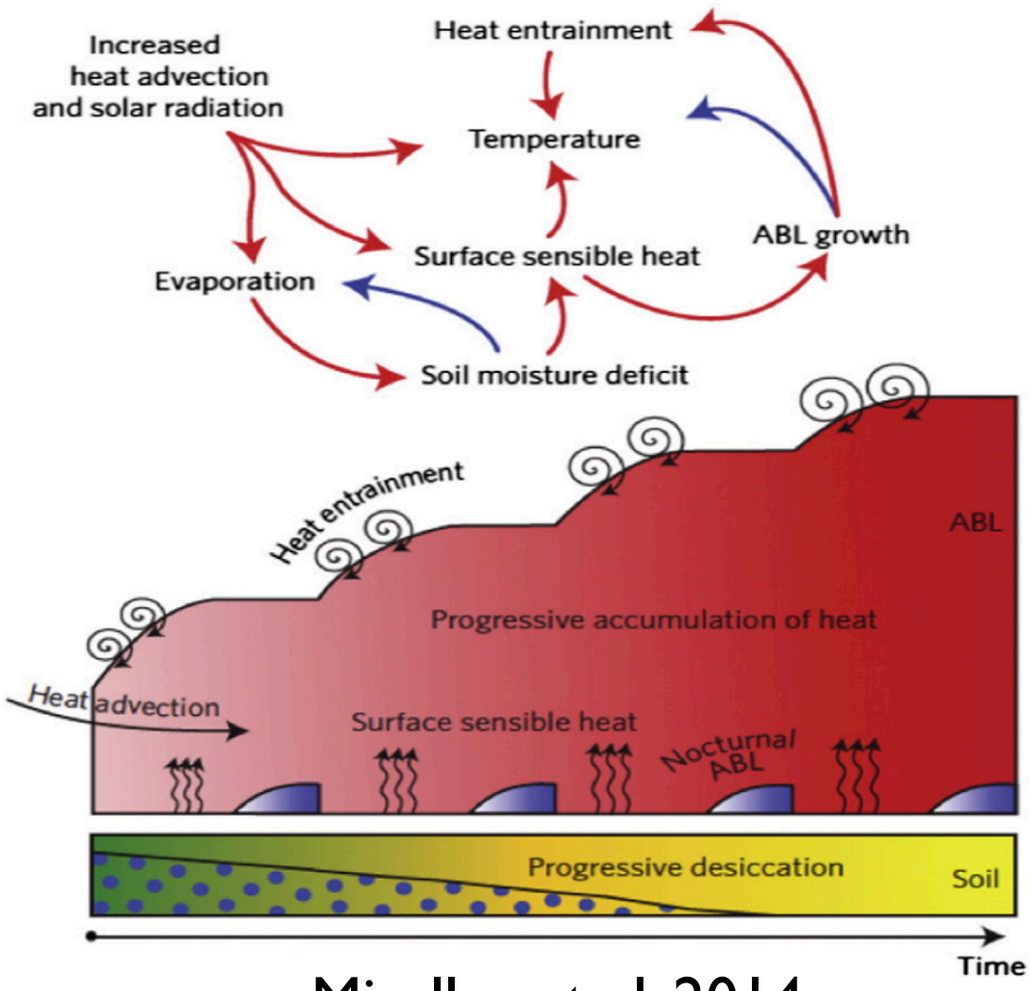
Bouchet, Rolland, Simonnet, Phys. Rev. Lett. 2019

- Computational techniques to guide numerical models to oversample rare dynamical paths
- Long history in statistical physics, recently ported to geophysical and climate problems
- Different methods for different applications



Heatwaves



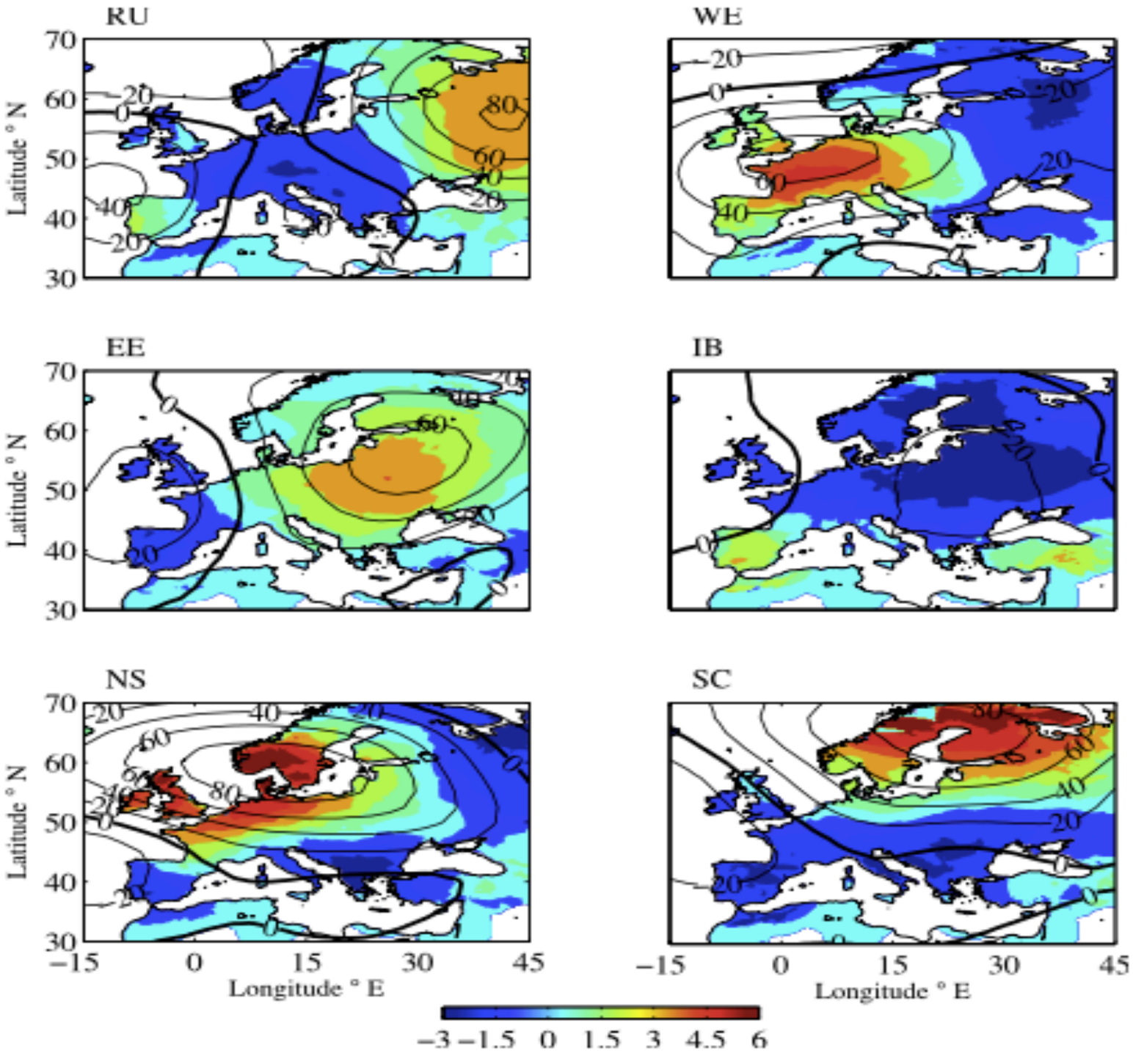


Miralles et al. 2014

- Midlatitude heatwaves typically associated to weather patterns called blockings

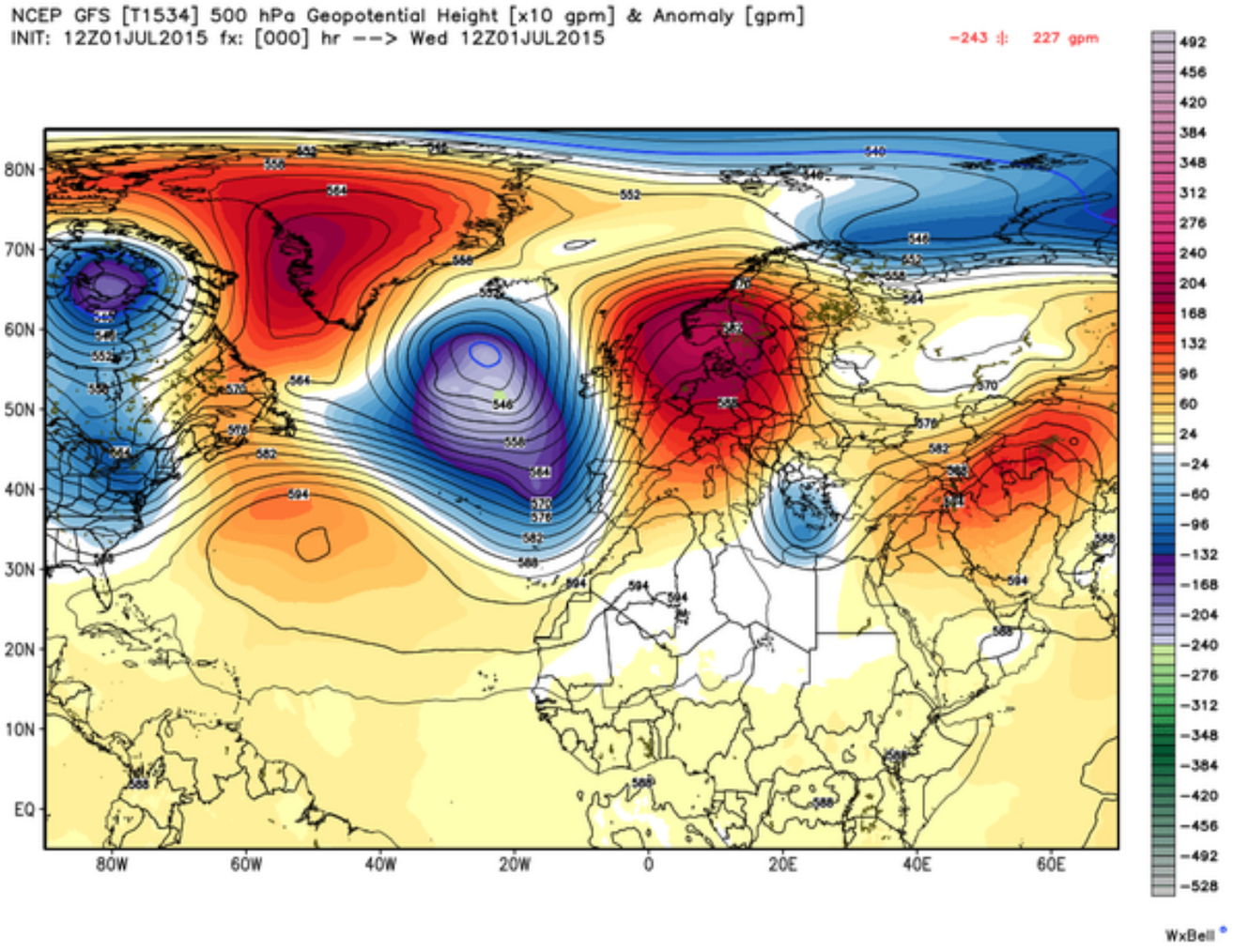
- Persistent anticyclonic conditions lead to surface warming due to subsidence and enhanced shortwave radiation fluxes, plus feedbacks (e.g. soil moisture feedback)

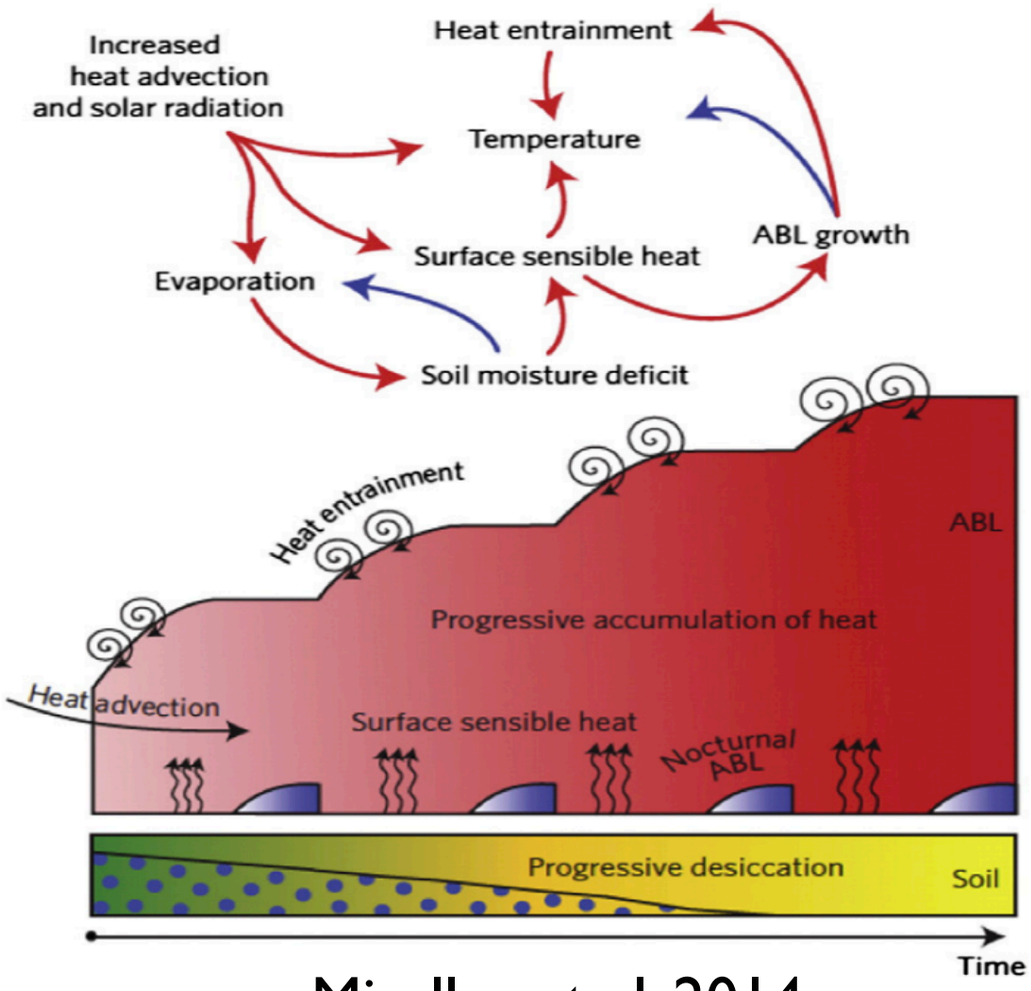
Heatwaves



- European heatwave clusters (Stefanon et al. 2012)

Heatwaves



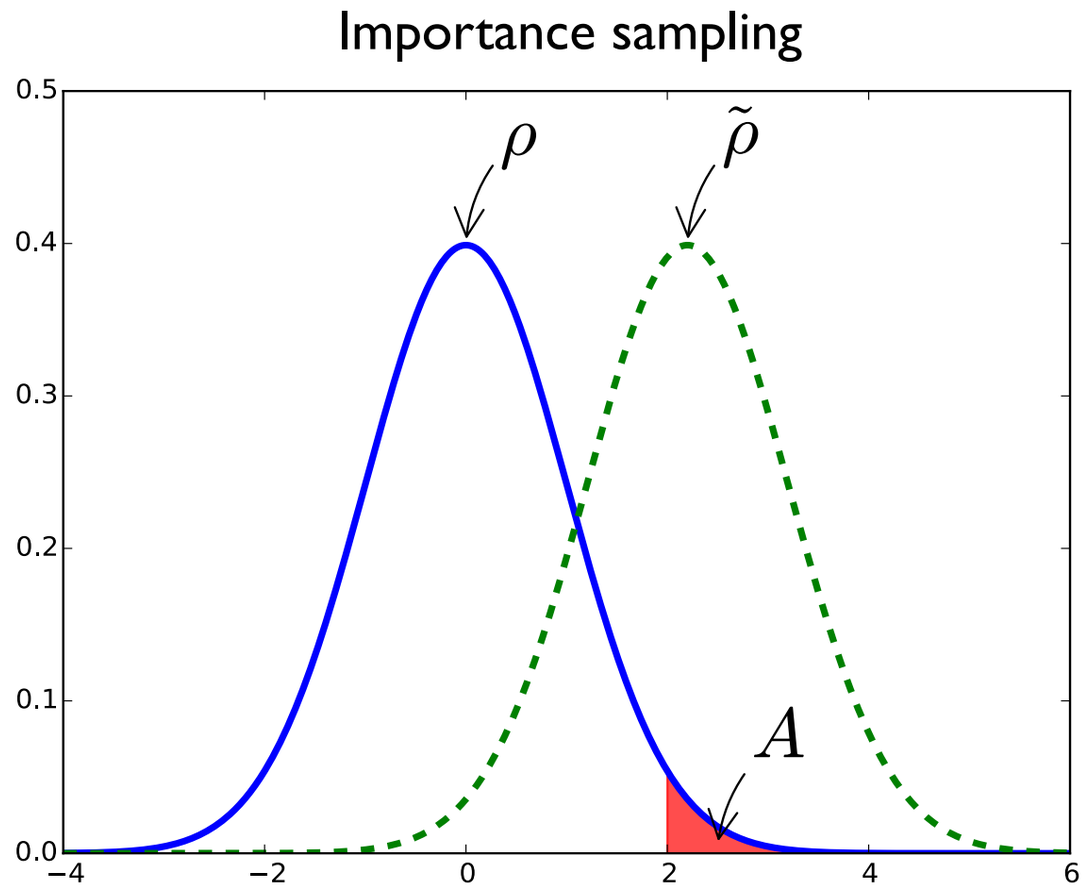


Miralles et al. 2014

- Class of extreme events characterised by time persistence of quantity/dynamics

- We exploit this adapting the rare event algorithm of e.g. Del Moral and Garnier (2005); Giardina et al. (2011), that is efficient to study long lasting events.

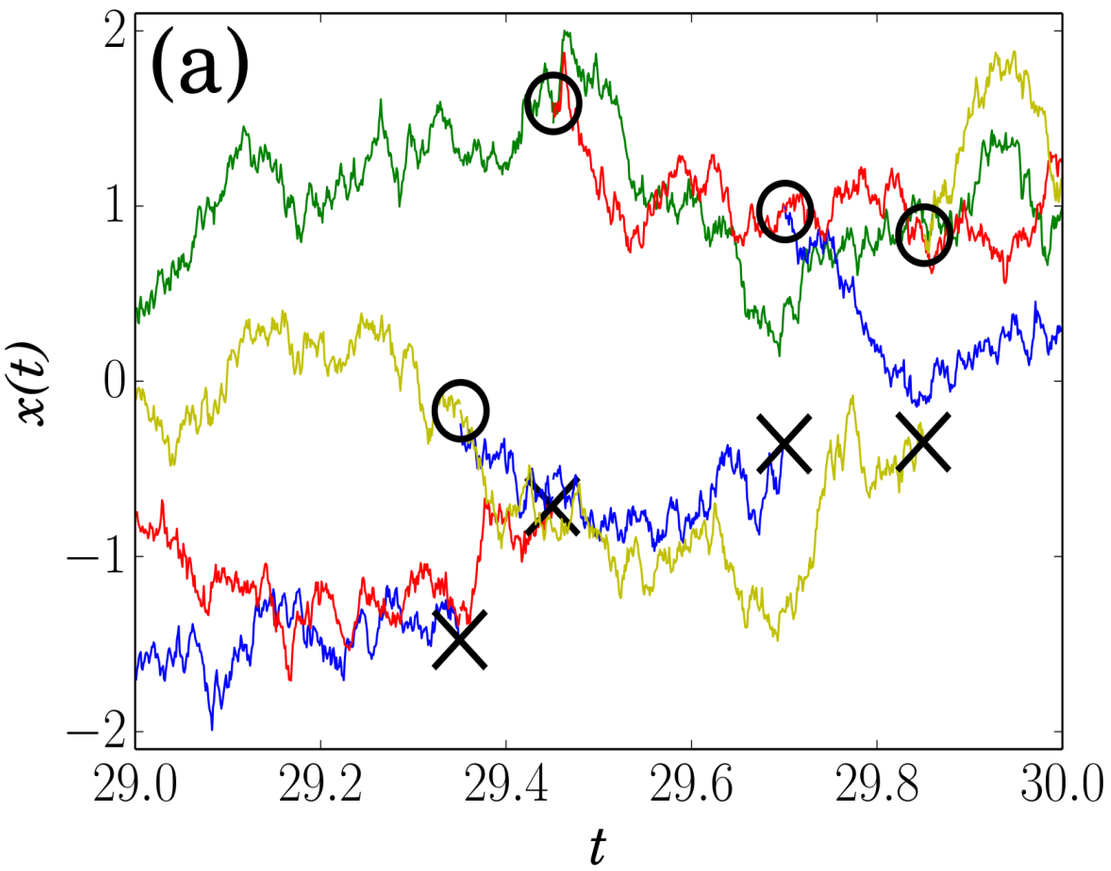
Rare event algorithm and importance sampling



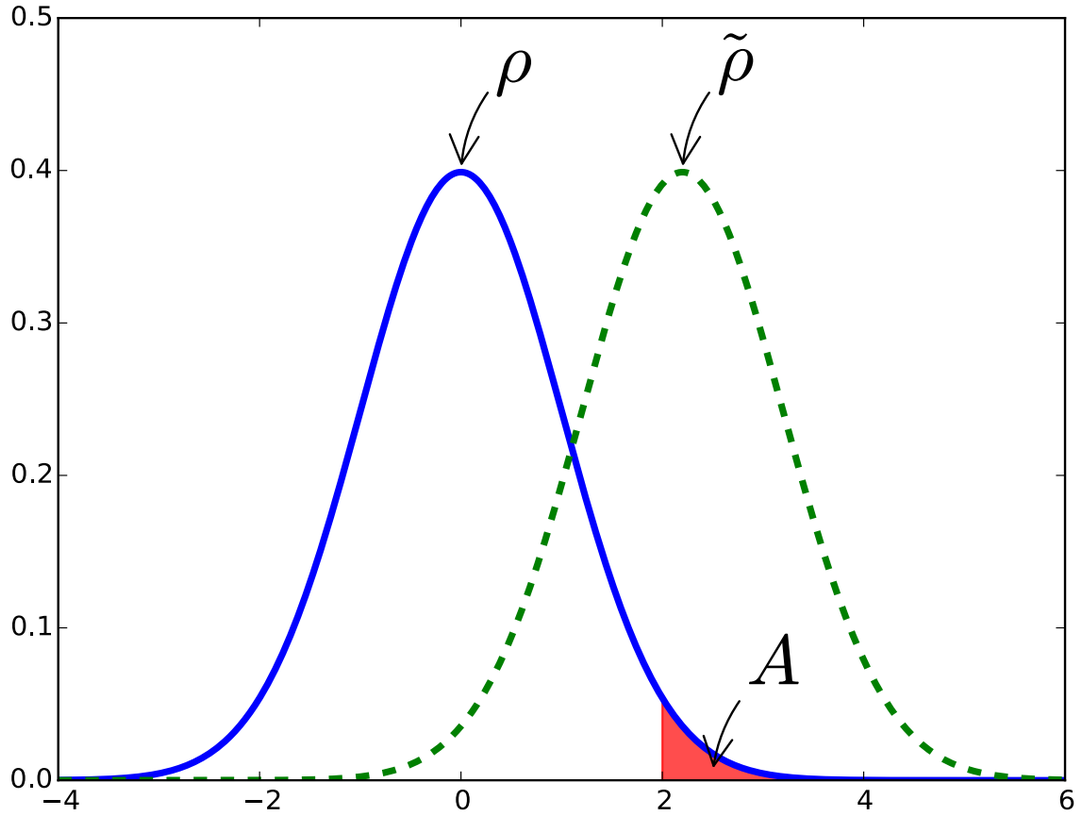
- Importance sampling: make rare events common

Rare event algorithm and importance sampling

Online trajectory selection



Importance sampling



- Importance sampling: make rare events common
- Ensemble simulations with numerical model + genetic algorithm
- Define observable of interest, e.g. surface temperature over region
- Every constant intervals of resampling time τ the trajectories are killed or cloned, based on weights that measure the likelihood to develop an extreme for the target observable

Rare event algorithm and importance sampling

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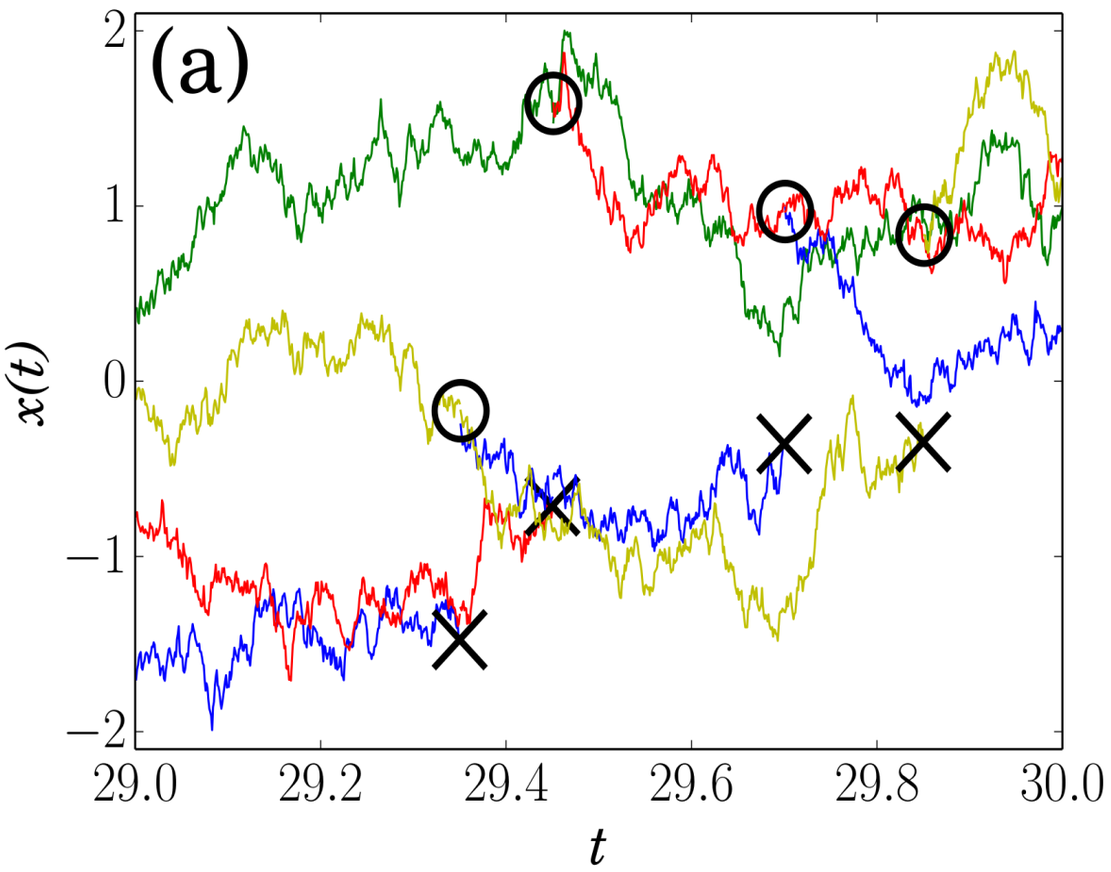
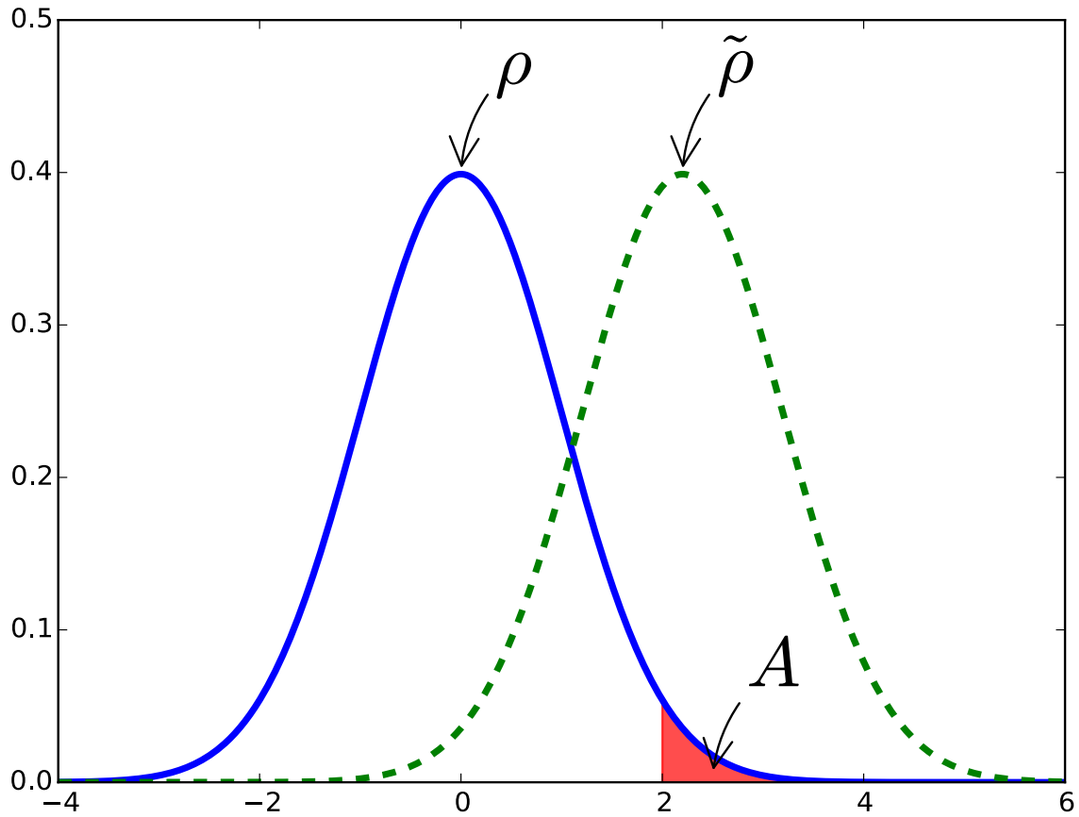


Importance sampling



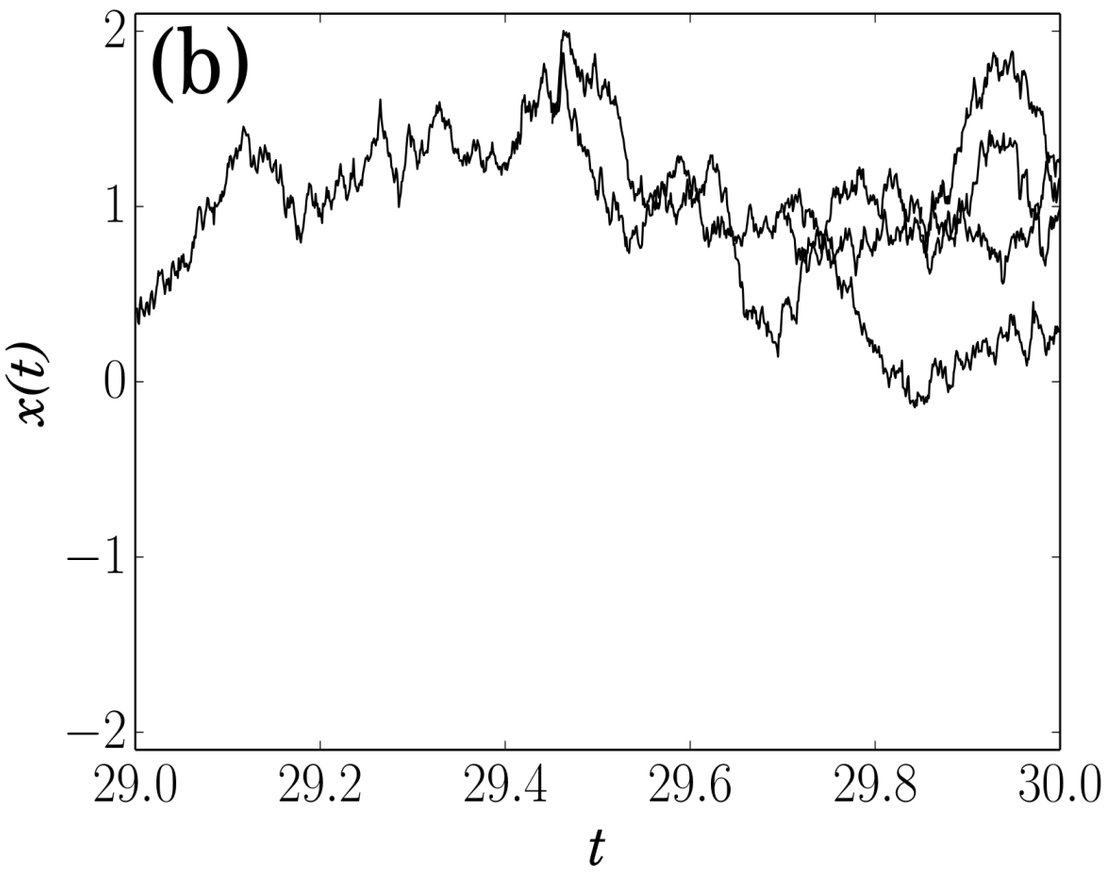
- Run N trajectories $X_j(t)$ $(j = 1,..,N)$ for total simulation time T_a
- Each trajectory generates at time $t_i = i\tau$ $(i = 1,..,T_a/\tau)$ a number of copies of itself given by weights

$$w_j(t_i) = \frac{e^{k\int_{t_{i-1}}^{t_i} f(X_j(t))dt}}{Z_i}, \qquad Z_i = \frac{1}{N}\sum_{j=1}^{N} w_j(t_i)$$

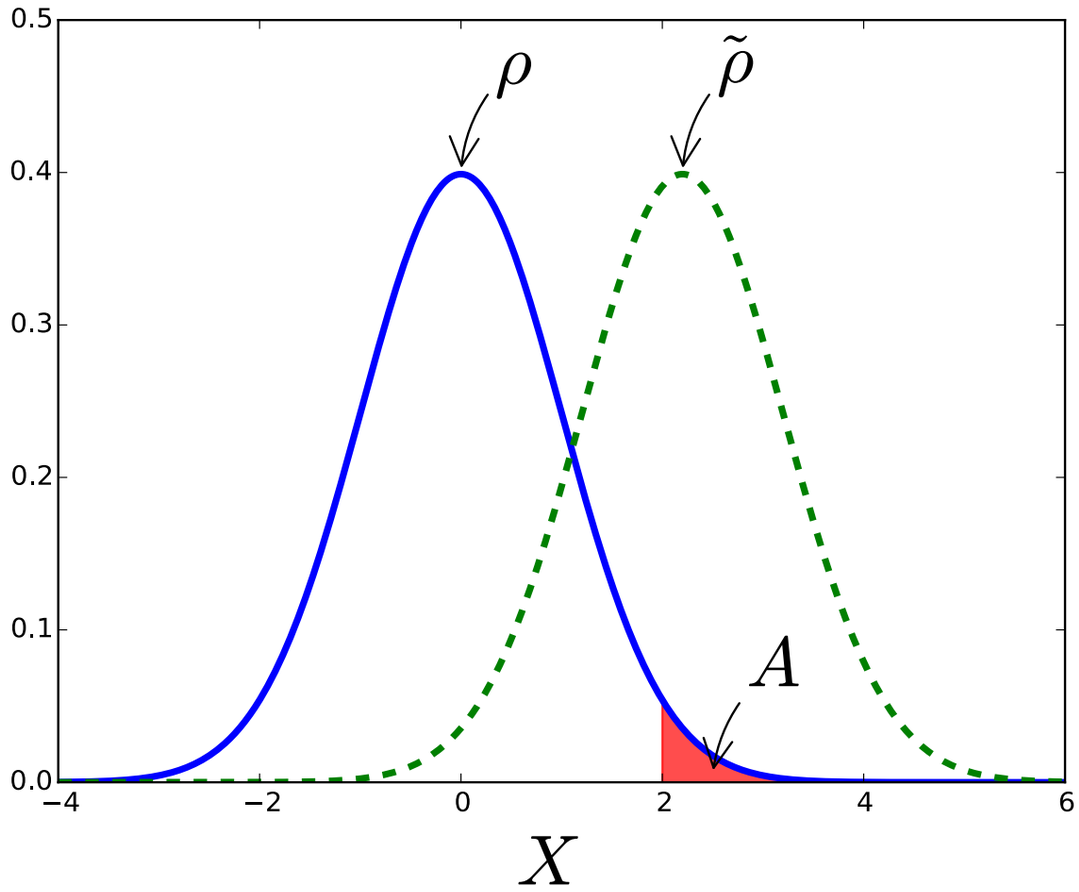
with *f(X(t))* observable of interest, *k* control parameter.

Rare event algorithm and importance sampling

Online trajectory selection



Importance sampling



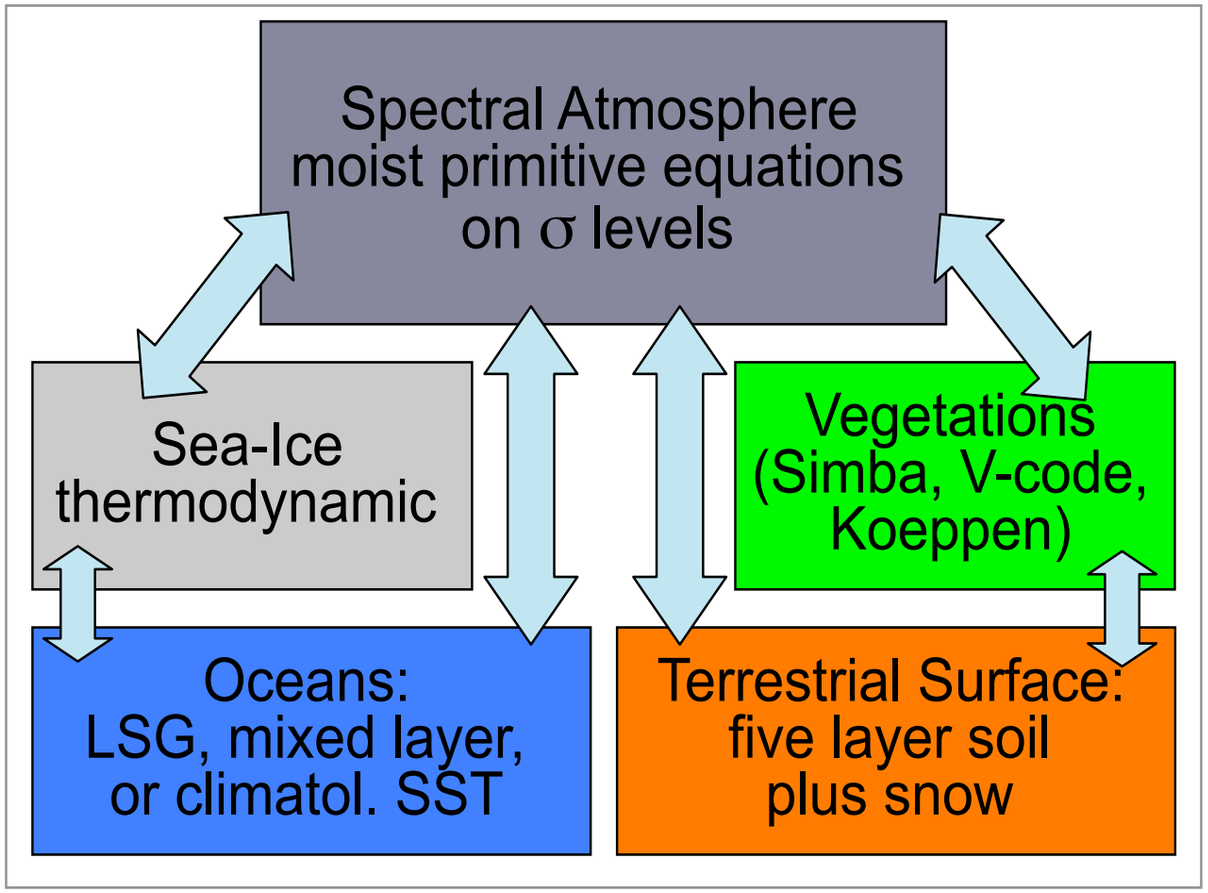
- Importance sampling of trajectories: tilting the probability of dynamical paths

$$\mathbb{P}_k\left(\{X(t)\}_0^{T_a}\right) = \frac{e^{k\int_0^{T_a} f\left(X(t)\right)dt}}{Z}\mathbb{P}_0\left(\{X(t)\}_0^{T_a}\right)$$

- Trajectories with large values of time average of observable are much more likely to occur
- Reduces statistical errors and generates ultra-rare events: conditional statistics on rare events estimated much more precisely (composites, return times, correlations…)

Experiments with climate model Plasim

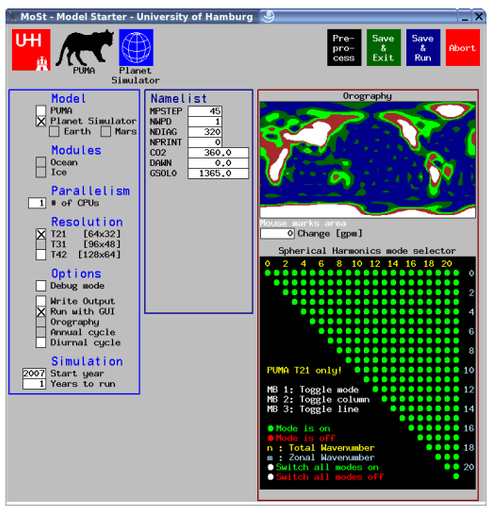
- Plasim, intermediate complexity GCM

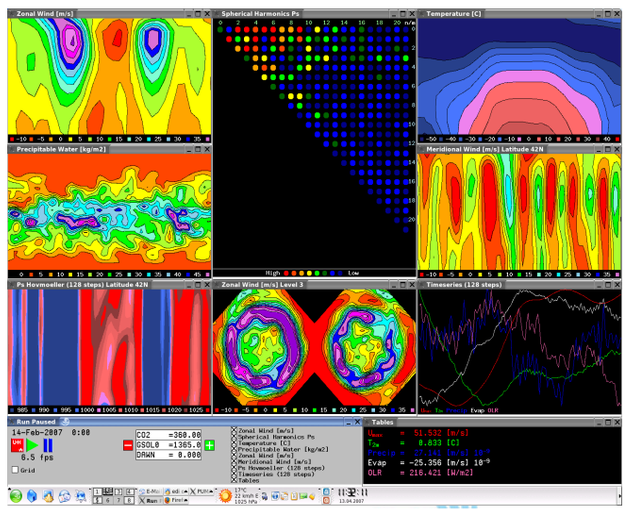


Key features

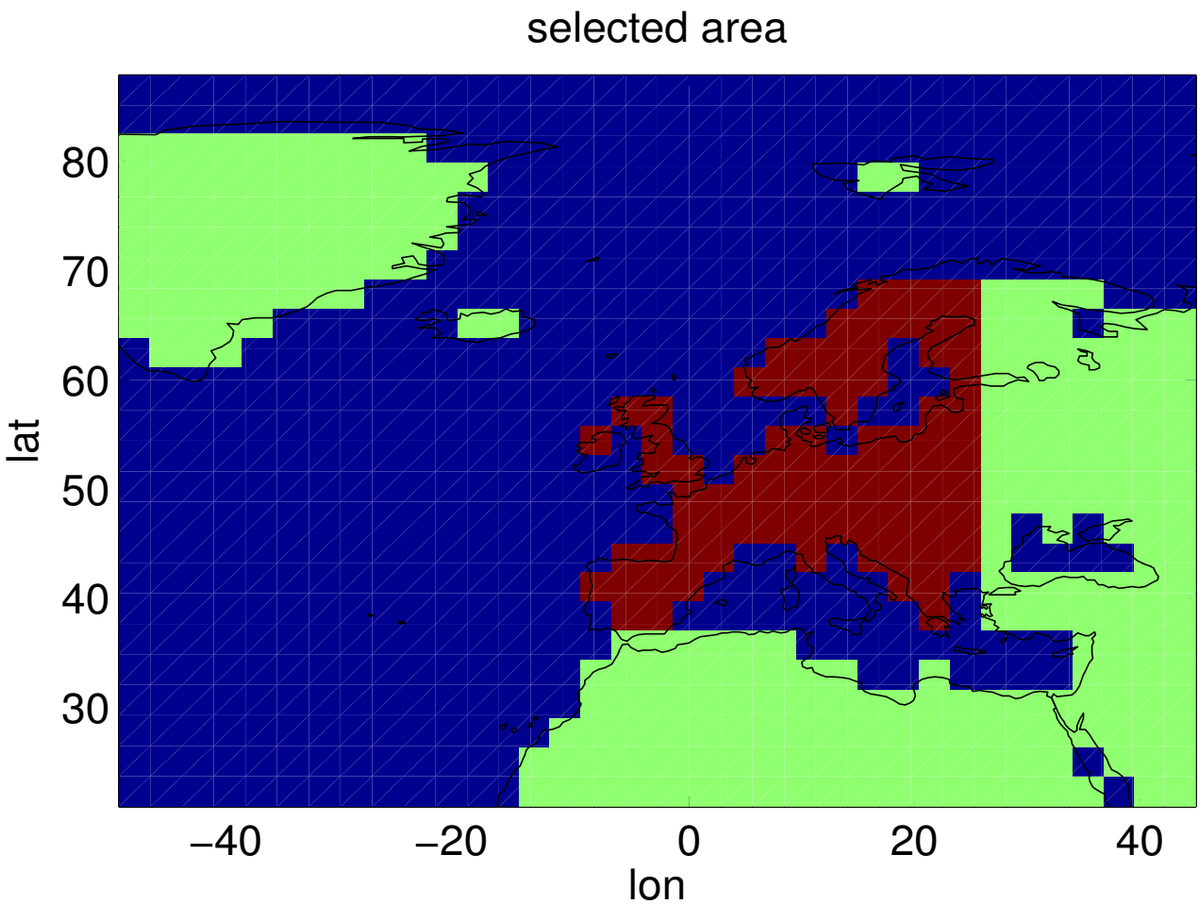
- portable
- fast
- open source
- parallel
- modular
- easy to use
- documented
- compatible

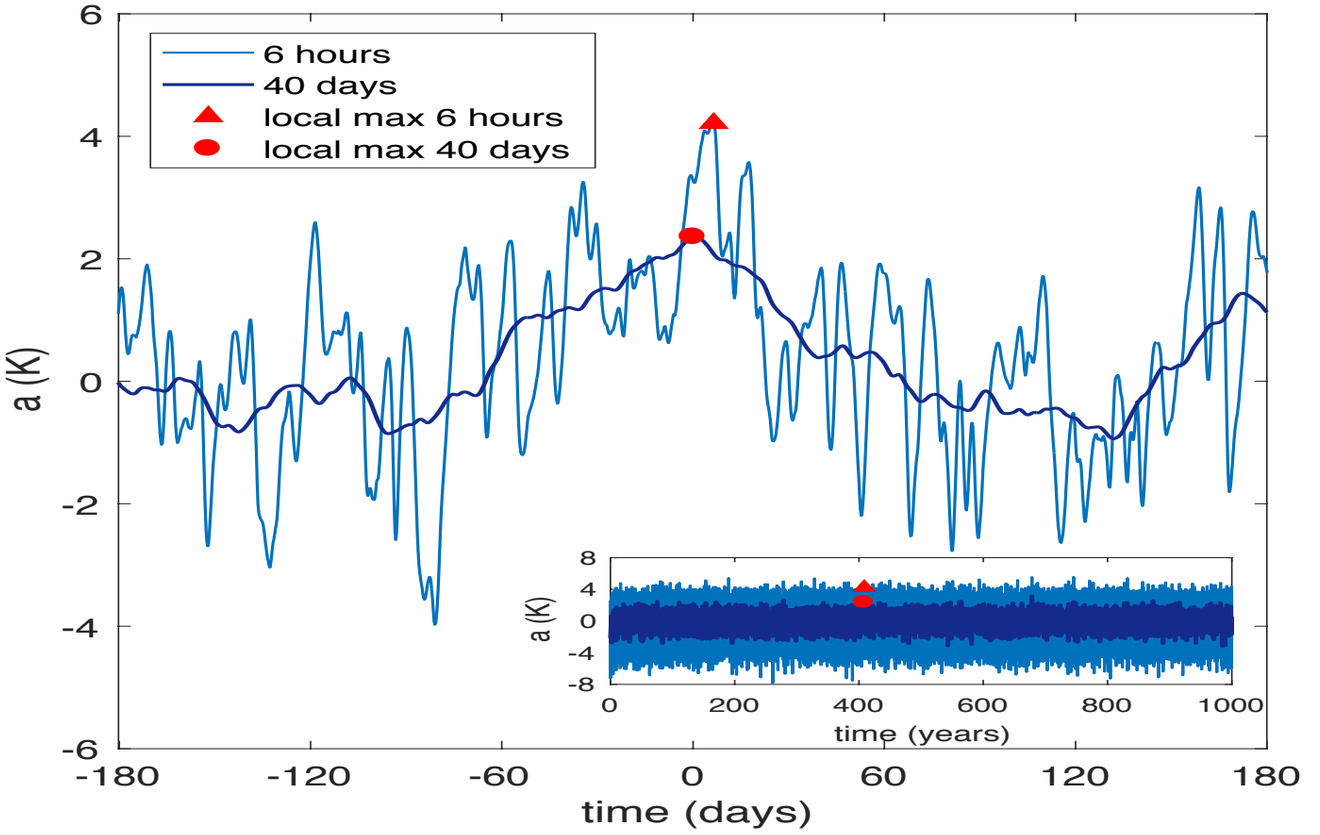
Model Starter
and
Graphic User Interface





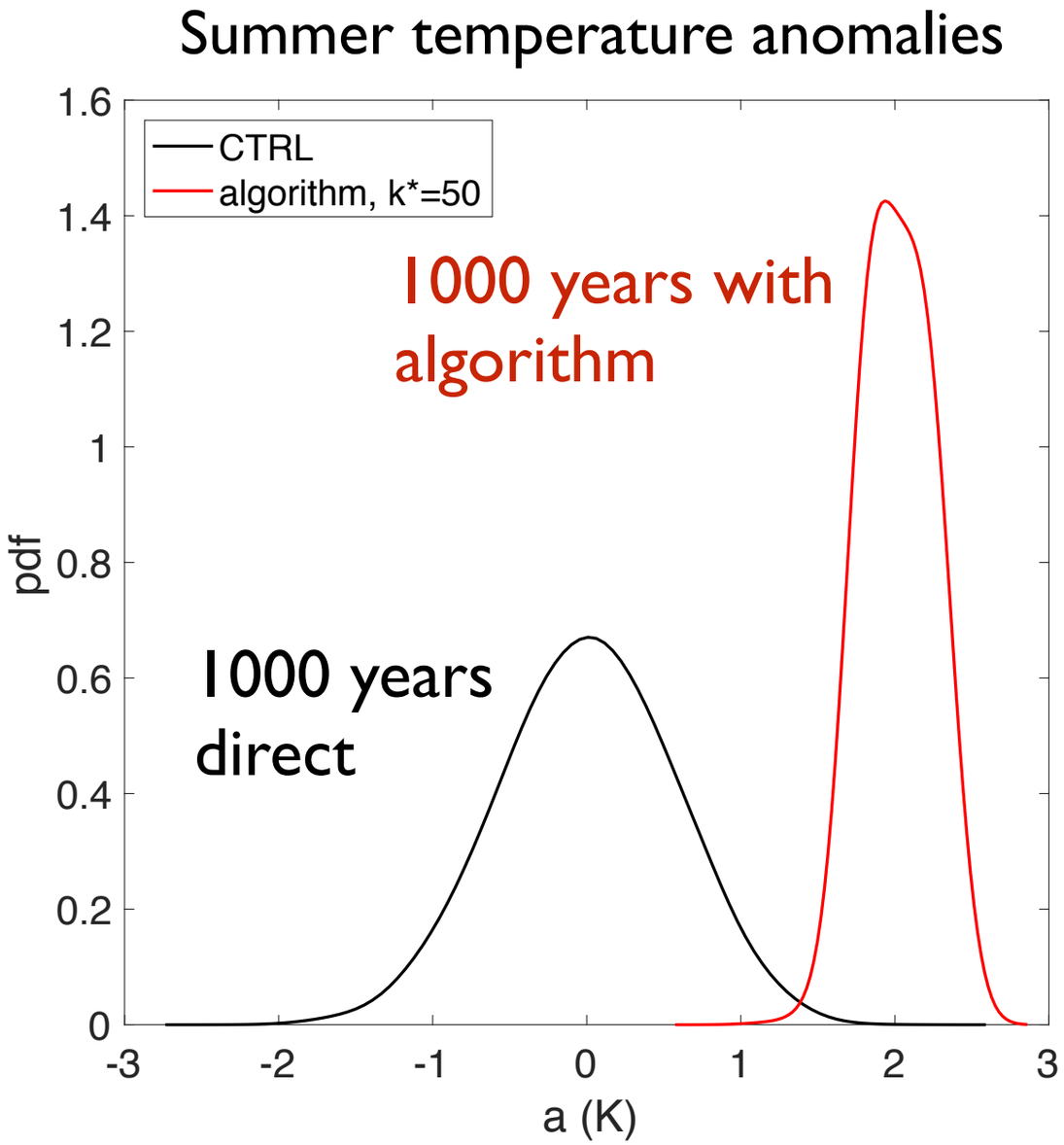
Experiments with climate model Plasim





- T42 horizontal resolution (64x128), 10 vertical layers, order 10^6 degrees of freedom.
- Prescribed sea surface temperature in perpetual summer setup
- Target: European surface temperature averaged on subeasonal/seasonal time scales
- Control run of 1000 years as reference
- Run 6 different ensembles of 512 trajectories each with algorithm for 128 days (total about 1000 years), with resampling time 8 days, independent initial conditions sampled from control run

Heatwaves and warm summers in Plasim

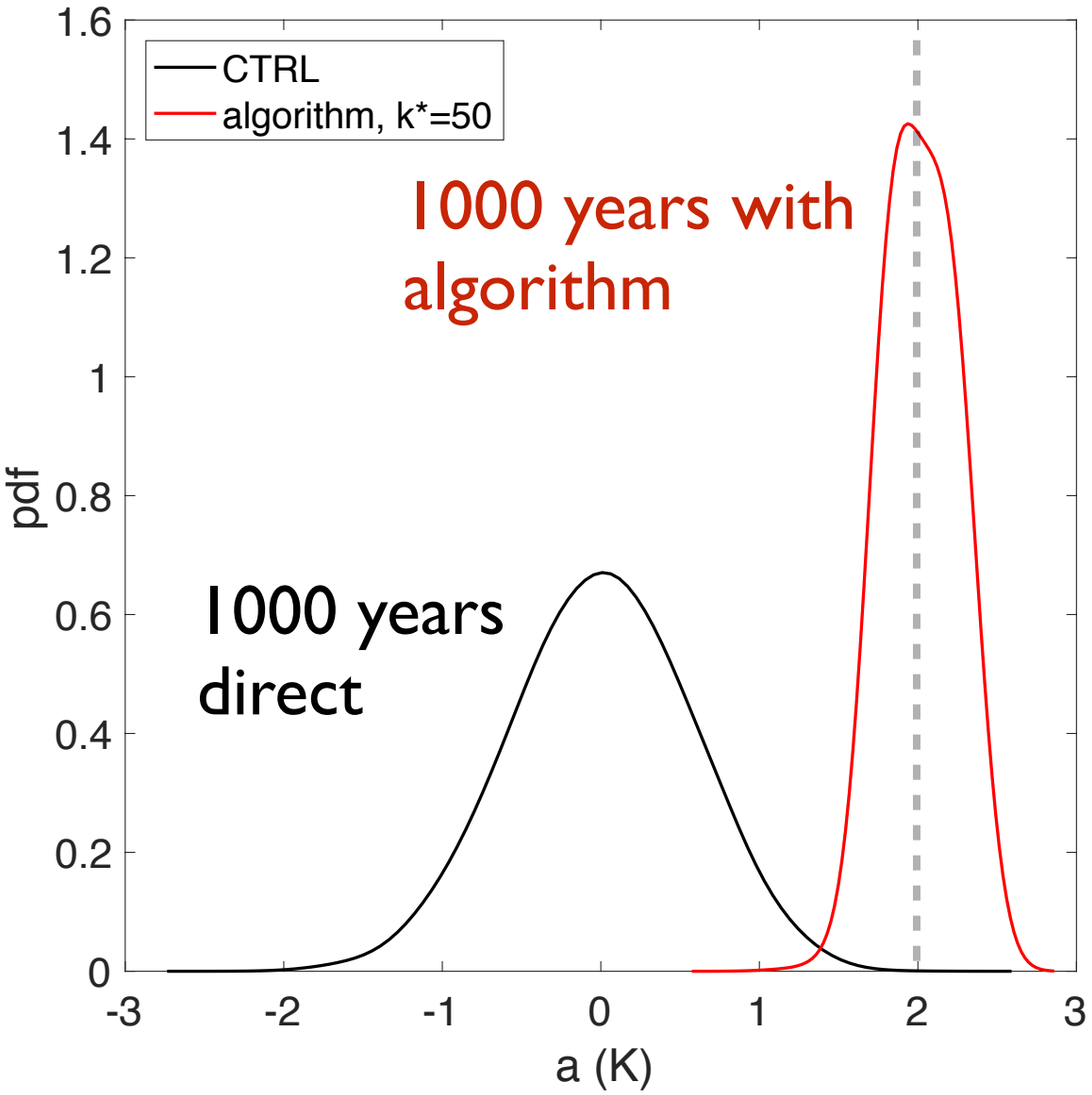


Ragone, Wouters, Bouchet. *PNAS* 2018

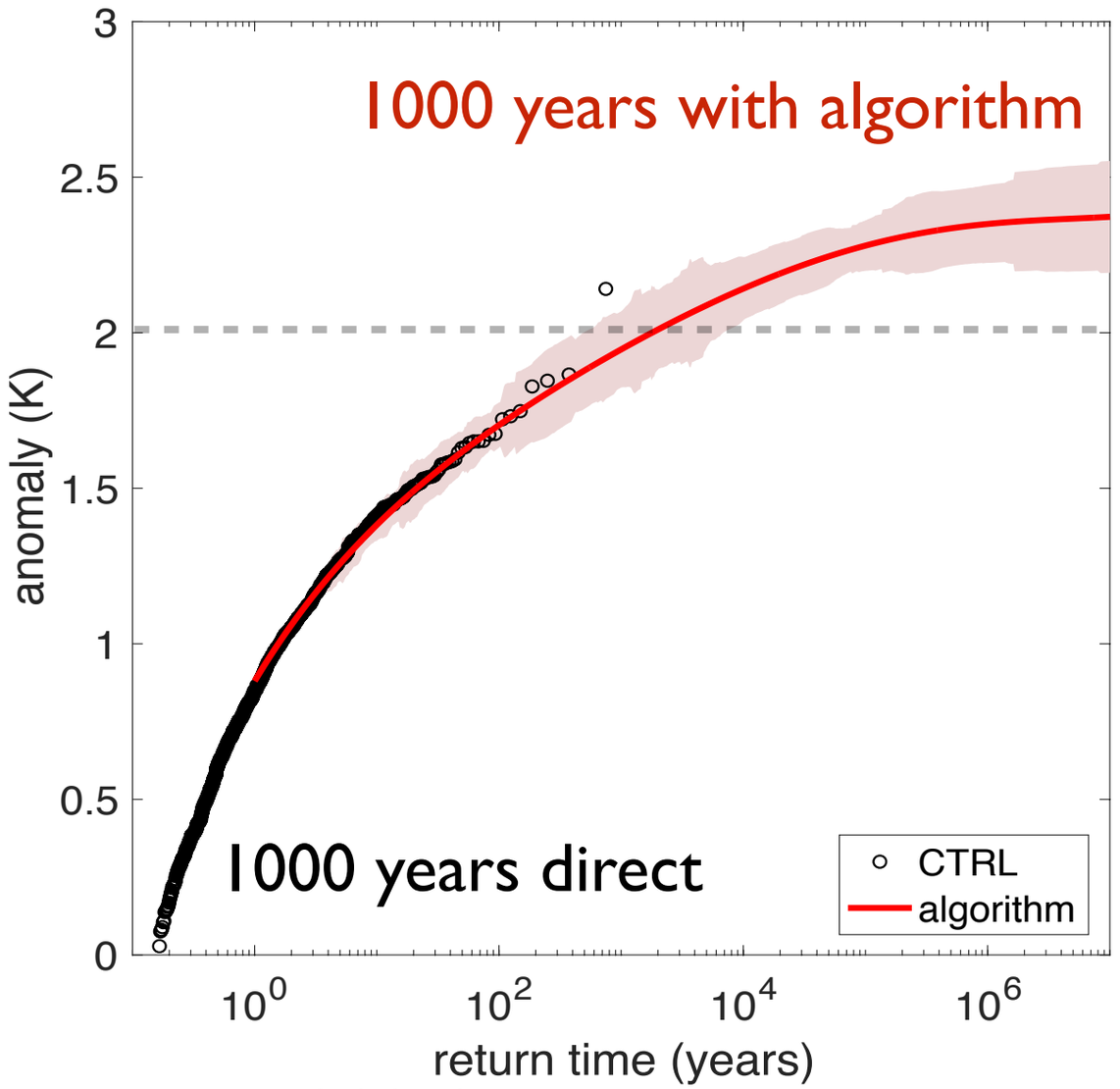
- Importance sampling of 90-days European heatwaves

Heatwaves and warm summers in Plasim

Summer temperature anomalies



Return times



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- Importance sampling of 90-days European heatwaves
- Allows to compute return times up to 10^6 years with computational cost of 10^3 years

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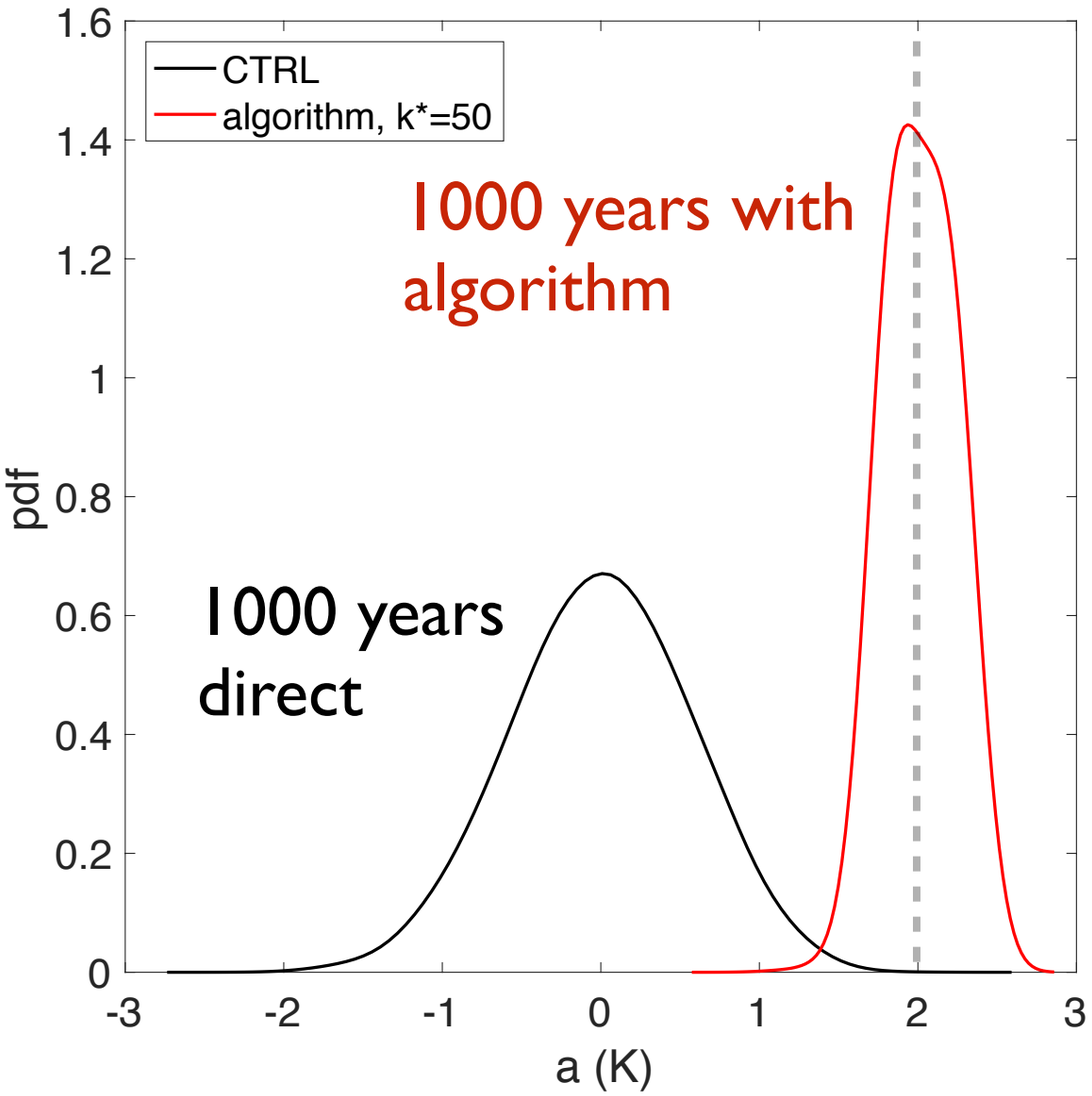

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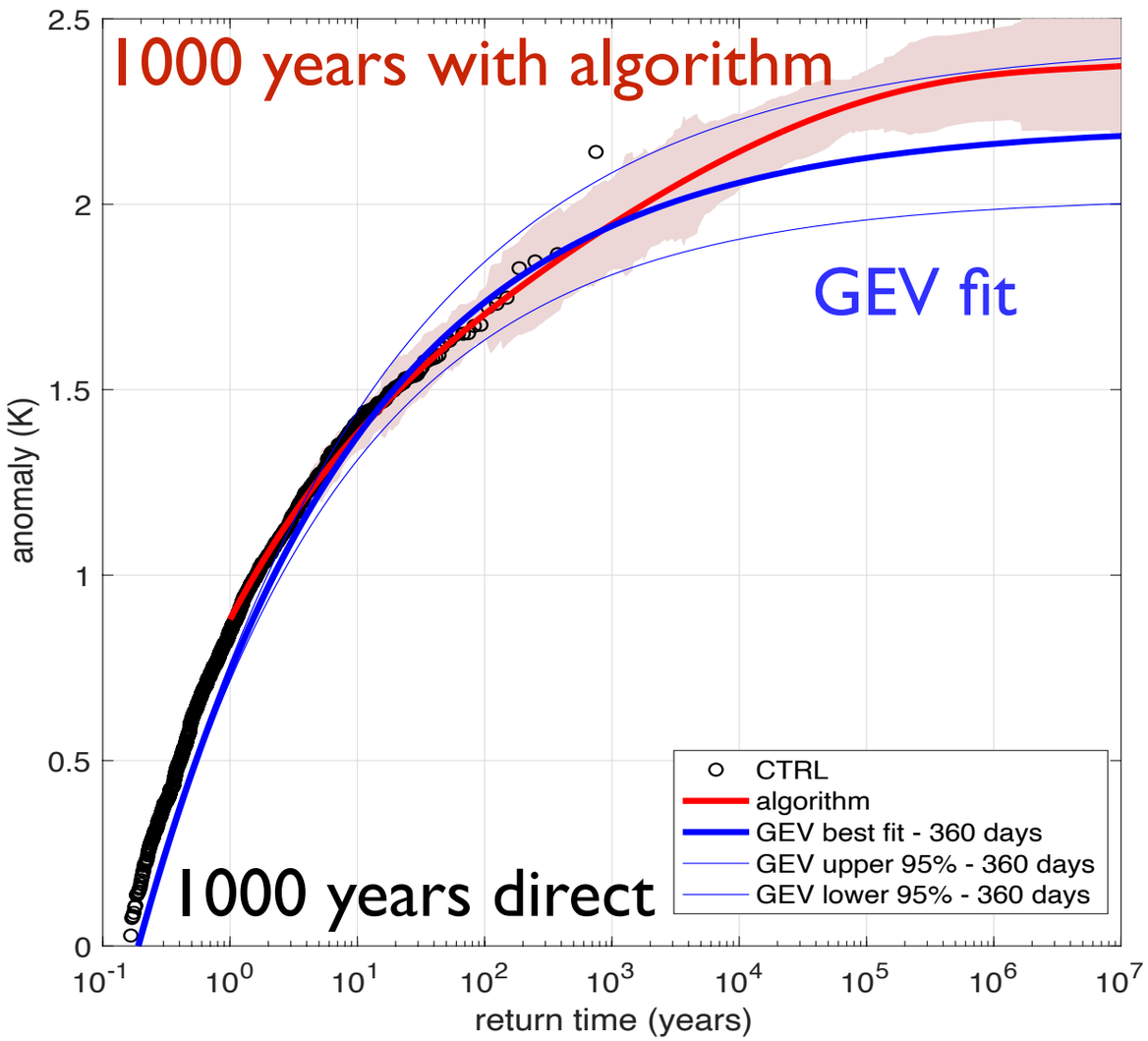
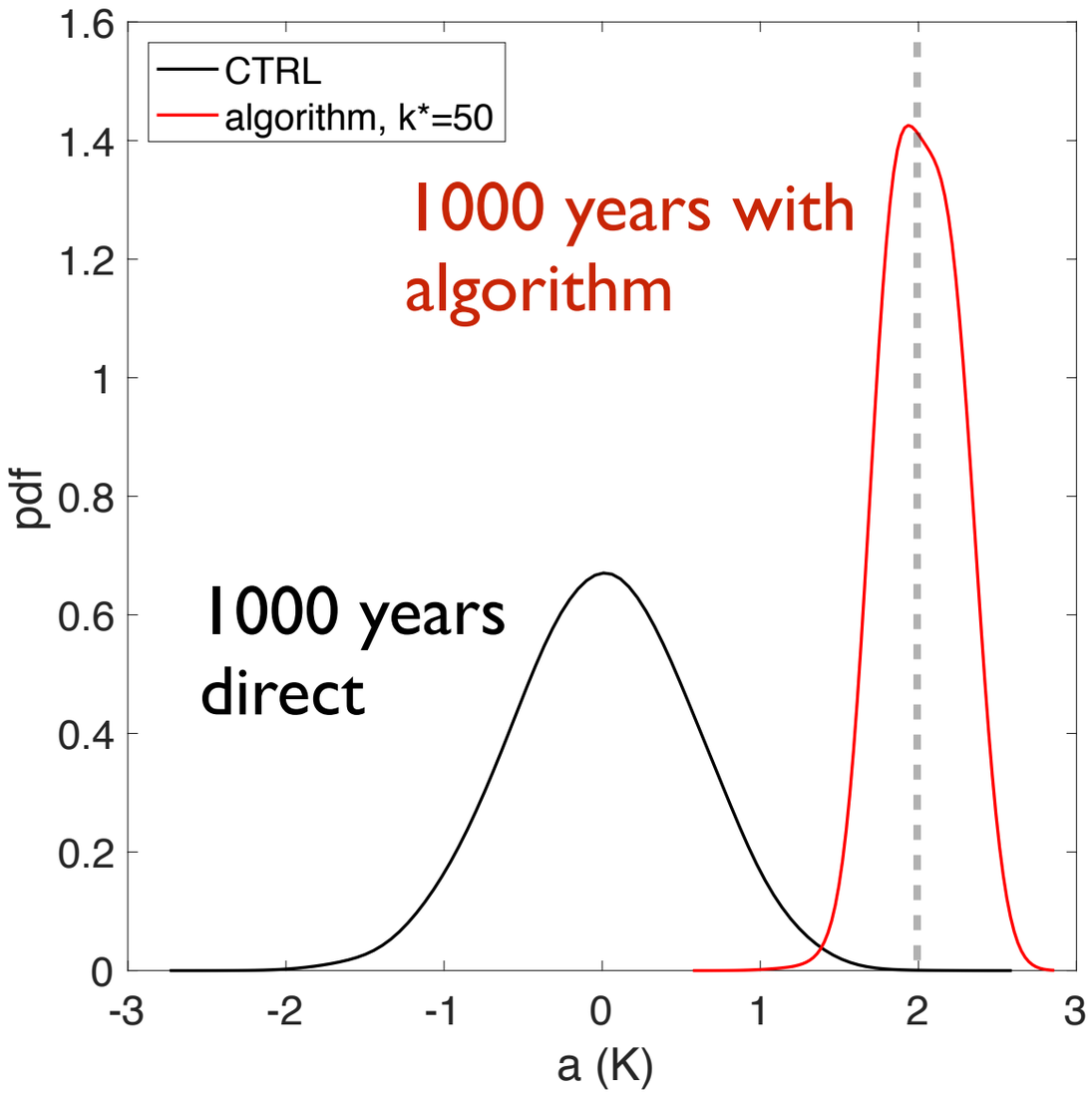


Ragone, Wouters, Bouchet. *PNAS* 2018

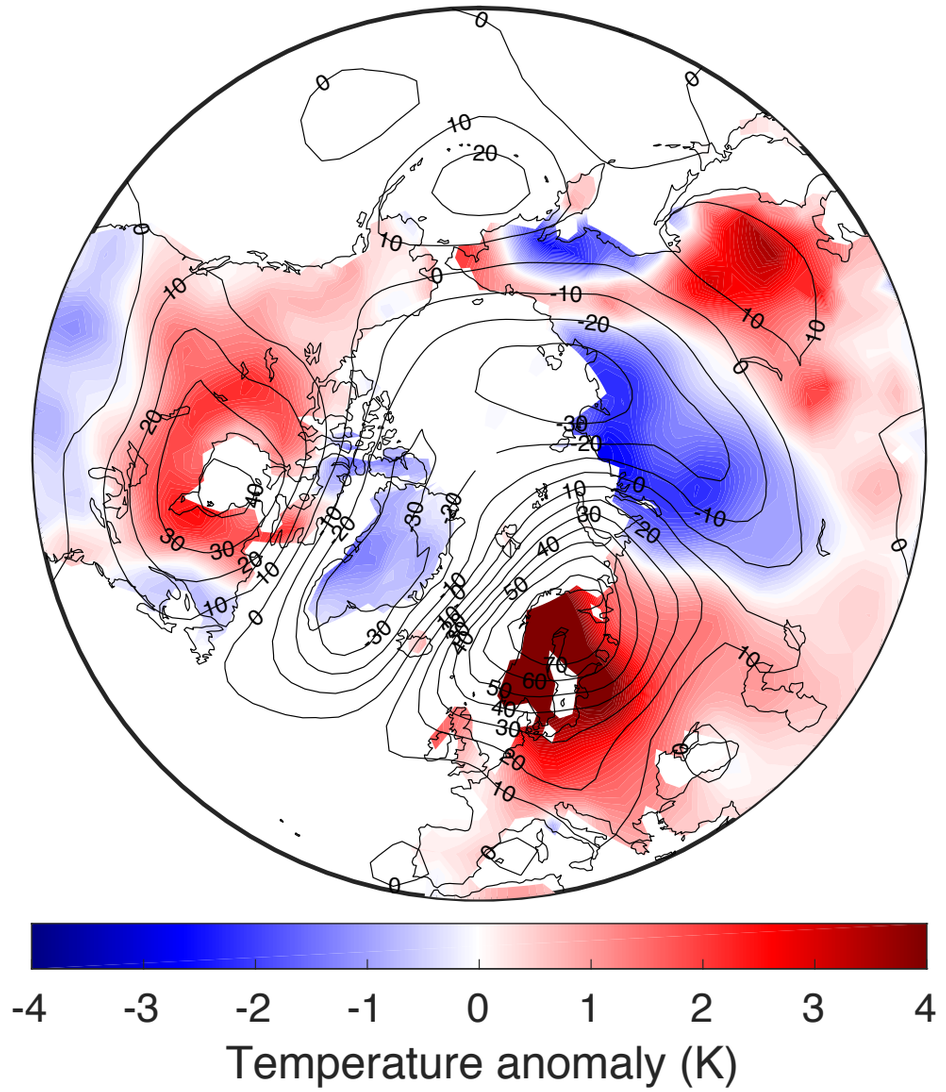
- Importance sampling of 90-days European heatwaves
- Allows to compute return times up to 10^6 years with computational cost of 10^3 years
- GEV estimate gives results somehow consistent but underestimates very rare events

Heatwaves and warm summers in Plasim

Summer temperature anomalies



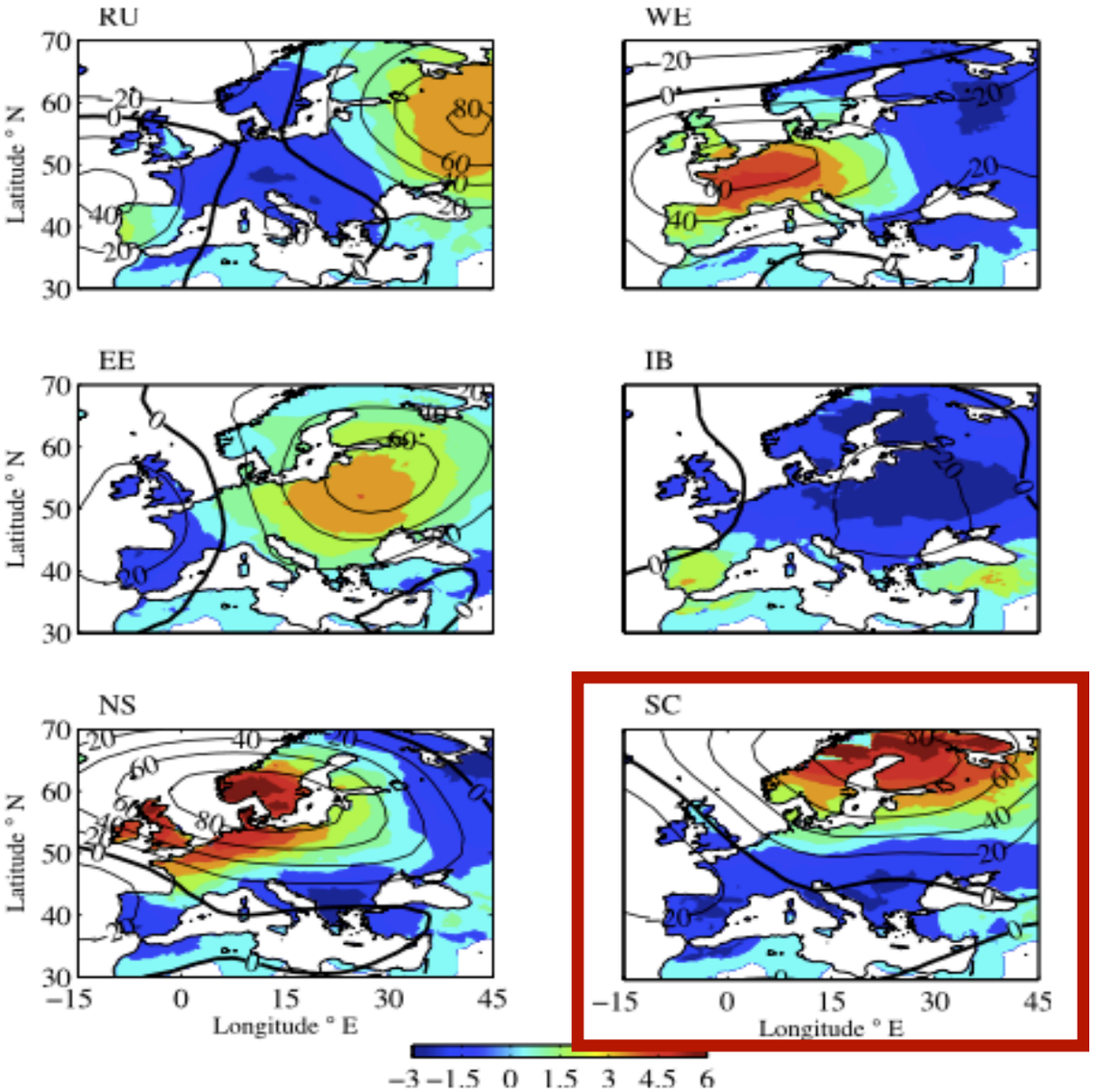
Composite heatwaves r>1000 years



Ragone, Wouters, Bouchet. *PNAS* 2018

- Importance sampling of 90-days European heatwaves
- Allows to compute return times up to 10^6 years with computational cost of 10^3 years
- Identification of teleconnection patterns for strongest heatwaves

Heatwaves and warm summers in Plasim



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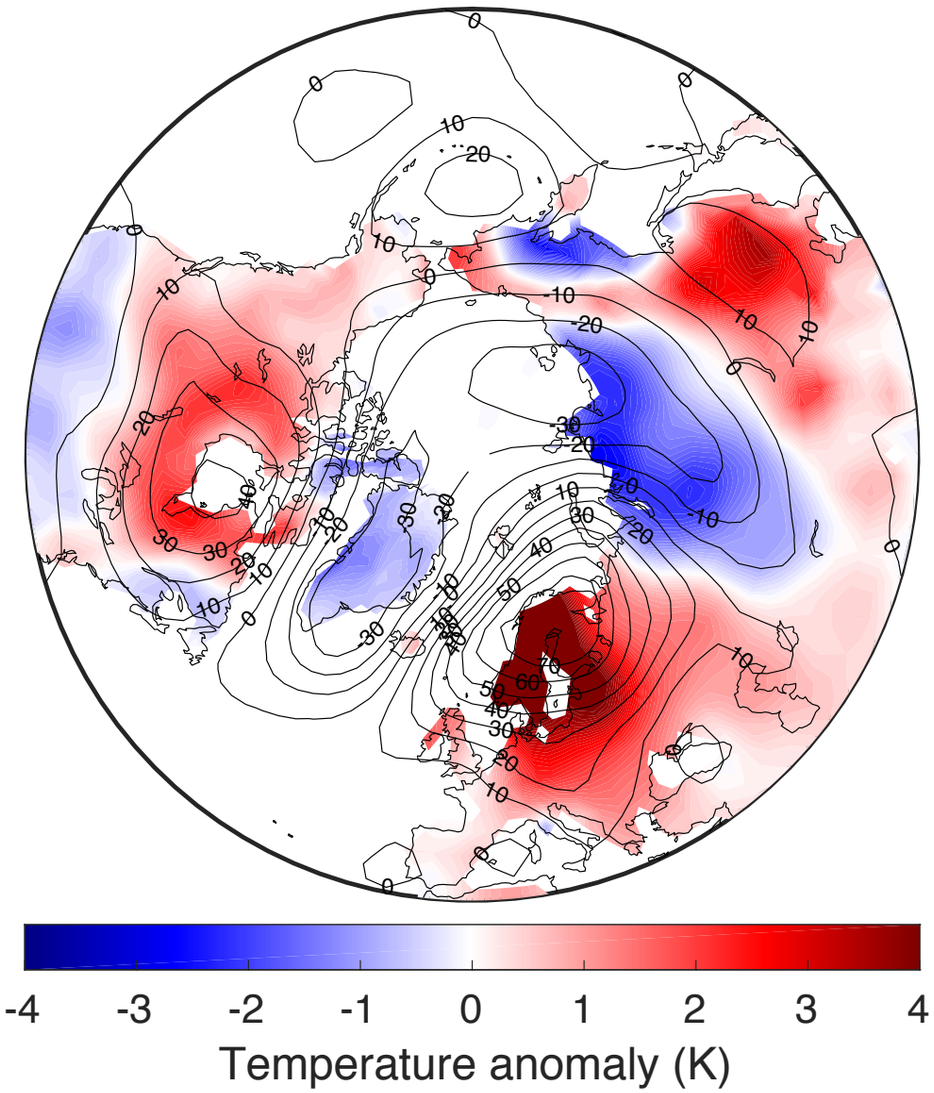
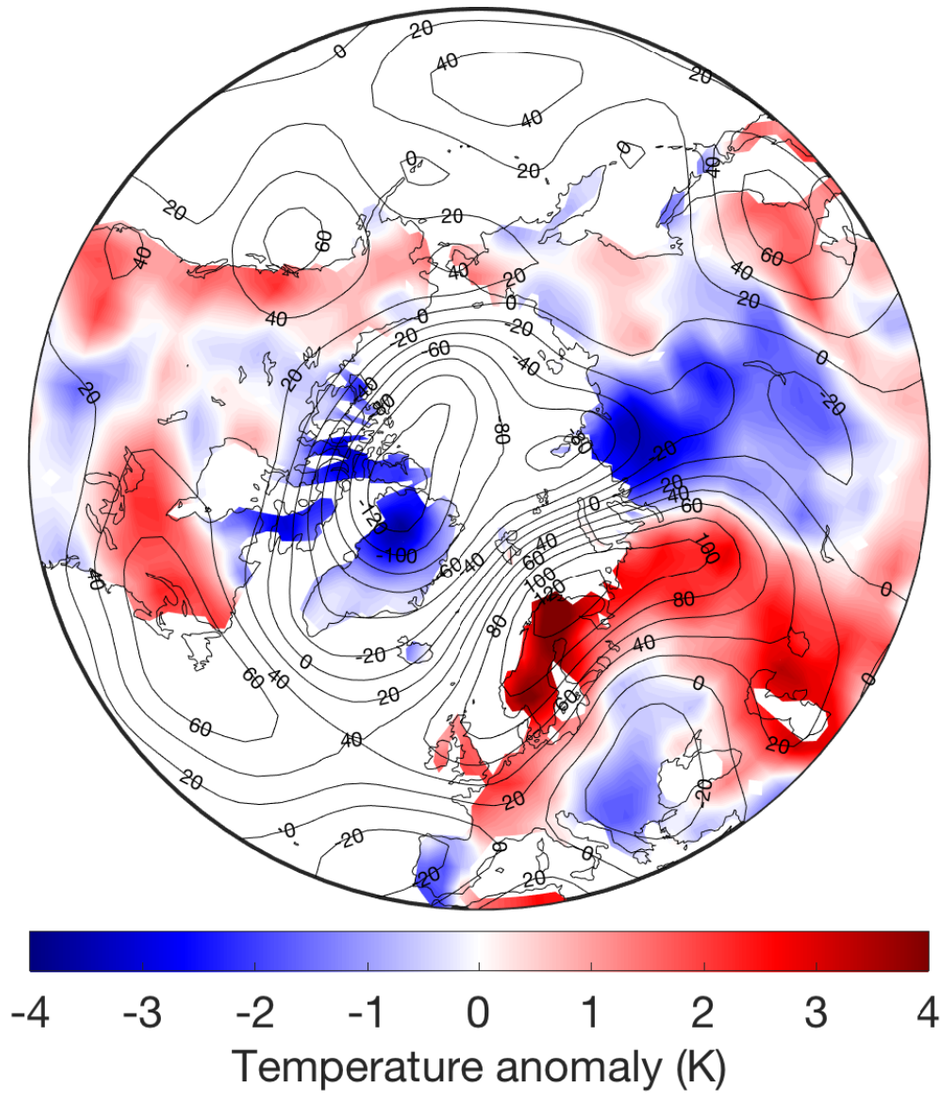


Ragone, Wouters, Bouchet. *PNAS* 2018

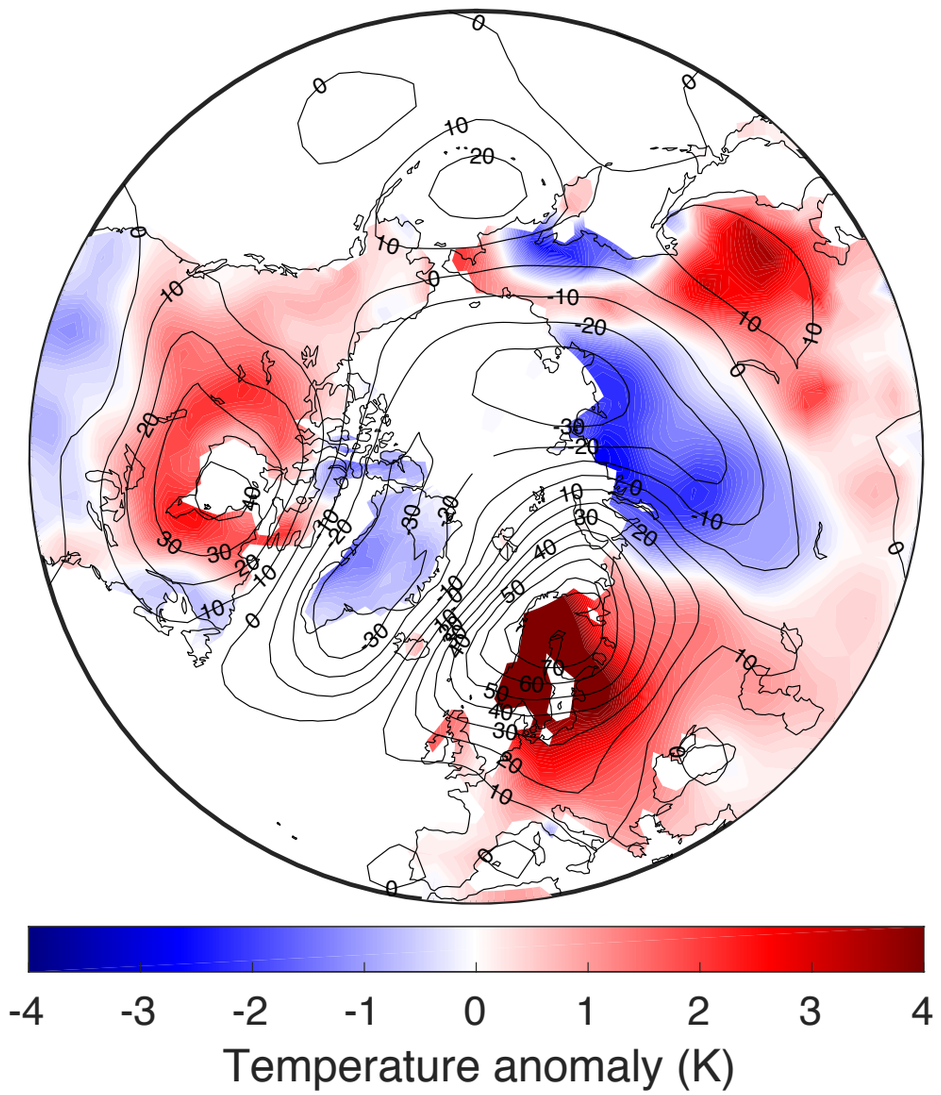
- Pattern broadly similar to Scandinavian heatwave cluster in observations
- And to July 2018 heatwave

Heatwaves and warm summers in Plasim

July 2018 heatwave (NCEP)



Composite heatwaves r>1000 years



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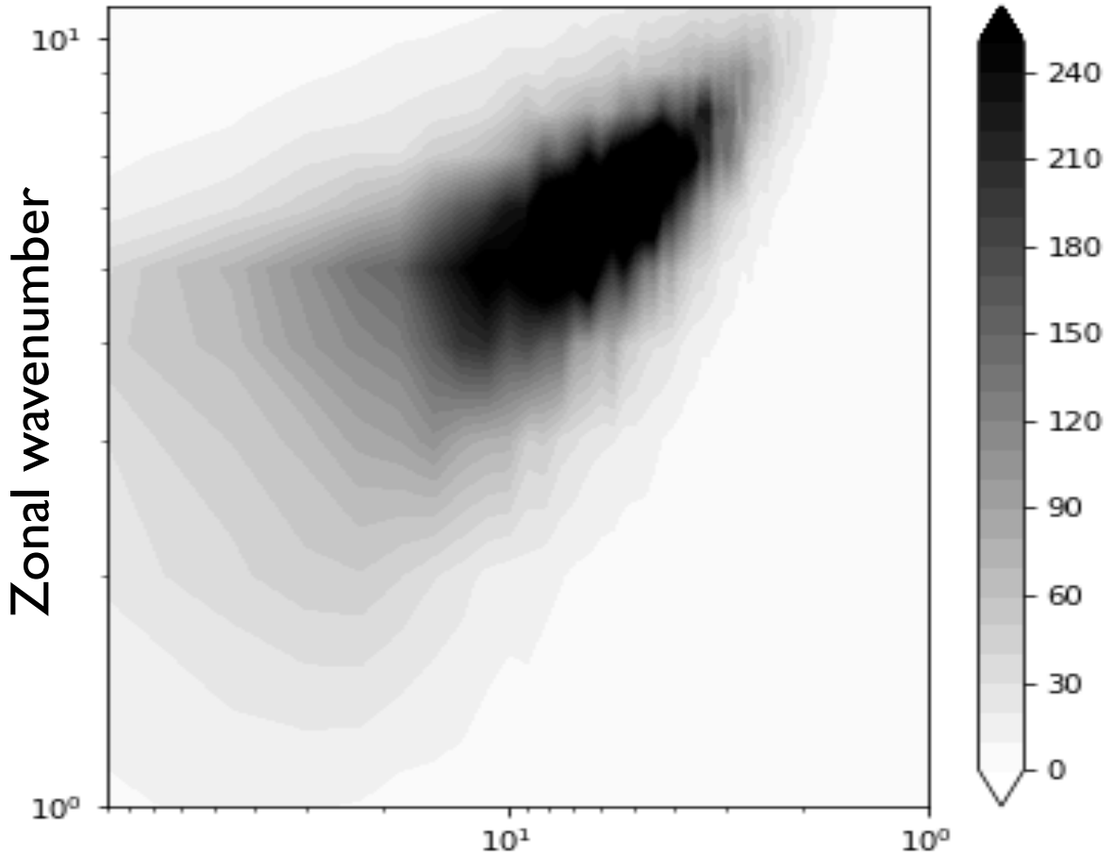
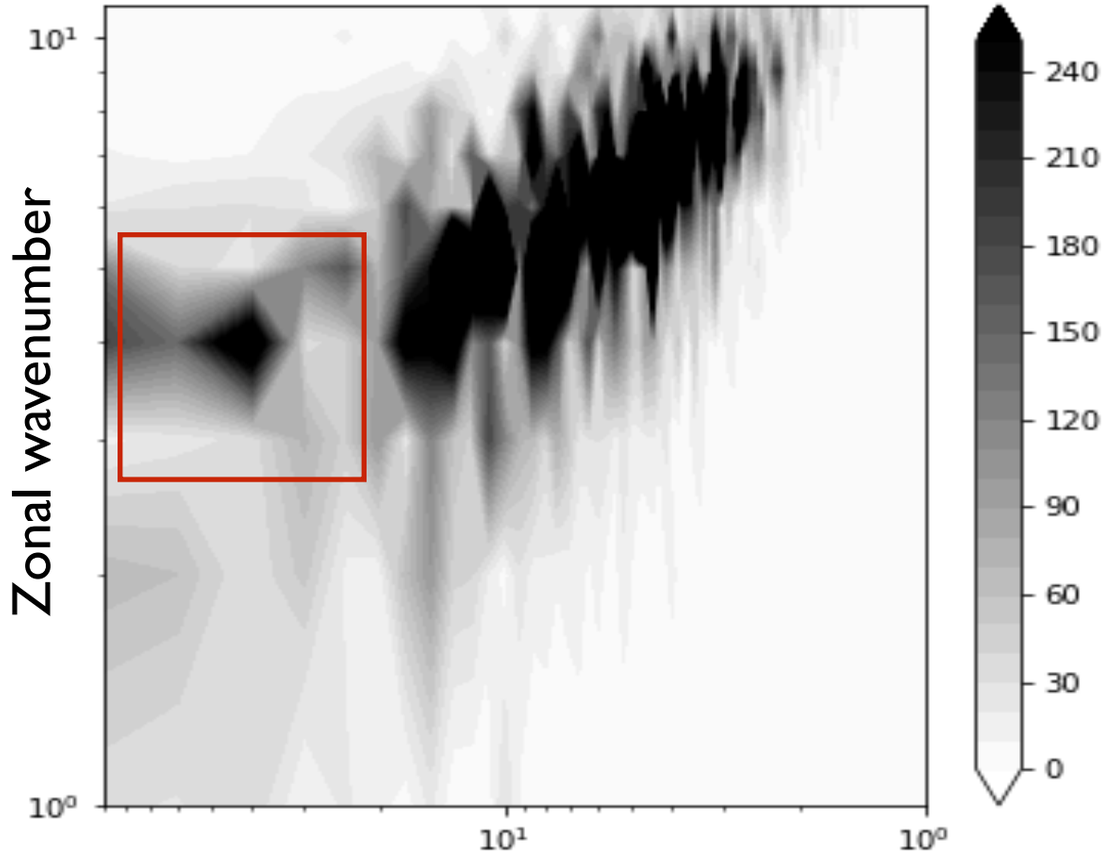
Heatwaves and warm summers in Plasim

Control spectrum

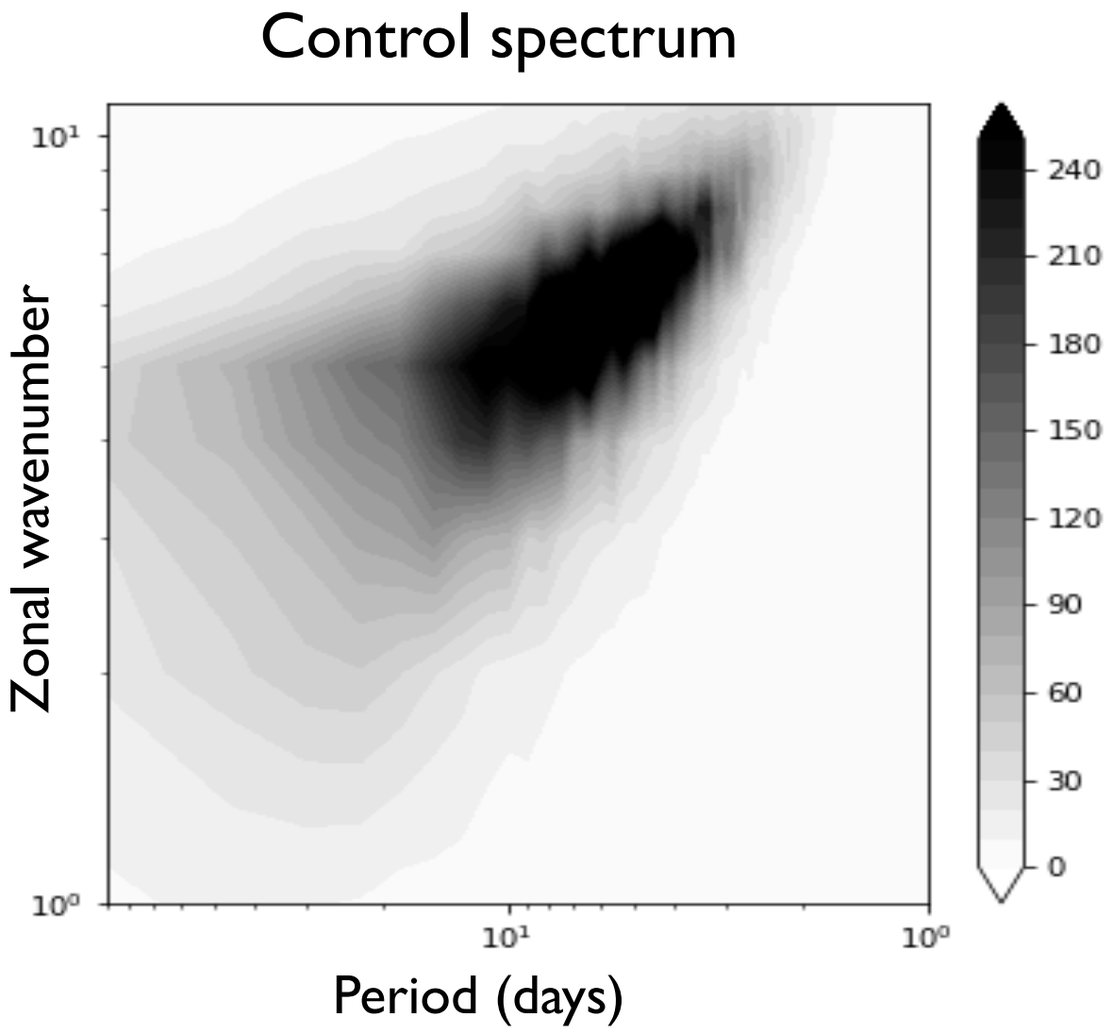


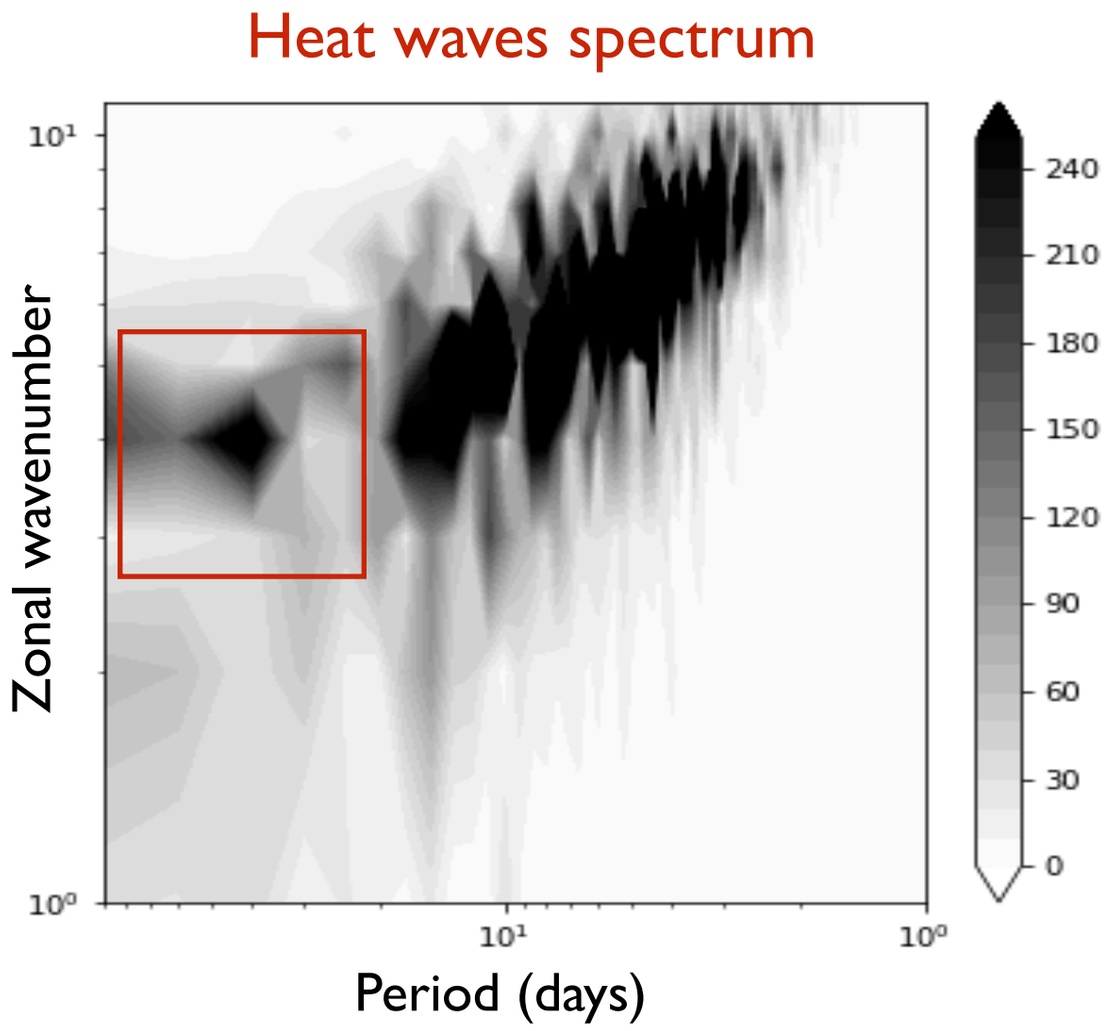
Heat waves spectrum



- Teleconnections associated with anomalous planetary wave activity
- Hayashi spectra: space-time spectral analysis of gph averaged between 30 and 75 °N
- Eastward propagating waves spectrum shows low wavenumber "slow" structure

Heatwaves and warm summers in Plasim

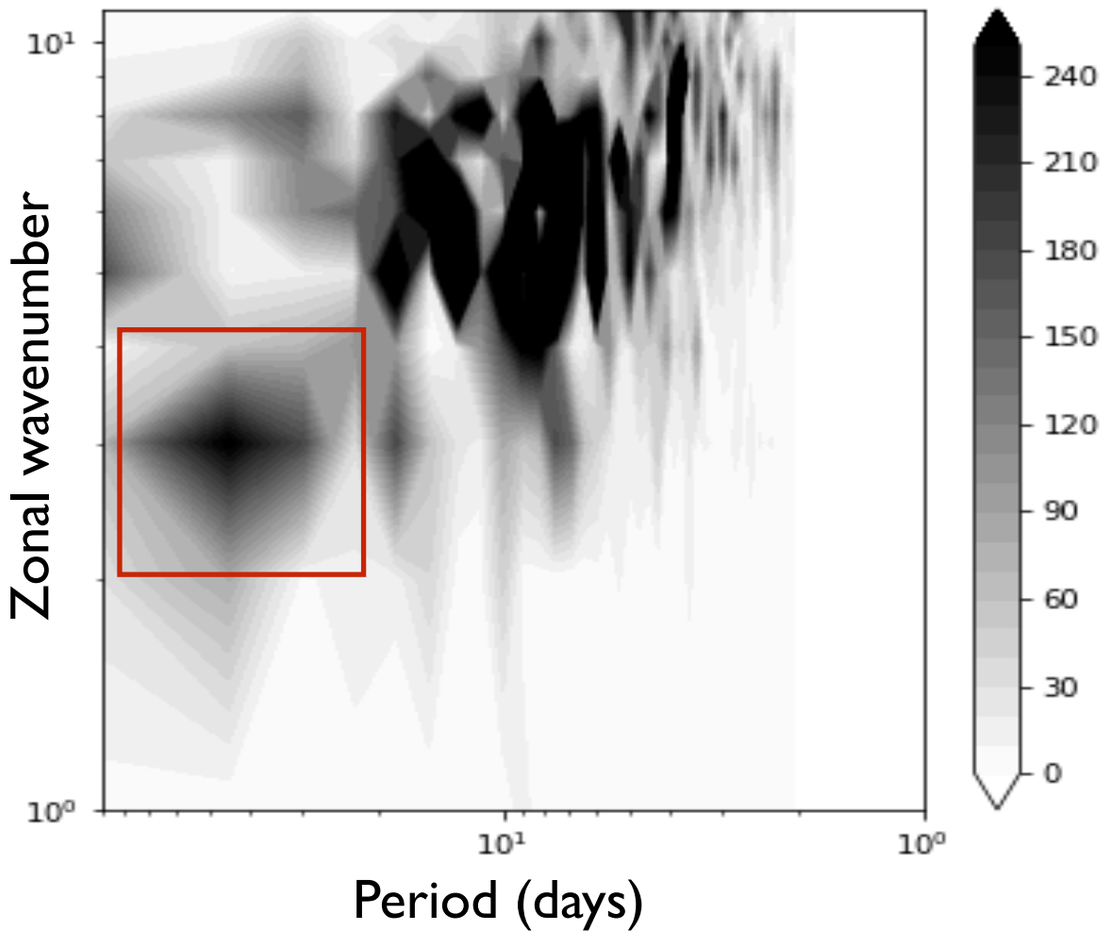




- Teleconnections associated with anomalous planetary wave activity
- Hayashi spectra: space-time spectral analysis of gph averaged between 30 and 75 °N
- Eastward propagating waves spectrum shows low wavenumber "slow" structure
- Amplification of quasi-stationary planetary waves? (e.g. Petoukhov et al., *PNAS* 2016)

Heatwaves and warm summers in Plasim

JJA 2018 spectrum from NCEP data



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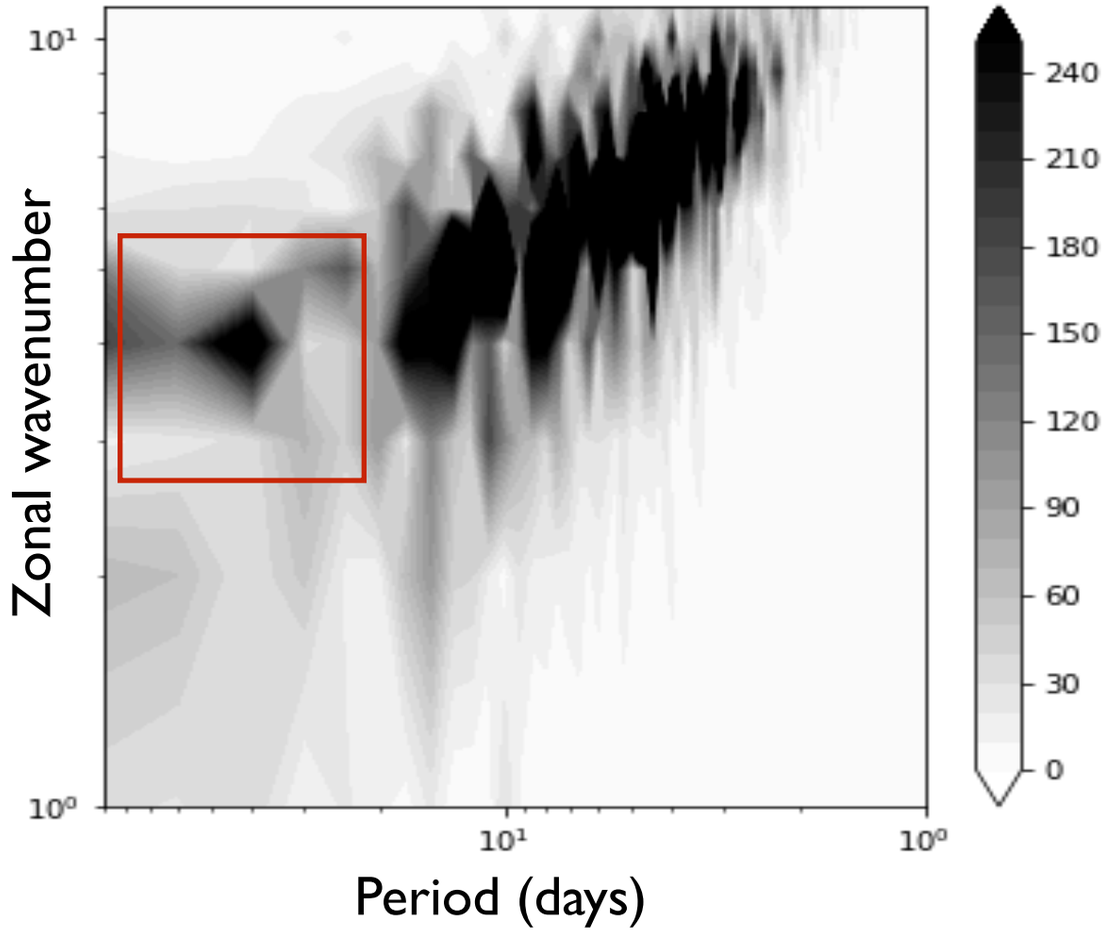
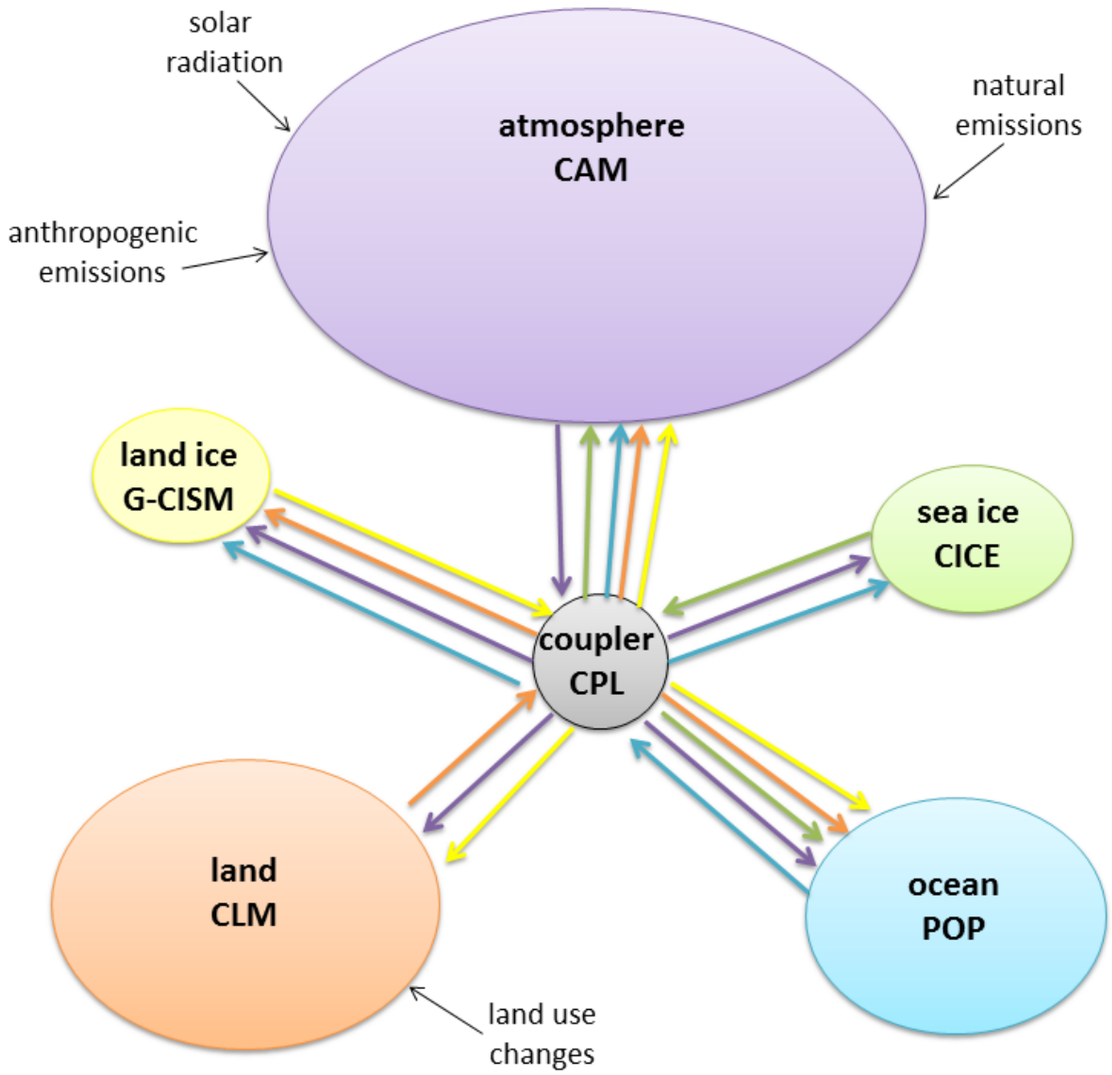


- Similar results for summer 2018: heat waves in Scandinavia, Japan and Canada

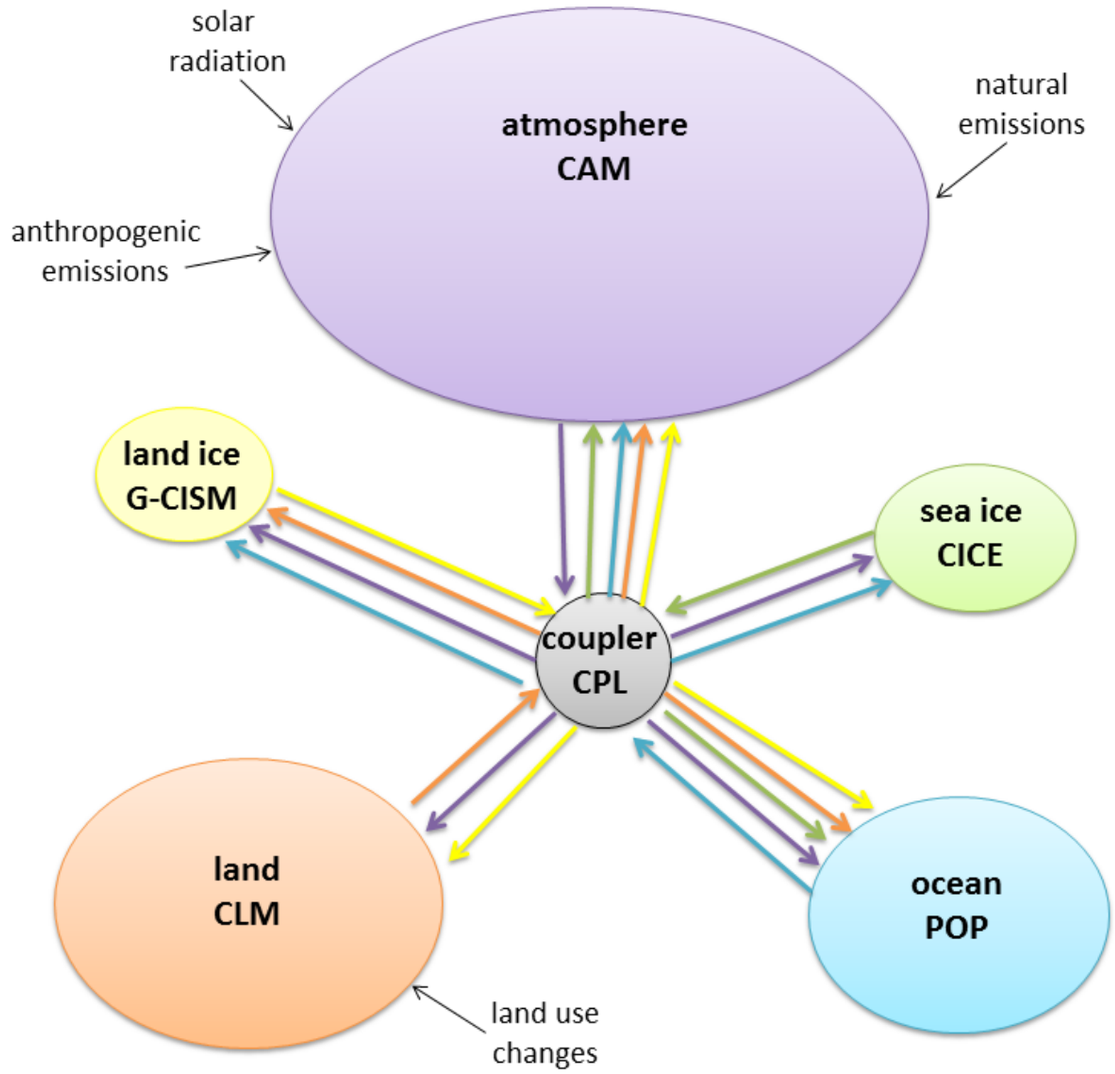
- Open discussion on role of wavenumber 7 structure for this event (Kornhuber & al., *ERL* 2019), lower wavenumbers for Alberta wildfires 2016, Russian heat waves and Pakistan floods 2010, and several other events… we can provide needed statistics!

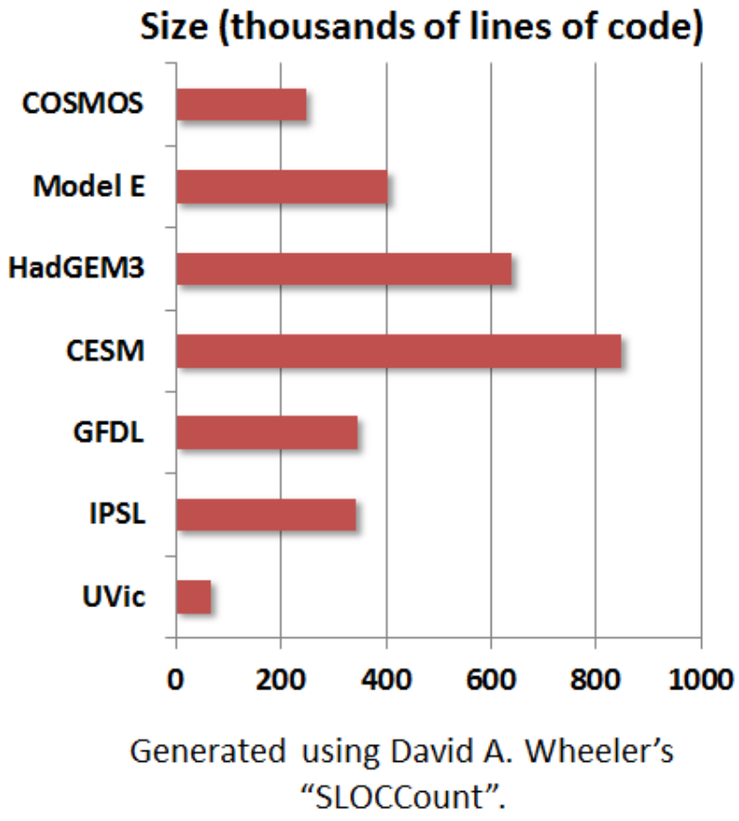
Experiments with climate model CESM



- Same exercise with CESM1.2, NCAR "IPCC-standard"
- Higher resolution (1° horizontal, 26 levels), MUCH more complex physics
- We still use prescribed SST (but with seasonal and daily cycles)

Experiments with climate model CESM





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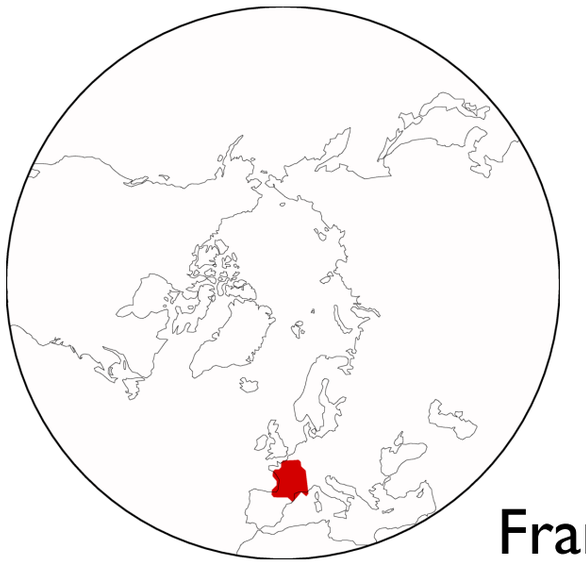
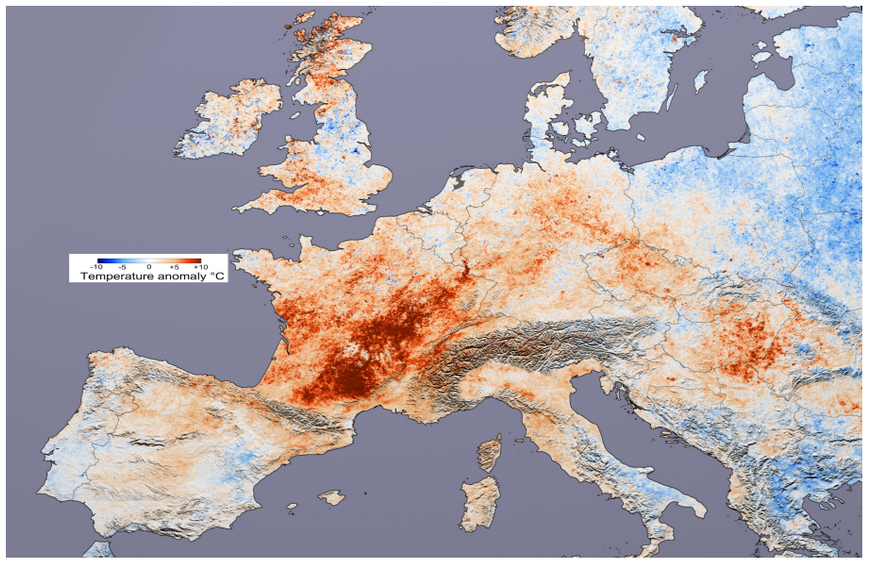
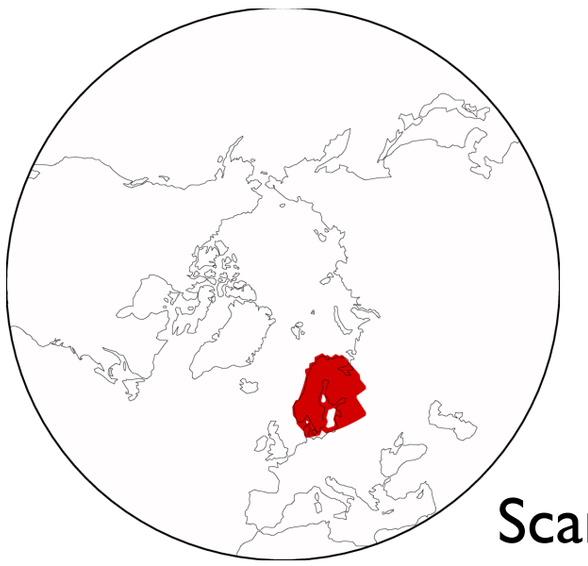


France

ca. 2003 area

WE cluster

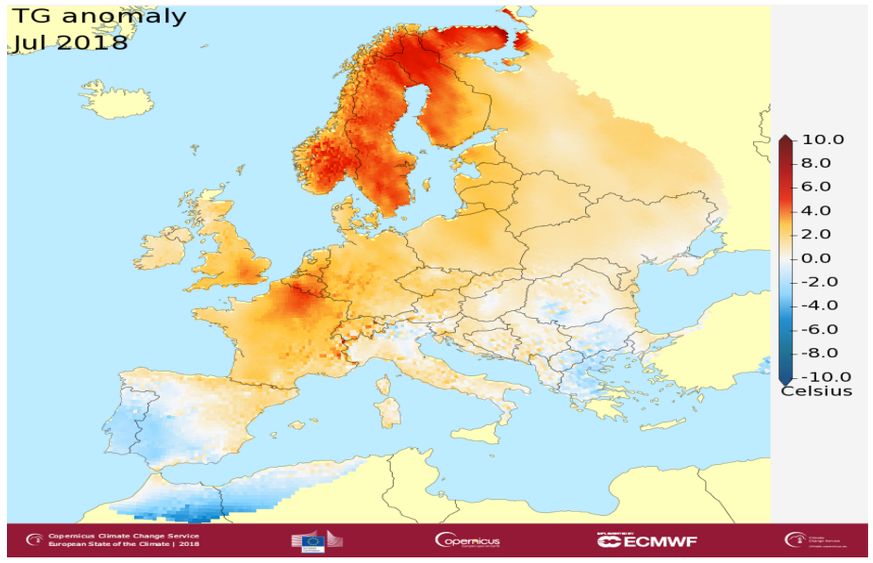




Scandinavia

ca. 2018 area

SC cluster

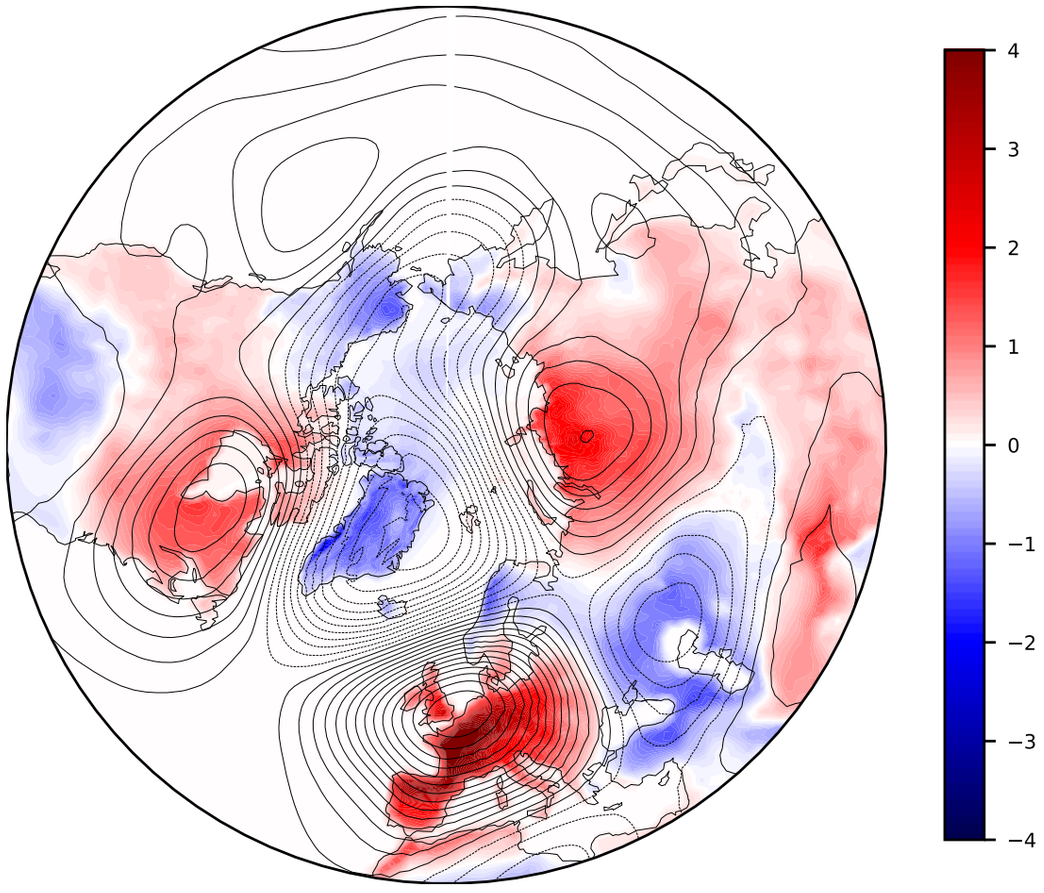


- Two sets of 10 experiments targeting temperature over France or Scandinavia

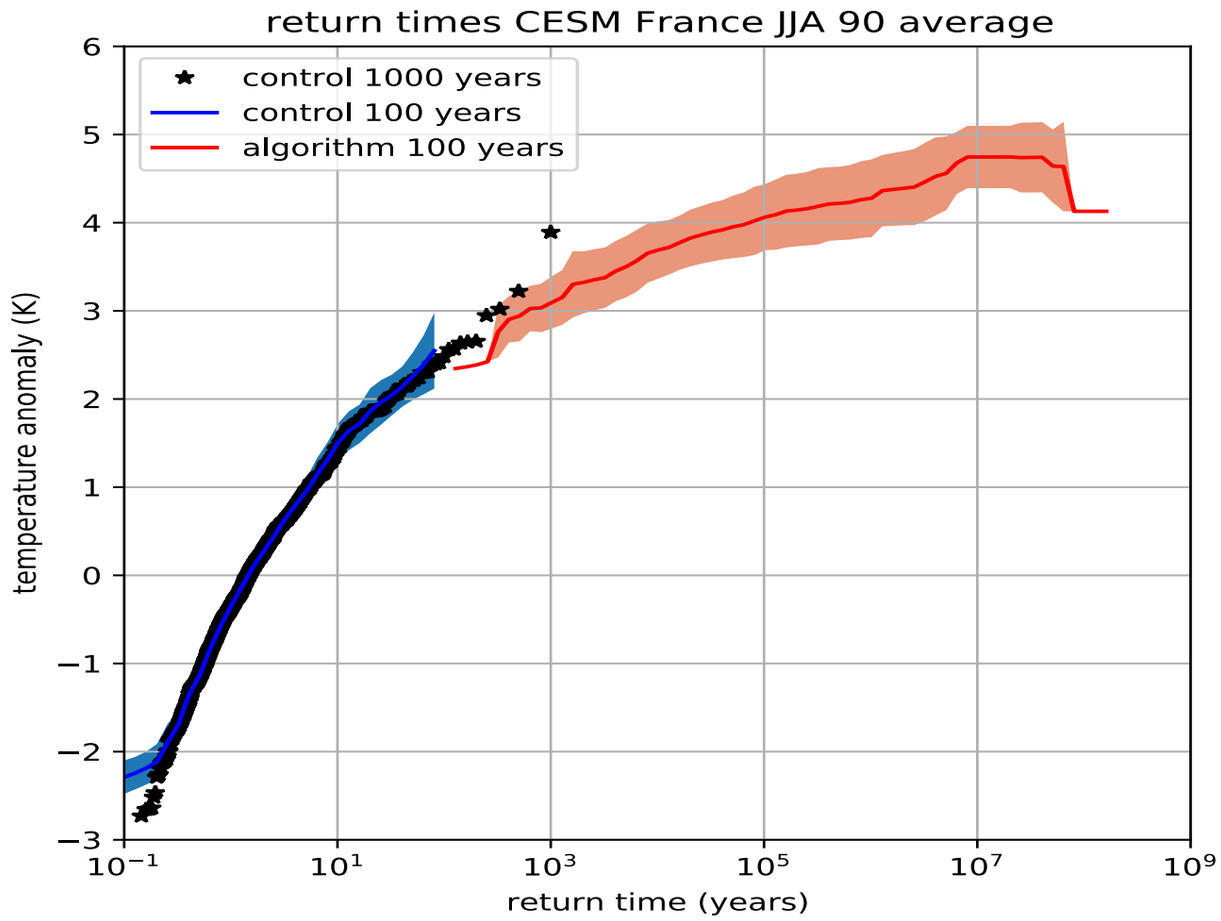
- Each experiment ensemble 100 trajectories running for one summer (JJA), 25 yers equivalent computational cost. Total for each region 250 years (manageable)

Experiments with CESM: heatwaves over France

France warm summers r>1000 years



return time summer temperature France



Ragone and Bouchet, *GRL* 2021

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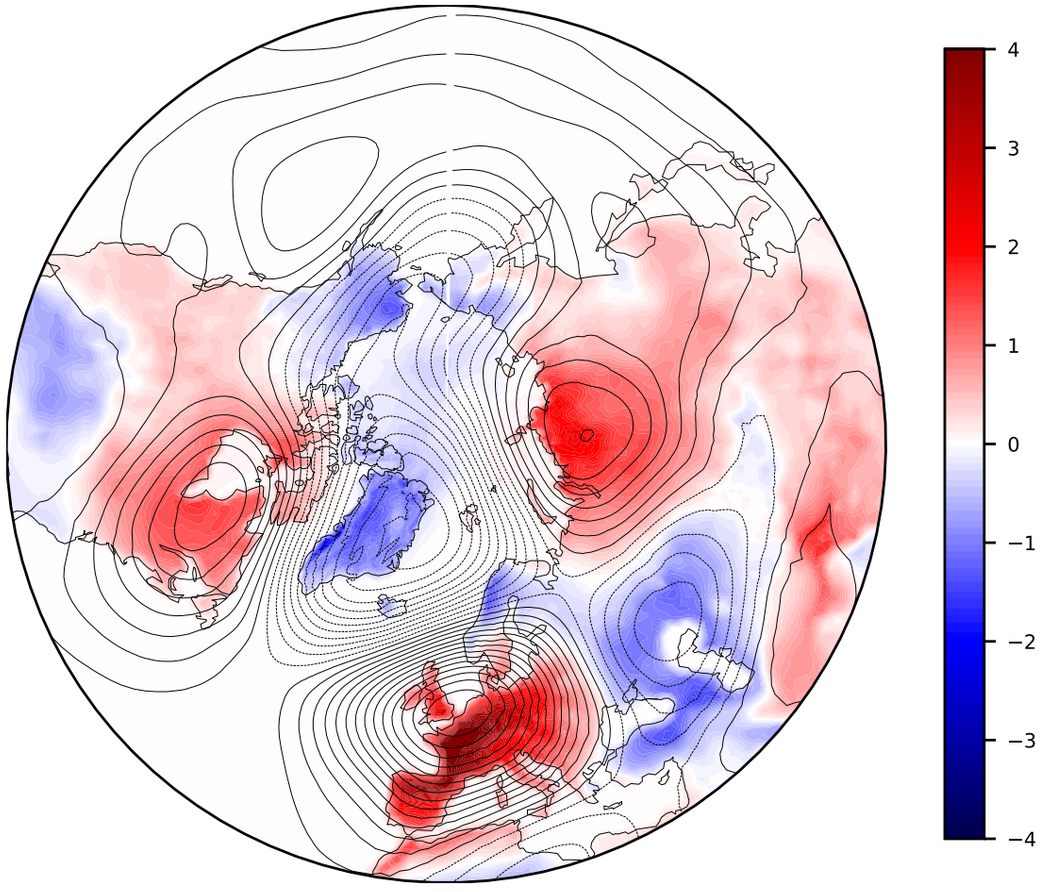
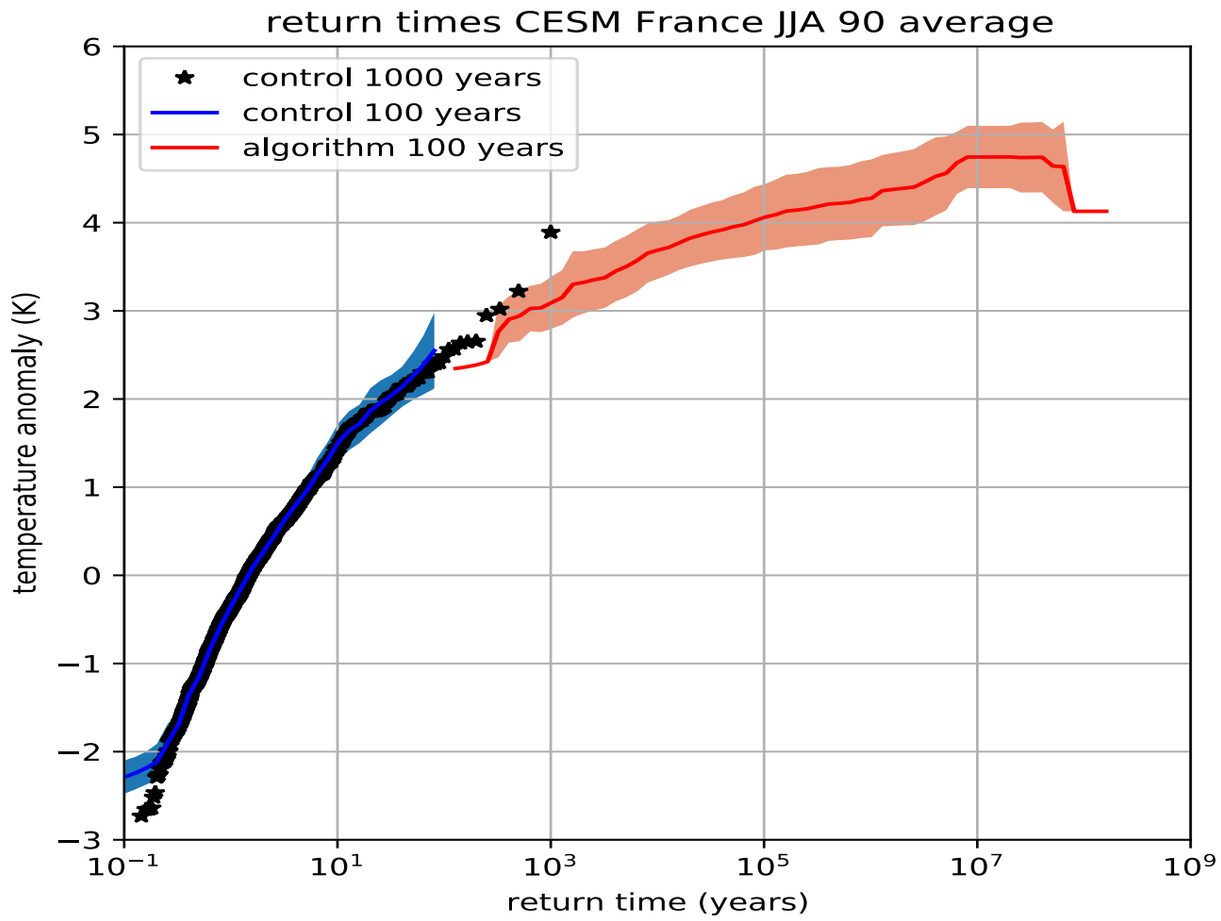


return time summer temperature France



Ragone and Bouchet, *GRL* 2021

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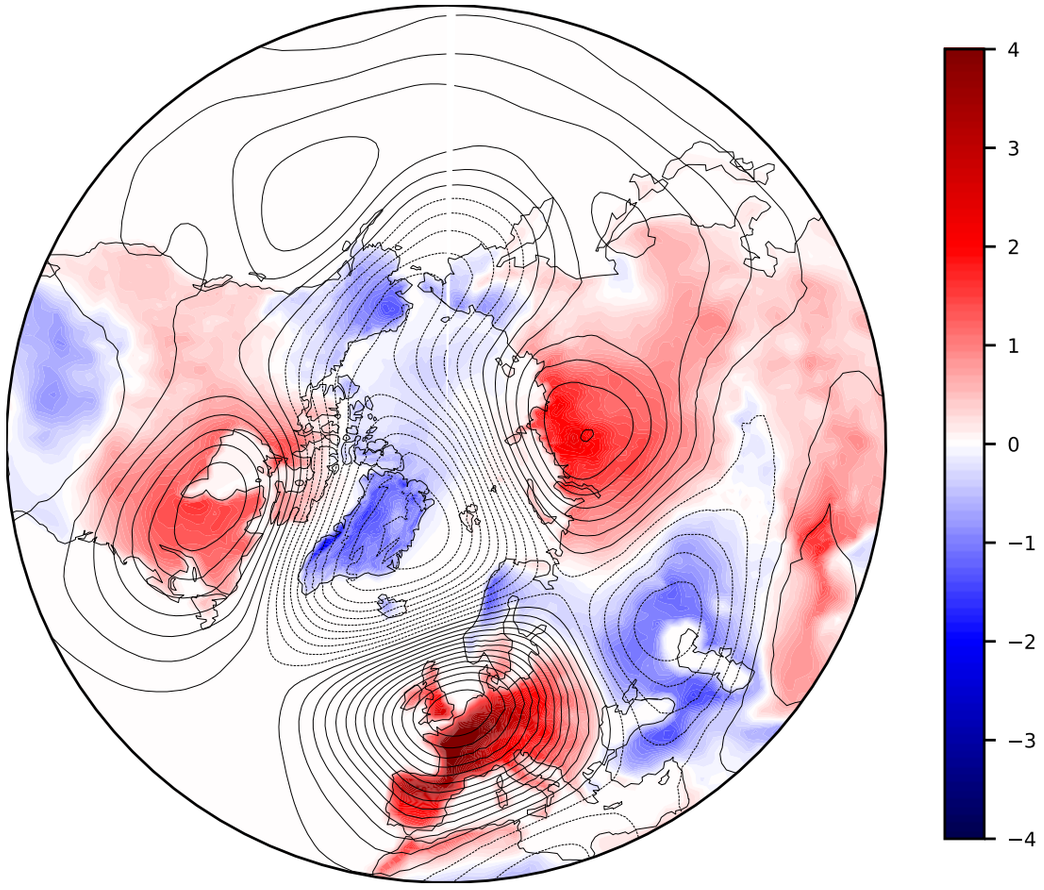
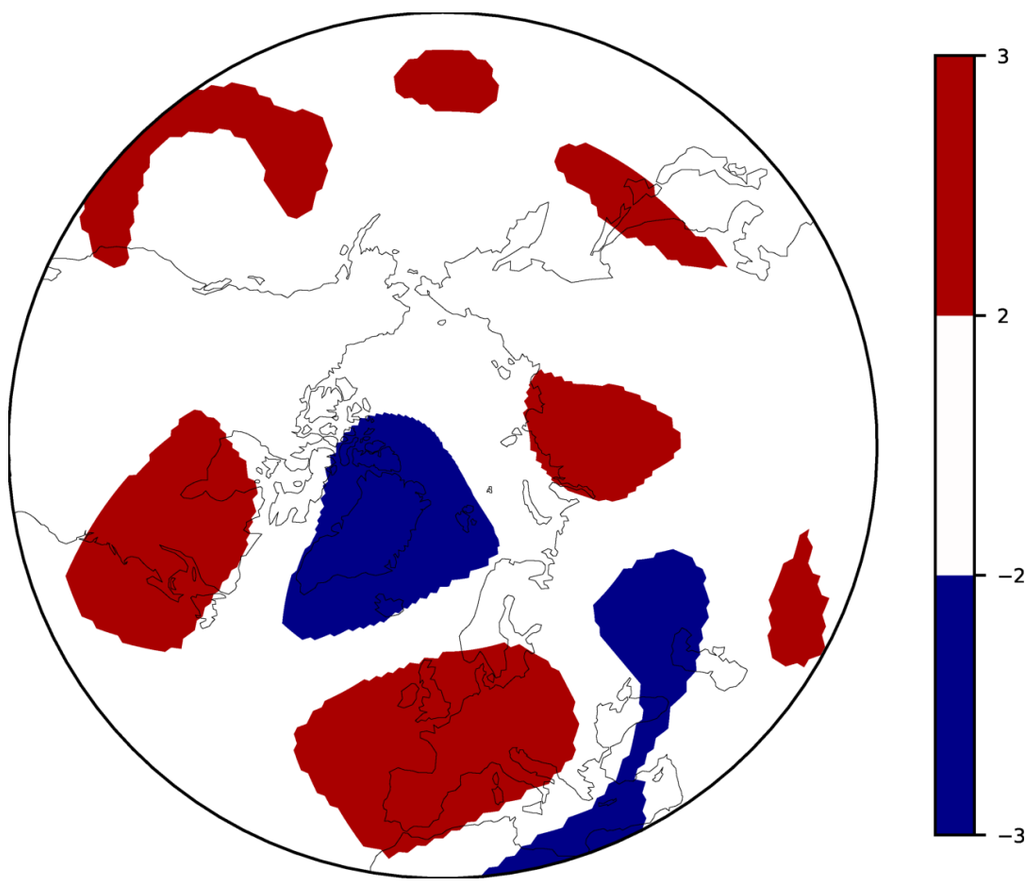


t-values

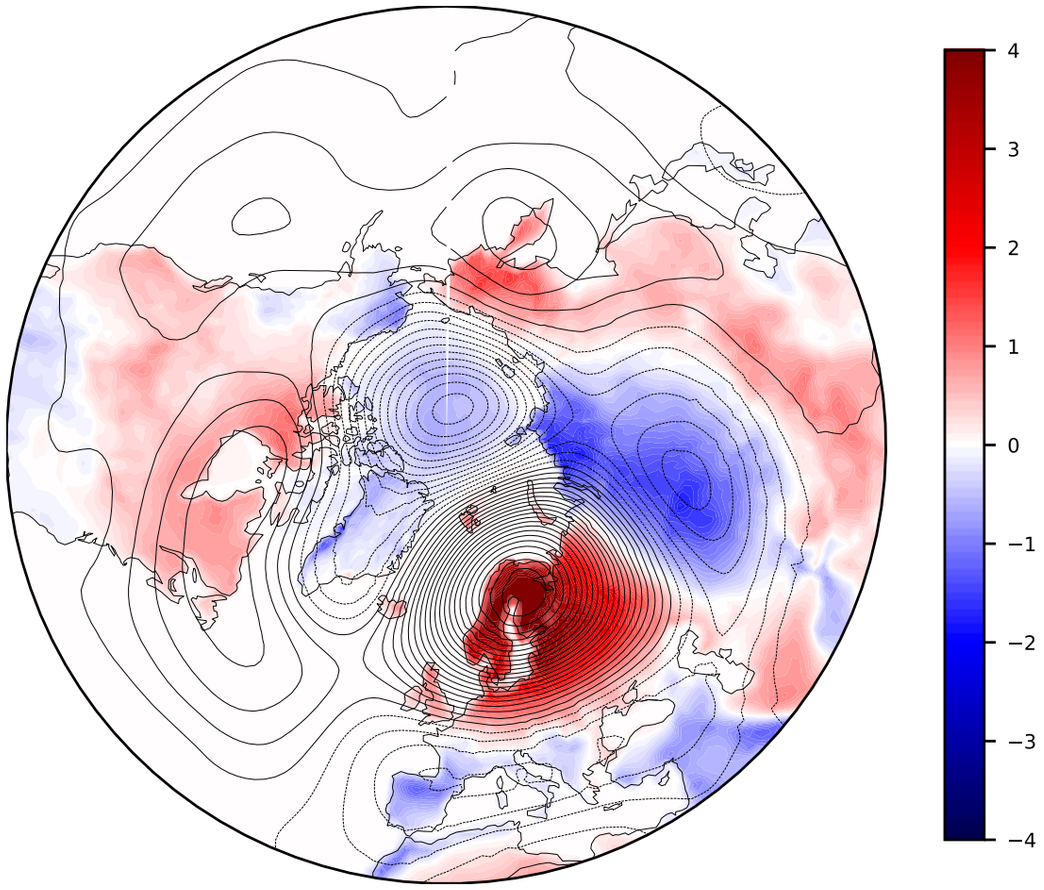


Ragone and Bouchet, *GRL* 2021

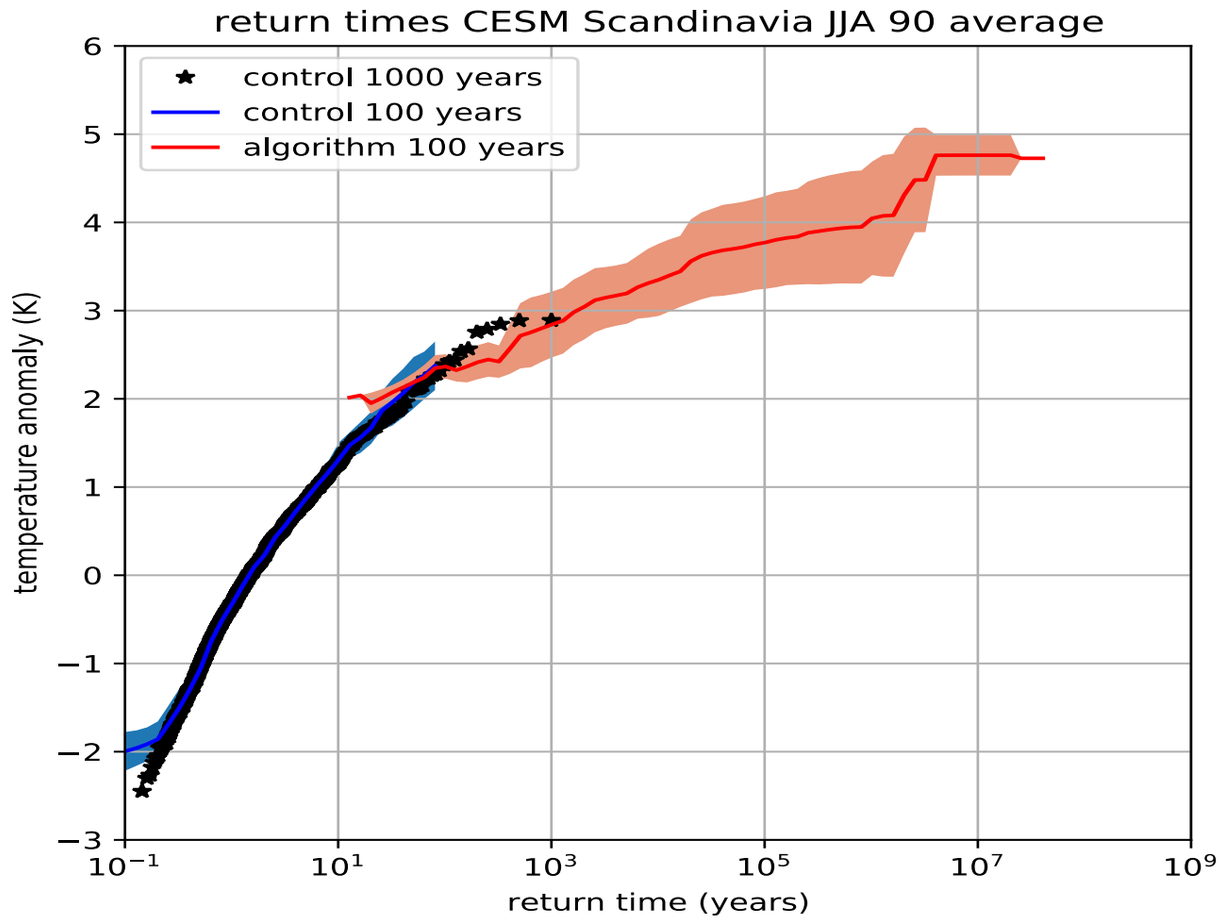
- Results confirmed: we can work with state-of-the-art global climate models
- Detected statistically significant teleconnection patterns with wavenumber 3-4
- Significancy analysis extremely hard in "normal" data (observation or direct simulations)

Experiments with CESM: heatwaves over Scandinavia

Scandinavia warm summers r>1000 years



return time summer temperature Scandinavia



Ragone and Bouchet, *GRL* 2021

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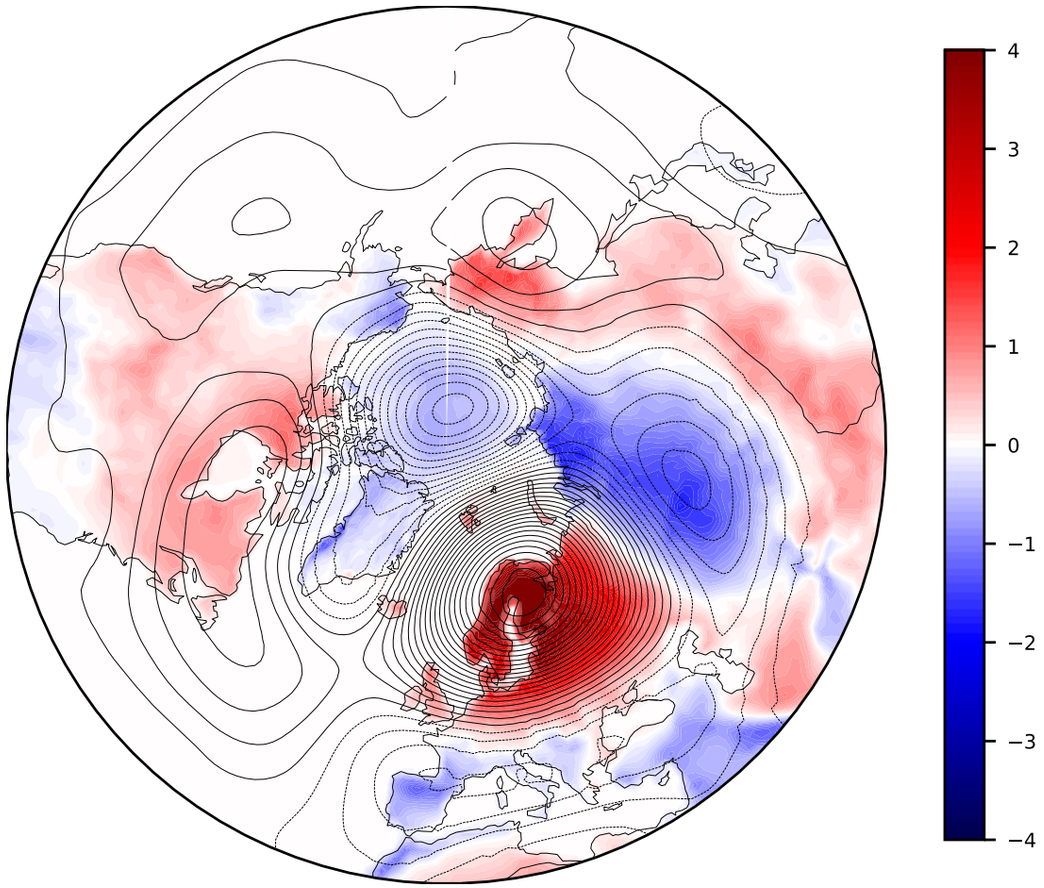
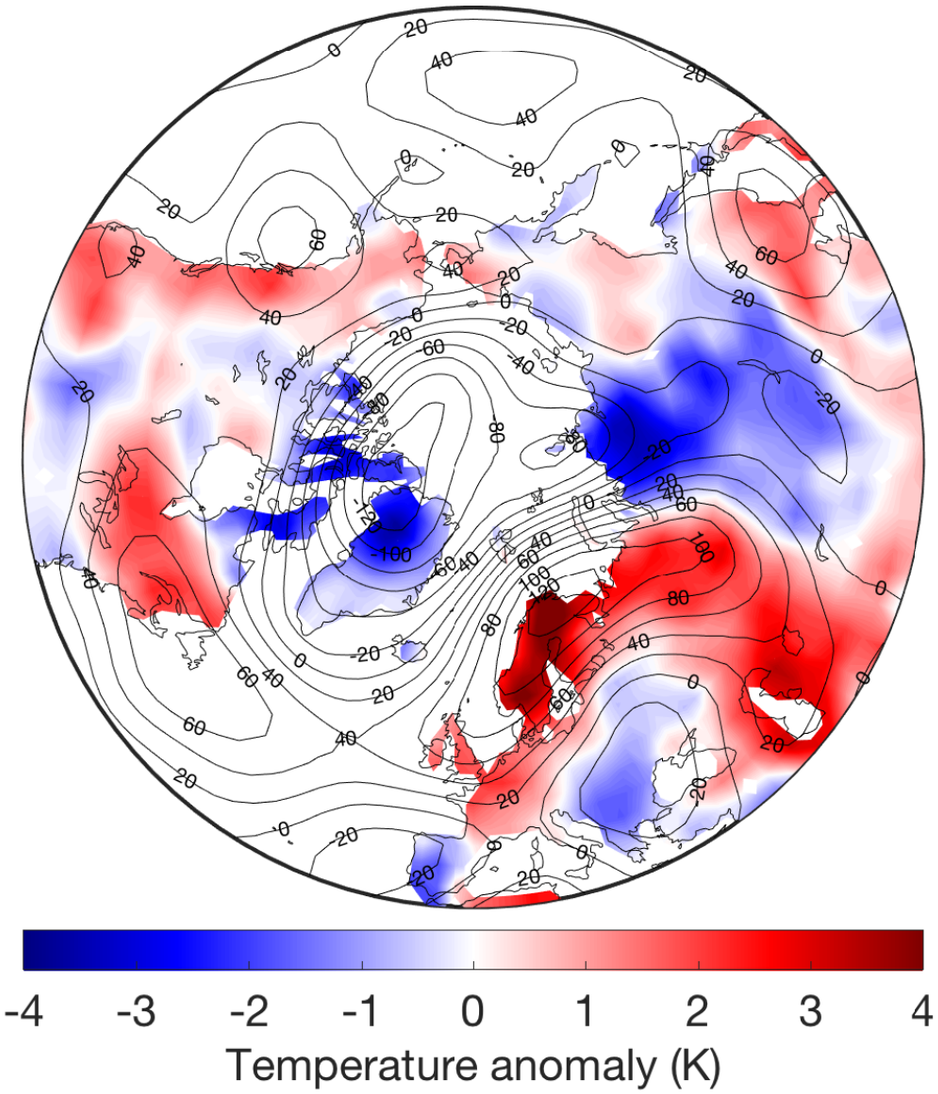


Ragone and Bouchet, *GRL* 2021

July 2018 heatwave (NCEP)



- Results confirmed: we can work with state-of-the-art global climate models
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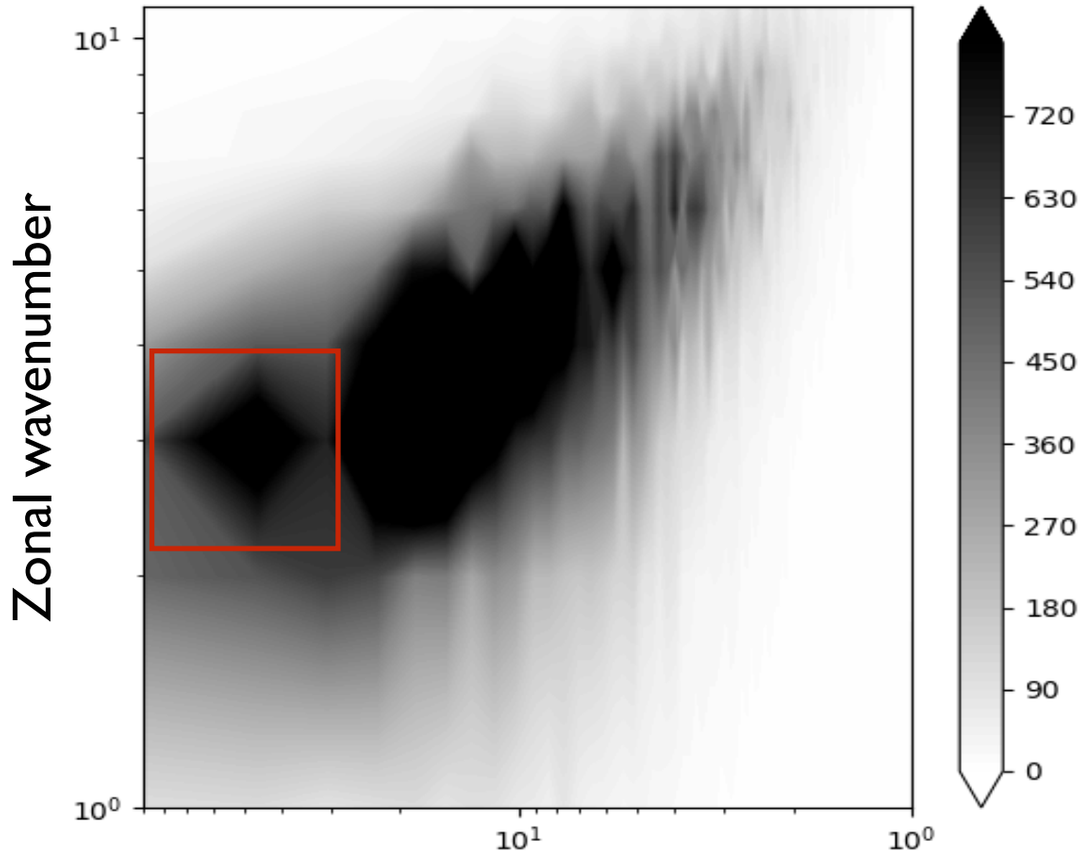
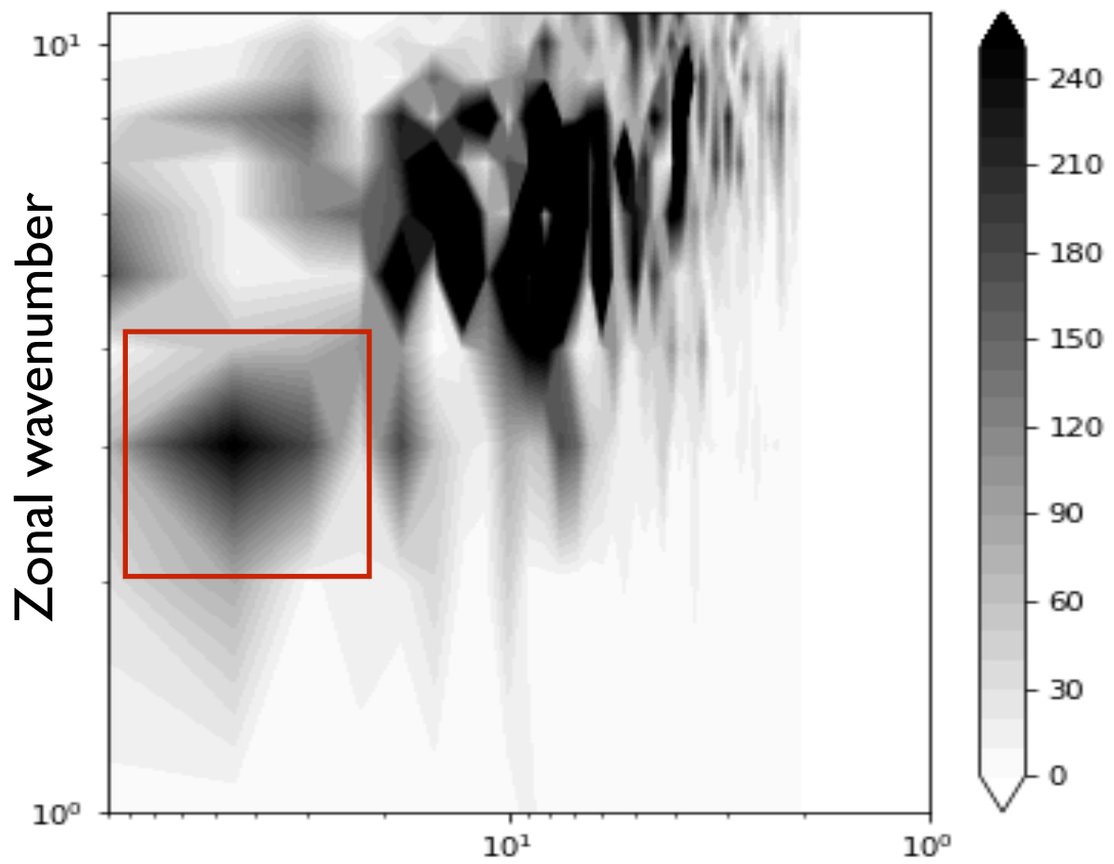
- Scandinavia pattern matches extremely well with observed 2018 event

Experiments with CESM: heatwaves over Scandinavia

Heat waves spectrum



JJA 2018 spectrum from NCEP data



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Experiments with CESM: heatwaves over Scandinavia

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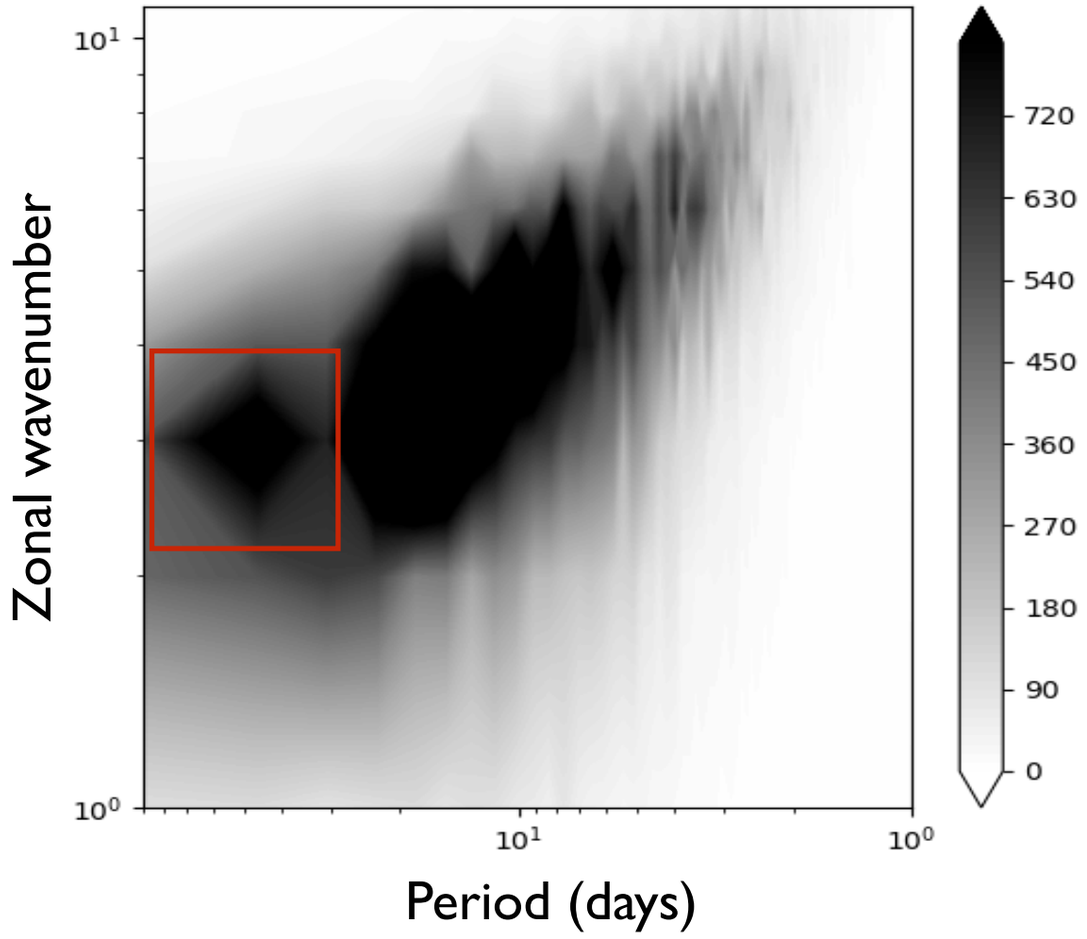


Heatwave July 2018

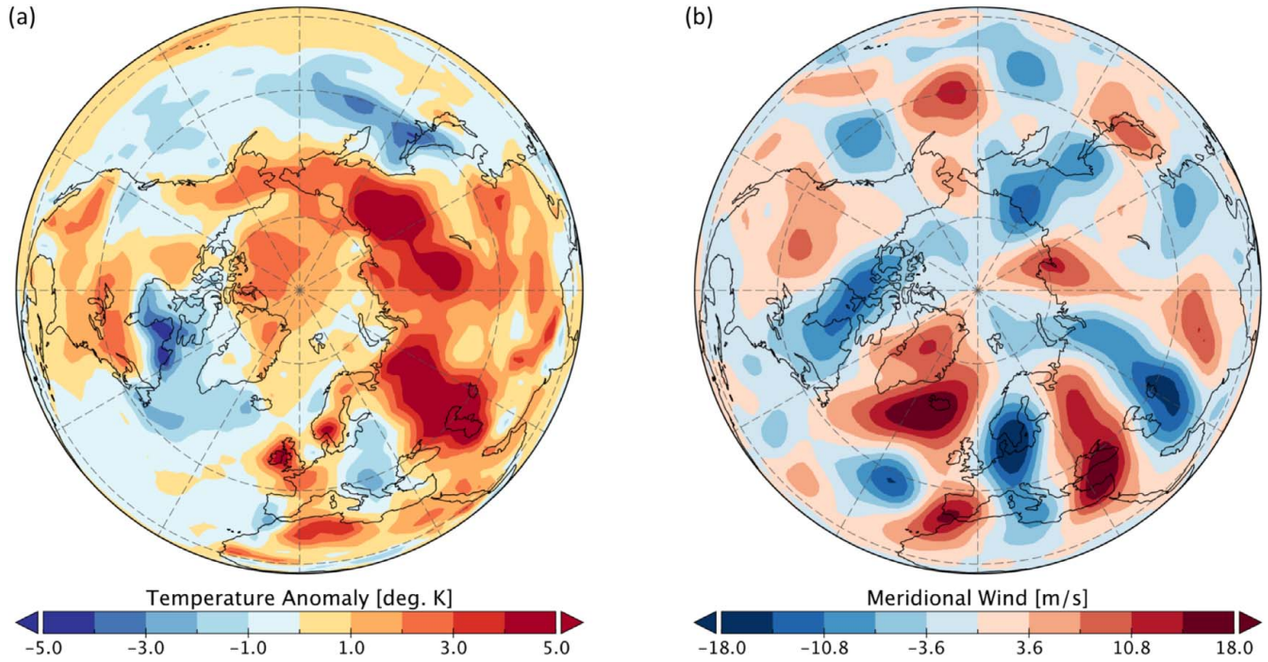
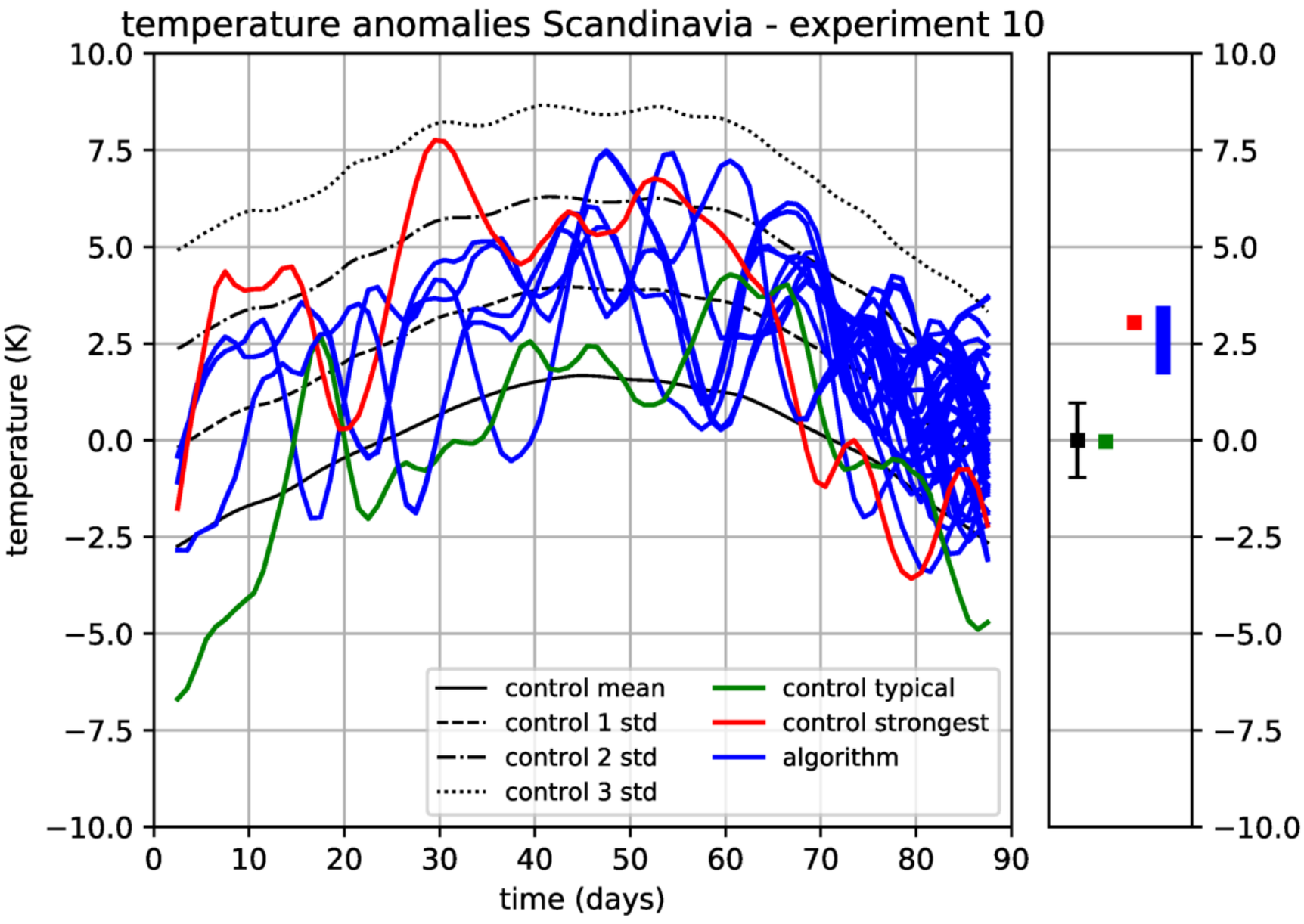


Figure 1. Northern Hemisphere temperature anomalies and stationary Rossby wave pattern in early July 2018. (a) Surface temperature anomalies (from 1981 to 2010 climatology; 15 d mean, centered on 1 July 2018). (b) As (a) but for meridional wind V (m s^{-1}) in the upper troposphere (300 mb). Dashed lines indicate the longitudes and latitudes grid at 30° separation.

Kornhuber et al, *Environ. Res. Lett.*, 2019

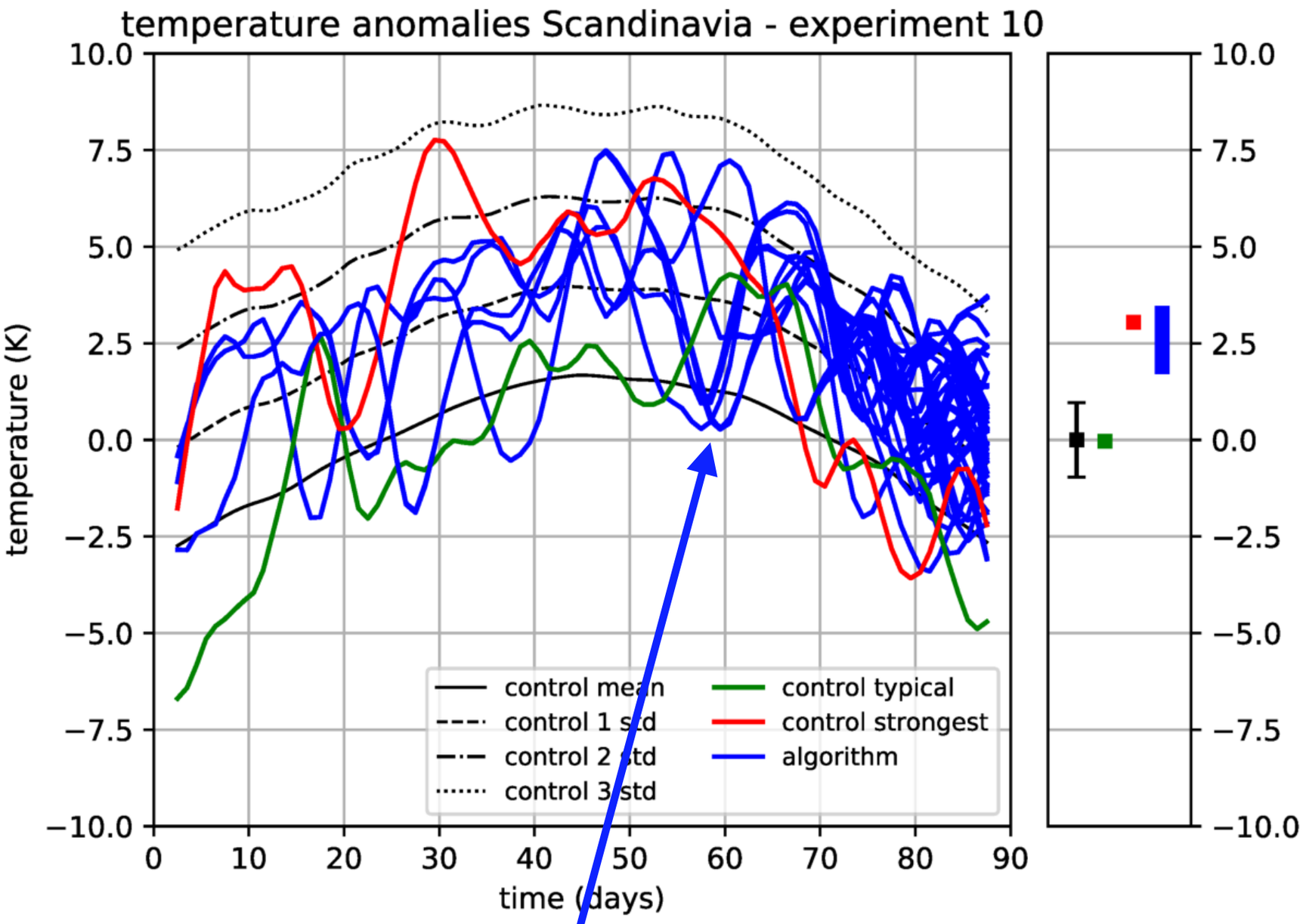
- Results confirmed: we can work with state-of-the-art global climate models
- Detected statistically significant teleconnection patterns with wavenumber 3-4
- Way to test proposed role of quasi-stationary Rossby waves during recent heatwaves?

Experiments with CESM: heatwaves over Scandinavia



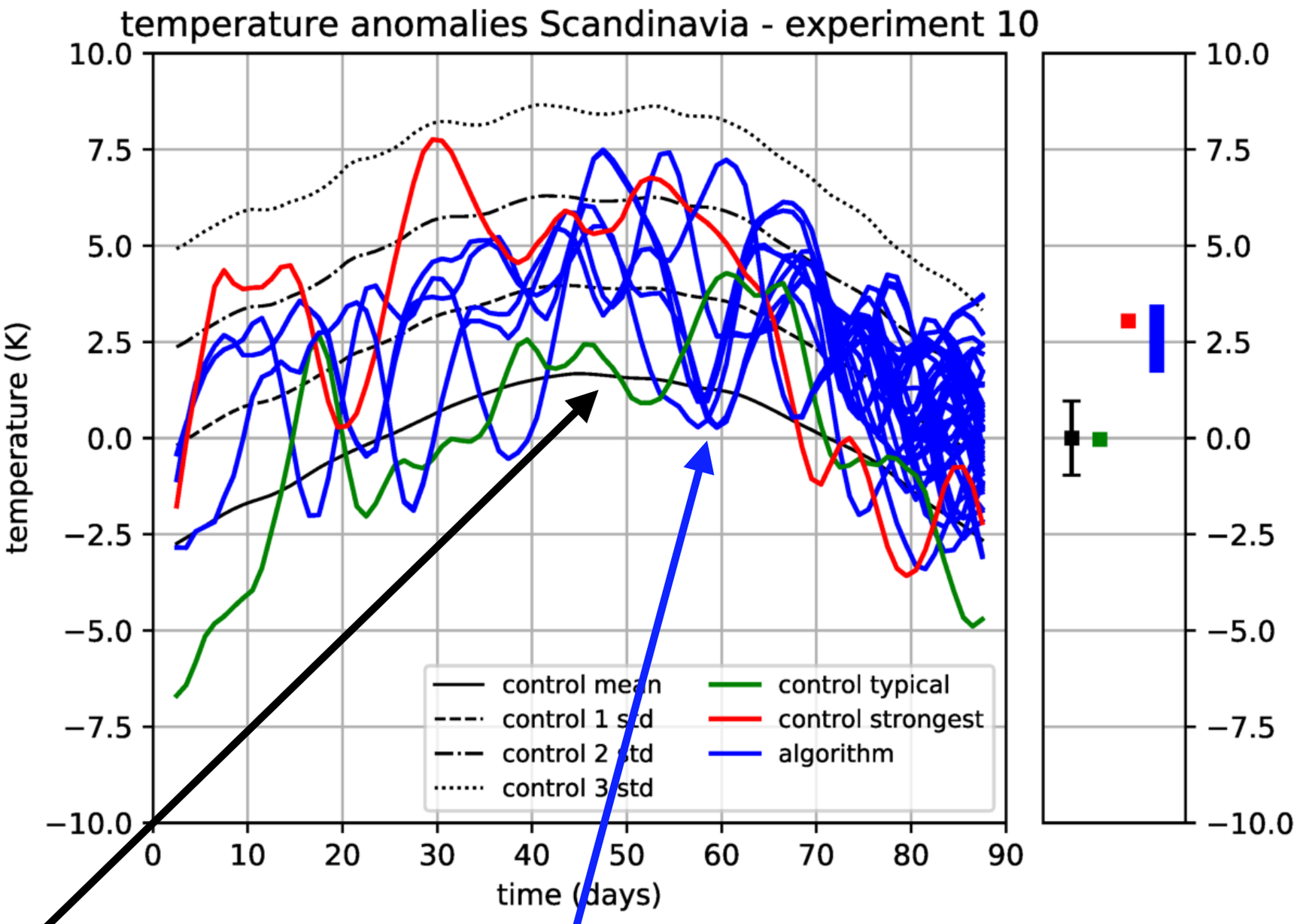
Seasonal averages

Experiments with CESM: heatwaves over Scandinavia



Rare event simulation trajectories

Experiments with CESM: heatwaves over Scandinavia



Climatology

Rare event simulation trajectories

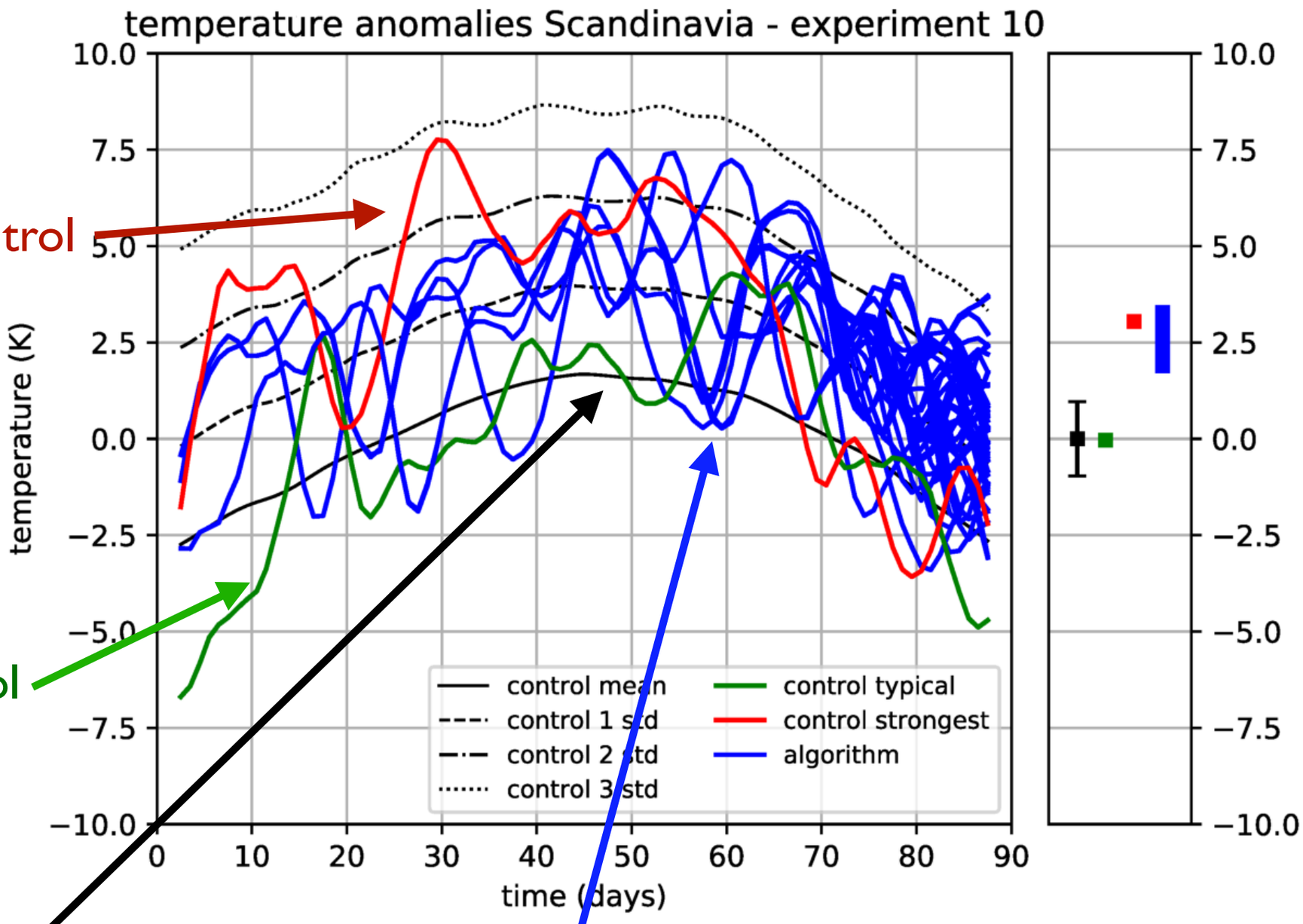
Experiments with CESM: heatwaves over Scandinavia

Strongest control

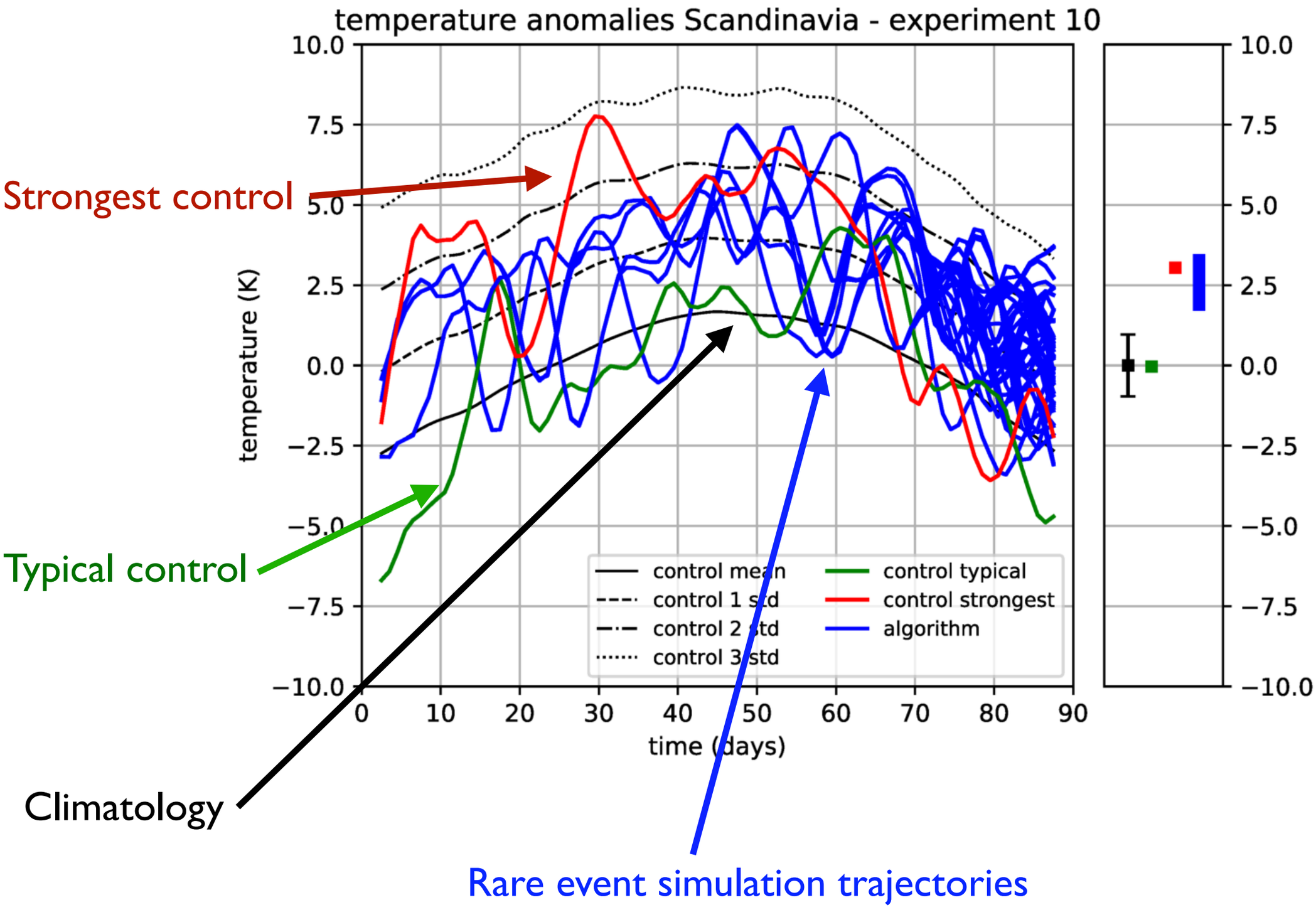
Typical control

Climatology

Rare event simulation trajectories



Experiments with CESM: heatwaves over Scandinavia



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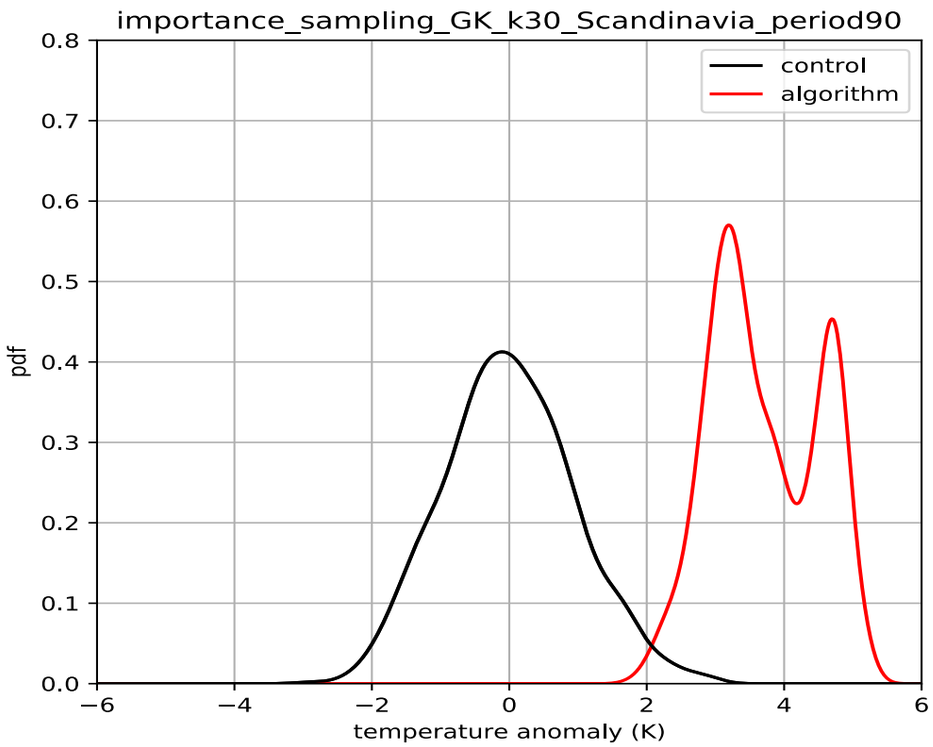
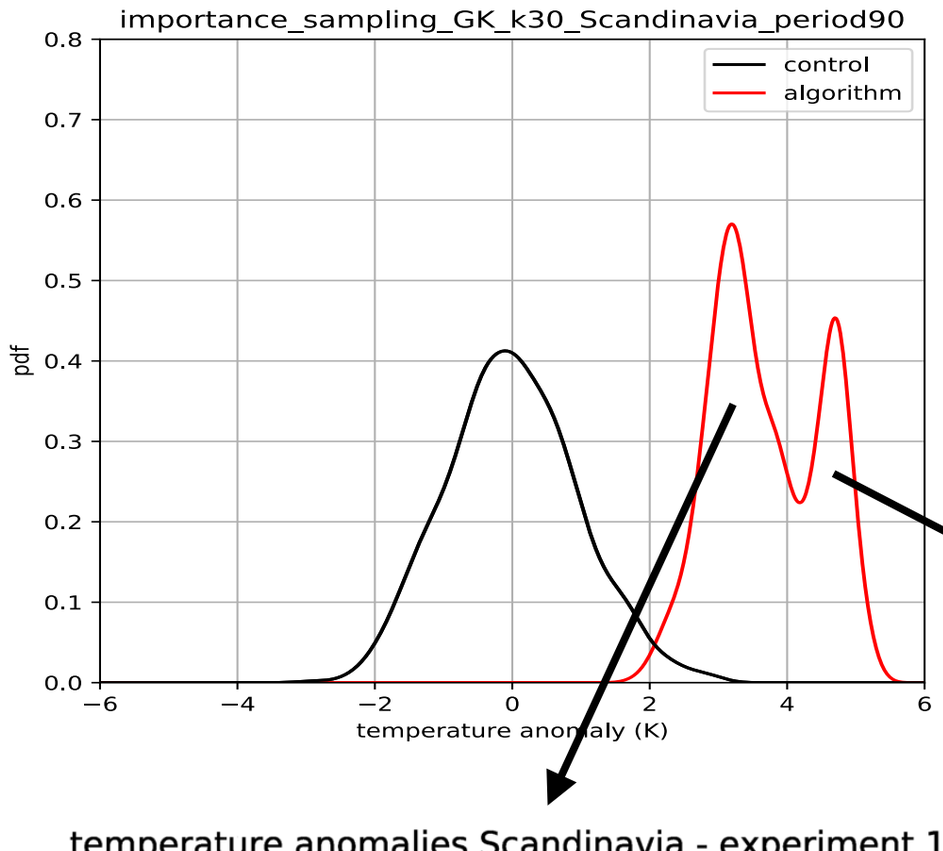


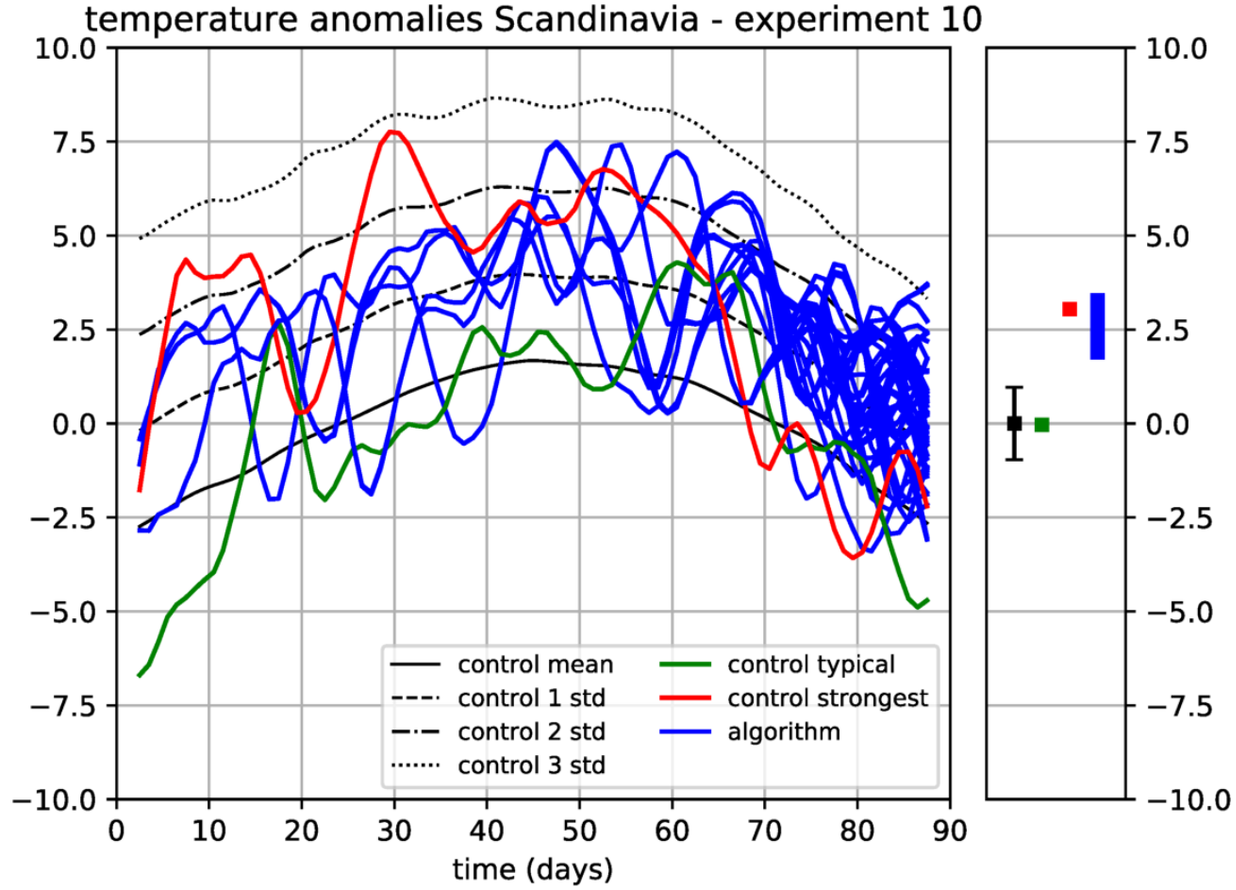
- For Scandinavia unexpected behaviour
- Bimodality distribution seasonal temperatures

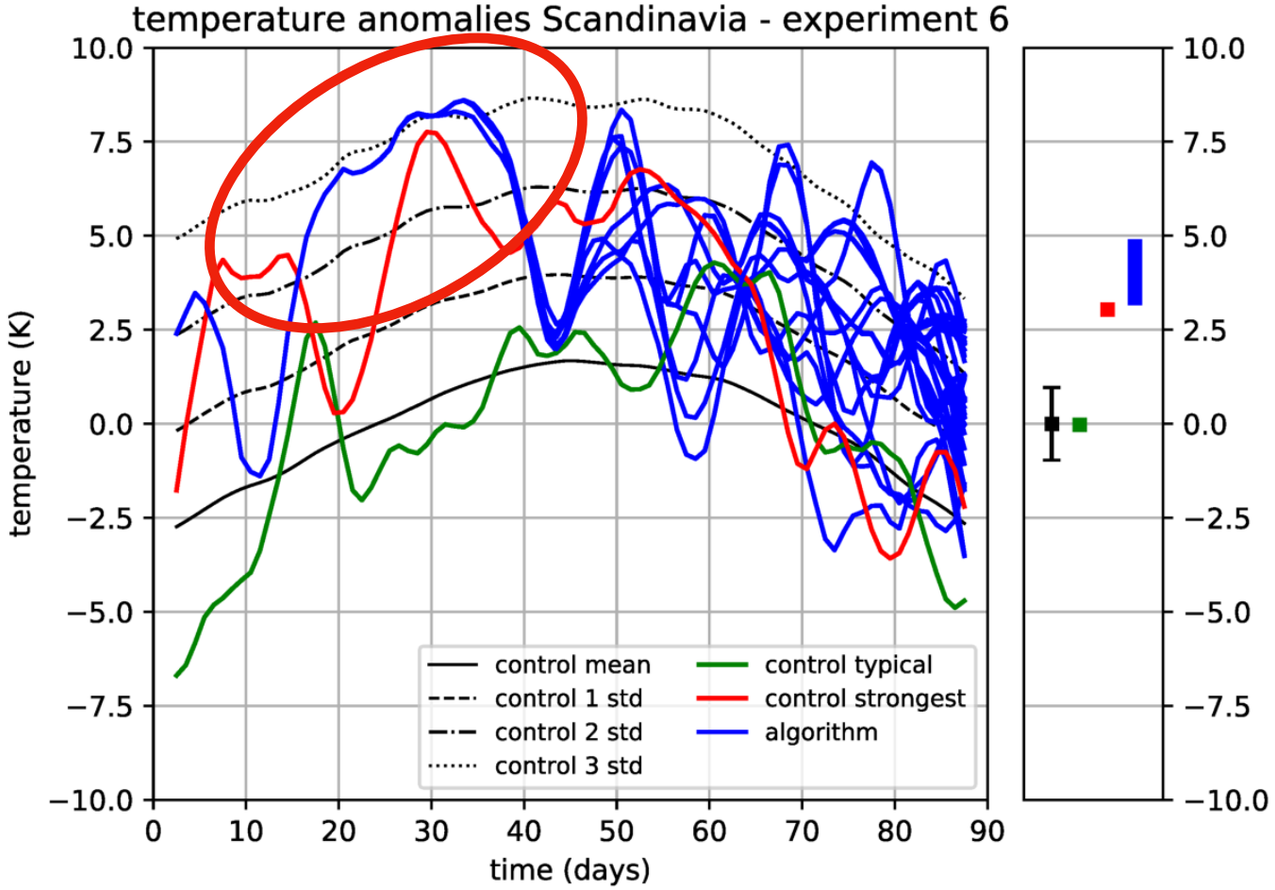
Experiments with CESM: heatwaves over Scandinavia



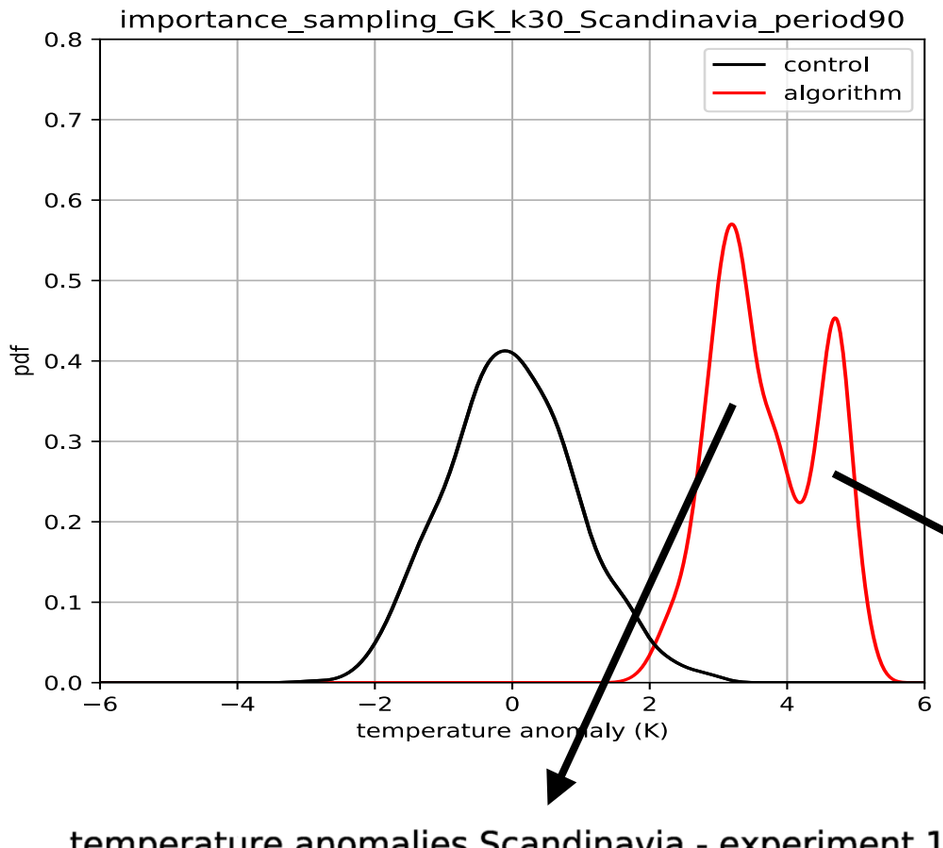
- For Scandinavia unexpected behaviour
- Bimodality distribution seasonal temperatures
- Upper mode hosts "mega-heatwave" June-July events with same characteristics in different ensembles

Ragone and Bouchet, *GRL* 2021



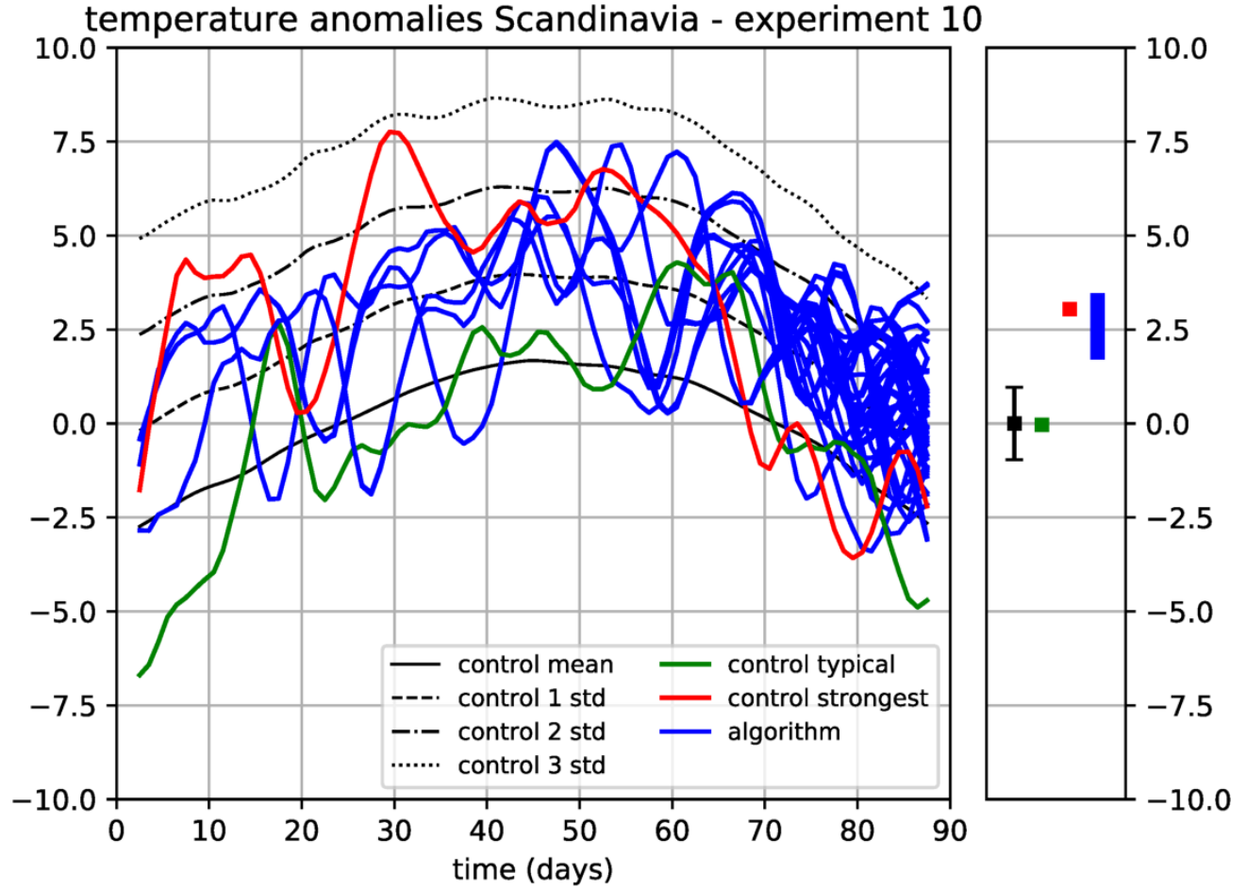


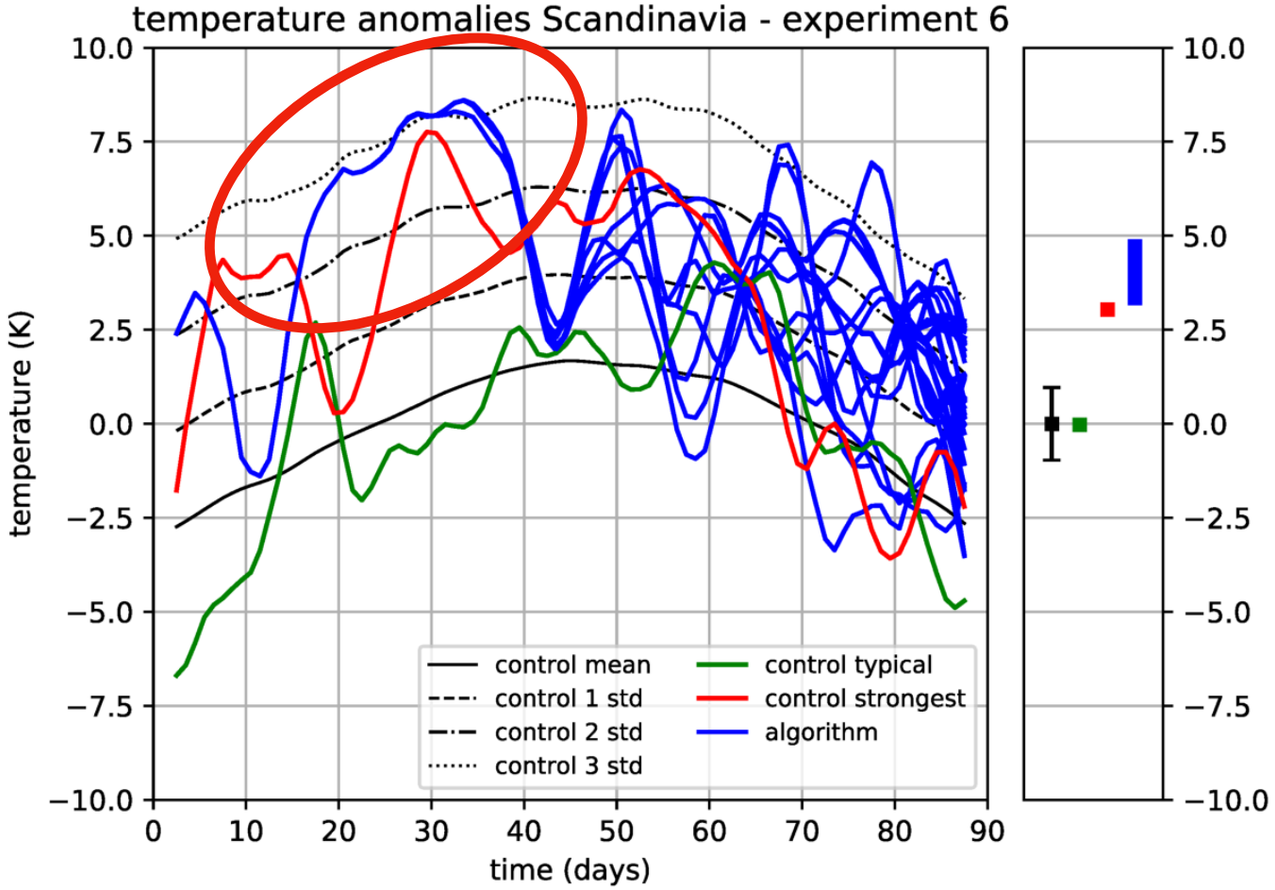
Experiments with CESM: heatwaves over Scandinavia



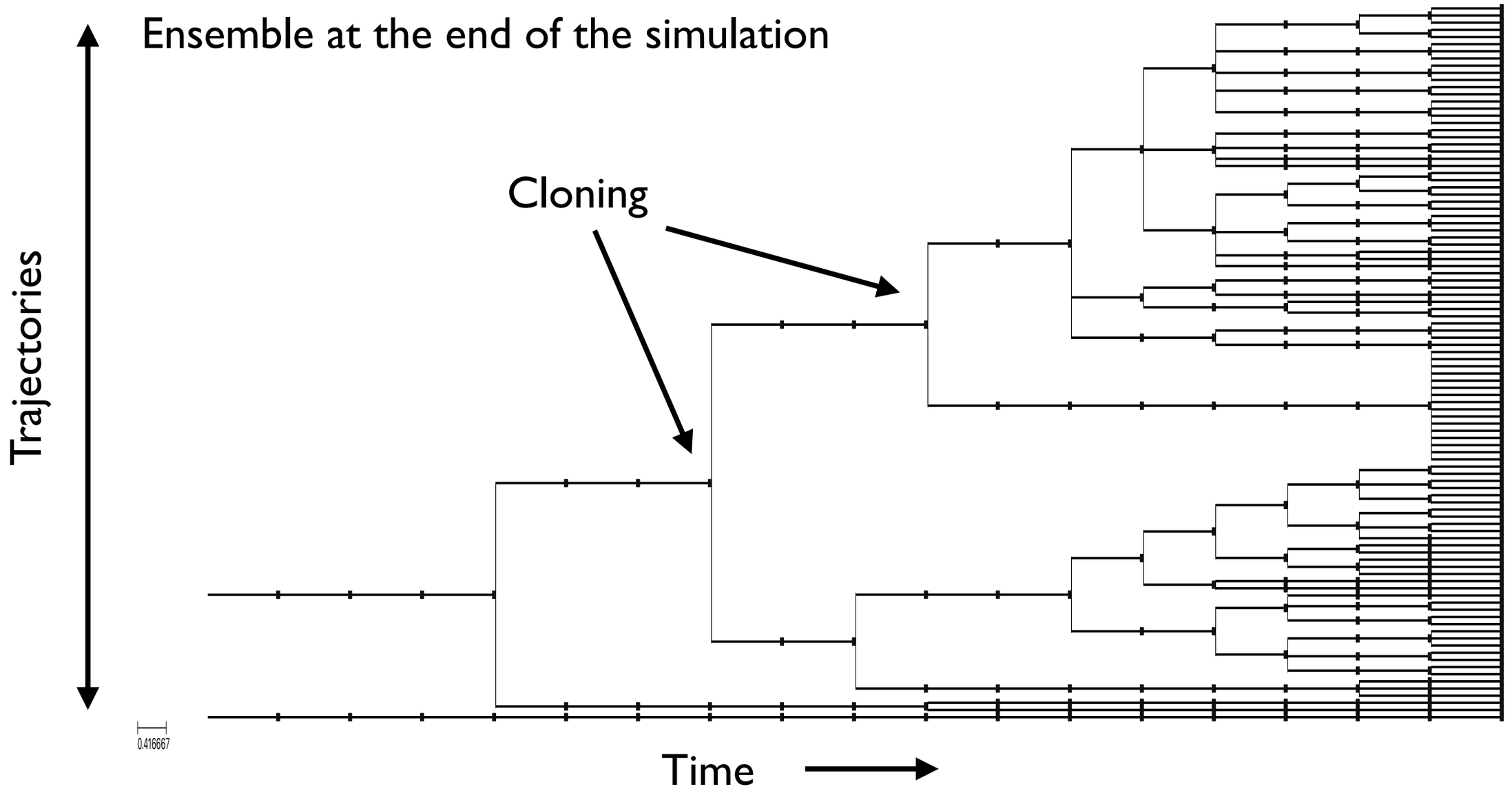
- For Scandinavia unexpected behaviour
- Bimodality distribution seasonal temperatures
- Upper mode hosts "mega-heatwave" June-July events with same characteristics in different ensembles
- Analysis of dynamics of the two regimes is currently work in progress

Ragone and Bouchet, *GRL* 2021



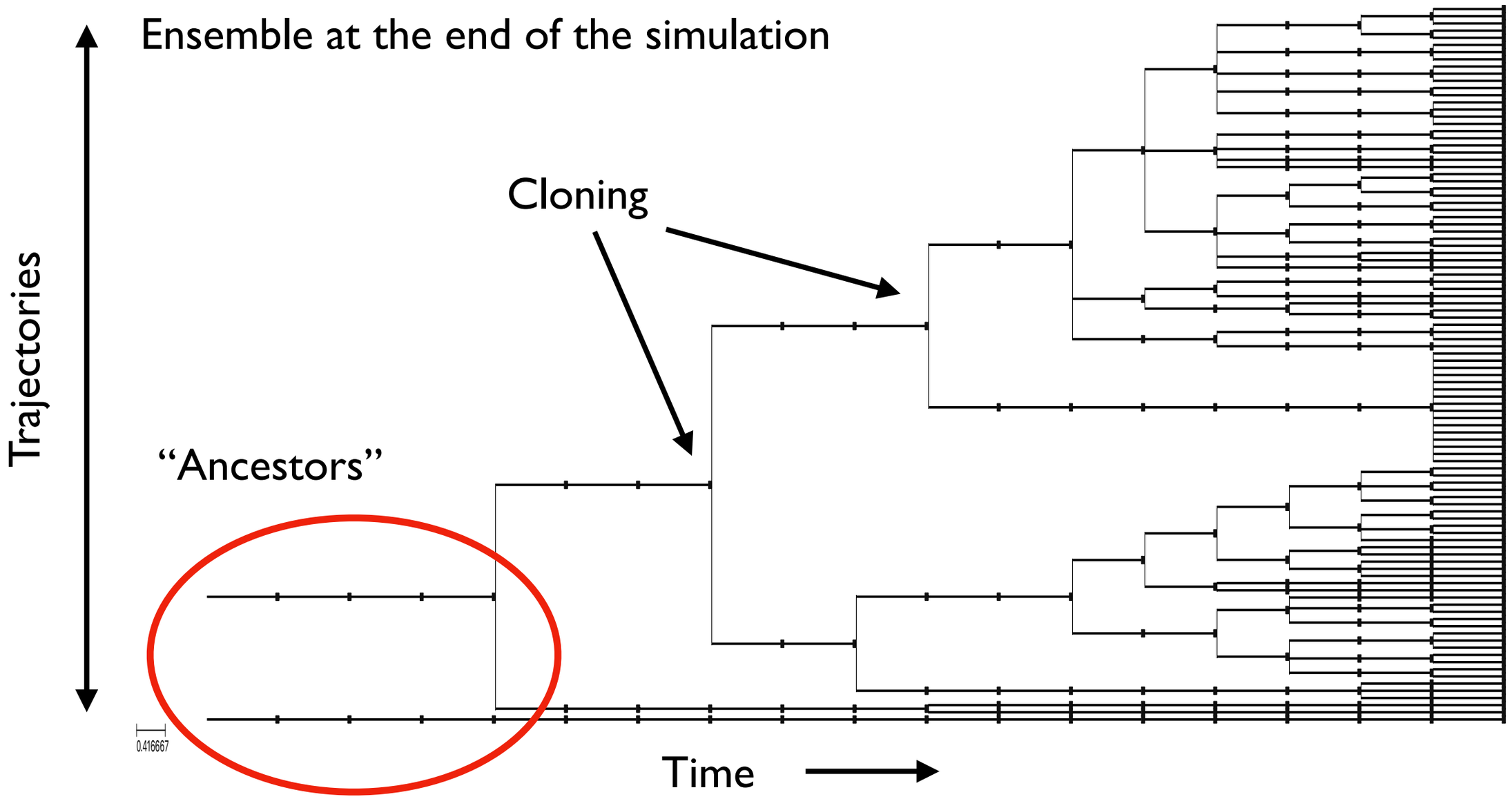


Analysis of trajectories branching



- Analysis of the branching of the trajectories due to the cloning

Analysis of trajectories branching



- Analysis of the branching of the trajectories due to the cloning
- What makes an "ancestor" trajectory successful?
- Precursors and climatic drivers: predictability of risk

Future perspectives

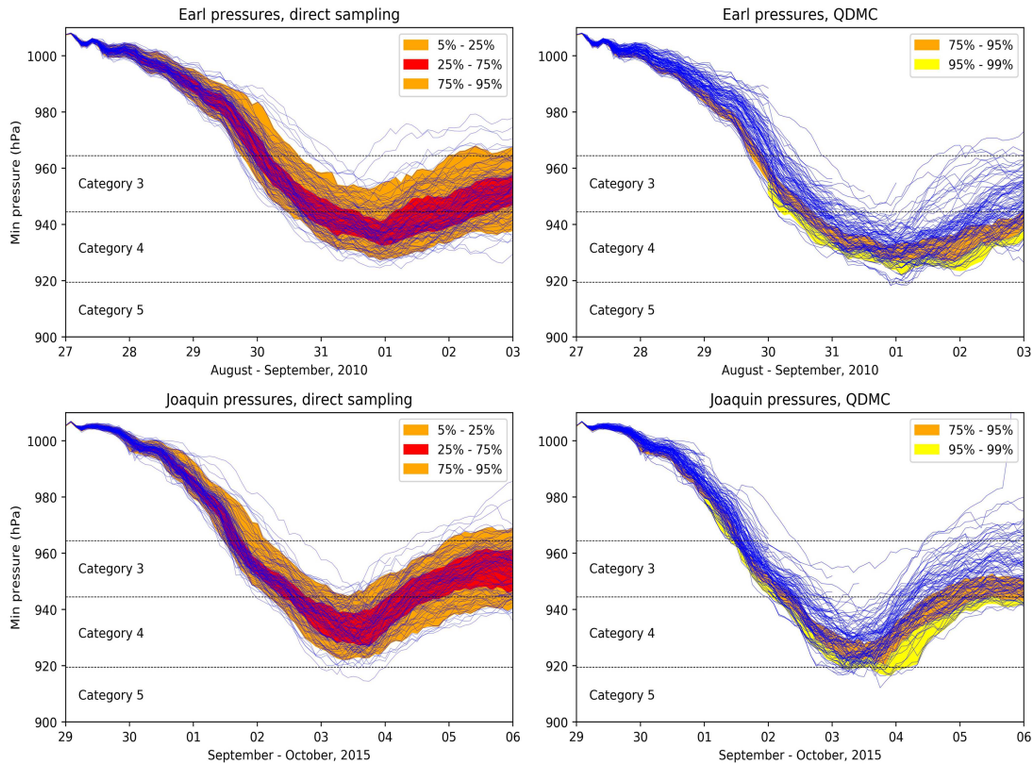
- Particle filtering for data assimilation share same DNA as method described here

- For the future: how to apply these techniques to predictability problems (move to coupled atmosphere-ocean models and/or constrain initial conditions to slow components)

- Possible applications to heatwaves outside midlatitudes, cold spells, floods, droughts

- Promising results with similar method on tropical storms with RCMs (Webber et al. 2019)

- Ongoing work:
  - extremes of sea ice reduction in the Arctic (PhD of Jerome Sauer)
  - large deviations of finite time Lyapunov exponents in simplified GCMs (with Jonathan Demaeyer)



Webber et al., *Chaos*, 2019

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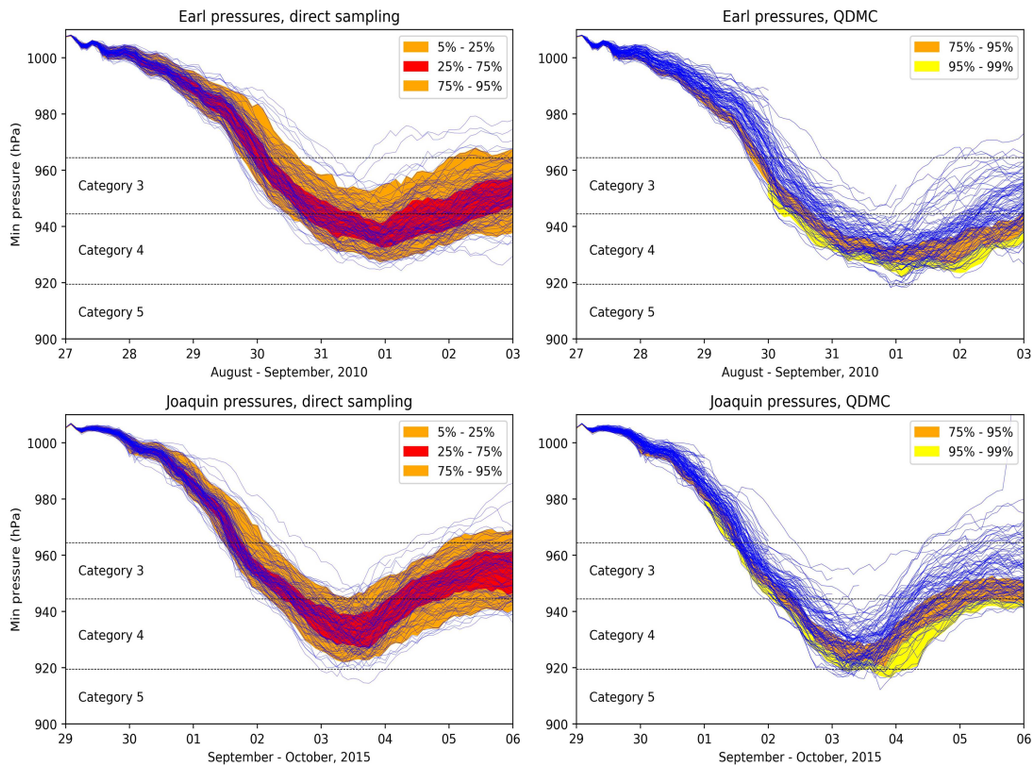

Webber et al., *Chaos*, 2019

Thank you for your attention