Simulation of extreme events in climate models with rare event algorithms

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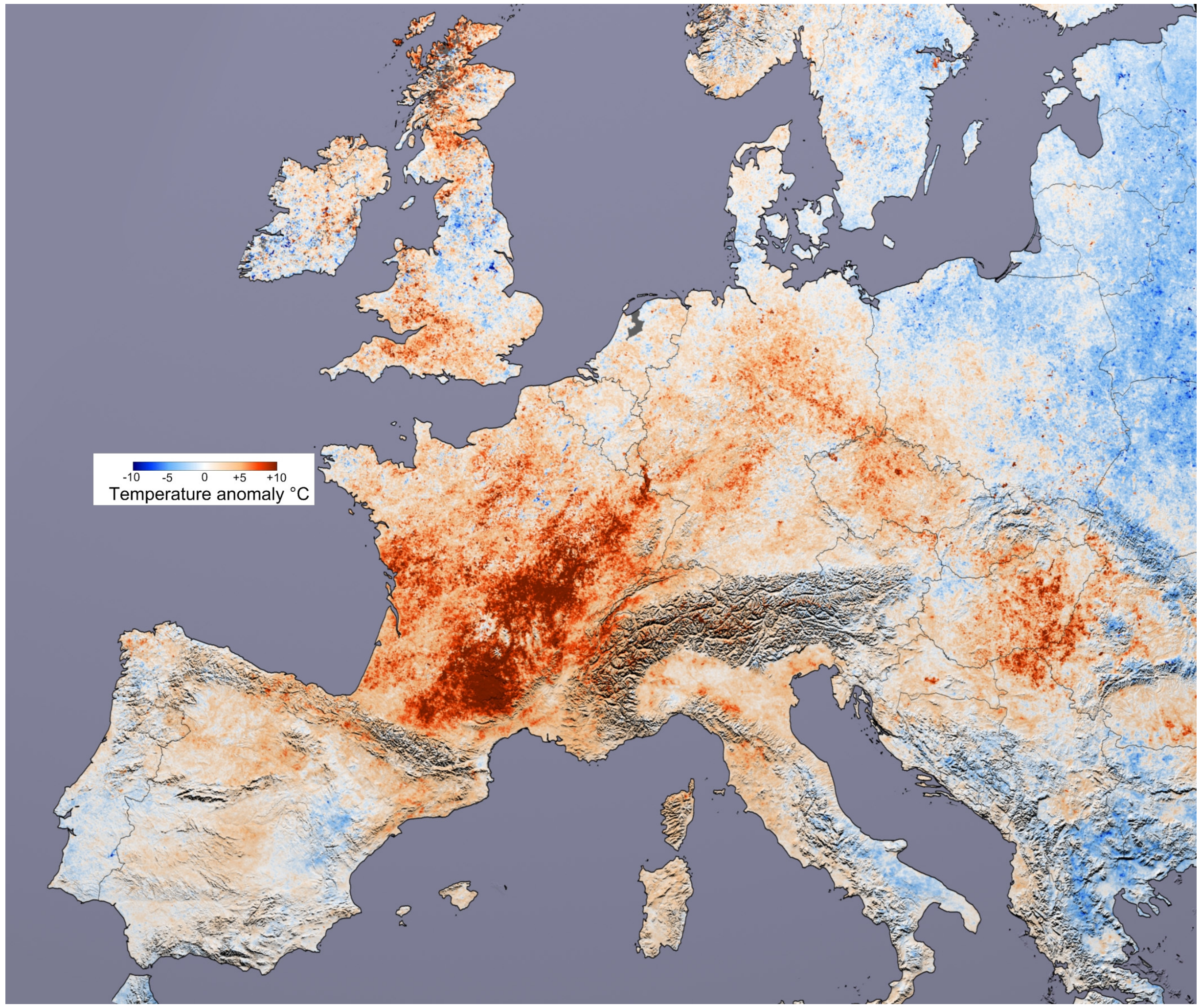
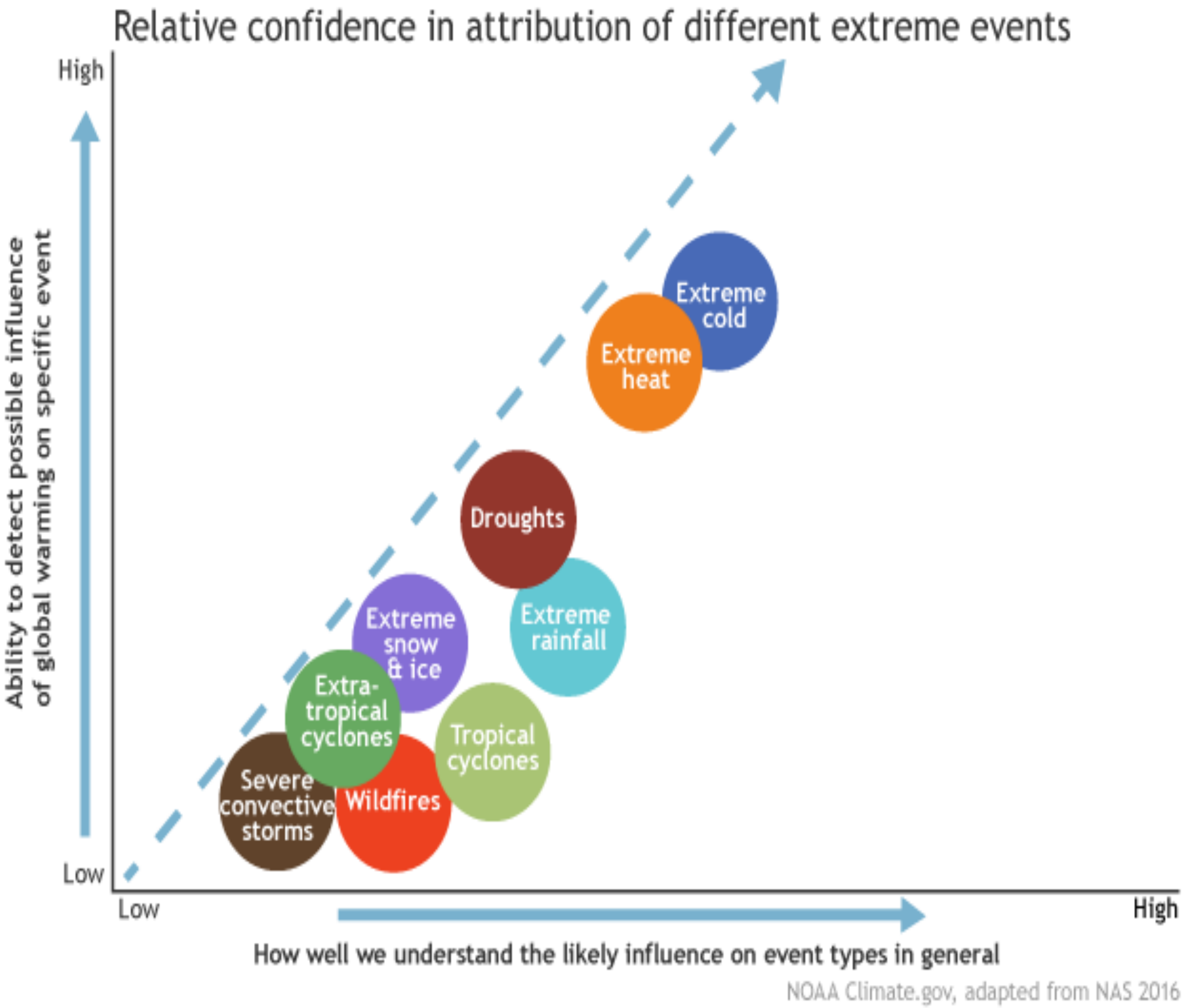
with Freddy Bouchet, Jeroen Wouters, Jerome Sauer, François Massonnet, Jonathan Demaeyer, Matteo Cini, Giuseppe Zappa, Susanna Corti

Rare events in the climate system

Summer 2003 heat wave over France





- Climate extremes or rare transitions: 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

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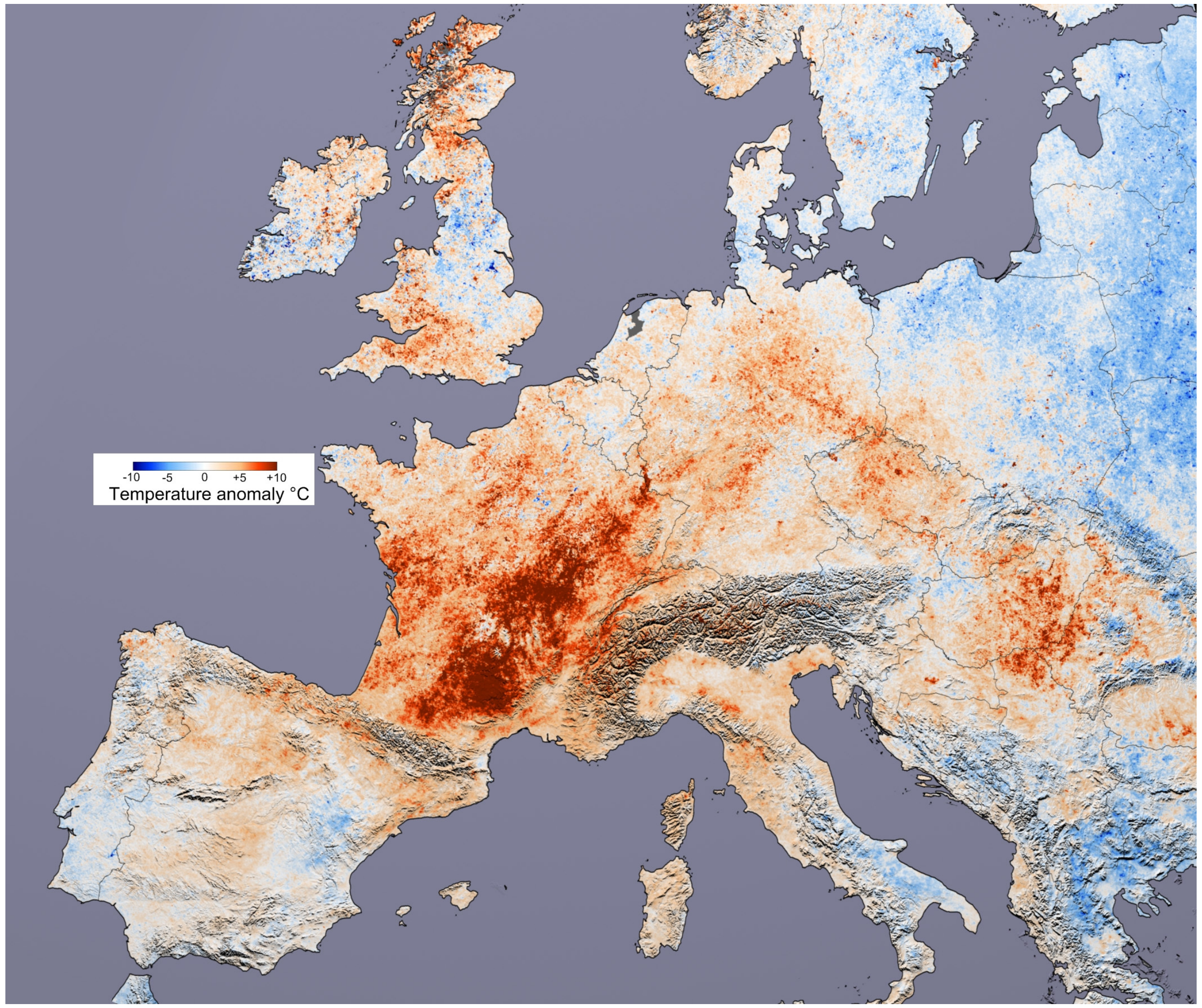

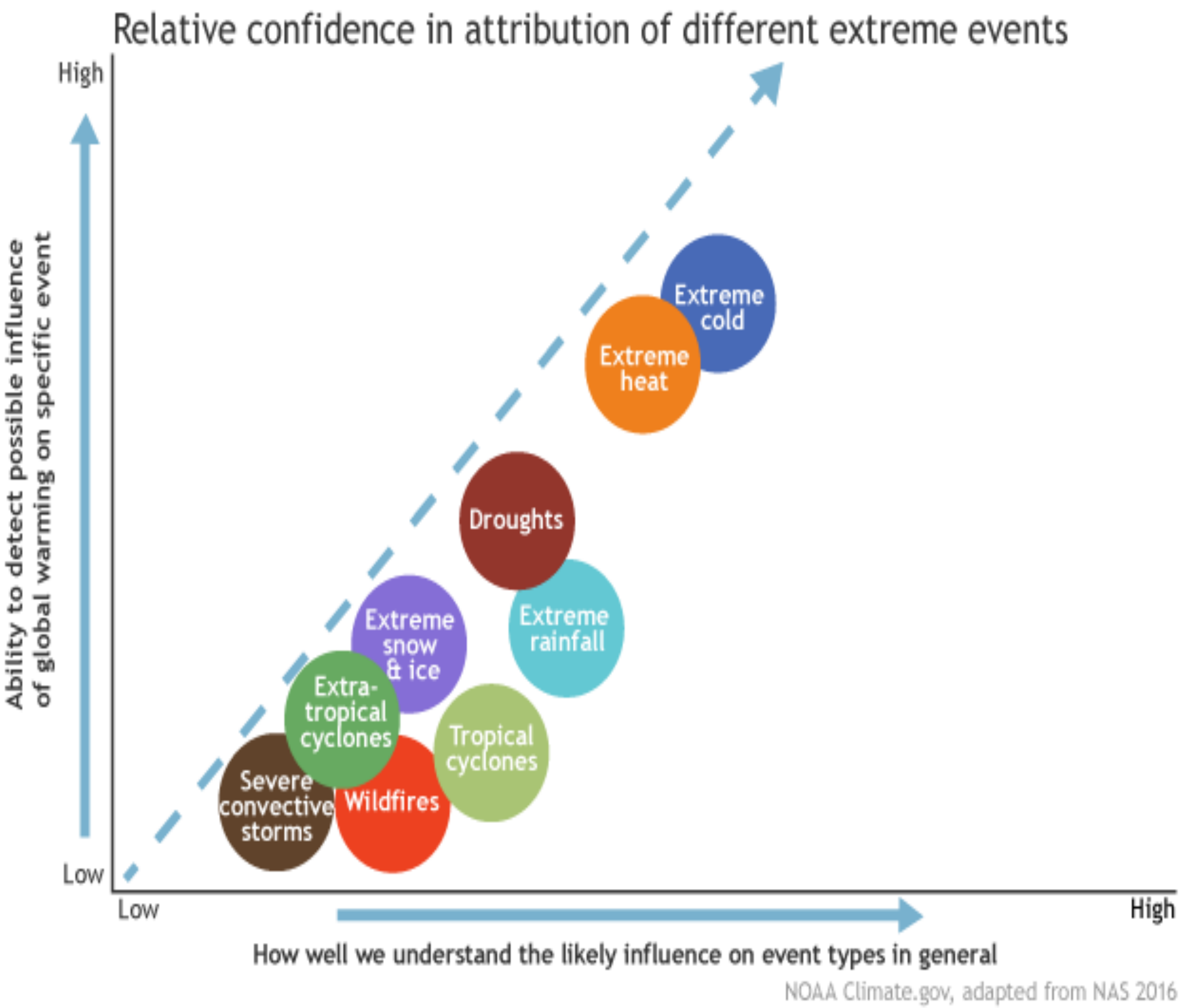

- Climate extremes or rare transitions: studies hindered by three problems

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

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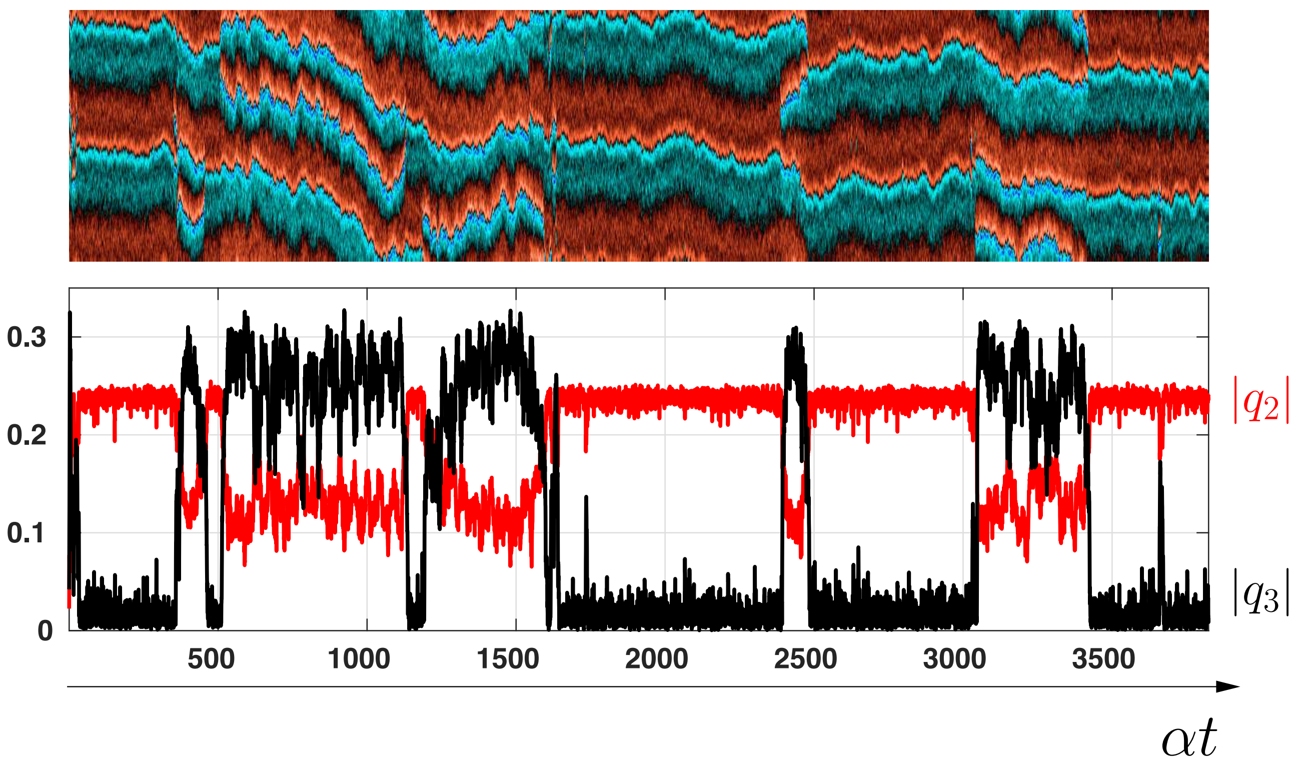
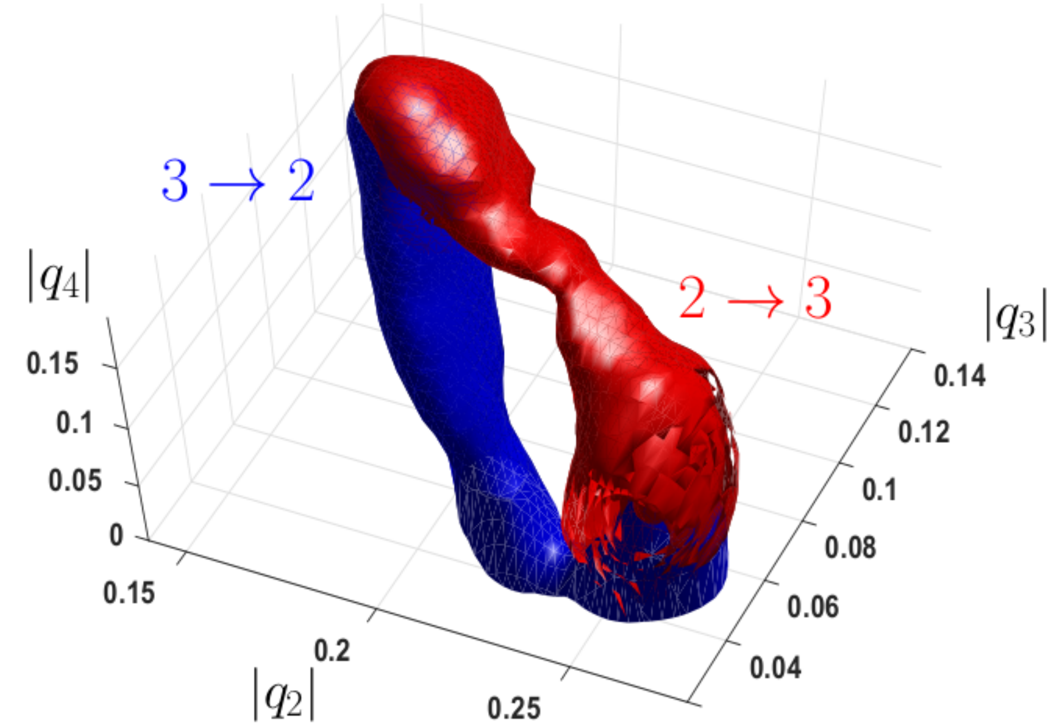
- Attempt at solving problem 2: improve sampling efficiency with rare event algorithms

Rare event algorithms



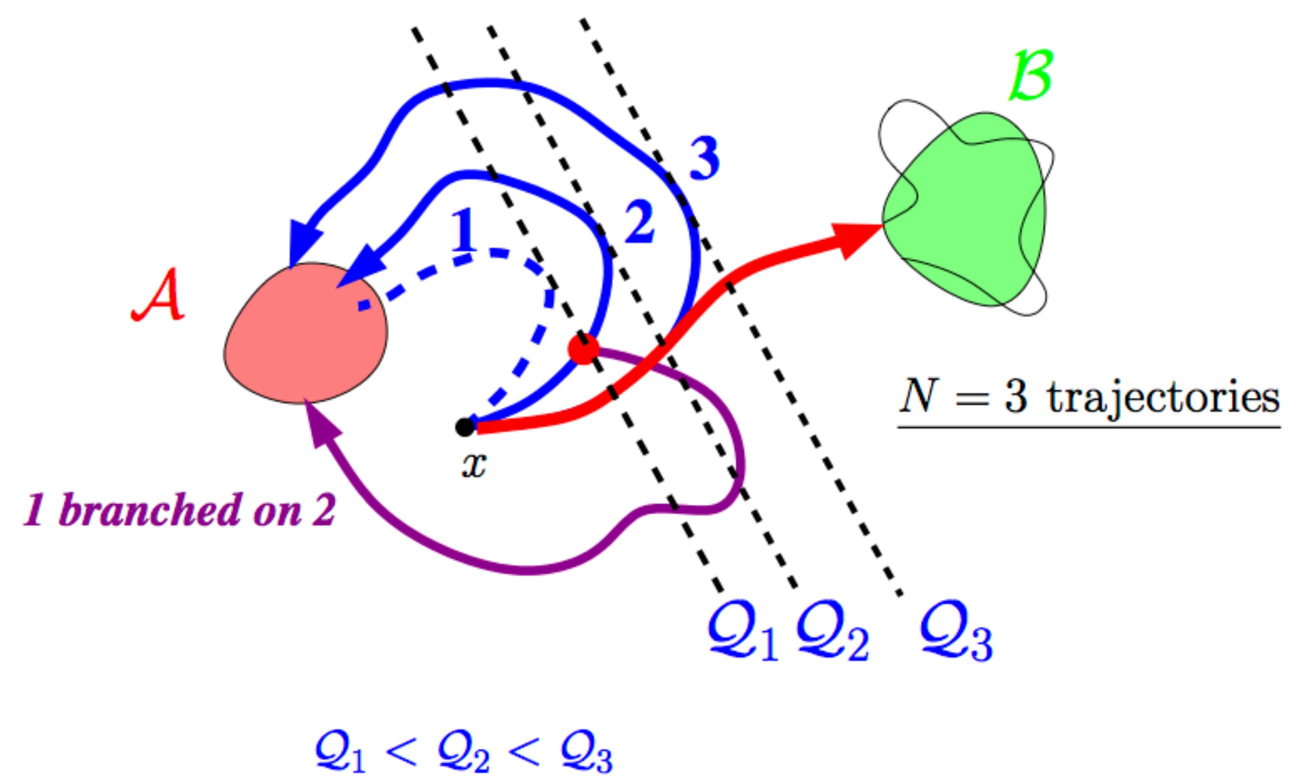


Bouchet, Rolland, Simonnet, Phys. Rev. Lett. 2019

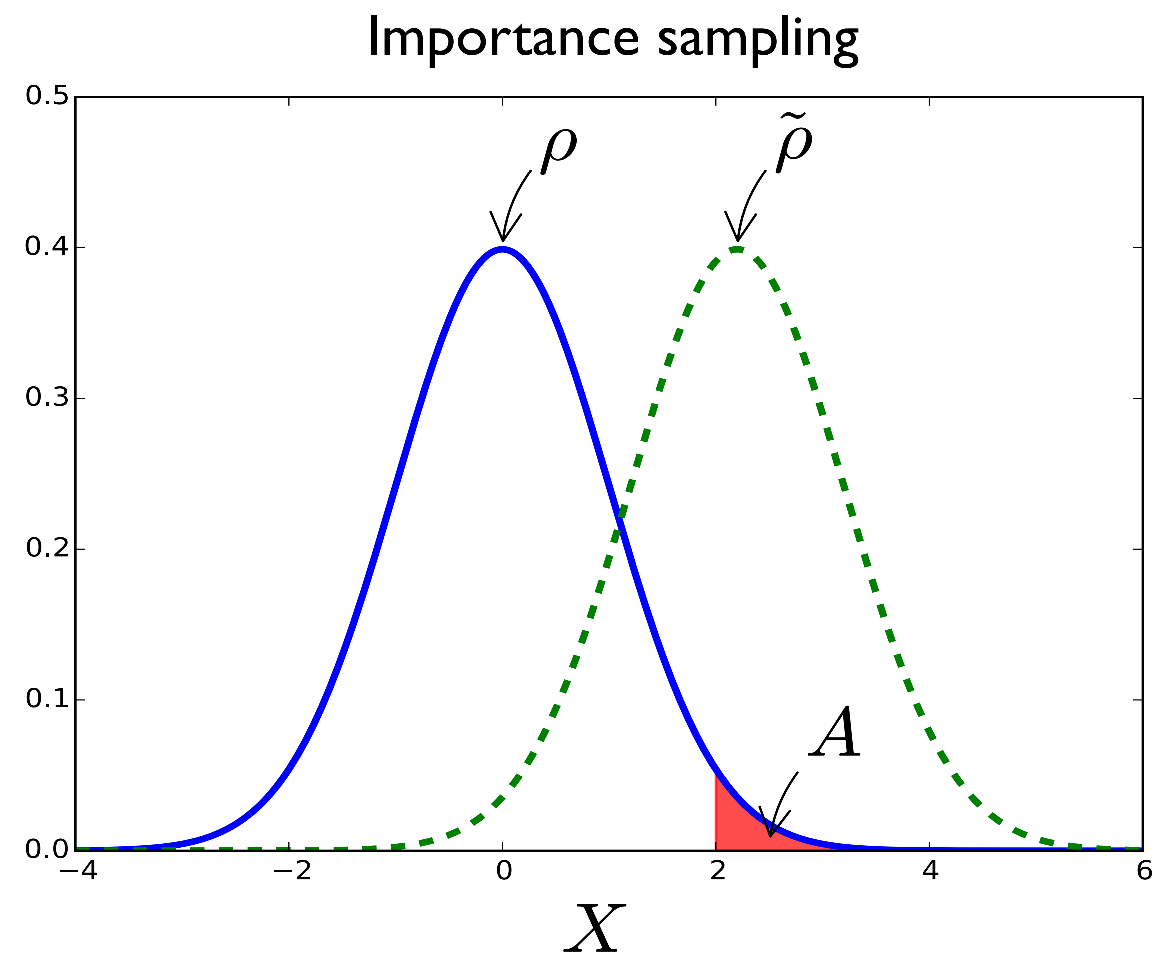
- Computational techniques to guide numerical models to oversample rare dynamical paths

- Long history in statistical physics, recently ported to geophysical and climate problems

- Different methods for different applications



Rare event algorithm and importance sampling



- Importance sampling: make rare events common

Rare event algorithm and importance sampling

Online trajectory selection

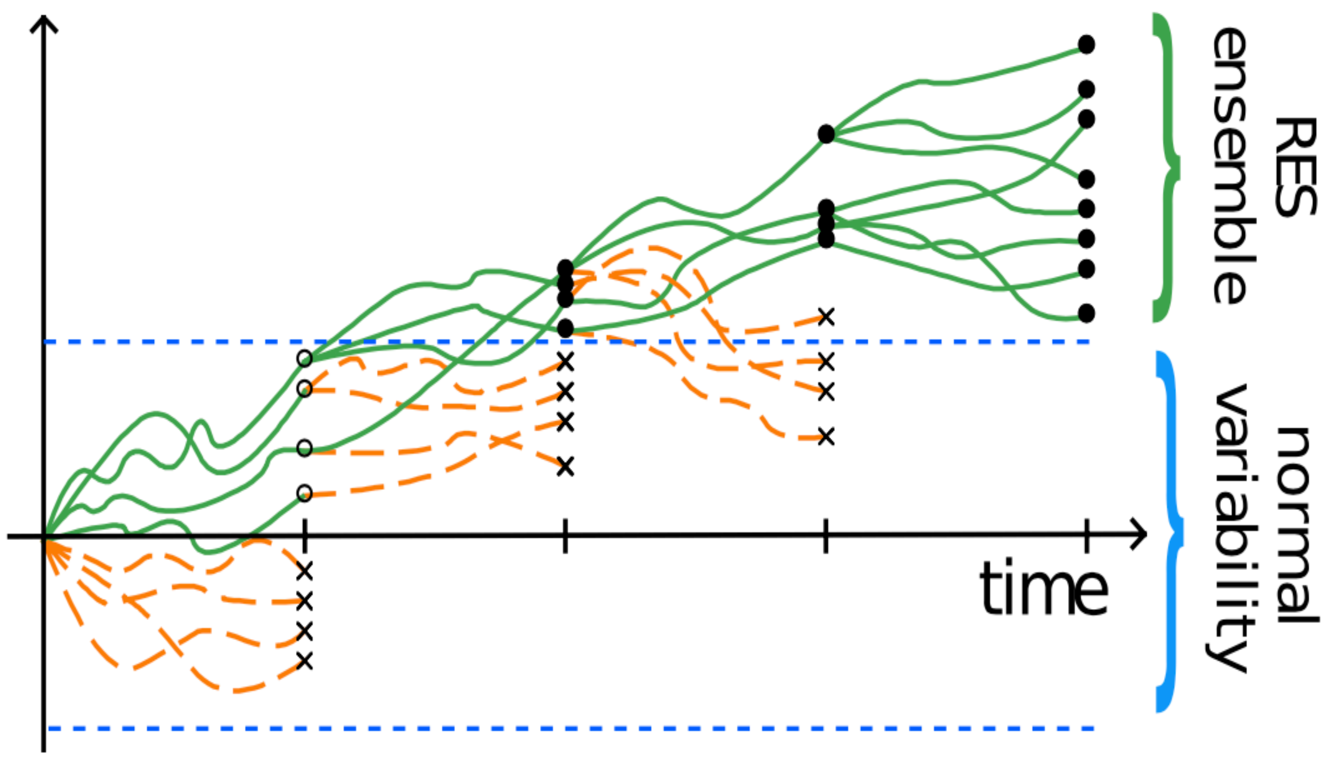
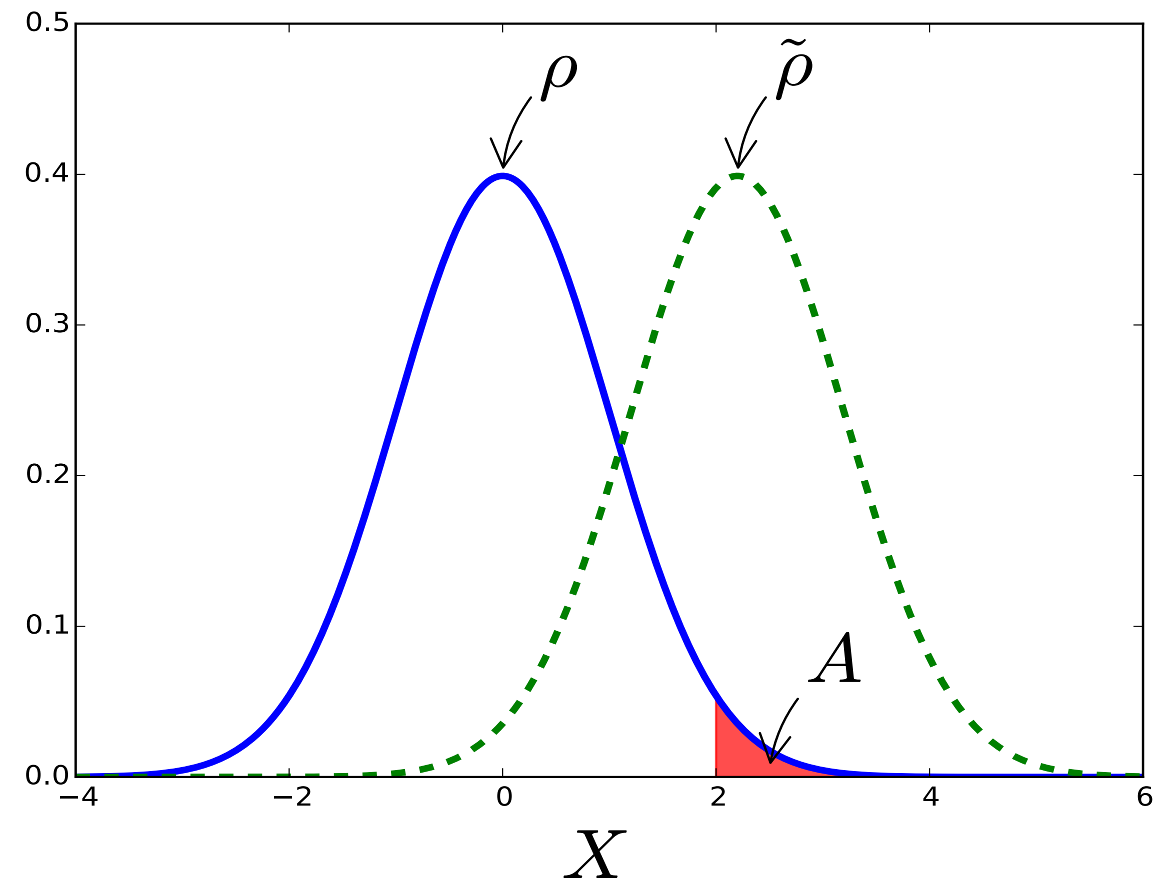


Figure from Wouters et al 2023

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

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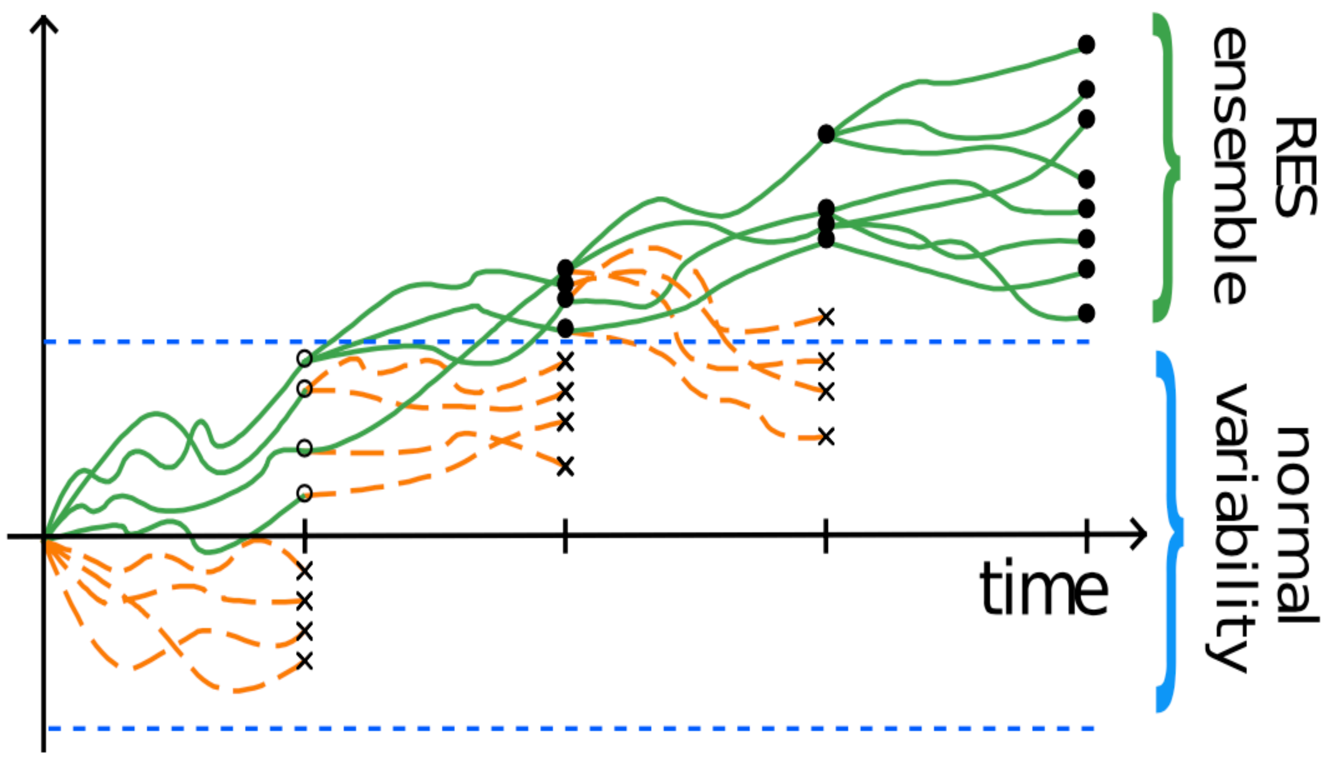

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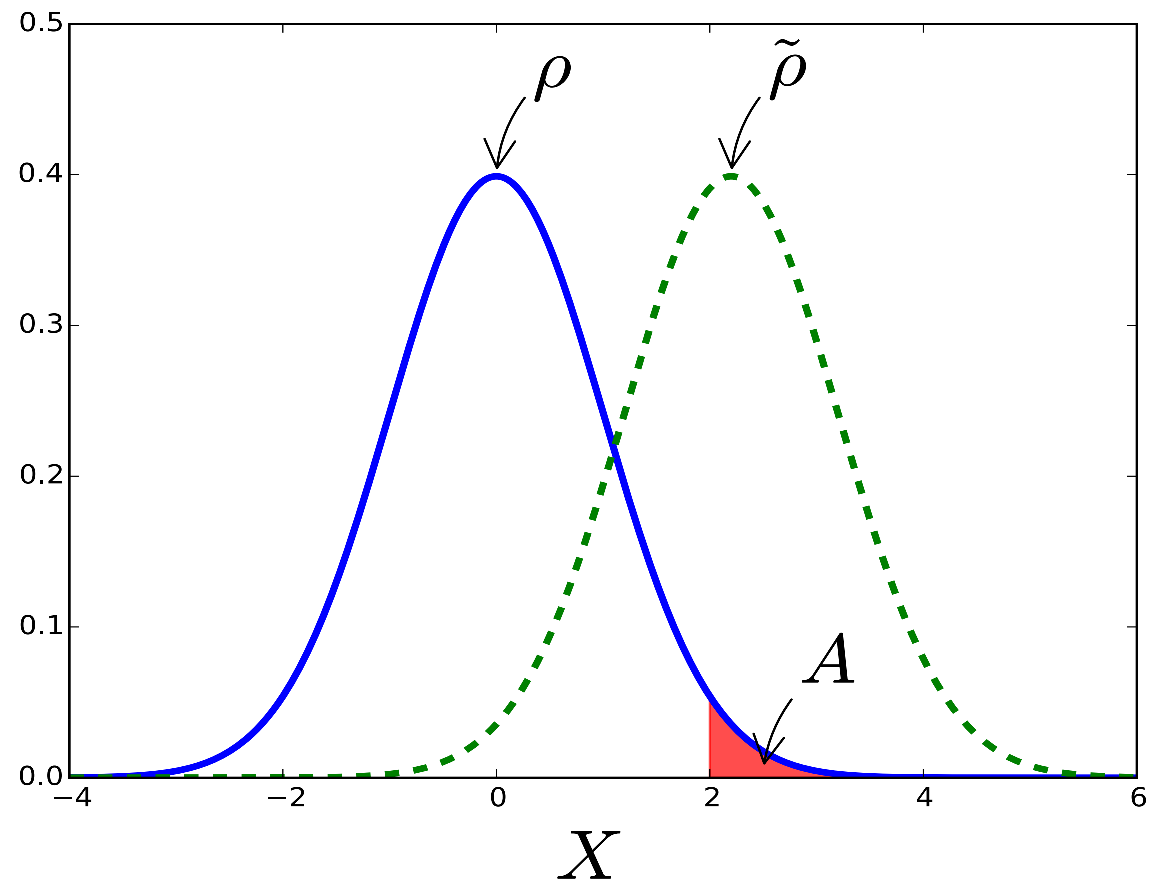

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- Define observable of interest, e.g. surface temperature over region. Every constant intervals of resampling time τ the trajectories are killed or cloned, based on weights that measure the likelihood to develop an extreme for the target observable
- Resampling rules adapted from Del Moral and Garnier (2005); Giardina et al. (2011), method is efficient to study long lasting events (Ragone et al. 2018)

Rare event algorithm and importance sampling

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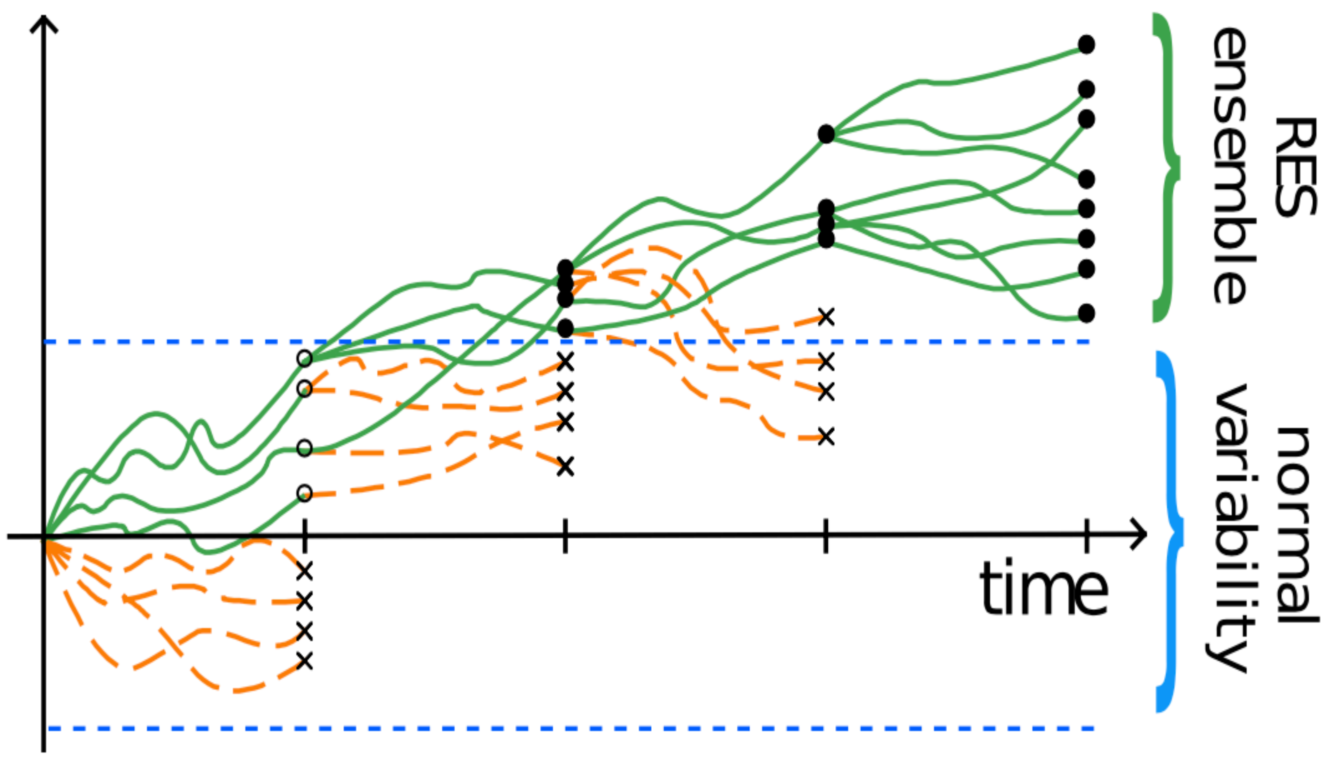

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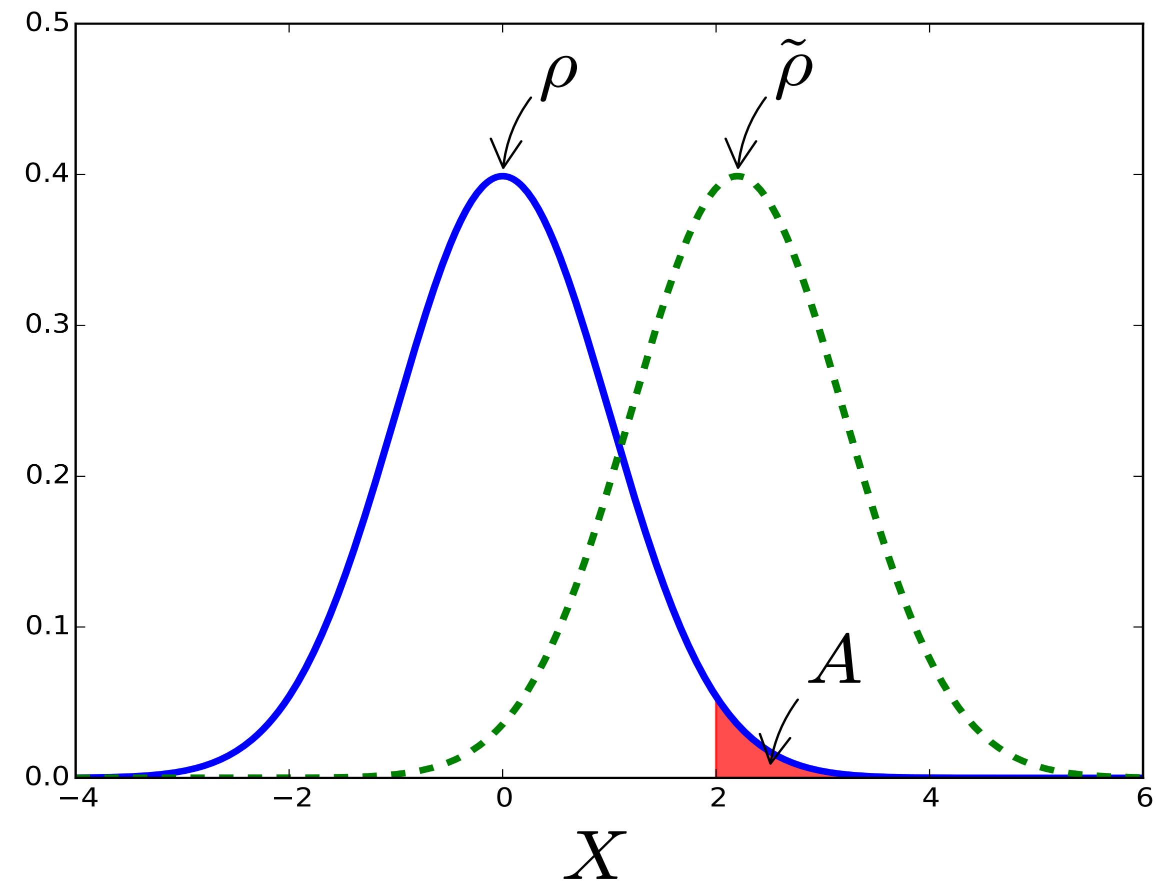

- Run N trajectories $X_j(t)$ $(j = 1,..,N)$ for total simulation time T_a
- Each trajectory generates at time $t_i = i\tau$ $(i = 1,..,T_a/\tau)$ a number of copies of itself given by weights

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

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

Rare event algorithm and importance sampling

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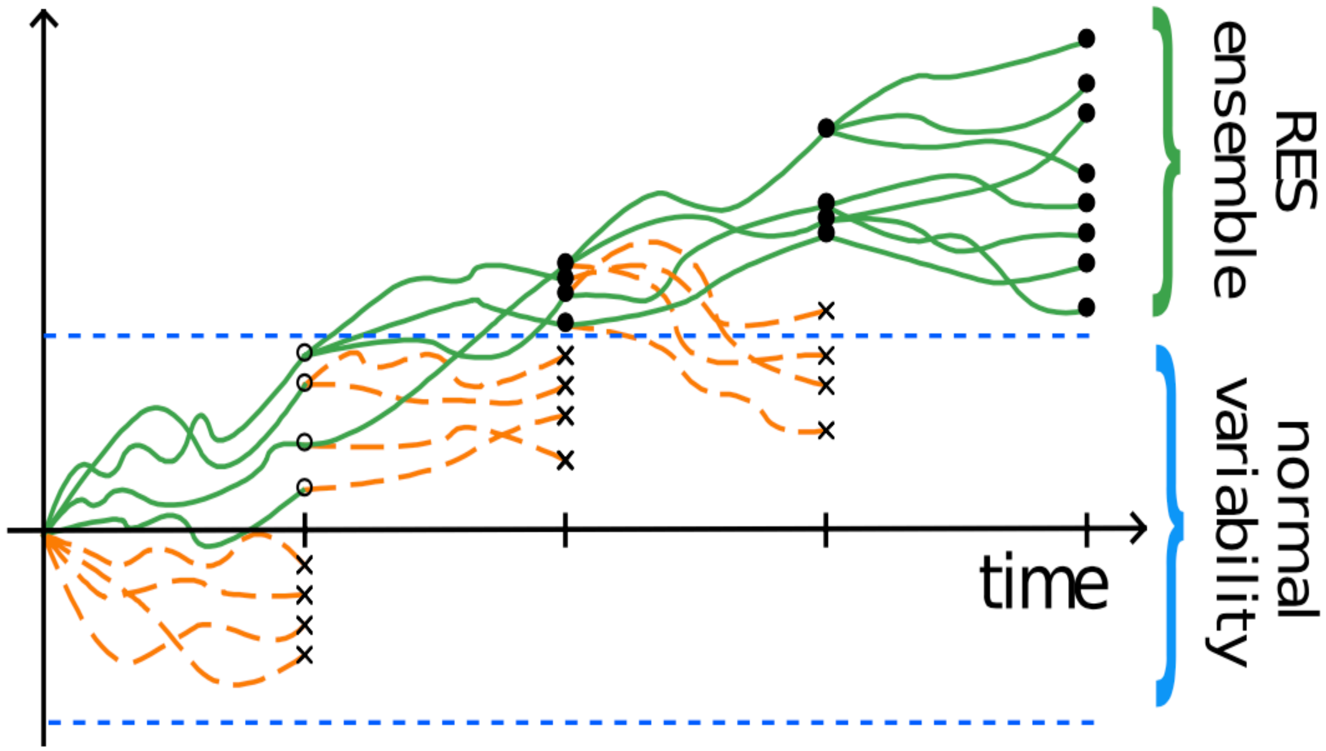

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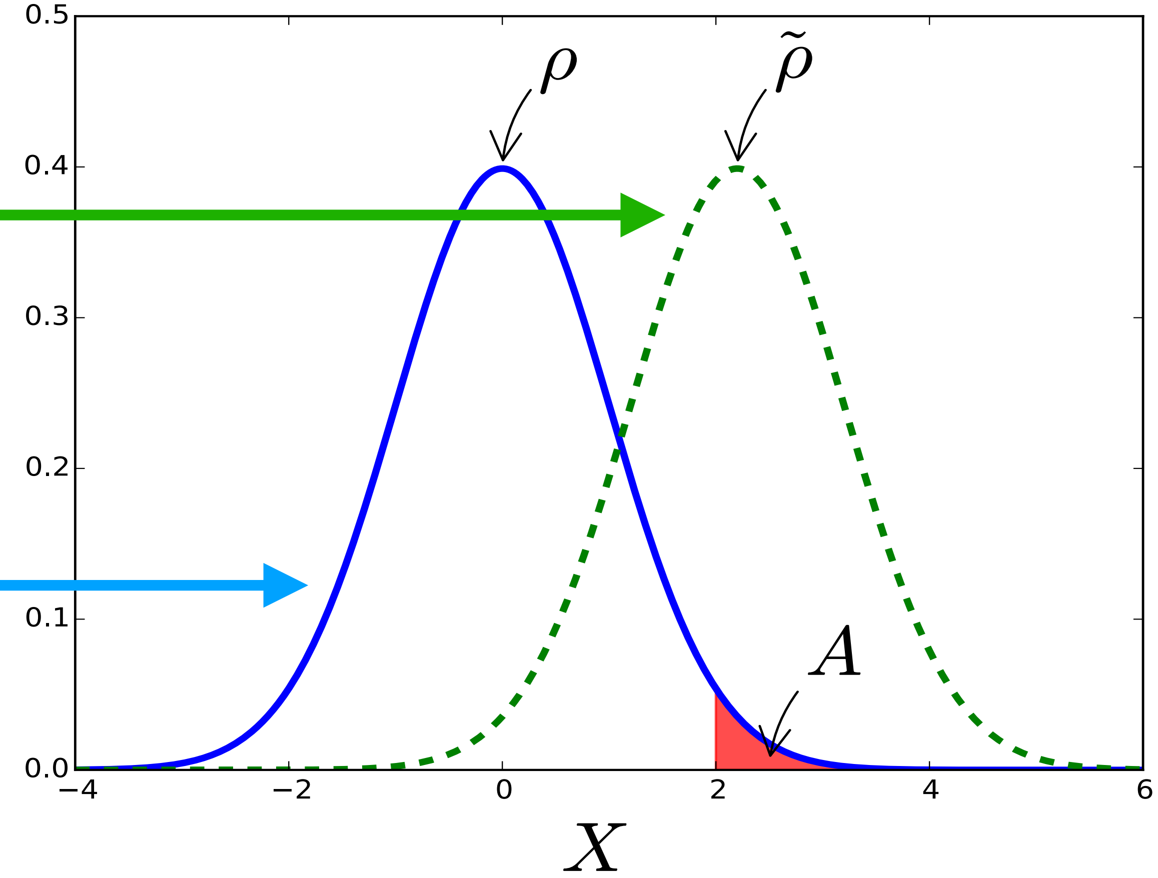

- Importance sampling of trajectories: probability of dynamical paths modified as

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

- 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…)

Rare event algorithm and importance sampling

- Applications:

    - European heatwaves in Plasim (intermediate complexity GCM)
    - France and Scandinavia heatwaves in CESM1.2
    - Arctic sea ice reduction in coupled Plasim-LSG
    - AMOC weakening and collapse in coupled Plasim-LSG

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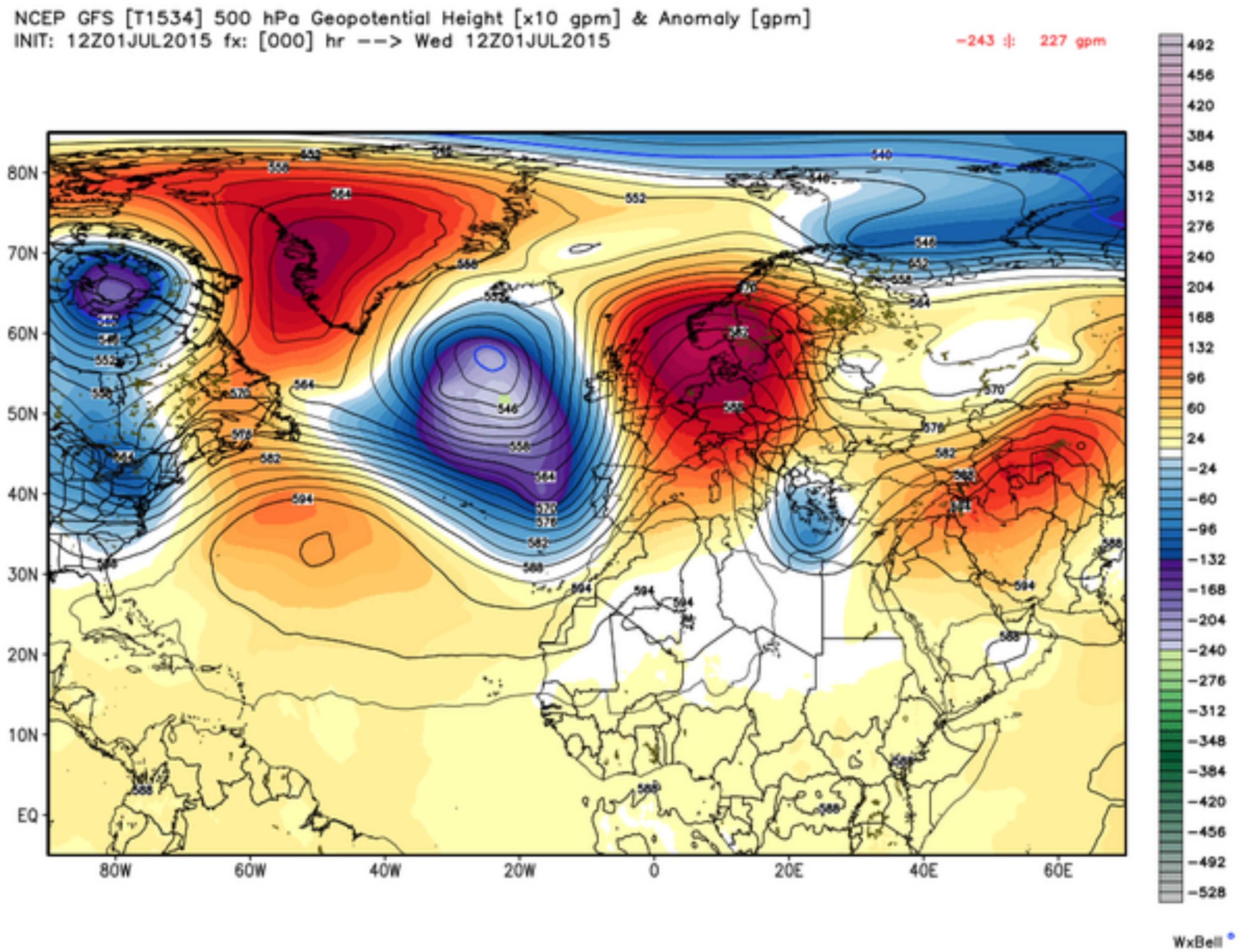
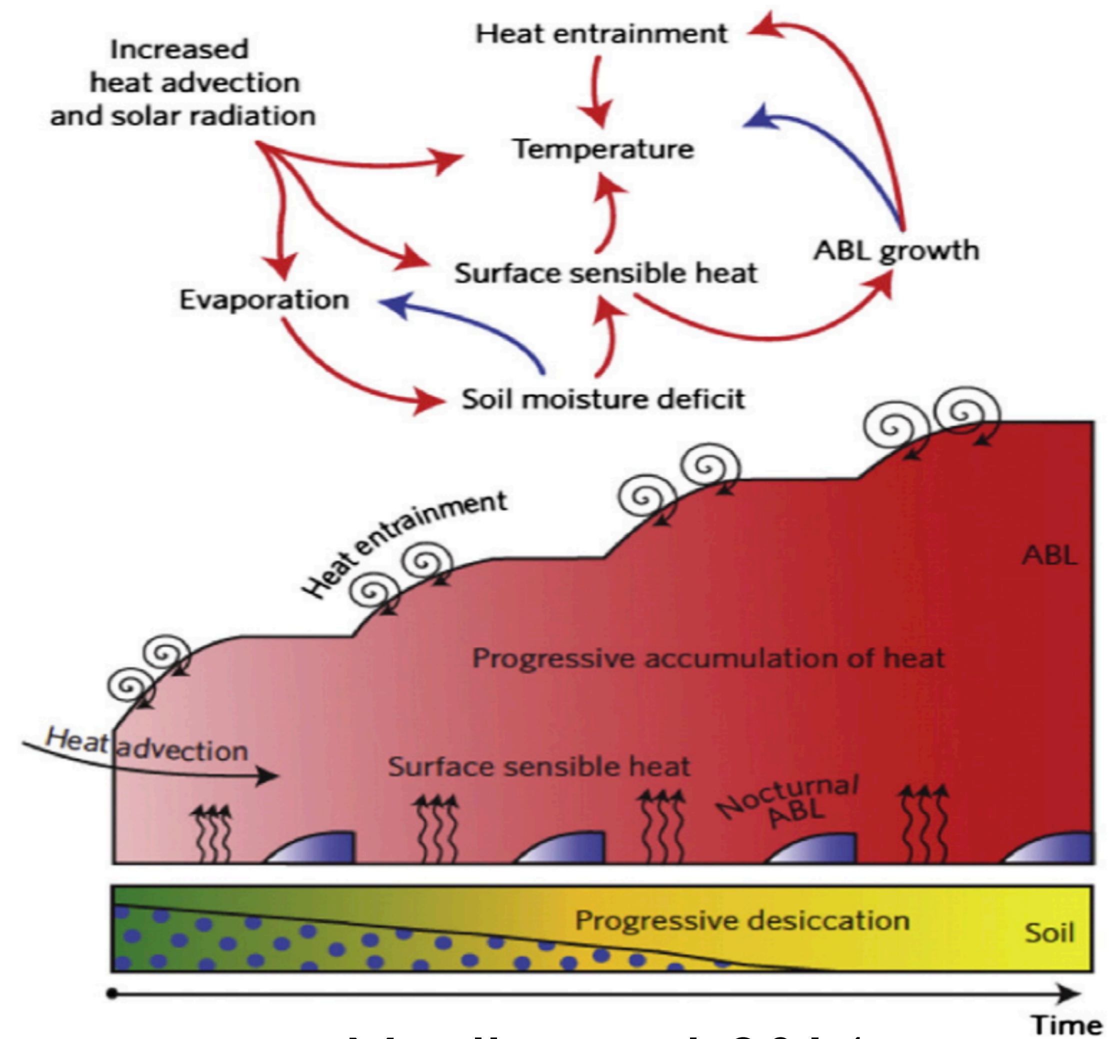
Heatwaves



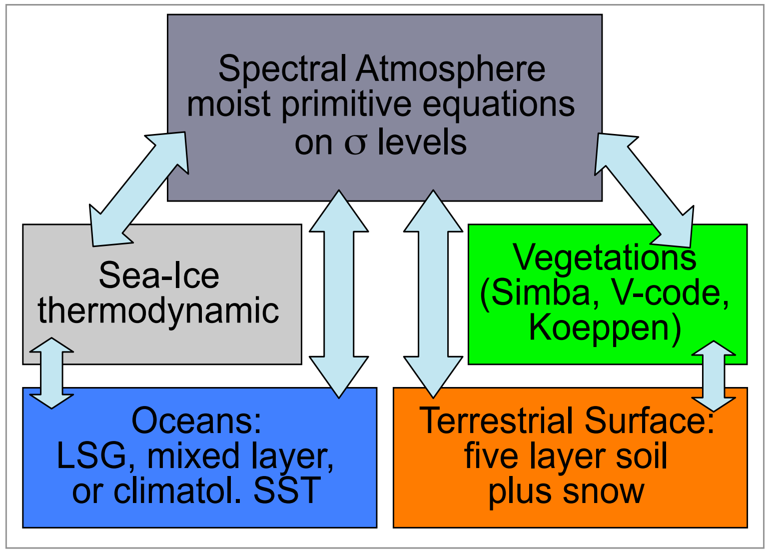


Miralles et al. 2014

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

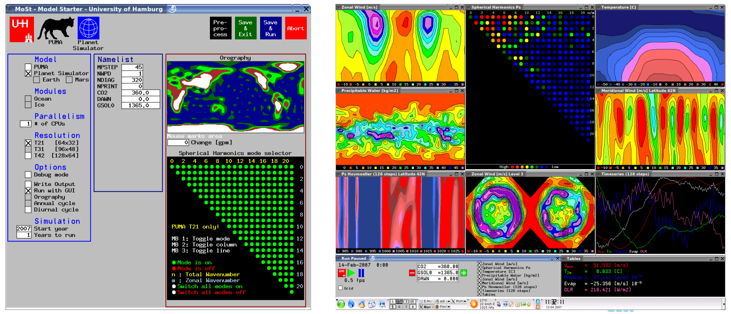
- Class of extreme events characterised by time persistence of quantity/dynamics

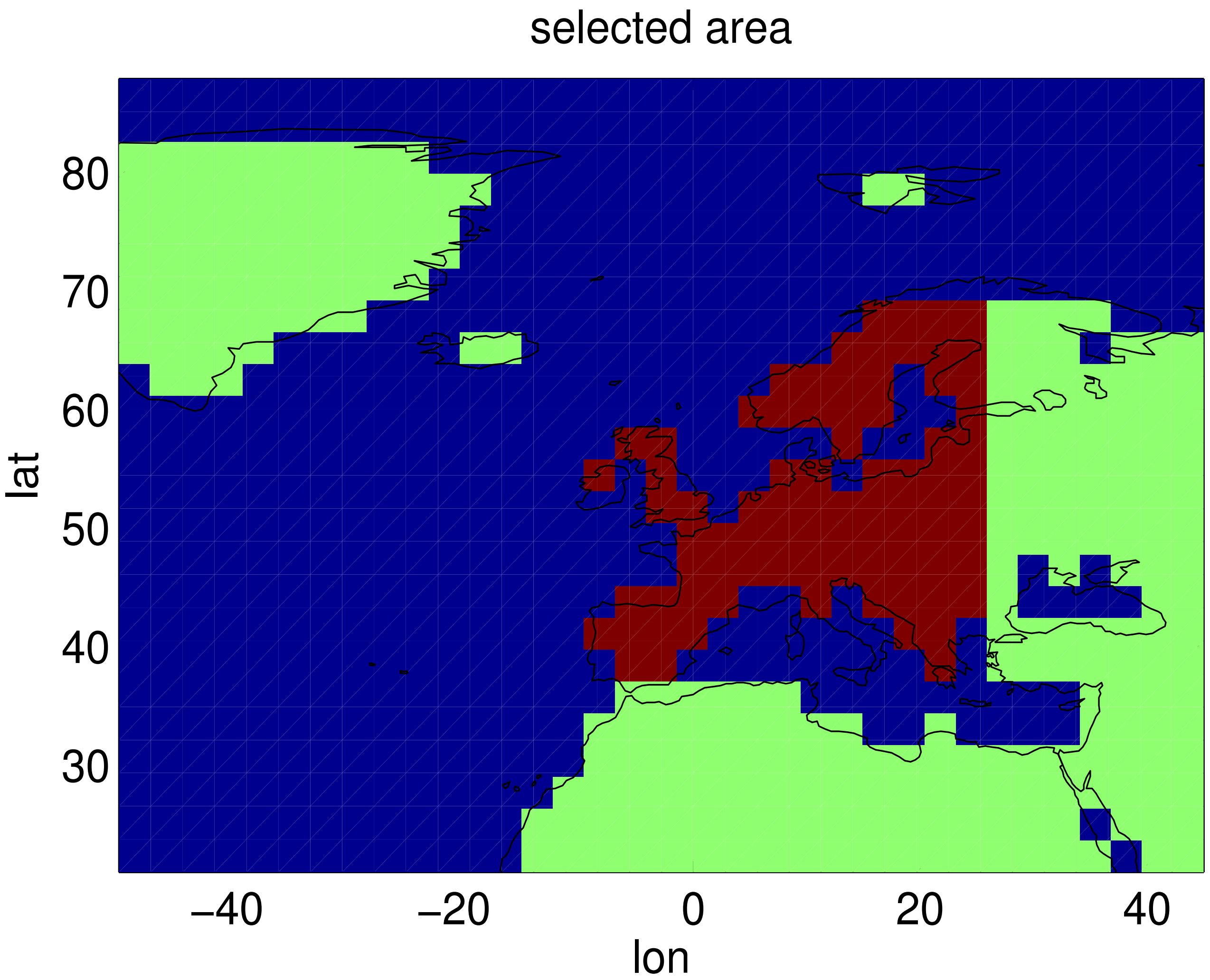
Experiments with climate model Plasim



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

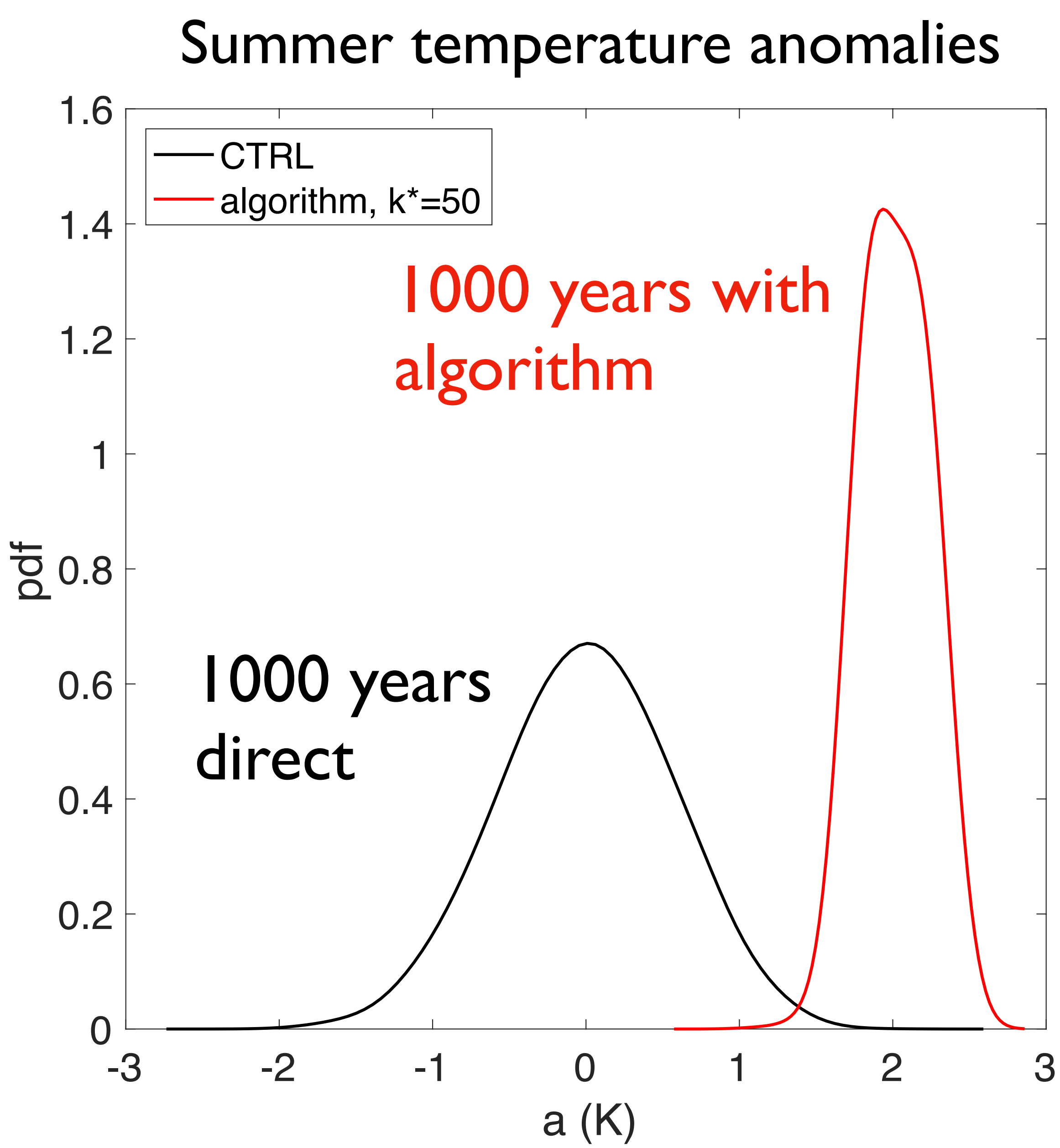
Model Starter
and
Graphic User Interface





- Intermediate complexity 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
- Resampling time 8 days

Heatwaves and warm summers in Plasim



Ragone, Wouters, Bouchet. *PNAS* 2018

- Importance sampling of 90-days European heatwaves

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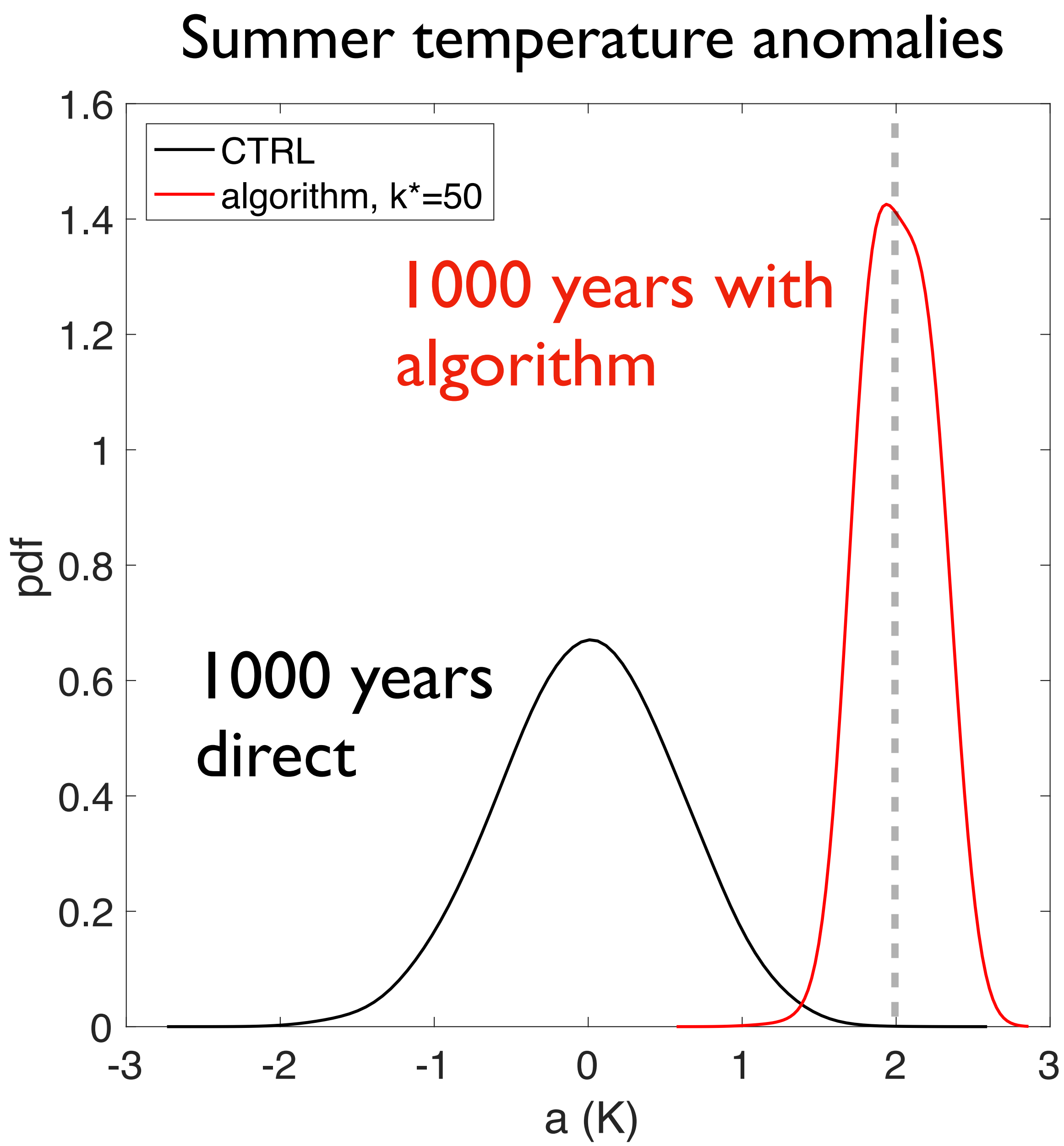

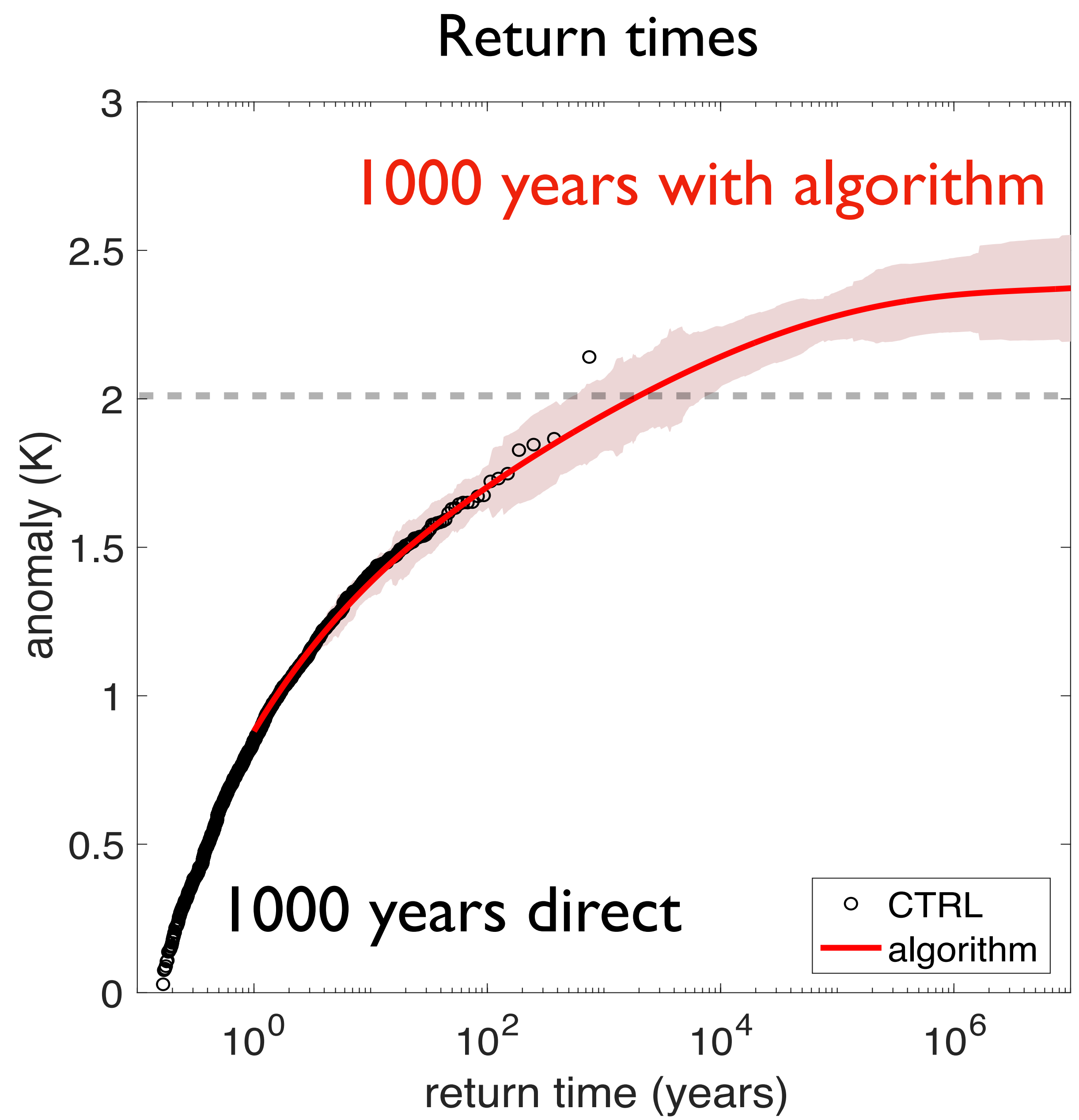

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- Allows to compute return times up to 10^6 years with computational cost of 10^3 years

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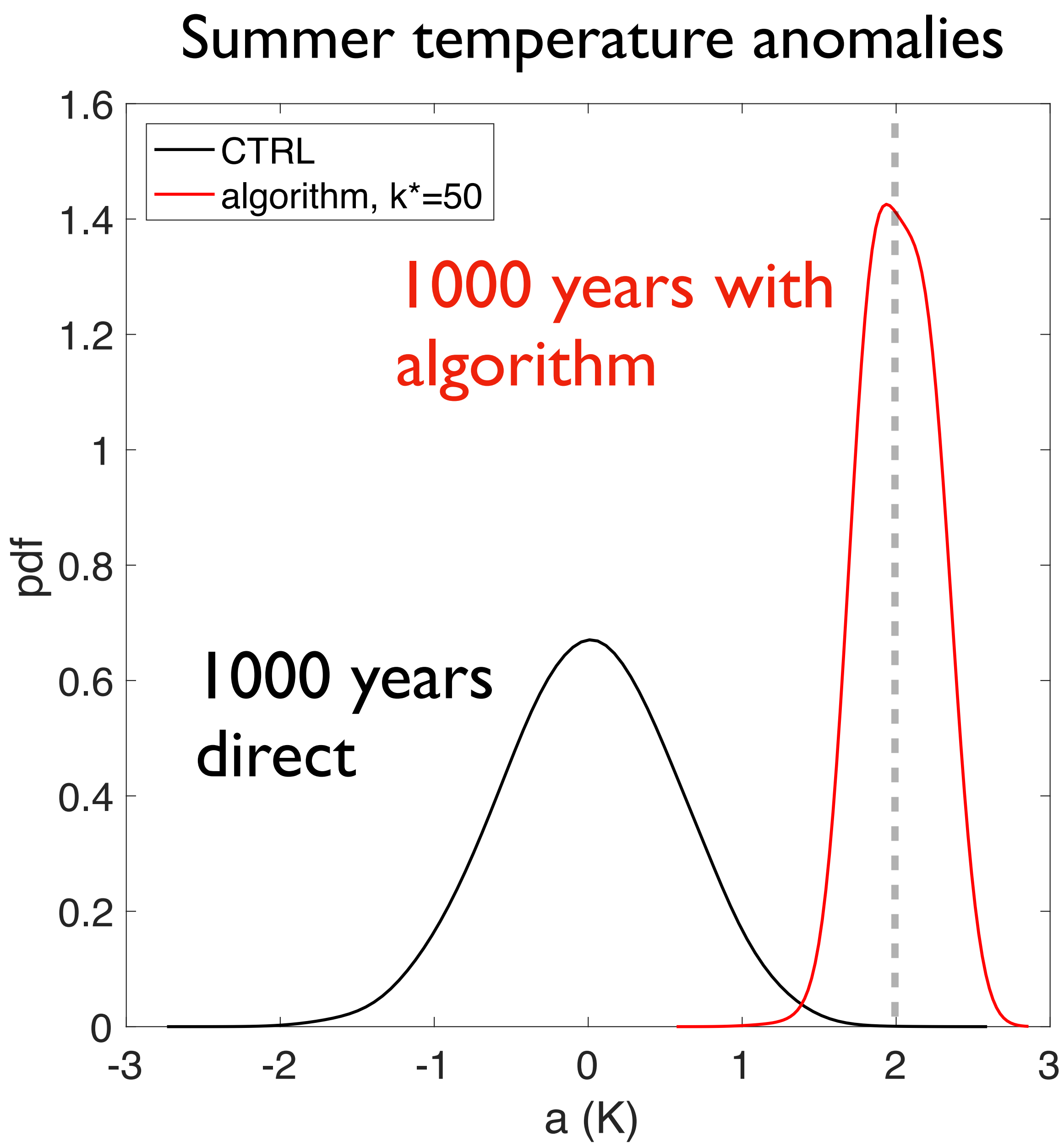

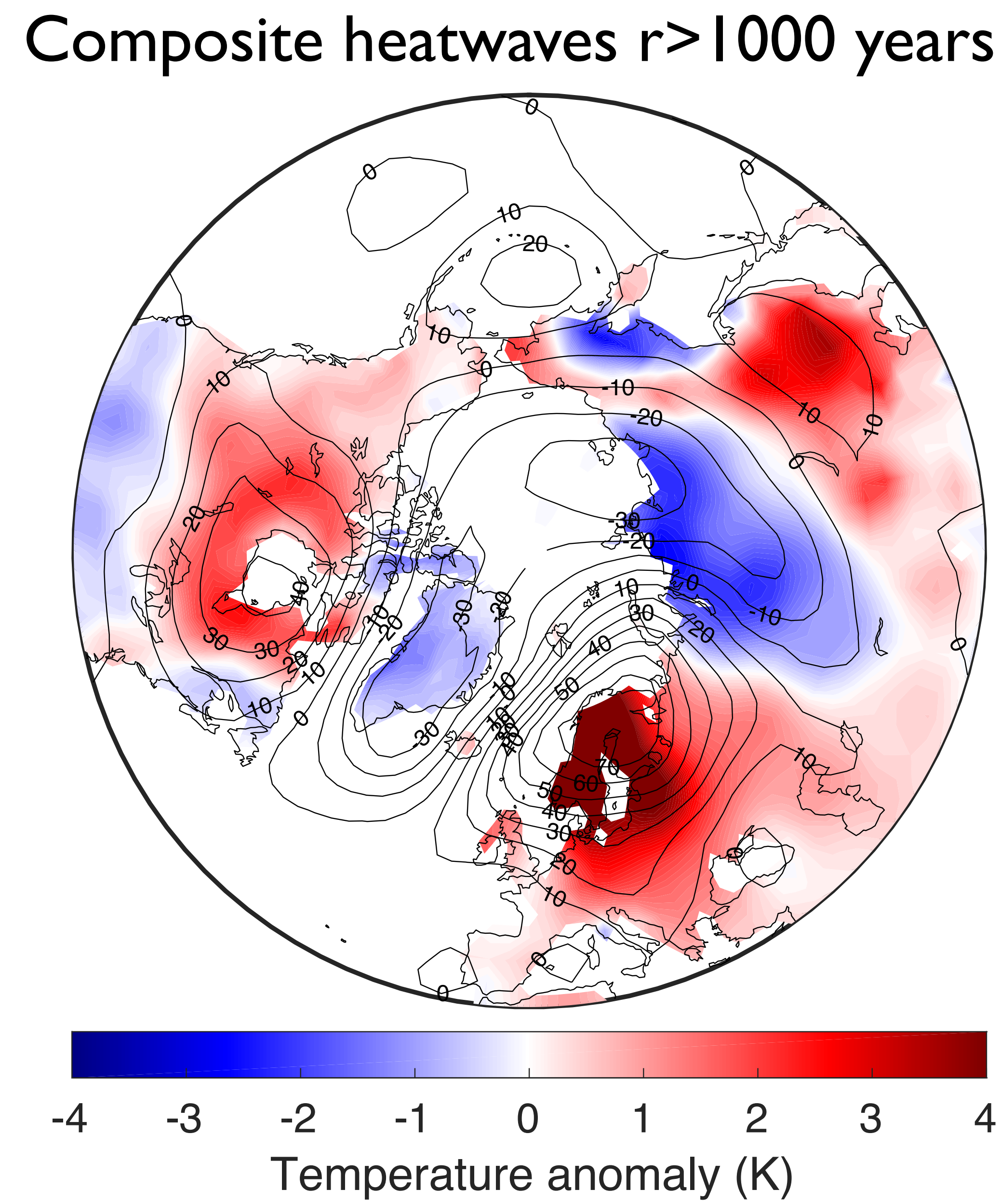

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- Importance sampling of 90-days European heatwaves
- Allows to compute return times up to 10^6 years with computational cost of 10^3 years
- Identification of teleconnection patterns for strongest heatwaves

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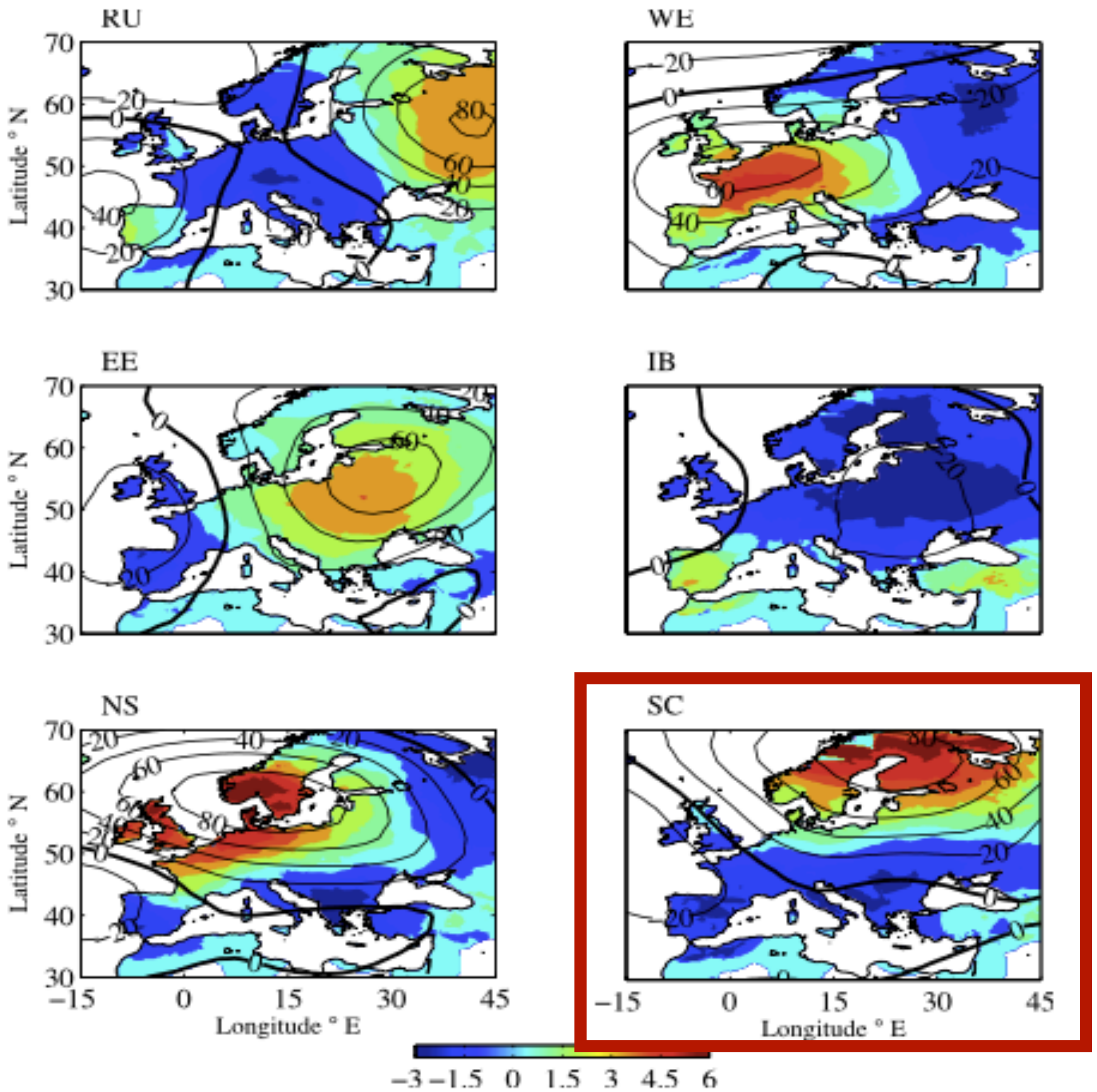
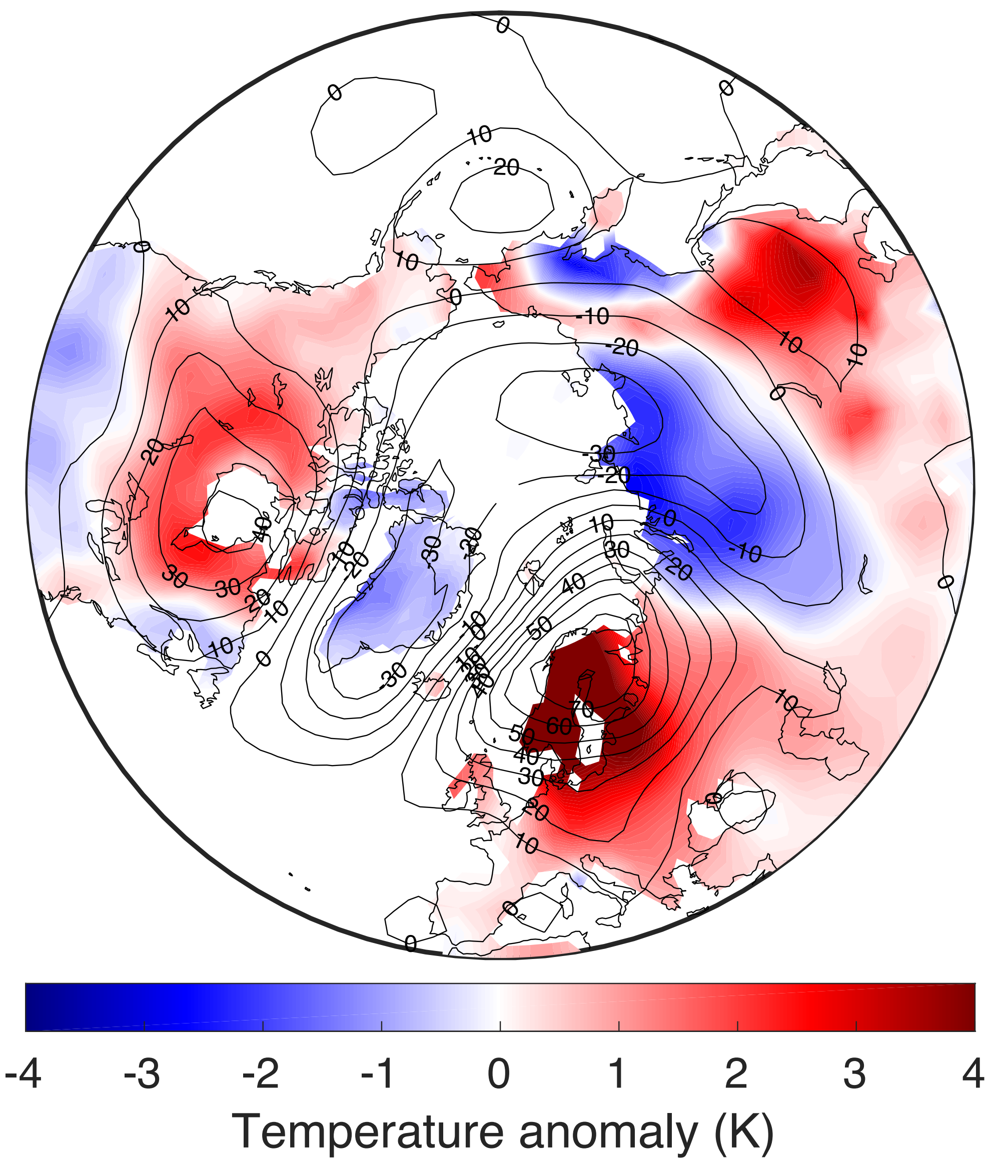


Stefanon et al. 2012

Composite heatwaves r>1000 years



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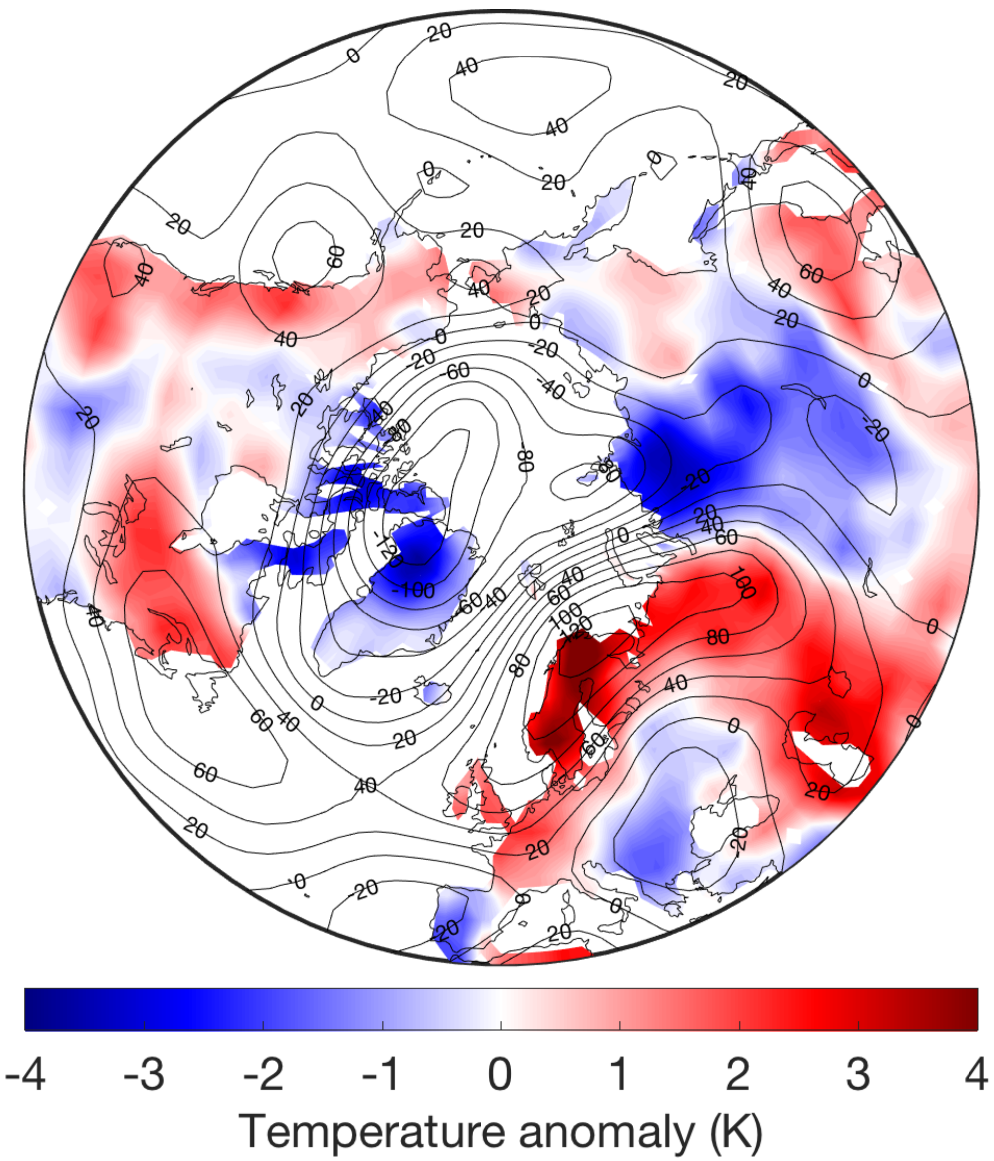
- Pattern broadly similar to Scandinavian heatwave cluster in observations

Heatwaves and warm summers in Plasim

July 2018 heatwave (NCEP)



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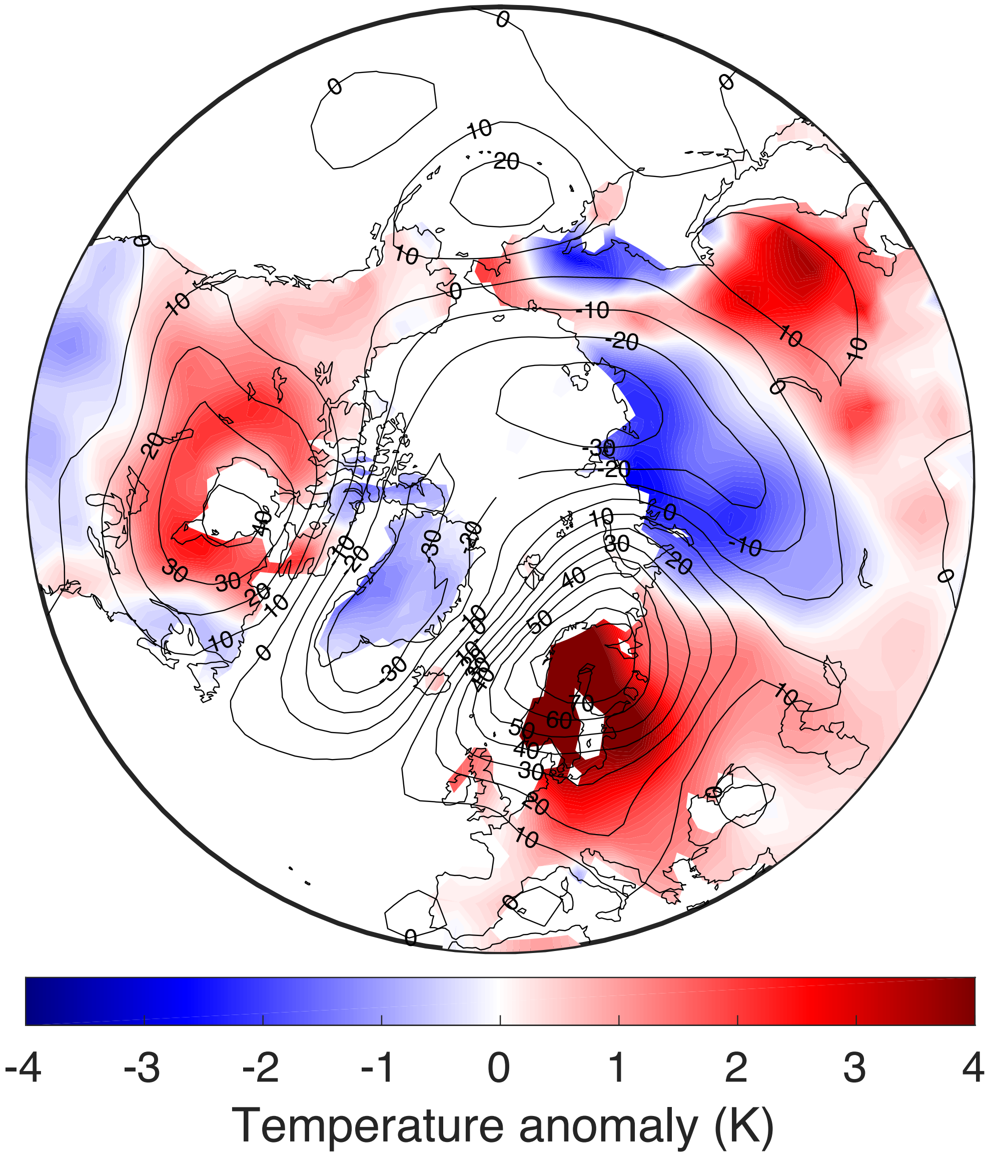

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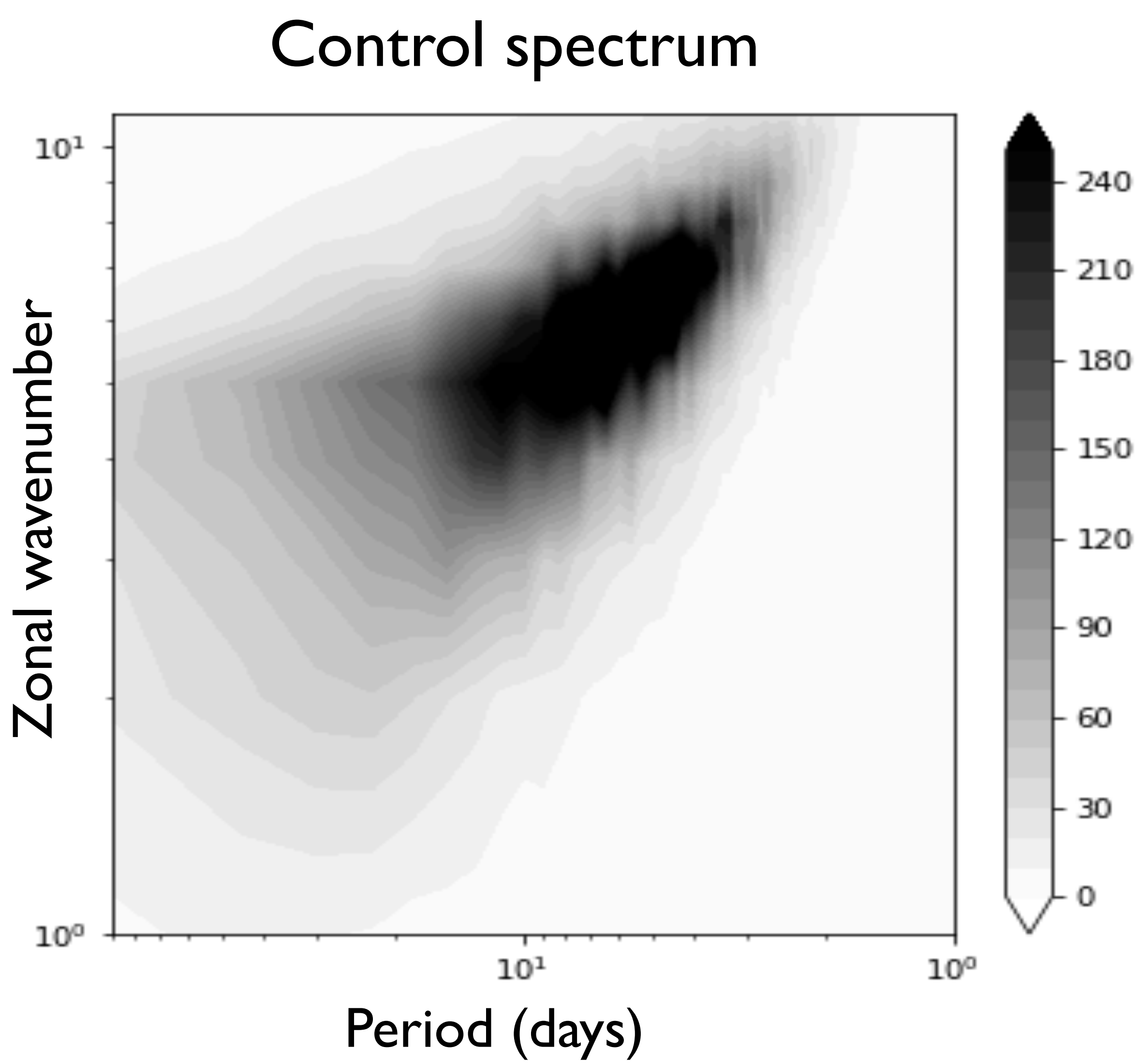
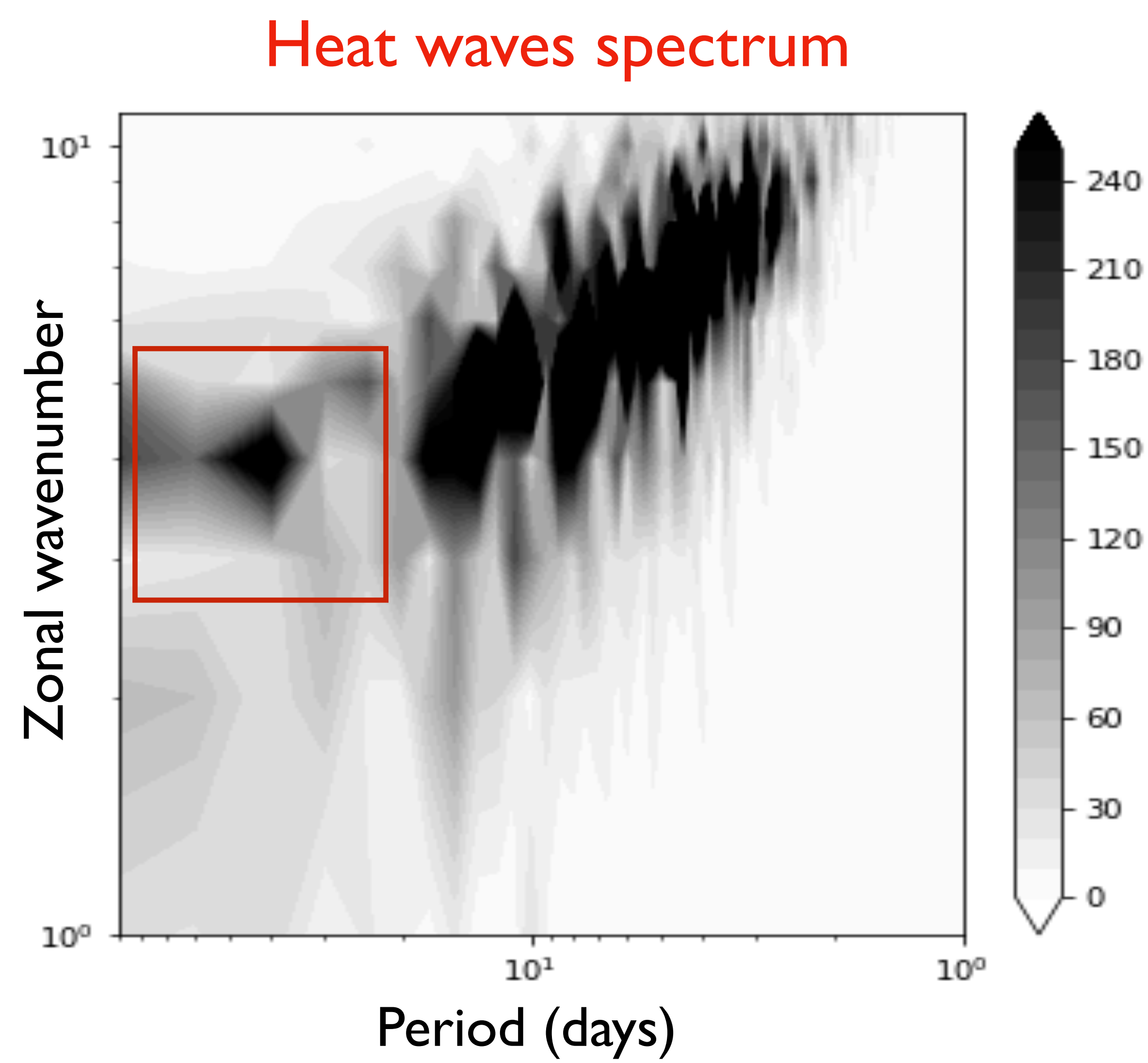
Heatwaves and warm summers in Plasim

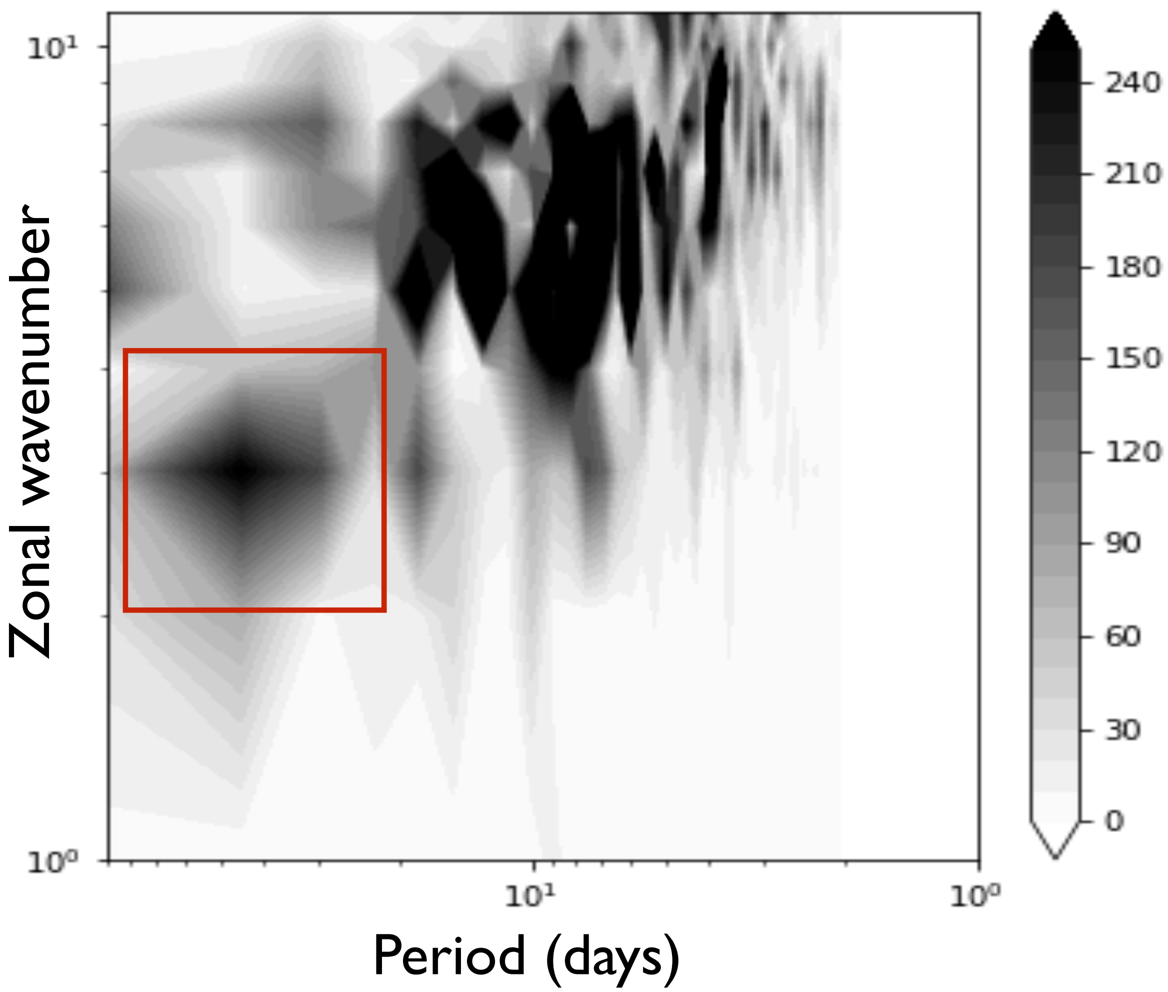




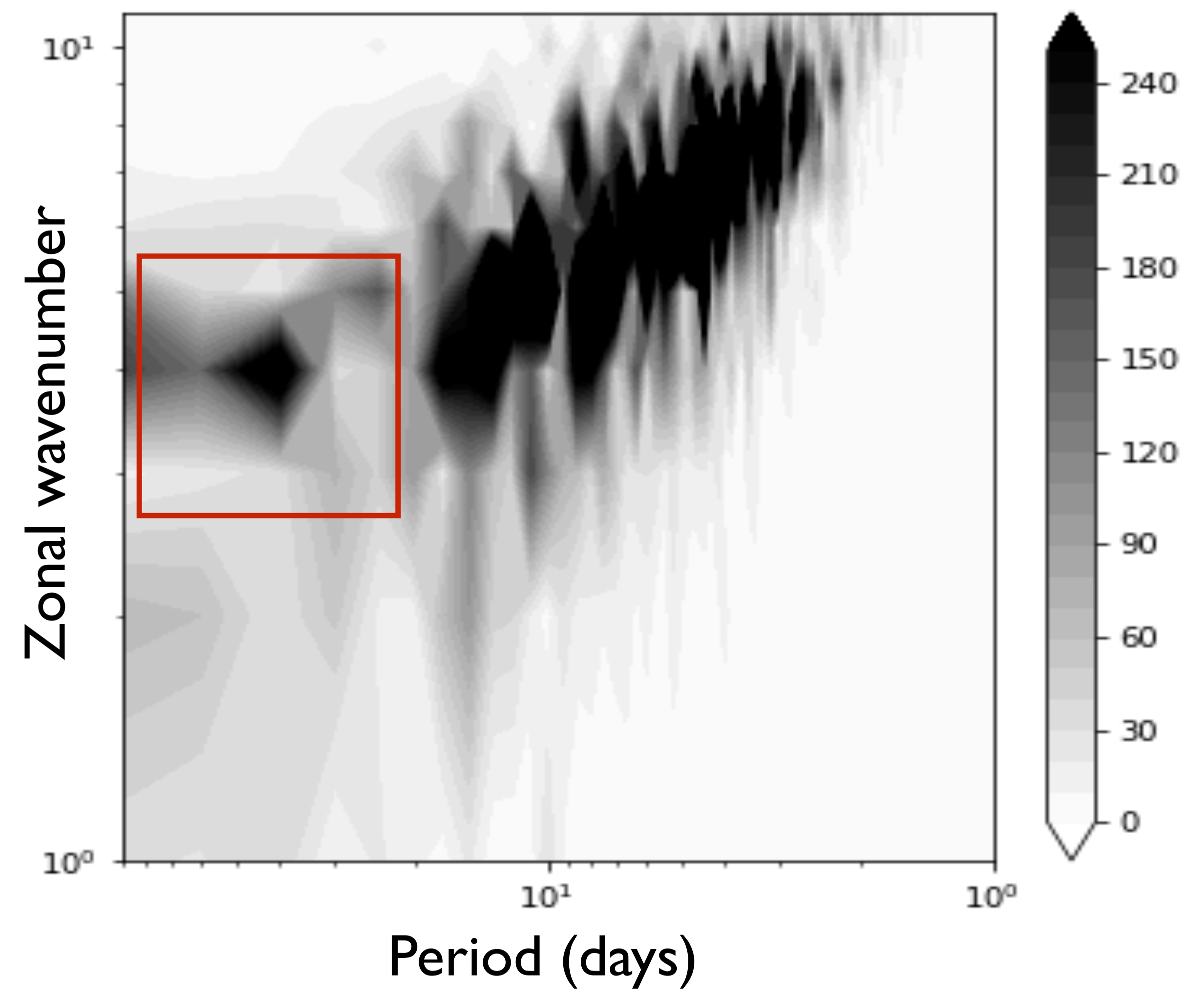
- Teleconnections associated with anomalous planetary wave activity
- Hayashi spectra: space-time spectral analysis of gph averaged between 30 and 75 °N
- Eastward propagating waves spectrum shows low wavenumber "slow" structure
- Amplification of quasi-stationary planetary waves? (e.g. Petoukhov et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

Heatwaves and warm summers in Plasim

JJA 2018 spectrum from NCEP data



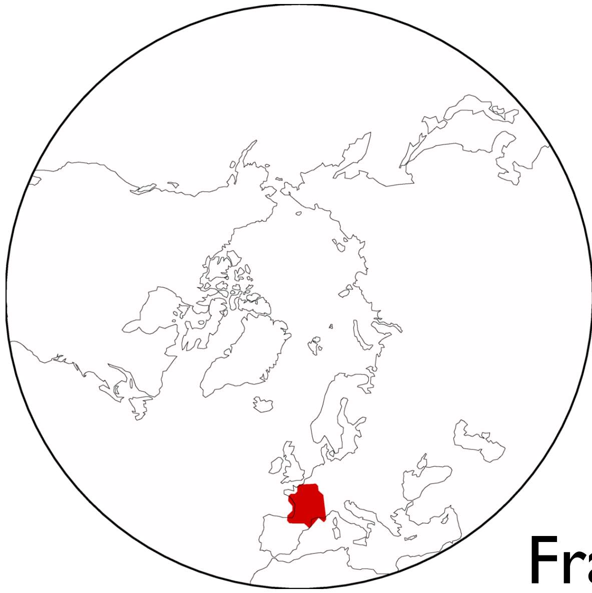
Heat waves spectrum



- 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!

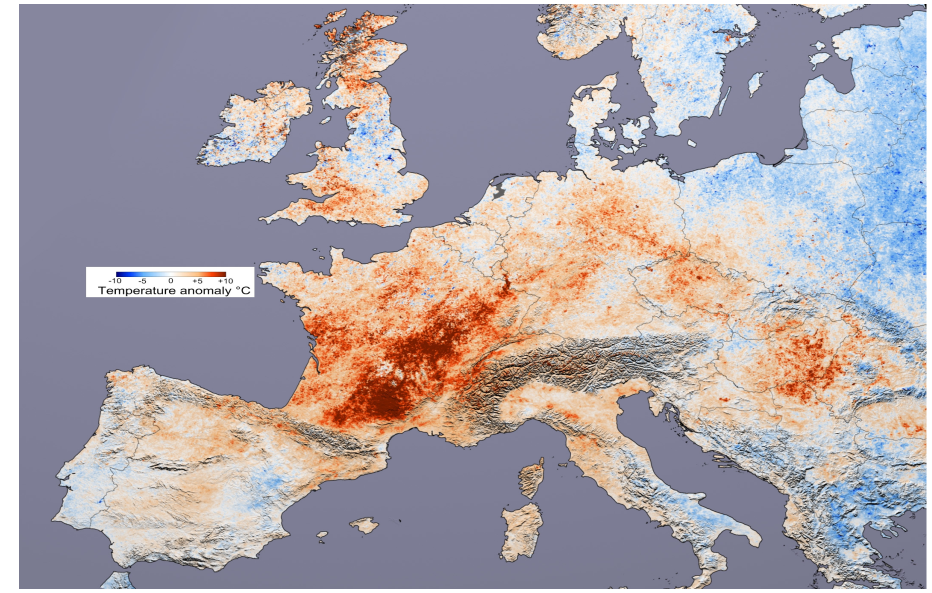
Experiments with climate model CESM

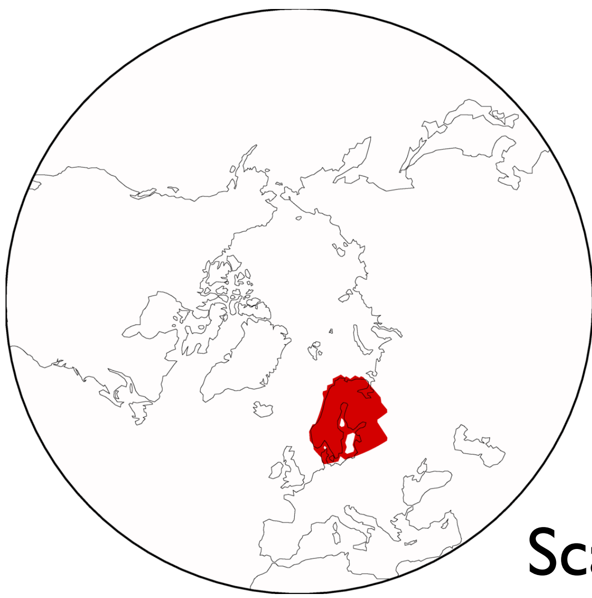


France

ca. 2003 area

WE cluster

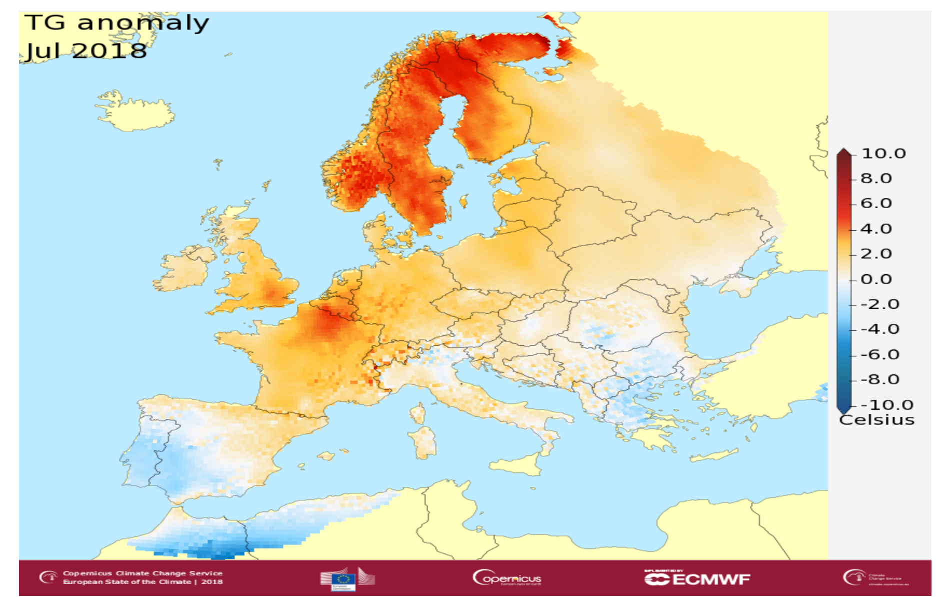




Scandinavia

ca. 2018 area

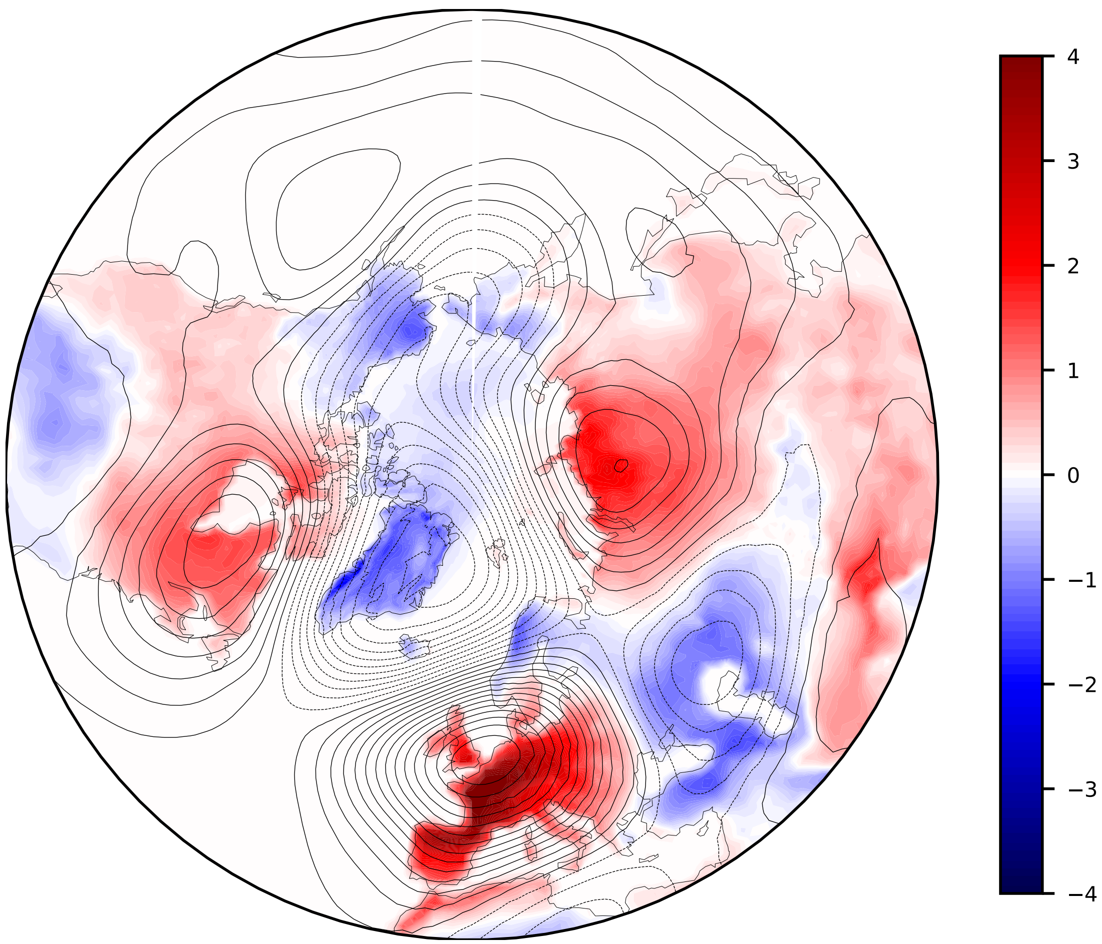
SC cluster



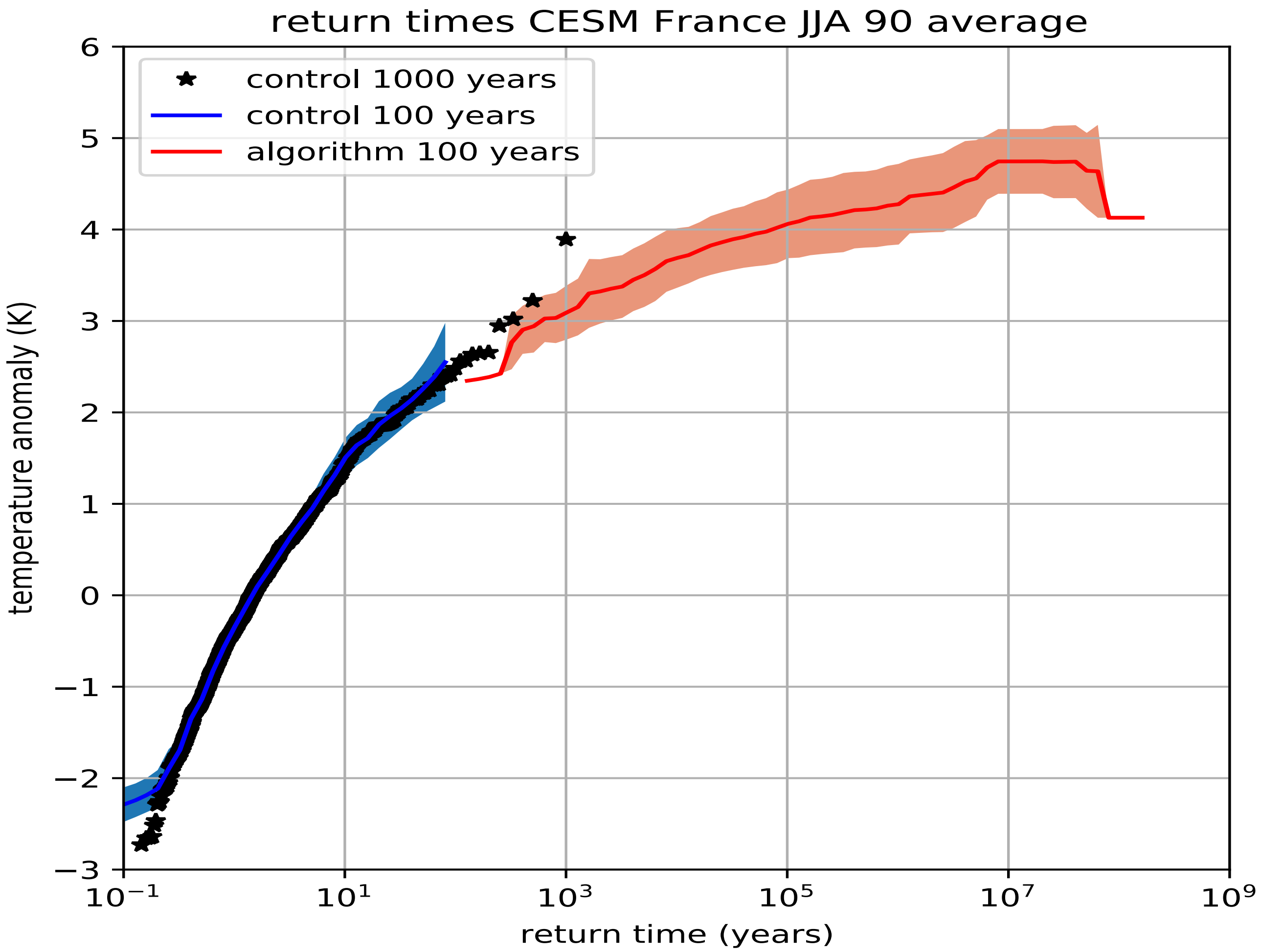
- Same experiments with CESM1.2, still prescribed SST but higher resolution (1° horizontal, 26 vertical levels), much more complex physics
- Two sets of 10 experiments targeting temperature over France or Scandinavia
- Each experiment ensemble 100 trajectories running for one summer (JJA), 25 yers equivalent computational cost. Total per region 250 years (doable with limited resources)

Experiments with CESM: heatwaves over France

France warm summers r>1000 years



return time summer temperature France



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

Experiments with CESM: heatwaves over Scandinavia

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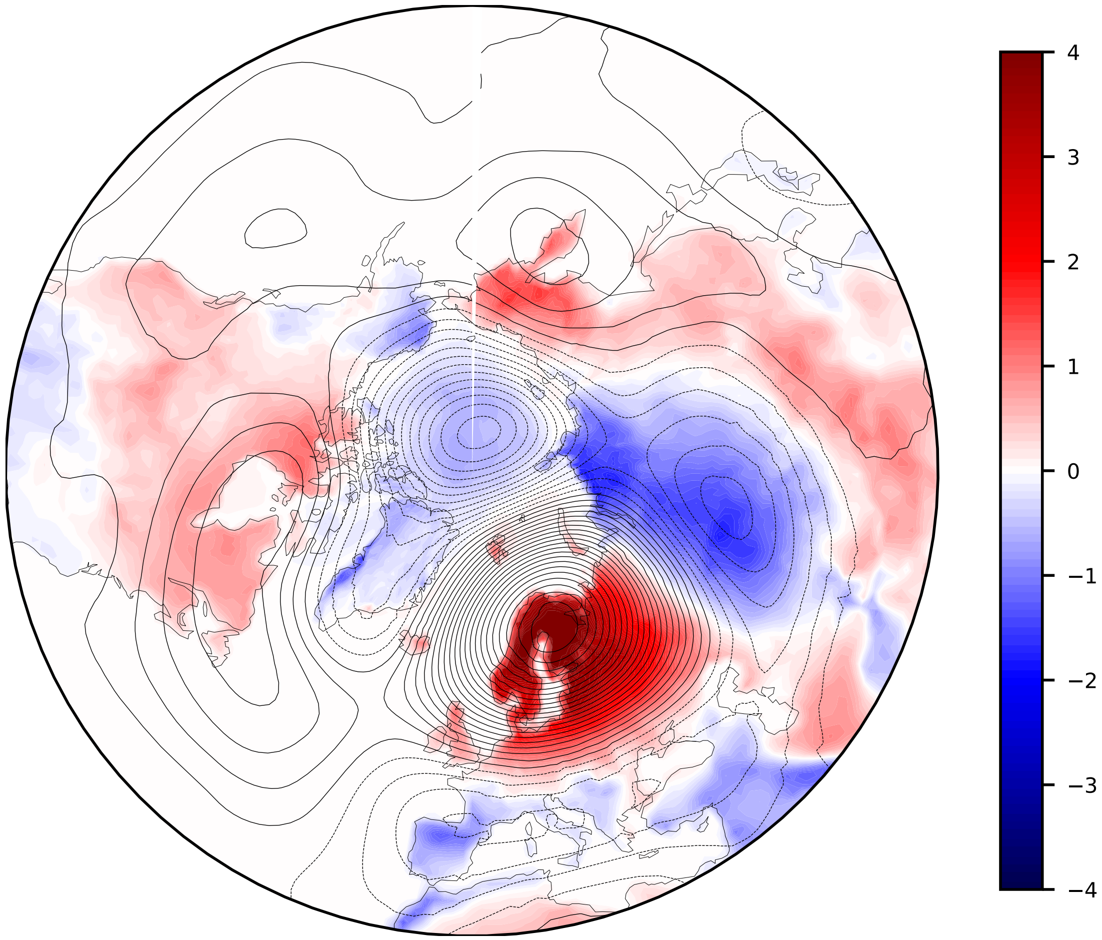

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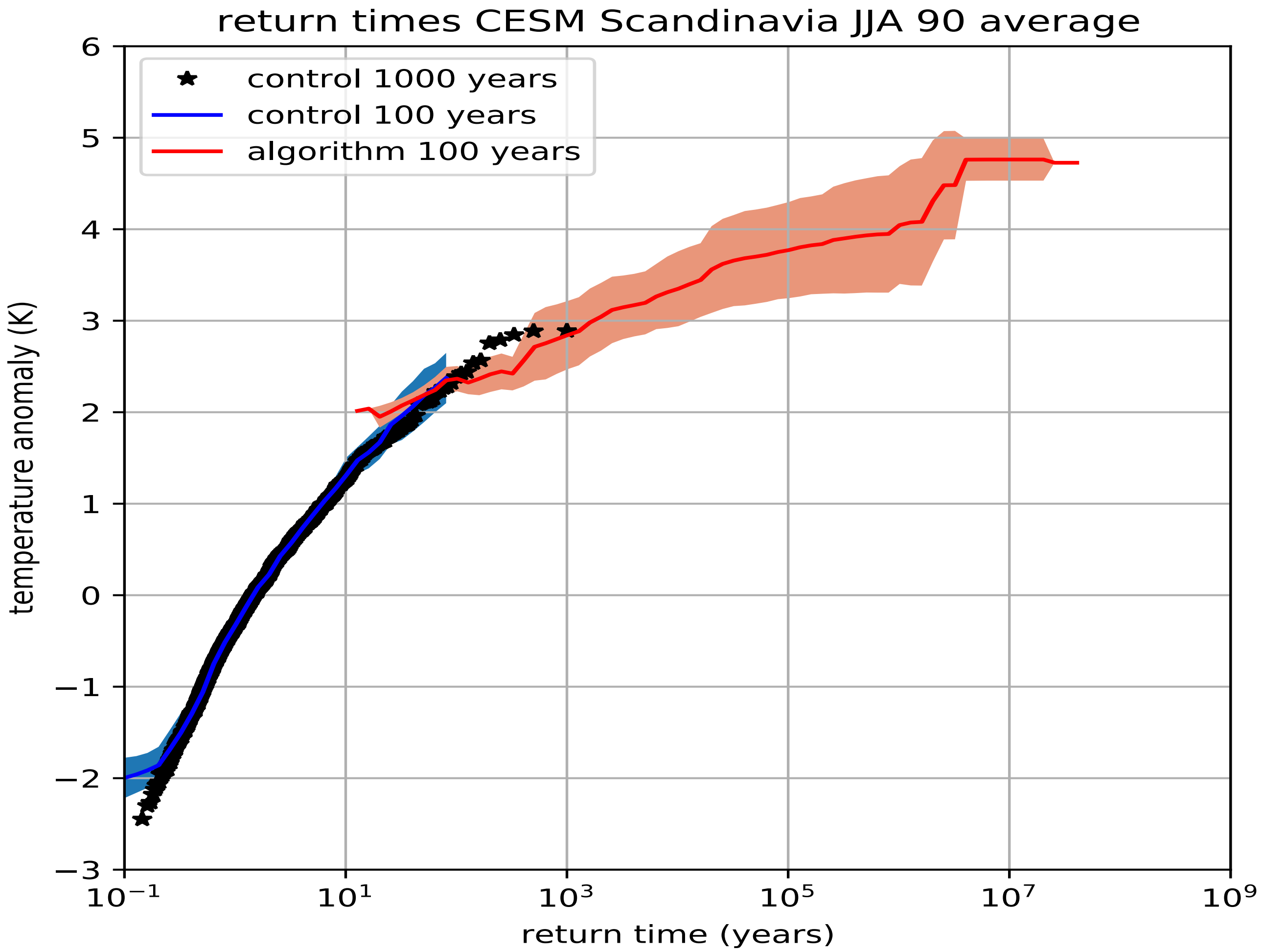

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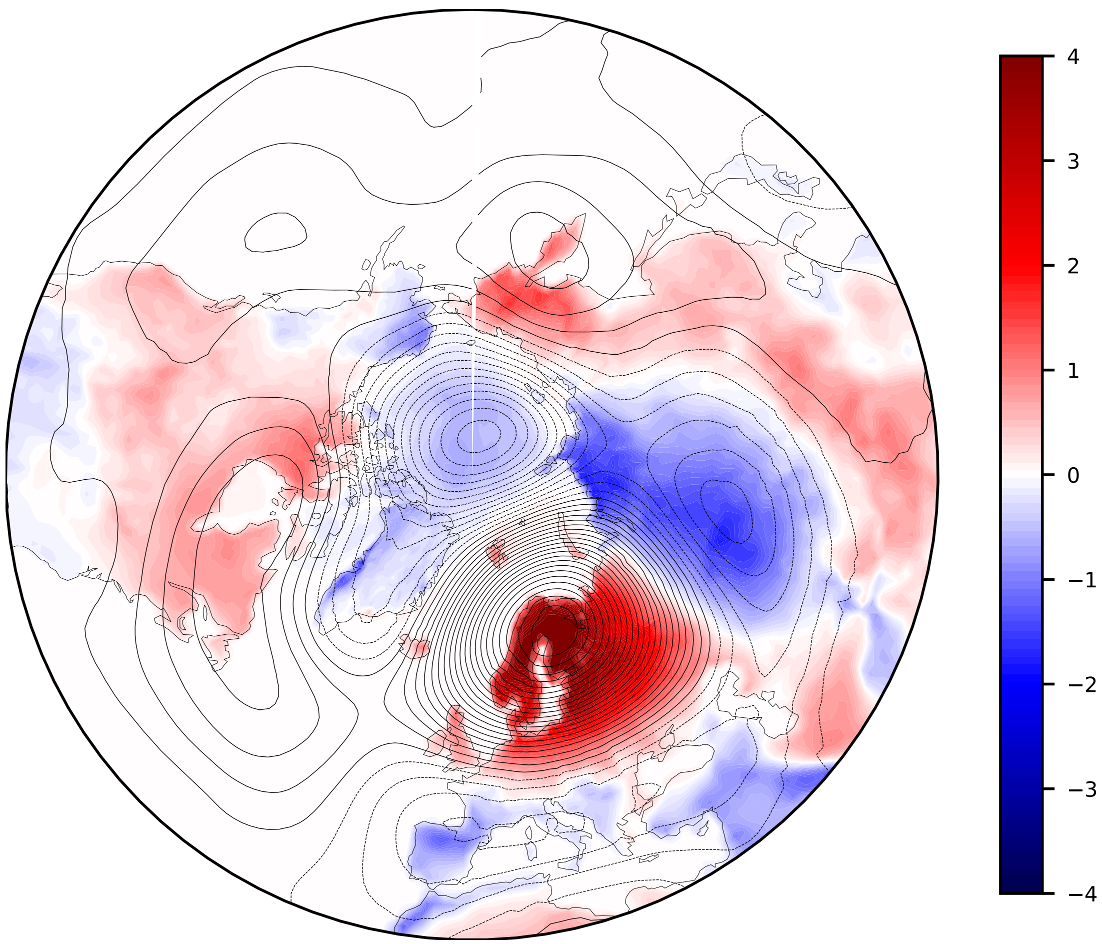

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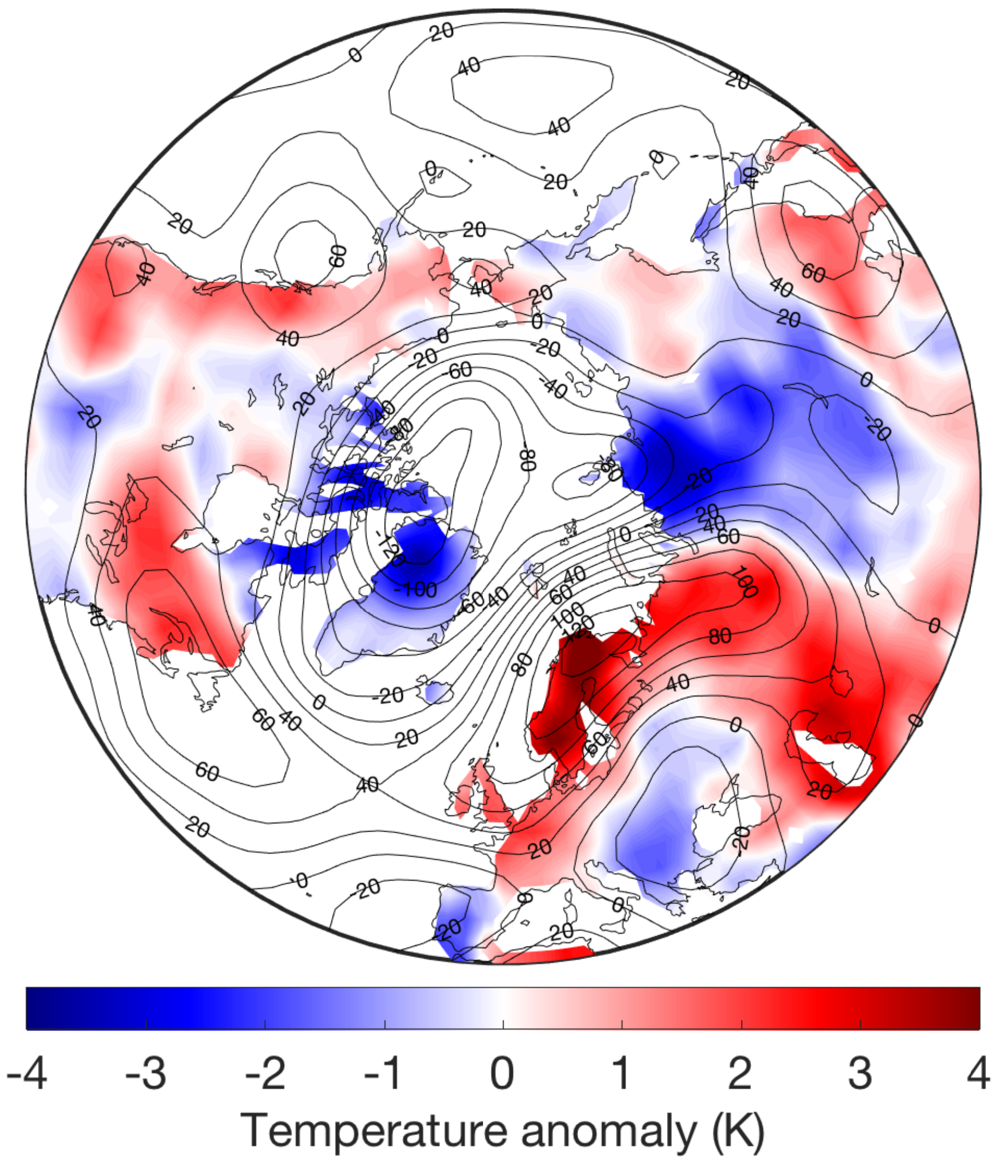

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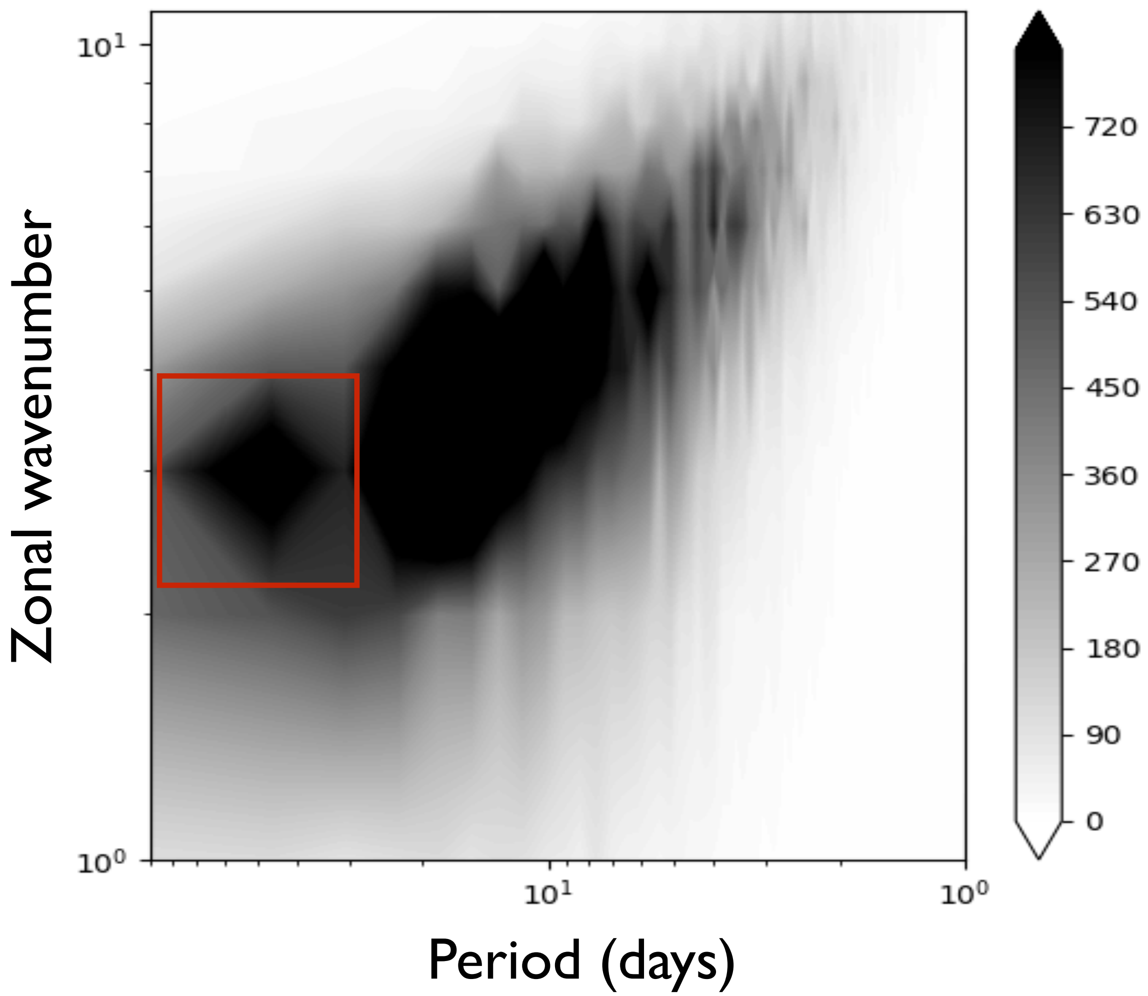
Heat waves spectrum



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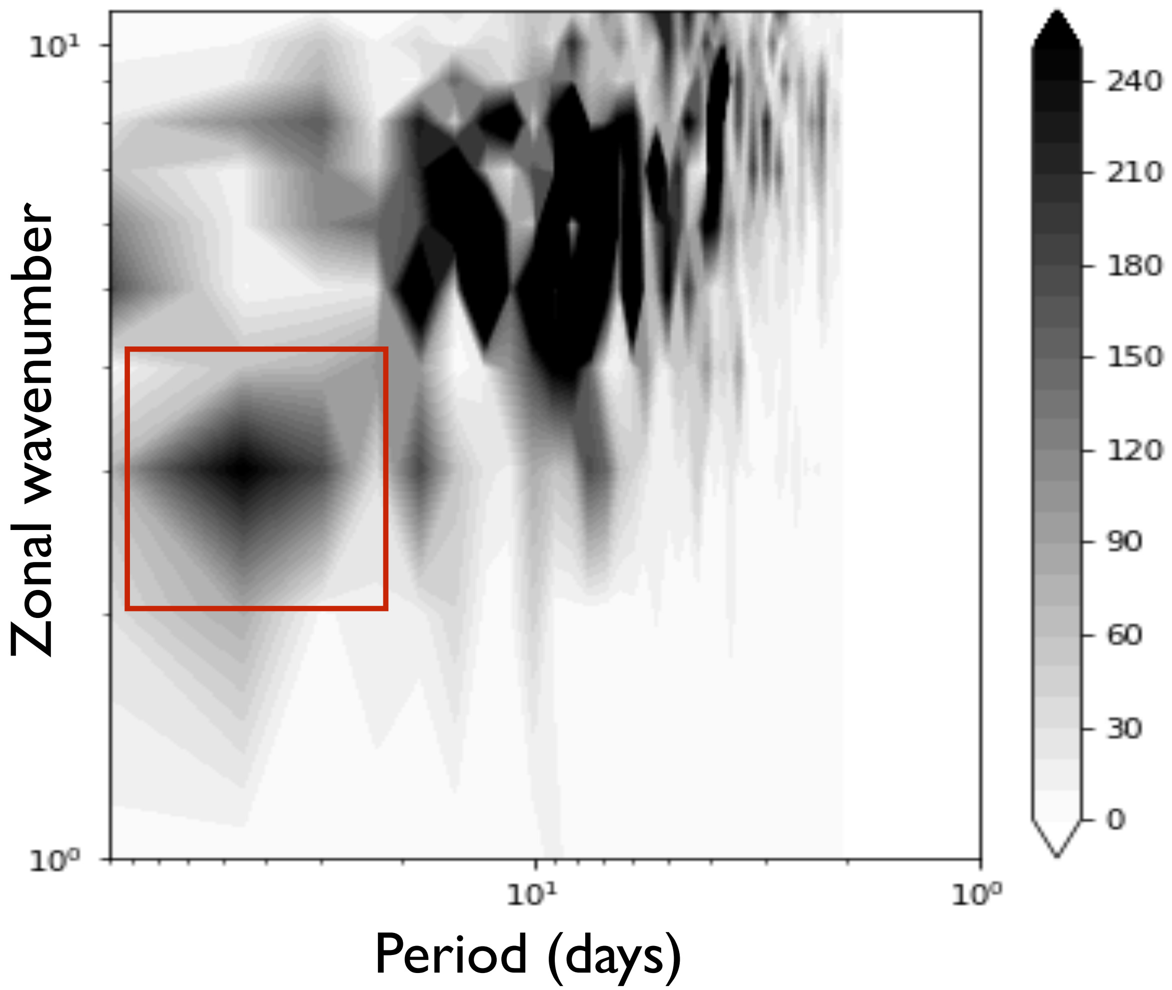

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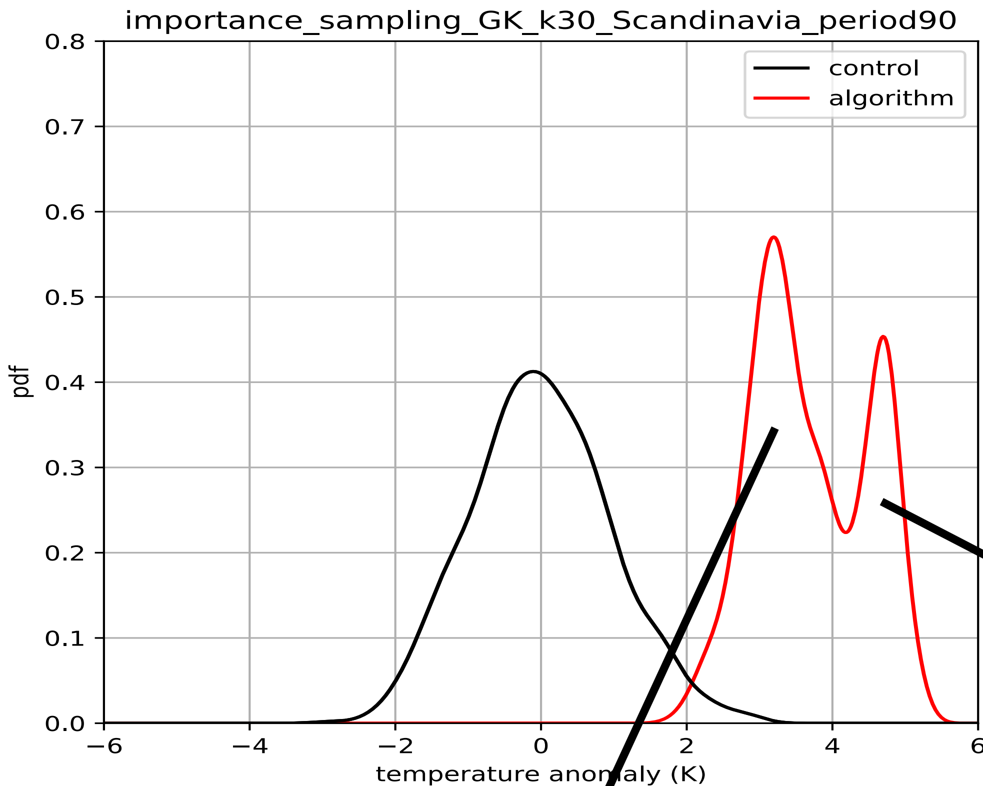
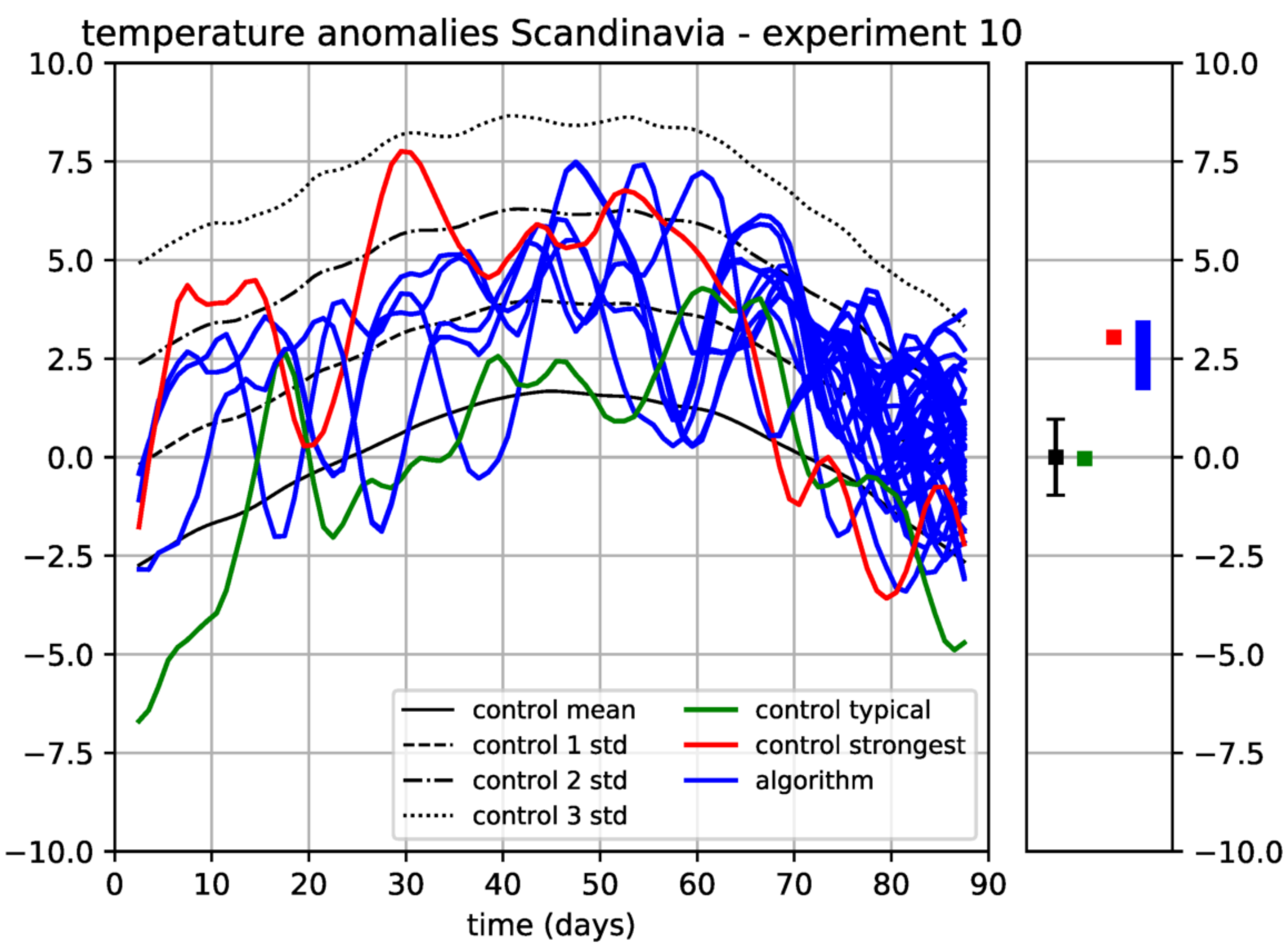
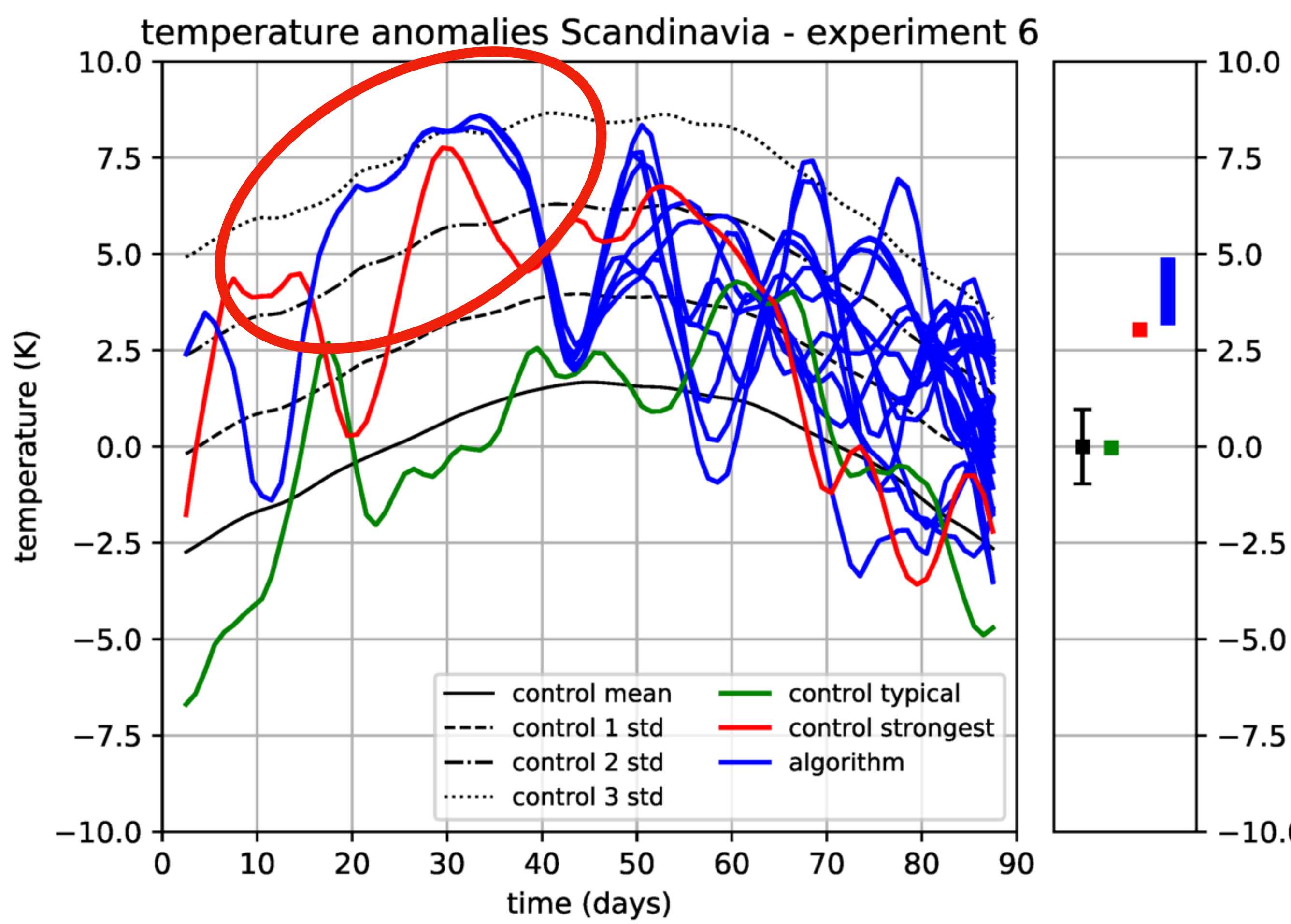


- For Scandinavia unexpected behaviour
- Bimodality distribution seasonal temperatures
- Upper mode hosts "mega-heatwave" June-July events with same characteristics in different ensembles

Ragone and Bouchet, *GRL* 2021





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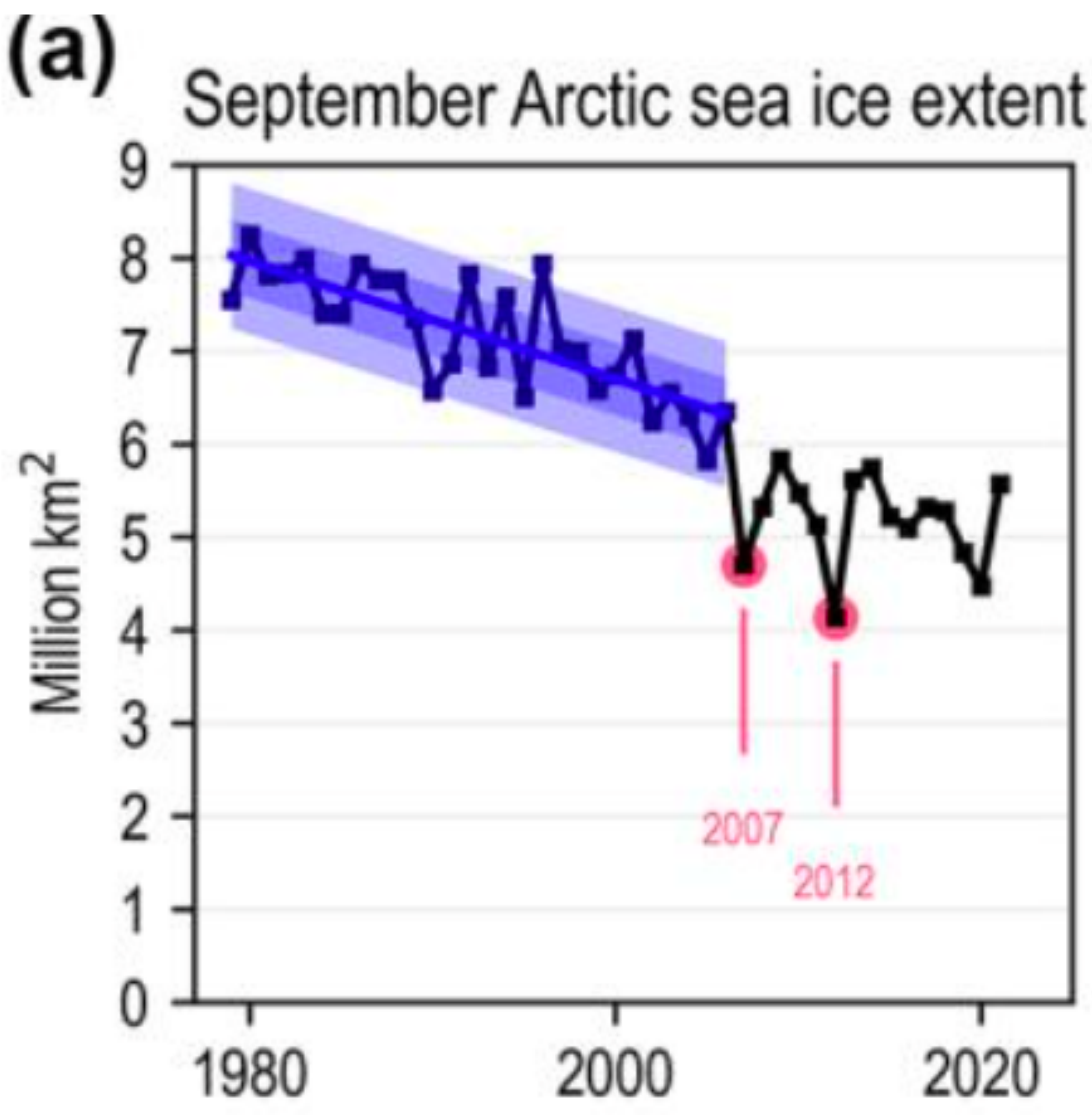
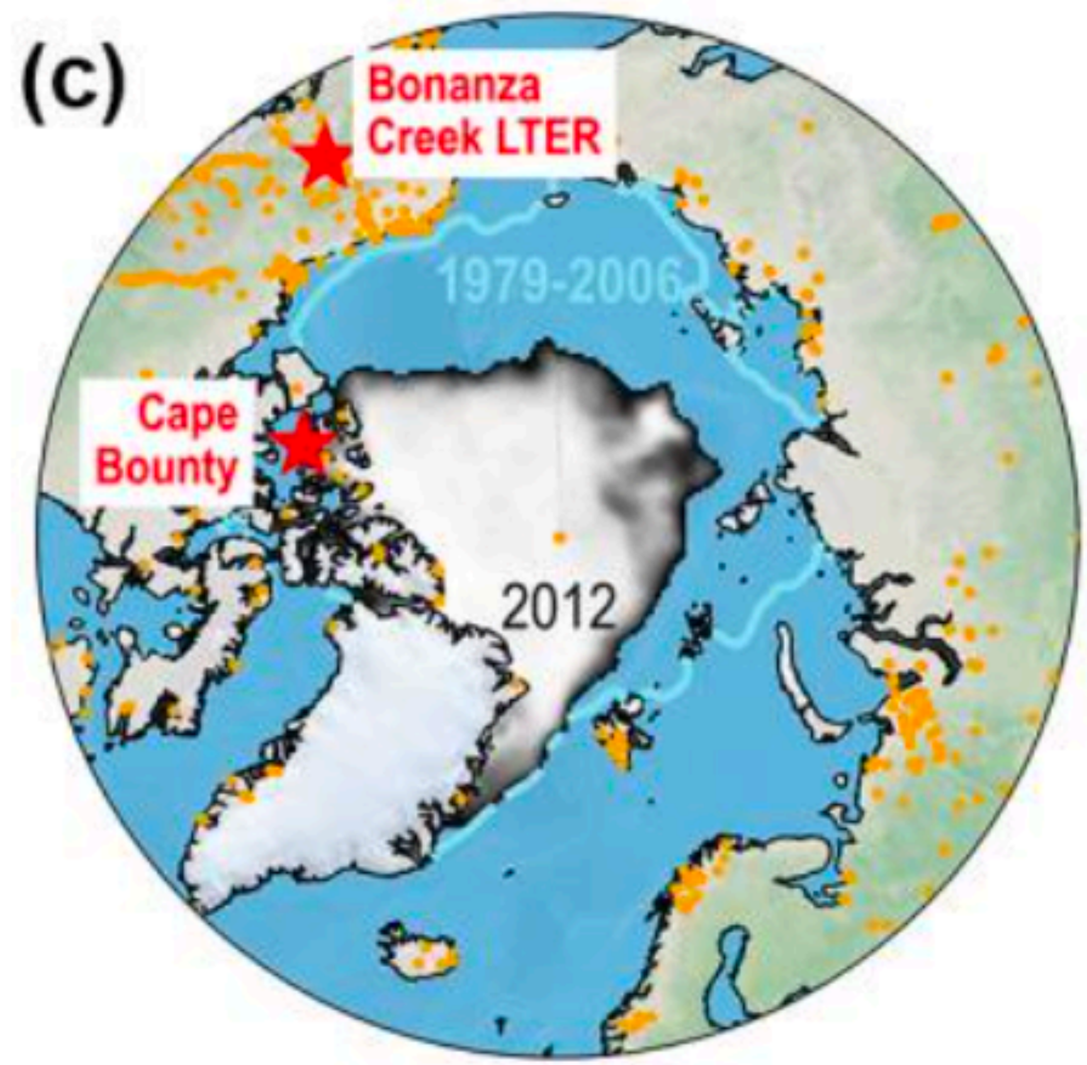
Arctic sea ice reduction in Plasm-LSG





- Arctic sea ice reduction extremes, Jerome Sauer (PhD UCLouvain), François Massonnet, Giuseppe Zappa, Jonathan Demaeyer

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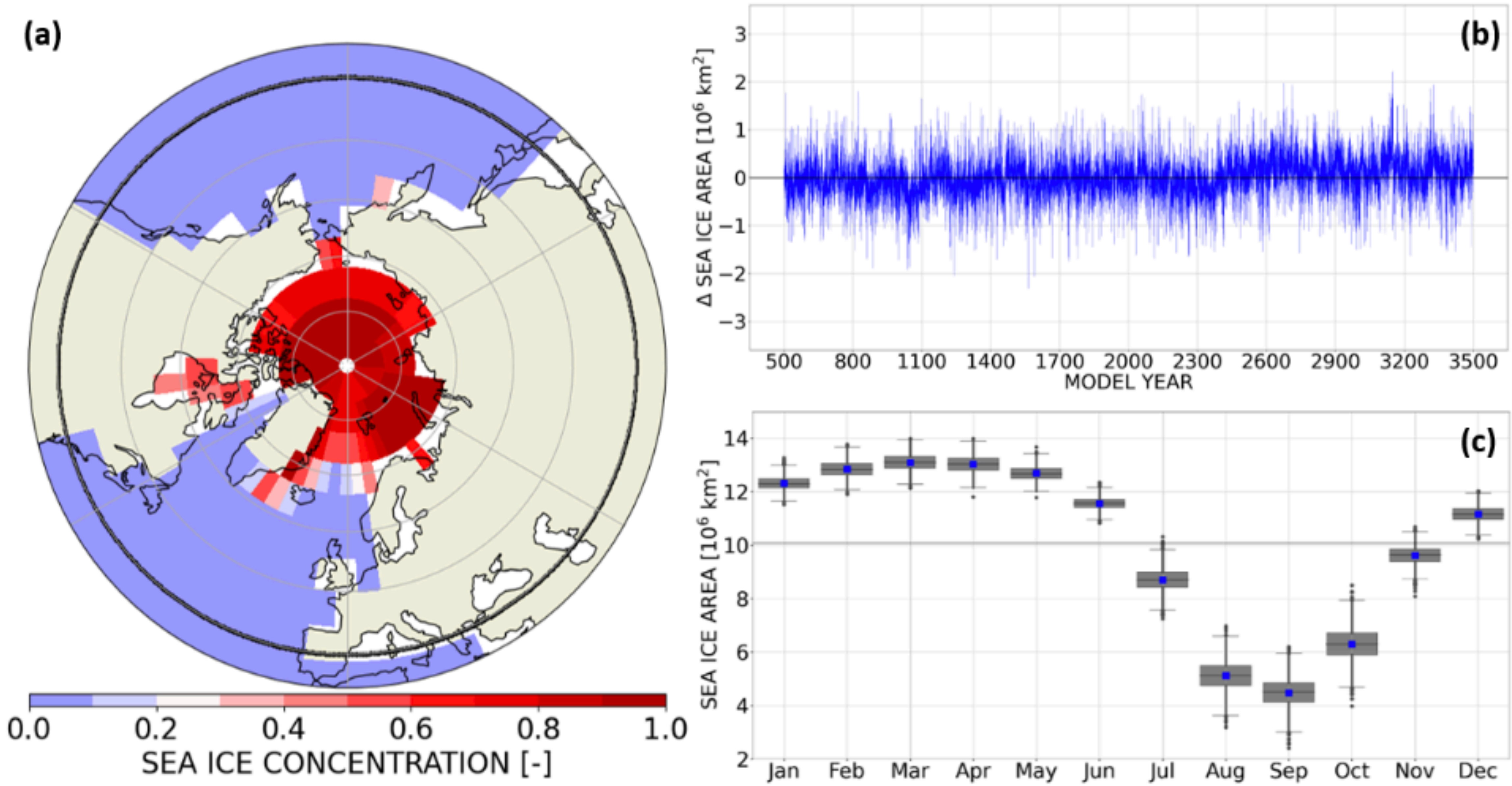
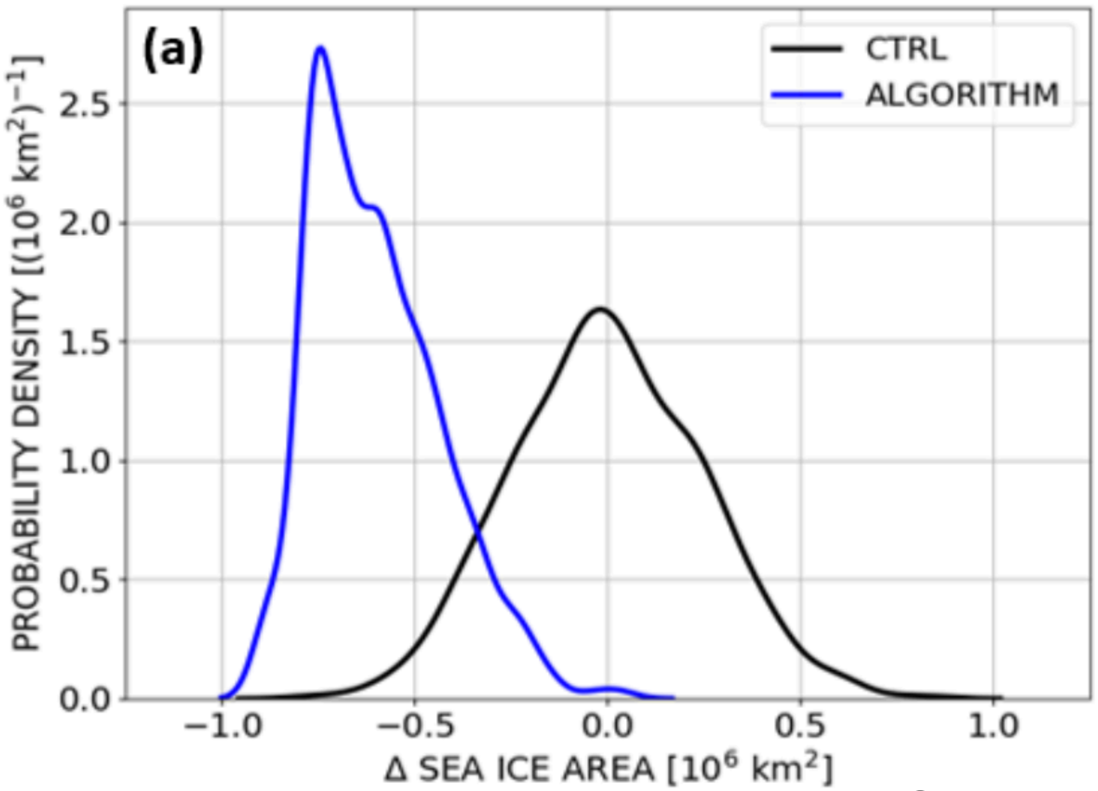
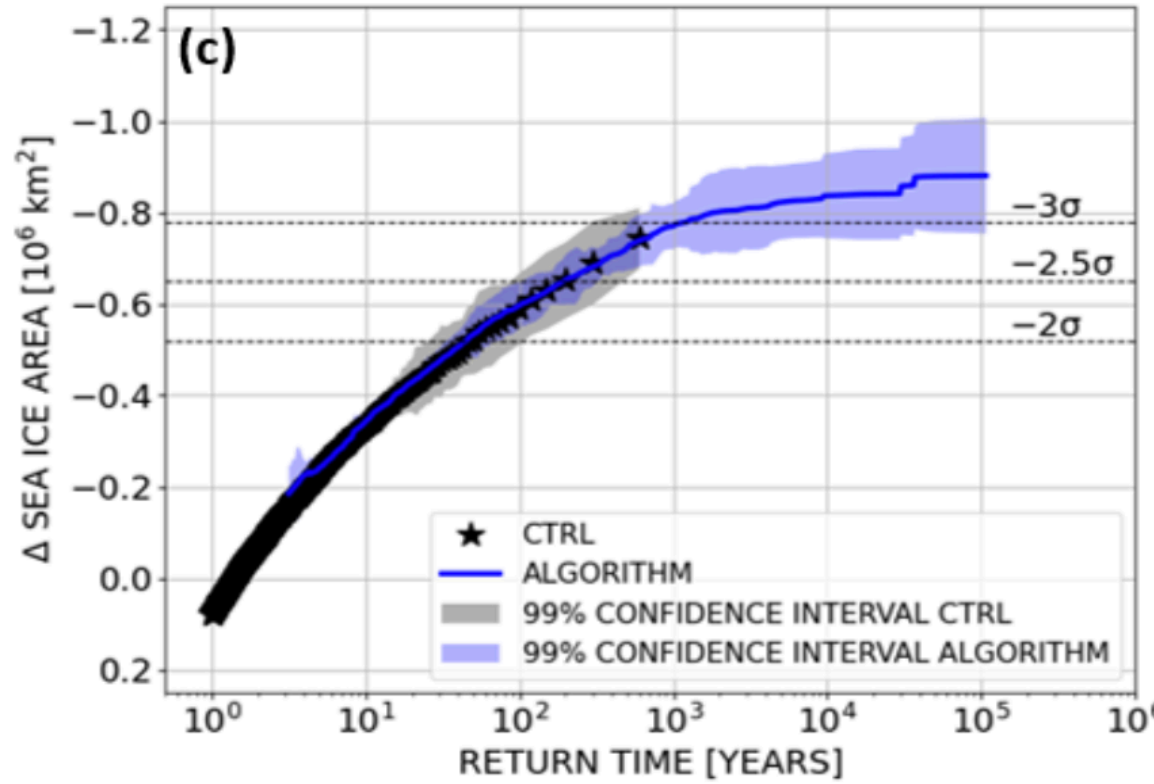


Sauer et al., submitted

- Simulations with Plasim coupled to LSG ocean model, T21 resolution, reasonable climate
- Experiments melting season (Feb-Sep), 5 days resampling time, target pan-Arctic sea ice

Arctic sea ice reduction in Plasm-LSG





Sauer et al., submitted

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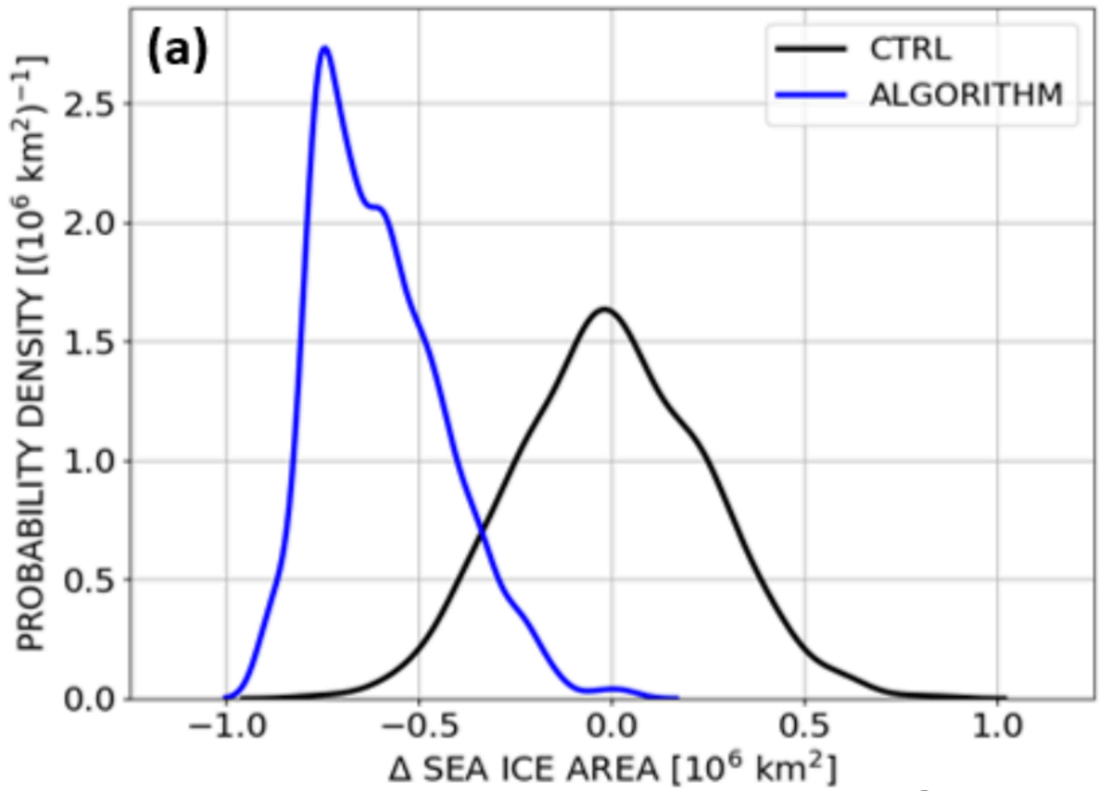

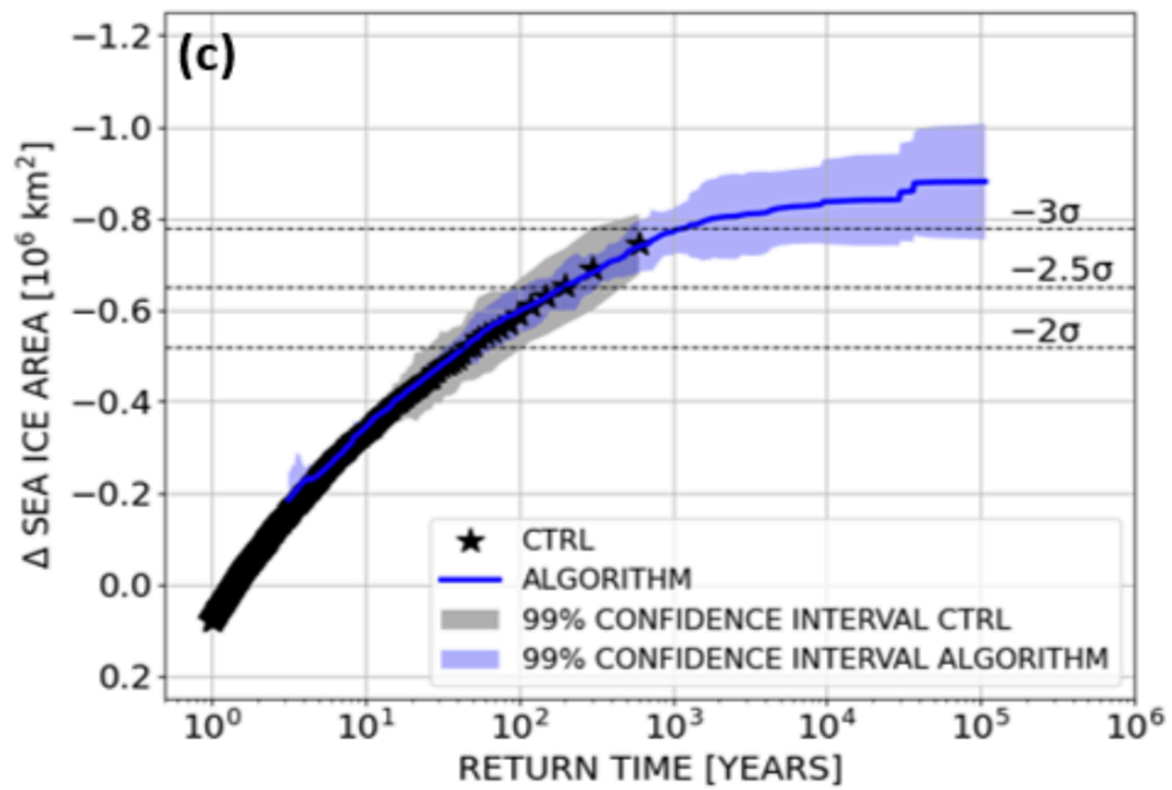

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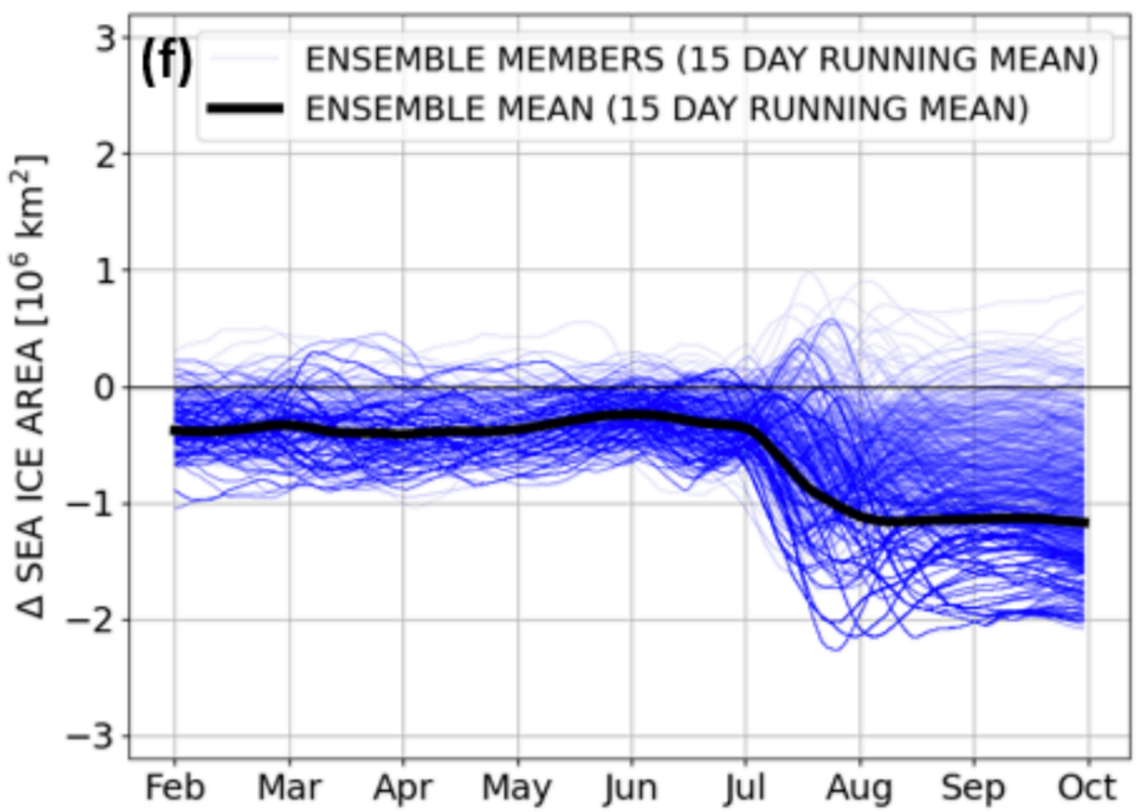

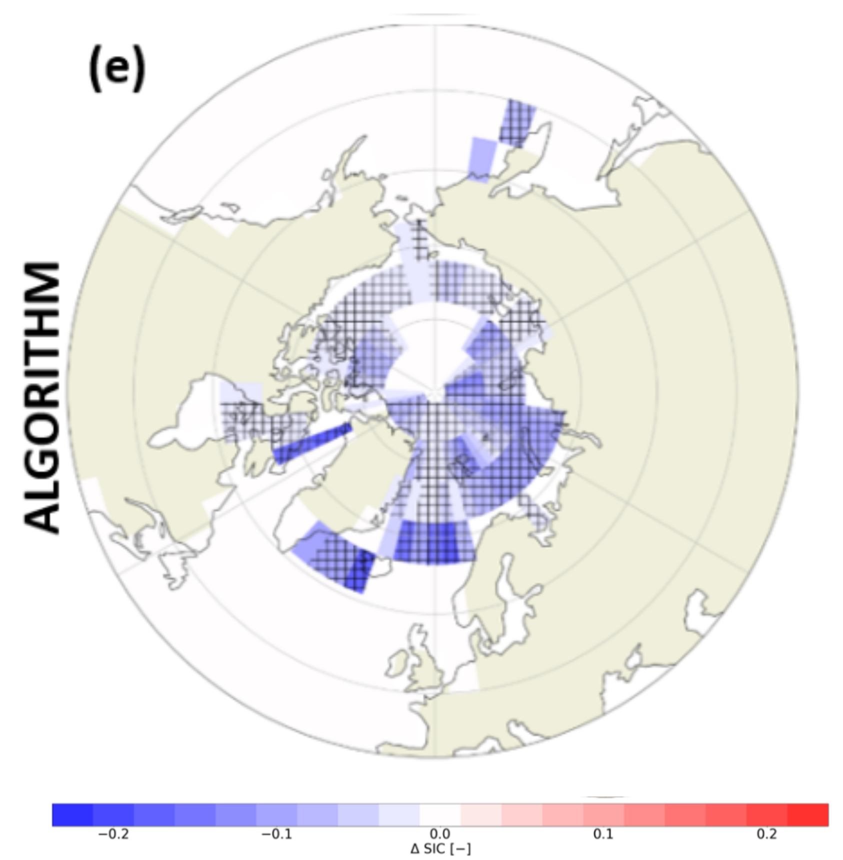

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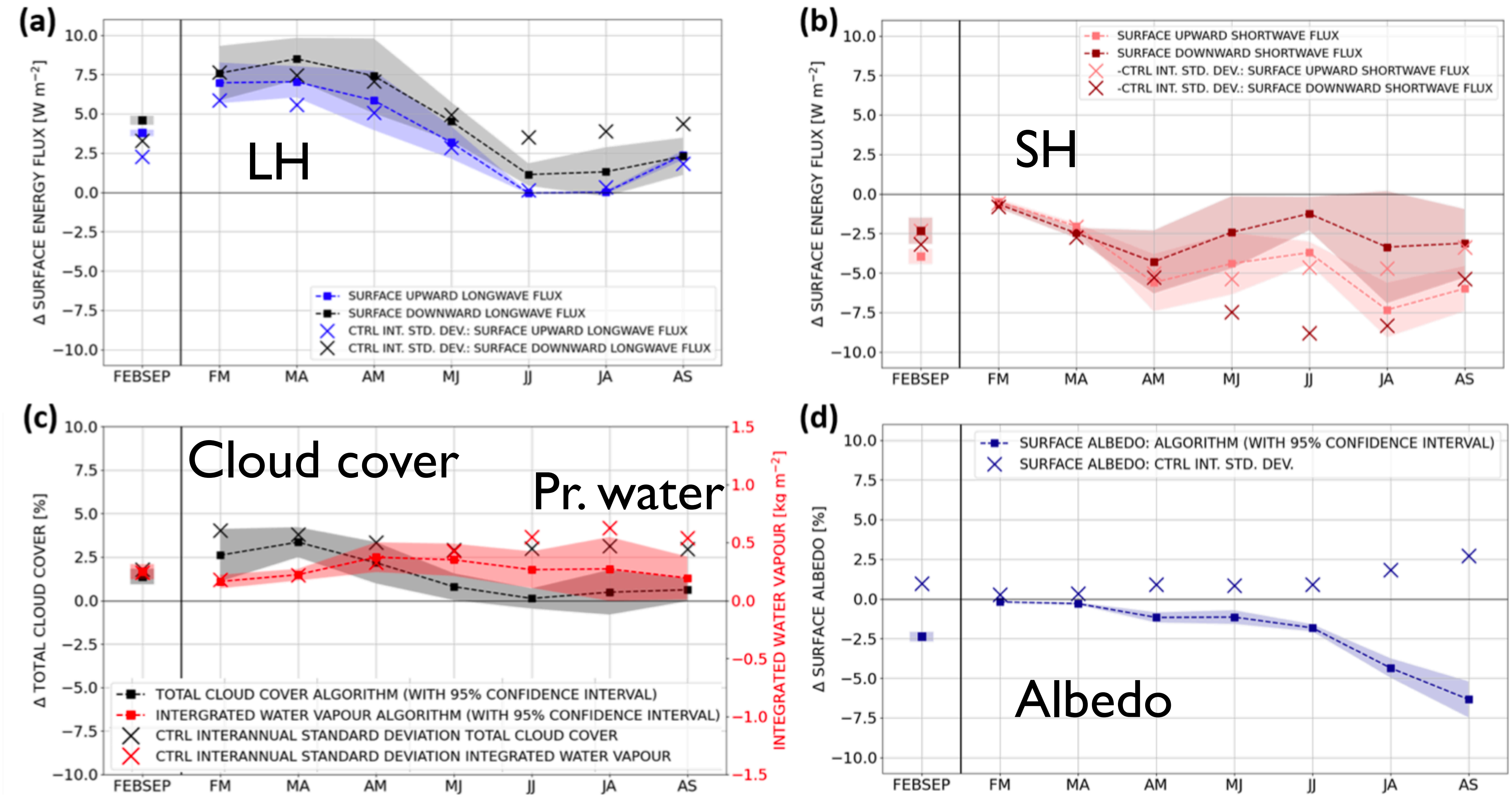
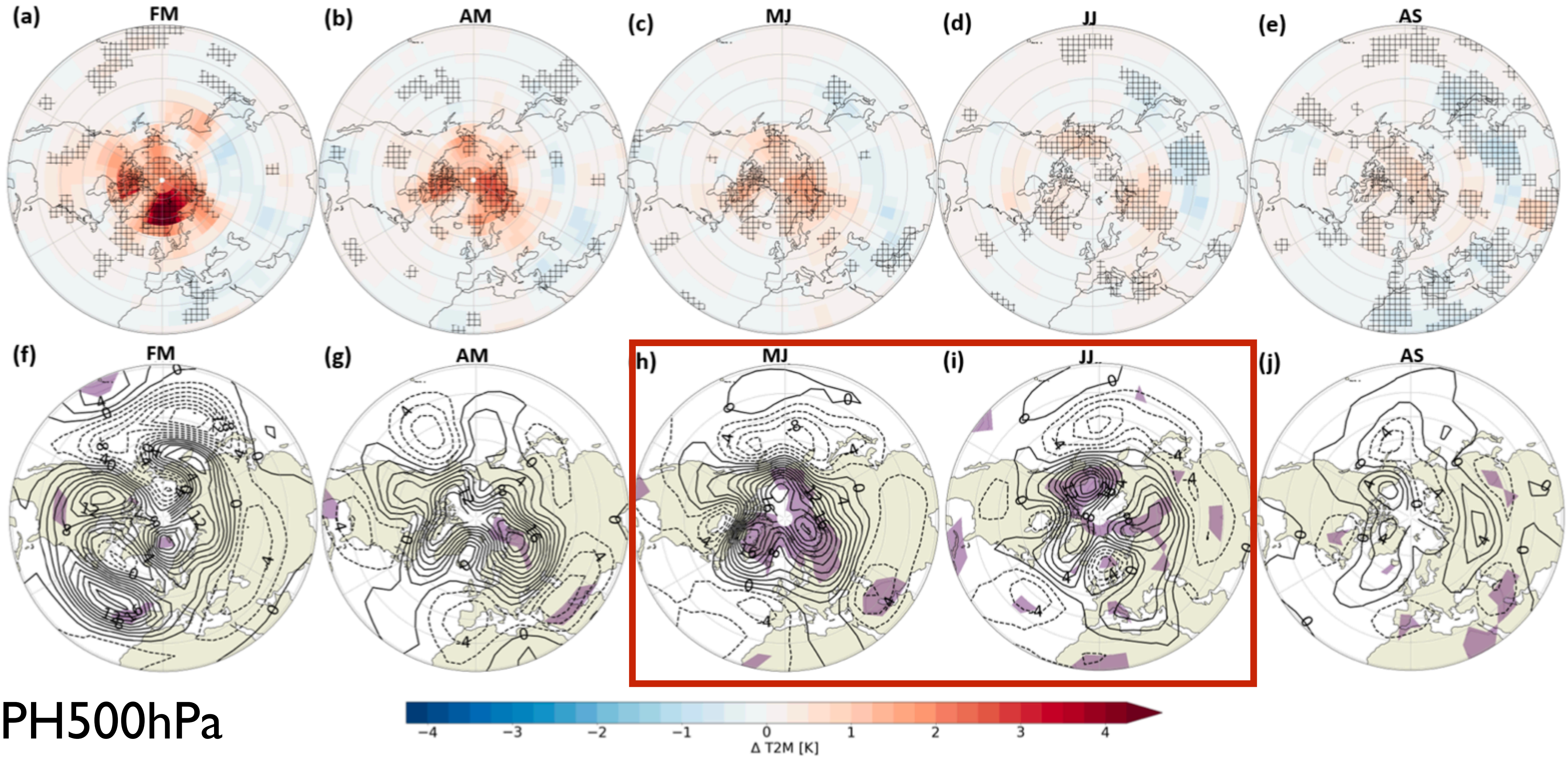


- Three ingredients are necessary to obtain a seasonal extreme of Arctic sea ice:
  - Preconditioning (memory and/or lack of sea ice thickening during winter)
  - Highly humid and cloudy Arctic atmosphere throughout late winter and spring
  - Arctic "heatwave" in early summer

Sauer et al., submitted

Arctic sea ice reduction in Plasm-LSG

T2M



GPH500hPa

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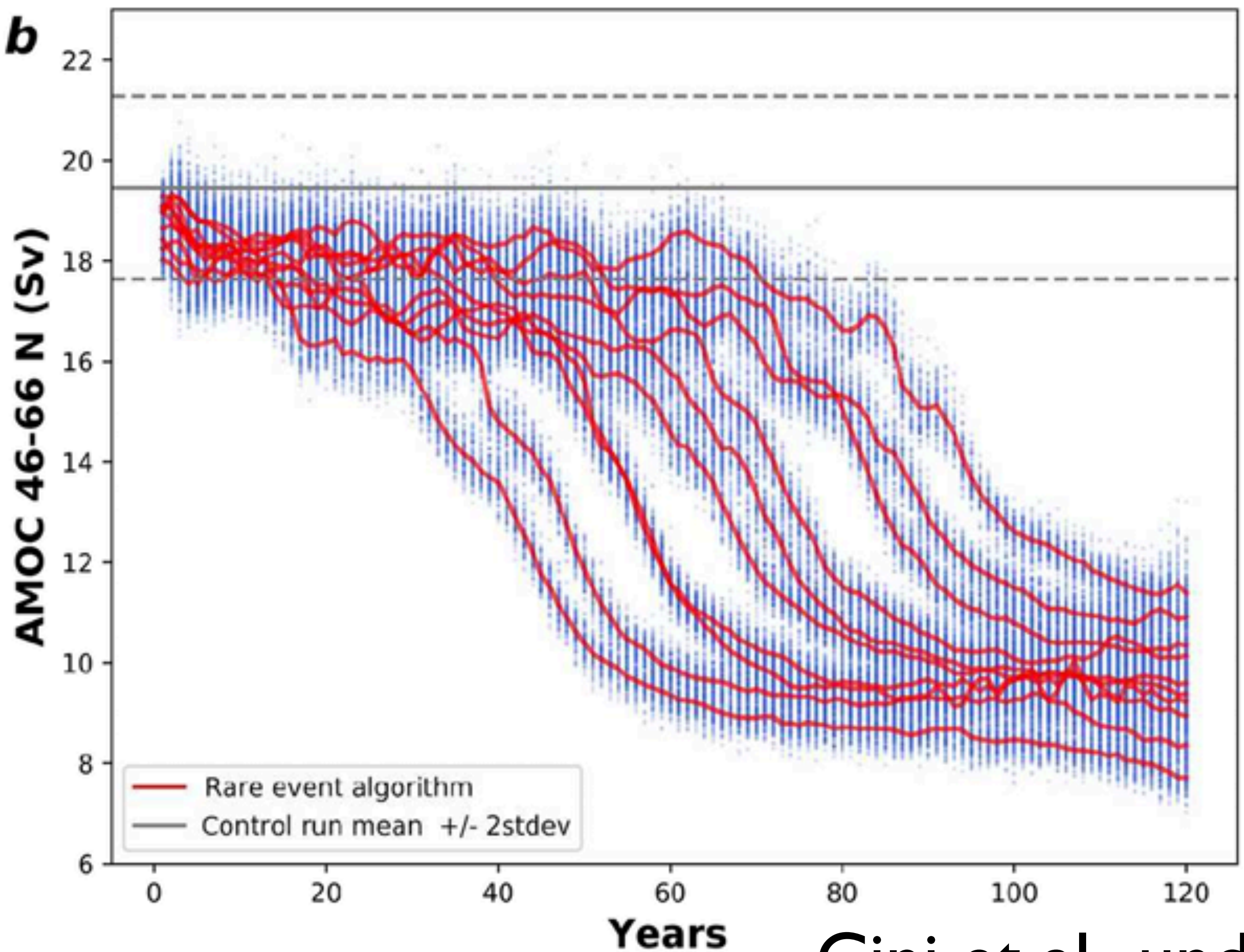
Rare event algorithm and importance sampling

- Applications:
  - European heatwaves in Plasim (intermediate complexity GCM)
  - France and Scandinavia heatwaves in CESM1.2
  - Arctic sea ice reduction in coupled Plasim-LSG
  - AMOC weakening and collapse in coupled Plasim-LSG

AMOC weakening and collapse in Plasim-LSG



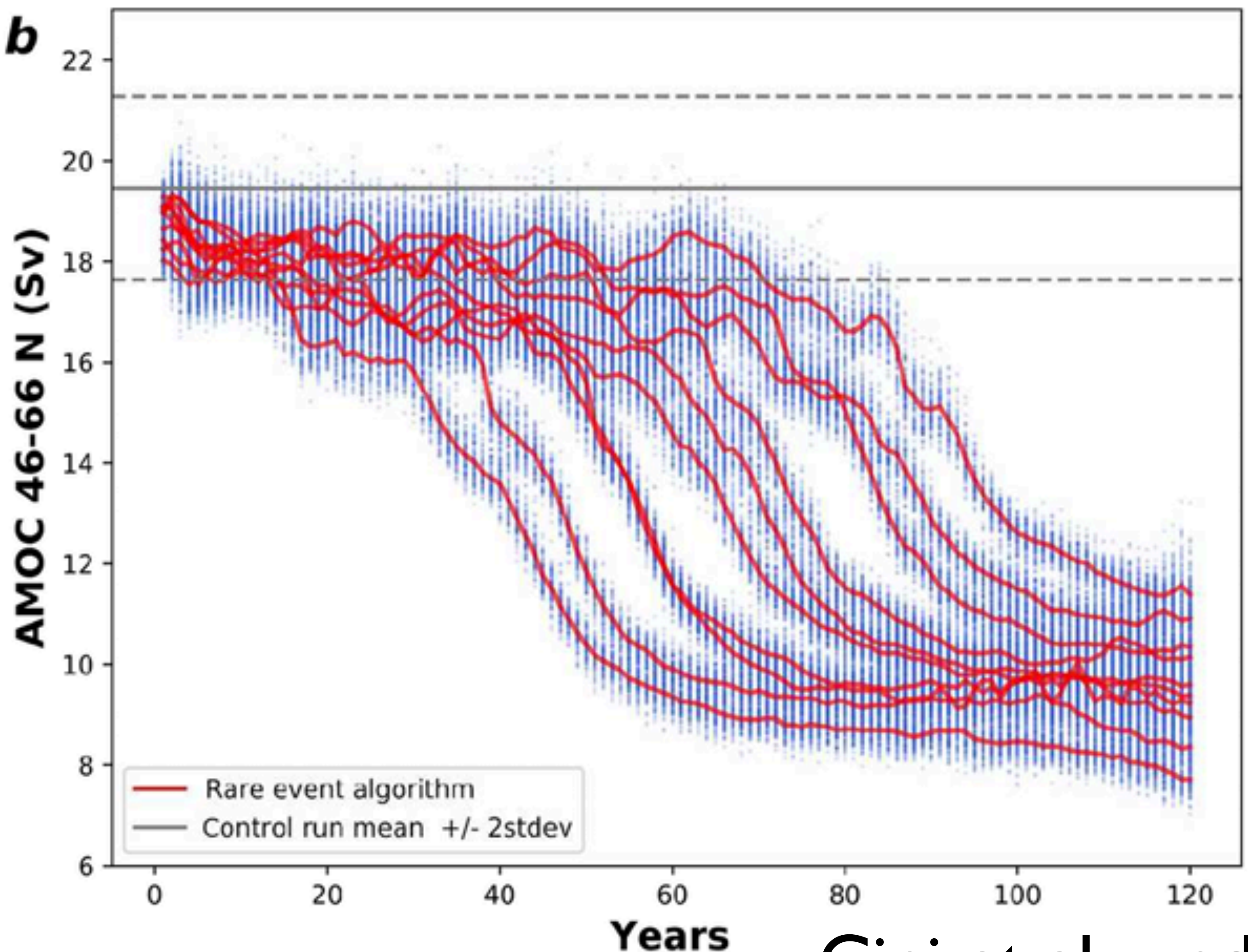
Cini et al., under review

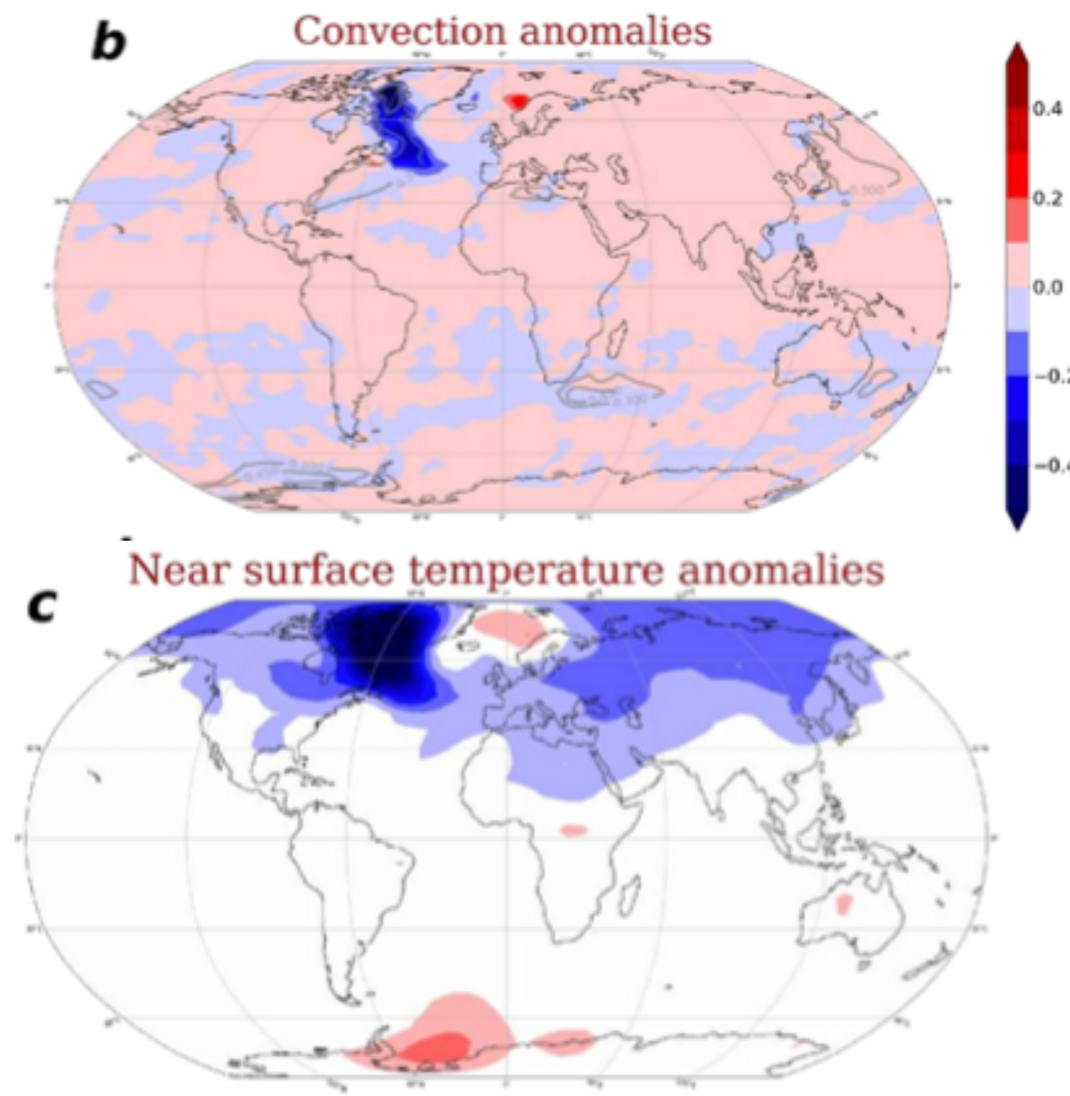
- AMOC weakening extremes, Matteo Cini (PhD University of Turin, ISAC, M.Sc. University of Bologna), Giuseppe Zappa, Susanna Corti

- Simulations with Plasim coupled to LSG ocean model, T21 resolution, resampling 1 year

- Target: AMOC strength obtained as maximum of the Atlantic meridional overturning streamfunction between 46° and 66°N and below 700m

AMOC weakening and collapse in Plasim-LSG





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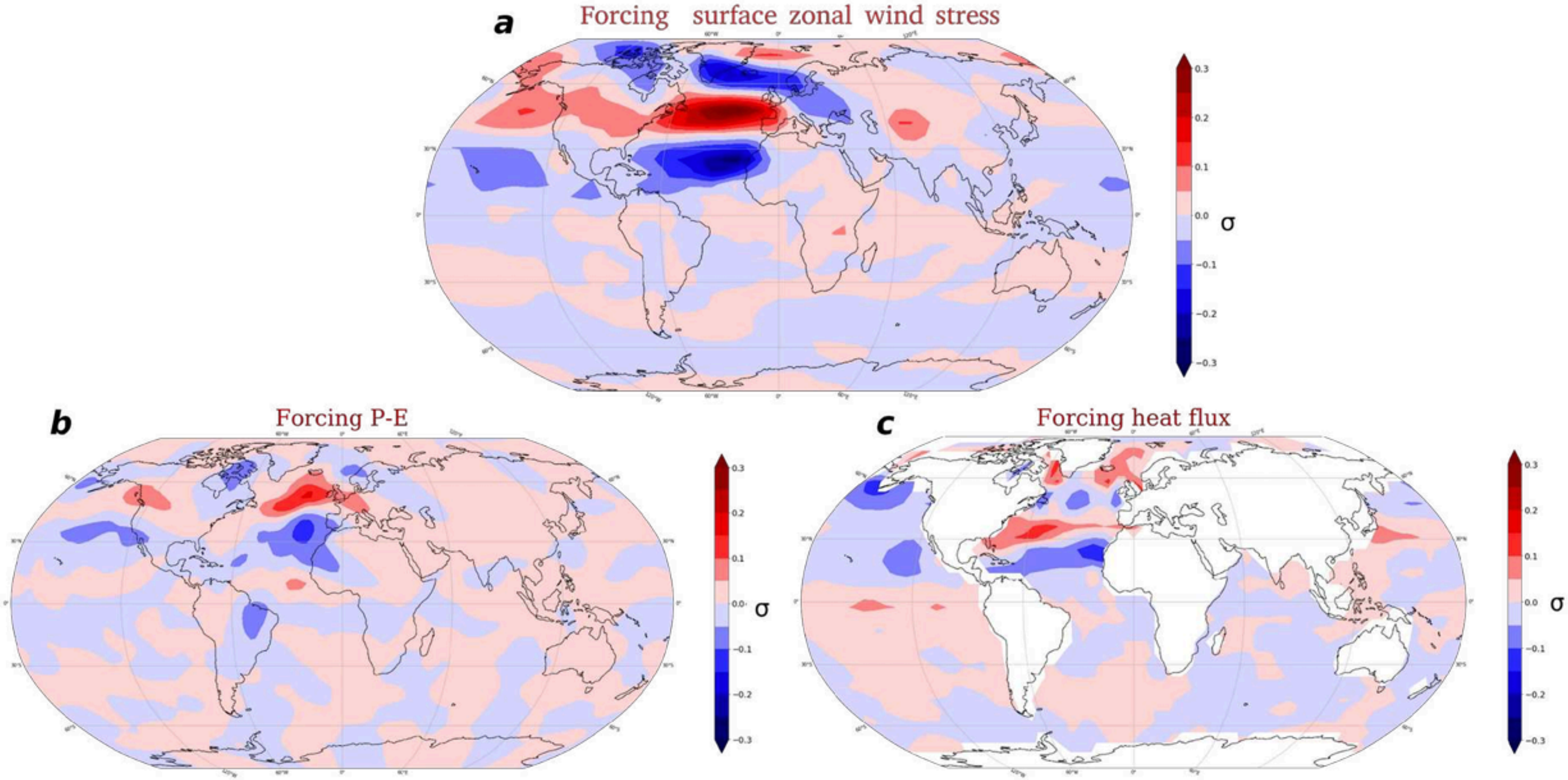
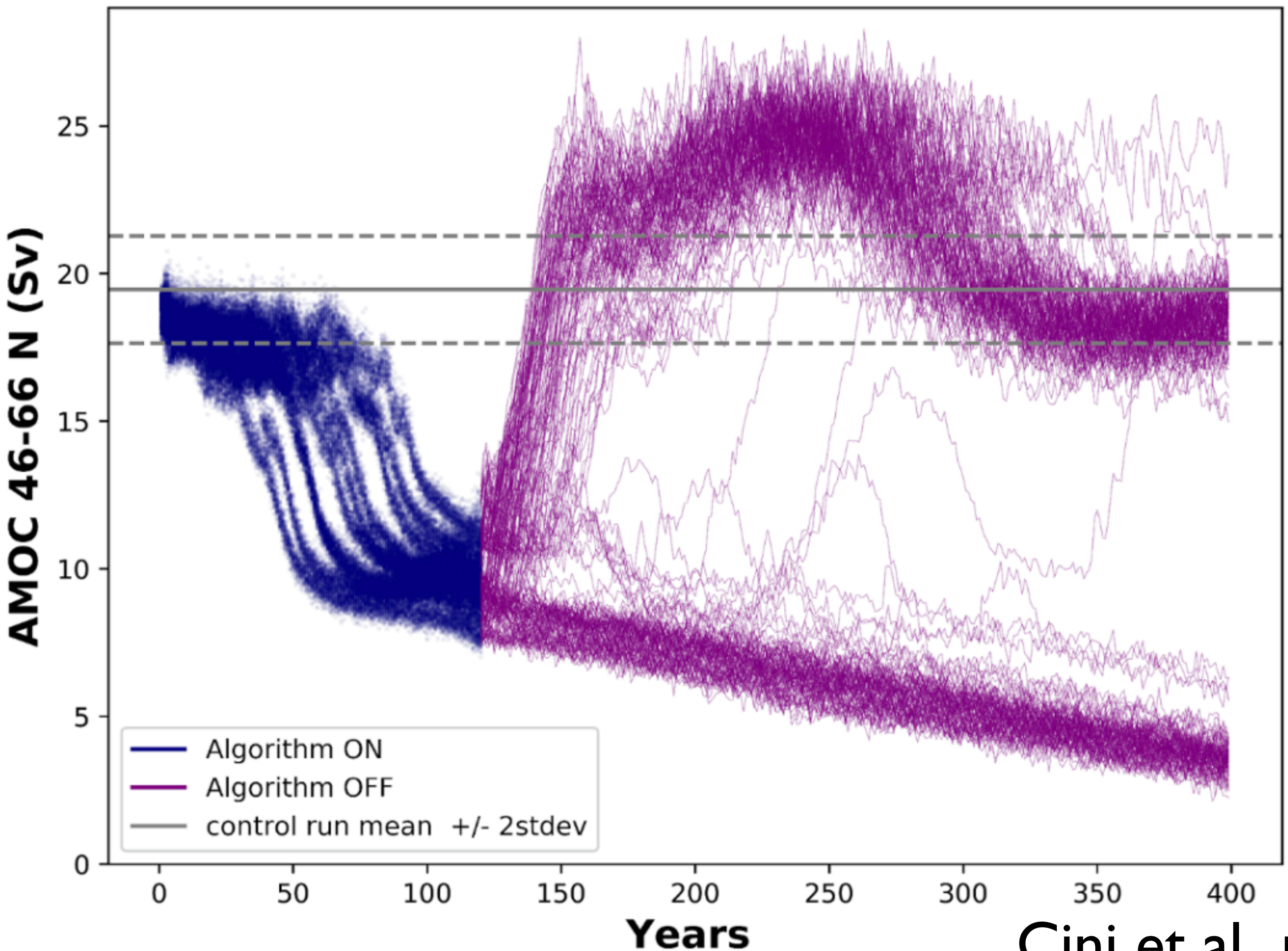


Cini et al., under review

- Atmospheric trigger via anomalous freshwater fluxes and zonal wind stress anomalies (contribution of Ekmann currents to AMOC weakening)
- Sampling of trajectories with extreme AMOC weakening only due to internal variability: experiments with no external forcing (no hosing, global warming, etc)

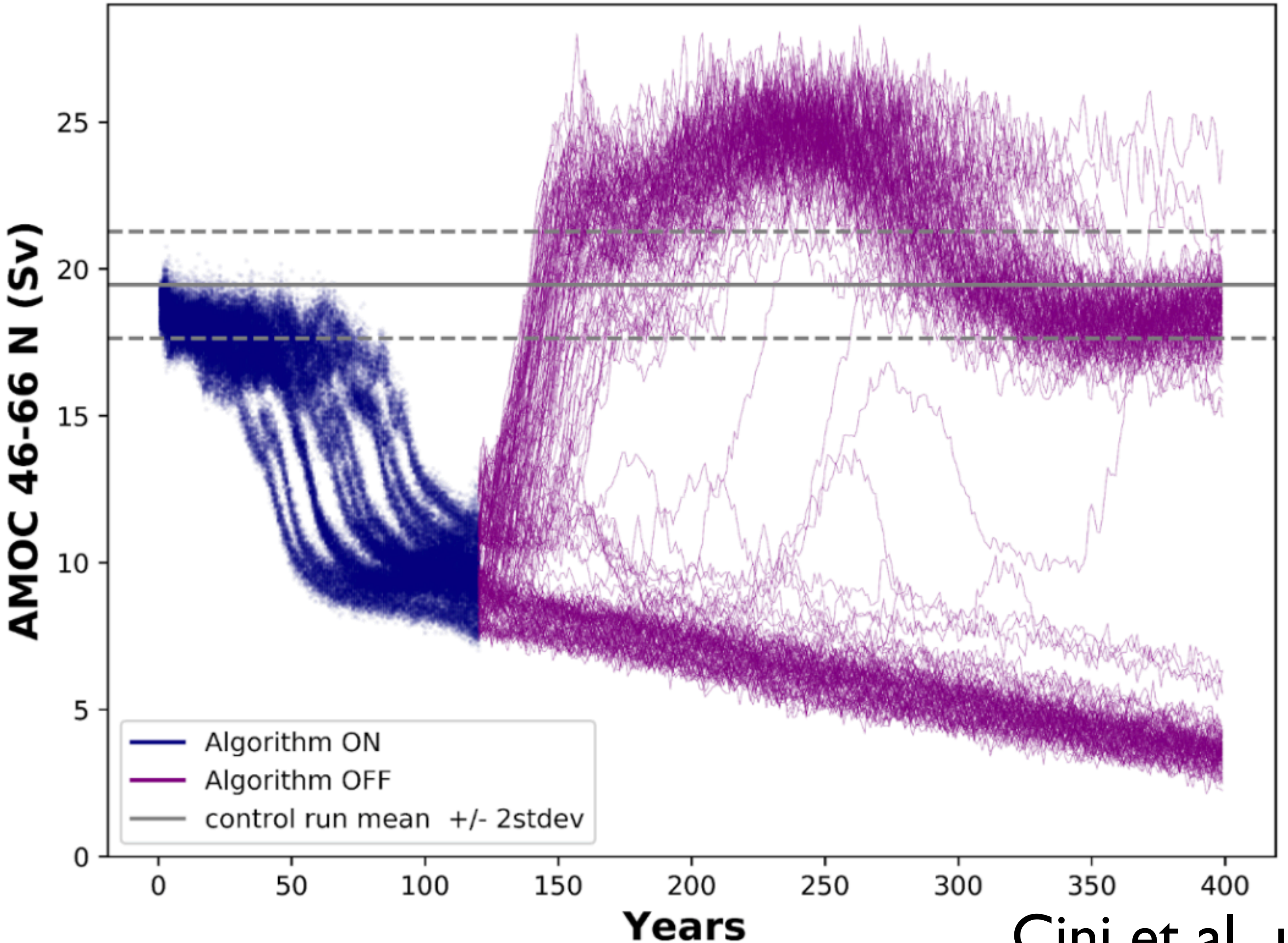
AMOC weakening and collapse in Plasim-LSG



Cini et al., under review

- Switching off the algorithm (purple) after reaching a weak AMOC state (blue) some trajectories recover, other keep drifting: reached basin of attraction of collapsed state

AMOC weakening and collapse in Plasim-LSG



Cini et al., under review

- Switching off the algorithm (purple) after reaching a weak AMOC state (blue) some trajectories recover, other keep drifting: reached basin of attraction of collapsed state
- Value of AMOC index does not fully identify likelihood of staying in collapsed vs active state: issue with using it standalone to study stability when changing a parameter?

Future perspectives

- For the future: how to apply these techniques to predictability problems (move to state of the art coupled models and constrain initial conditions to slow components)

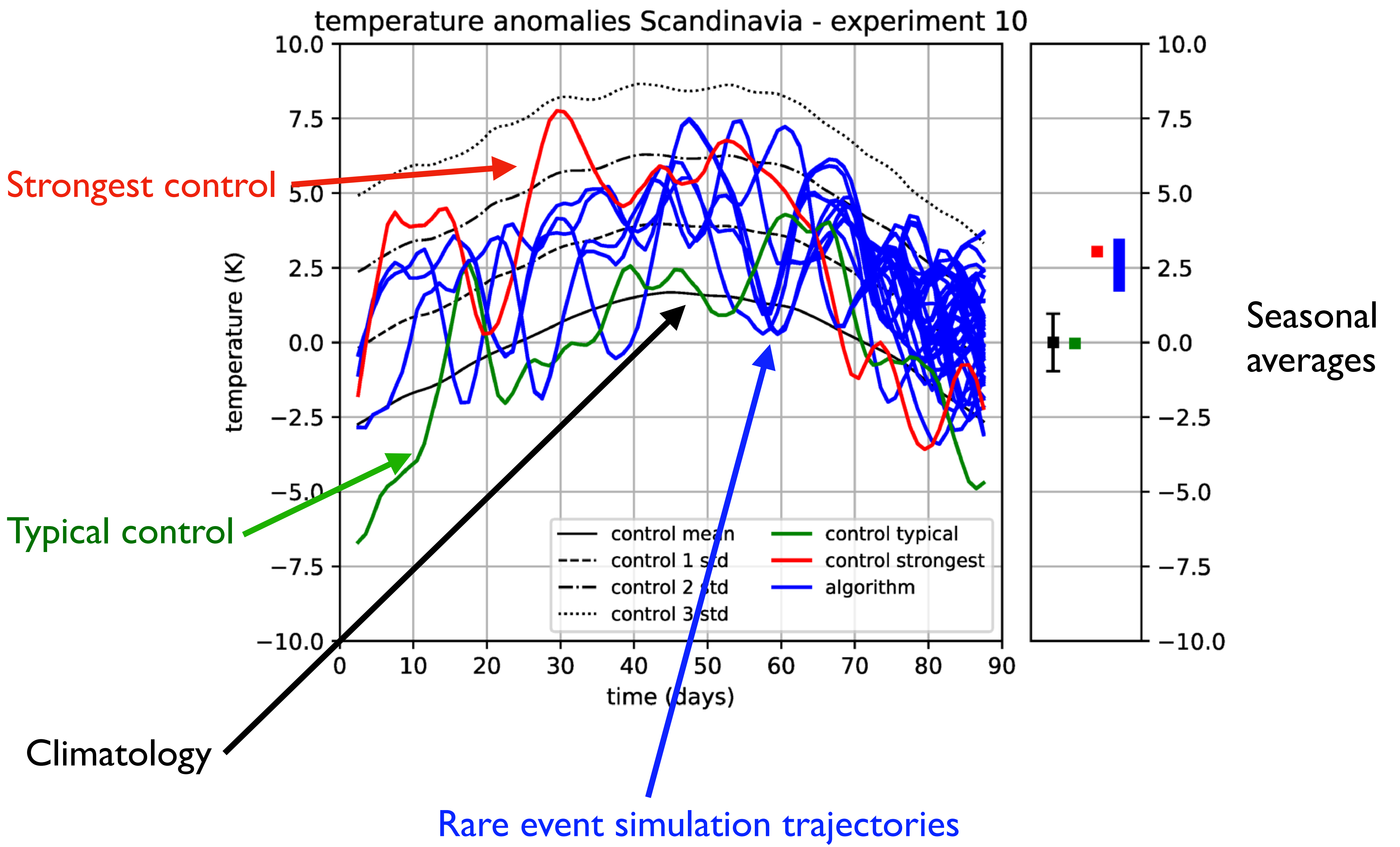
- Dedicated algorithms to analyse transitions could help to study tipping elements

- Application to non-stationary conditions?

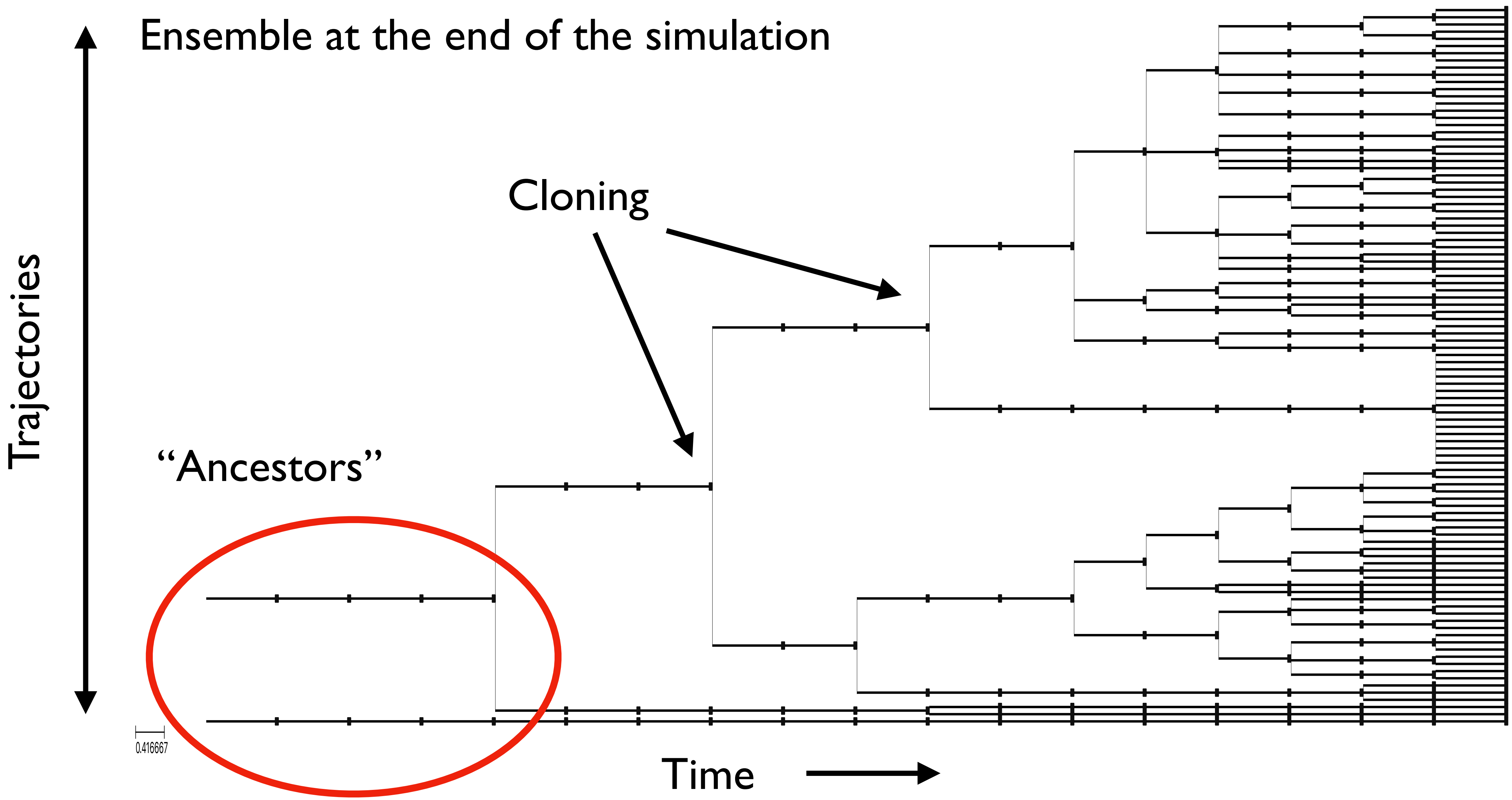
- Other current projects:
  - large deviations of finite time Lyapunov exponents (with Jonathan Demaeyer)
  - marine heatwaves in coupled GCMS and seasonal to decadal predictability

Thank you for your attention

Experiments with CESM: heatwaves over Scandinavia

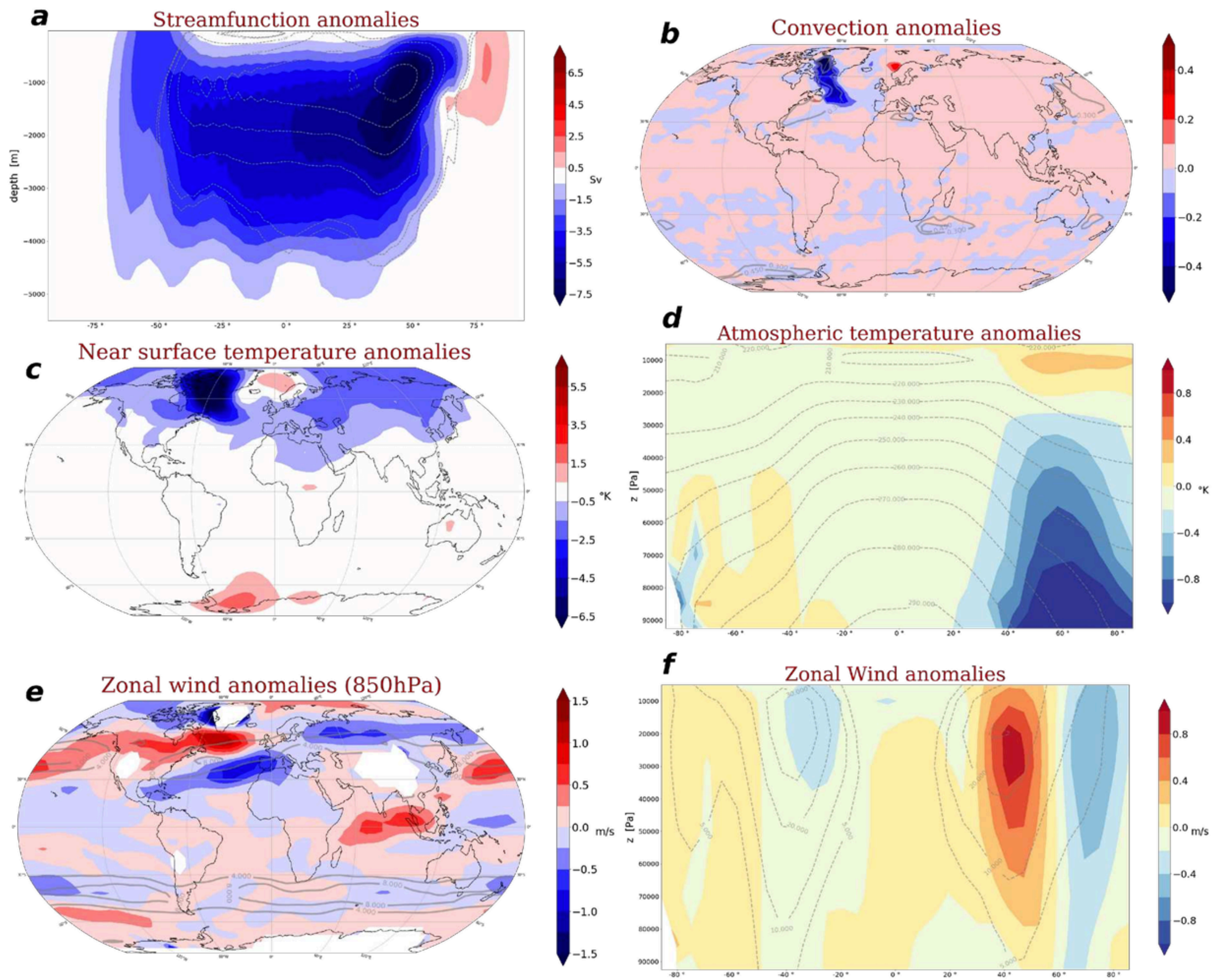


Analysis of trajectories branching



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

AMOC weakening and collapse in Plasim-LSG



AMOC weakening and collapse in Plasim-LSG