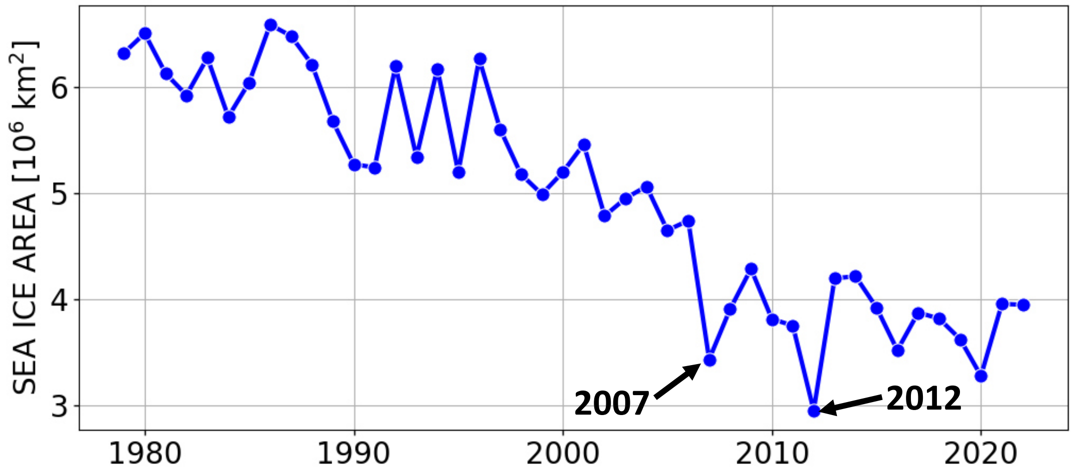
Studying extremes of summer Arctic sea ice reduction with rare event simulation methods

Jerome Sauer

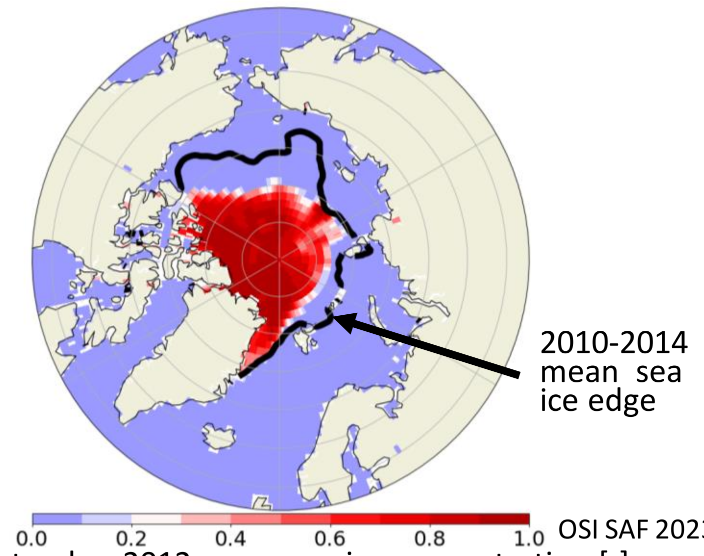
Université Catholique de Louvain, Louvain-la-Neuve, Belgium

with Francesco Ragone, François Massonnet, Jonathan Demaeyer, Giuseppe Zappa

Extreme reductions in summer pan-Arctic sea ice area



September monthly mean pan-Arctic sea ice area [10^6 km^2]. OSI SAF 2023.



OSI SAF 2023.

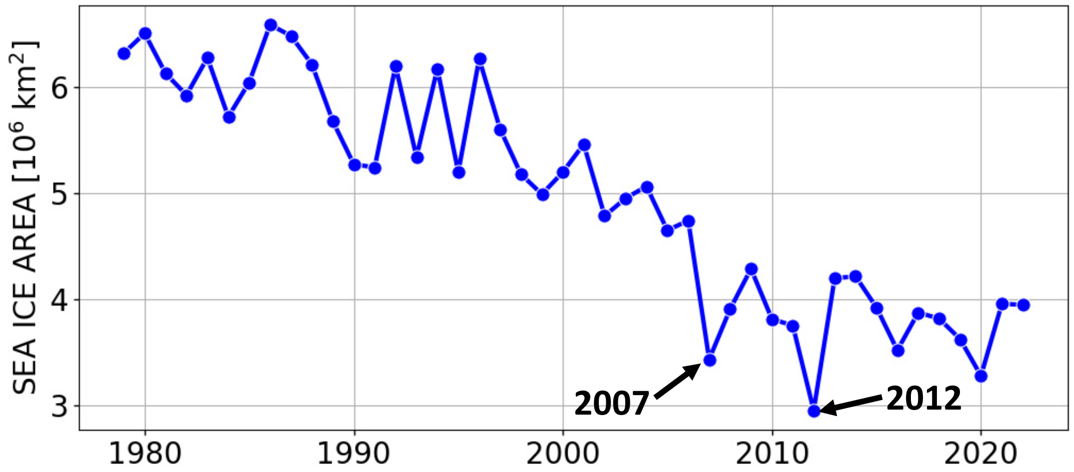
September 2012 mean sea ice concentration [-]

Overarching goal: Understanding **physical processes** leading to **extremes of summer Arctic sea ice reduction**

→ Oceanic and atmospheric circulations, preconditioning, self-amplifying feedbacks

Problem: Quantitative statistical and **dynamical studies** of **climate extremes** hindered by the **lack of data** in observations and in **numerical simulations with computationally expensive climate models**

Extreme reductions in summer pan-Arctic sea ice area



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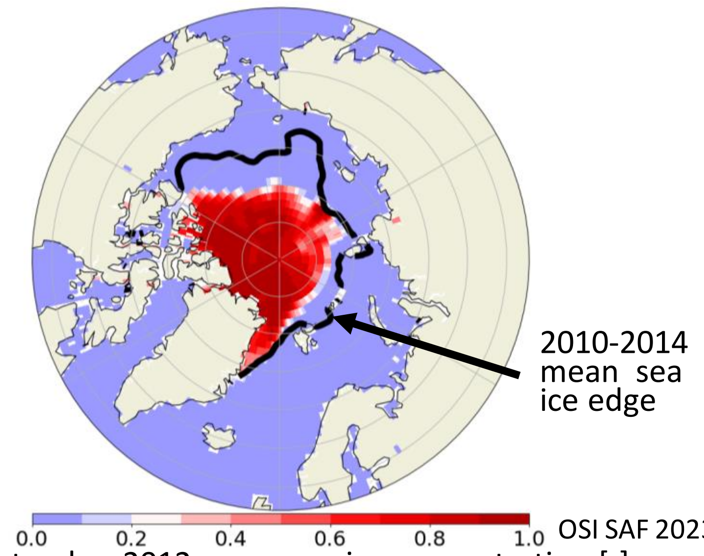


OSI SAF 2023.

September 2012 mean sea ice concentration [-]

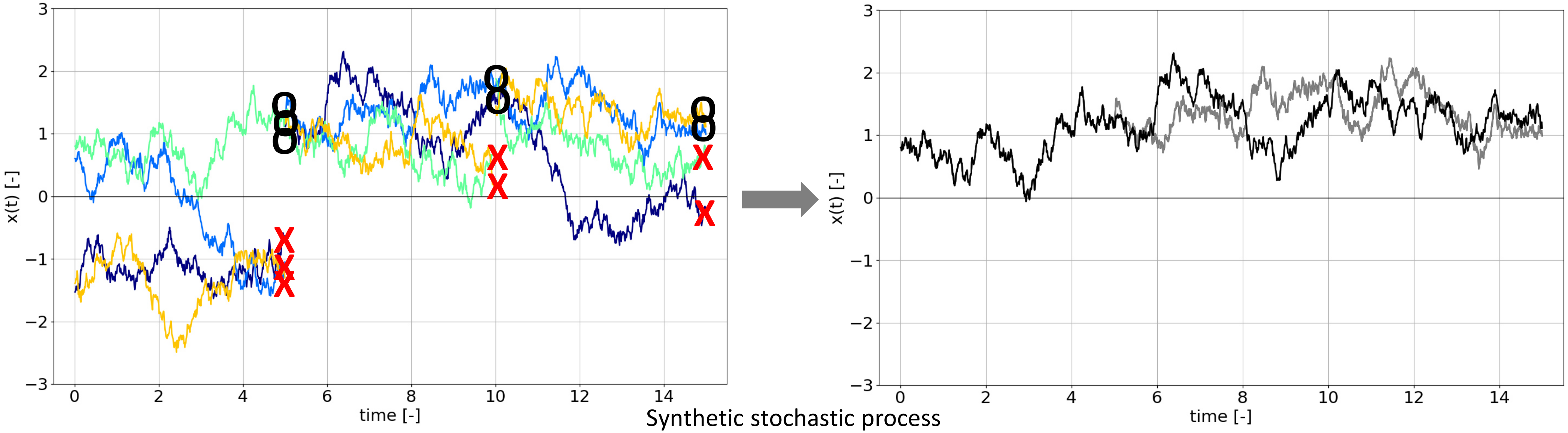
Problem: Quantitative statistical and **dynamical studies** of climate extremes are hindered by the lack of data

→ **Improve the sampling efficiency** of extreme events in **climate model simulations** with rare event algorithms

→ **Genealogical selection algorithm** adapted from Del Moral and Garnier (2005); Giardina et al. (2011) (Ragone et al. 2018; Ragone and Bouchet 2019; 2021): **Efficient to study time-persistent extremes**

Methodology: Rare event algorithm

- **Importance sampling** of trajectories in **ensemble simulation with numerical model**
  → make trajectories with **large anomalies** of a **time-averaged observable** common
  → more **precise conditional statistics on extremes** (e.g. composites, return times) + **generation of ultra-rare events**



Synthetic stochastic process

Methodology: Rare event algorithm

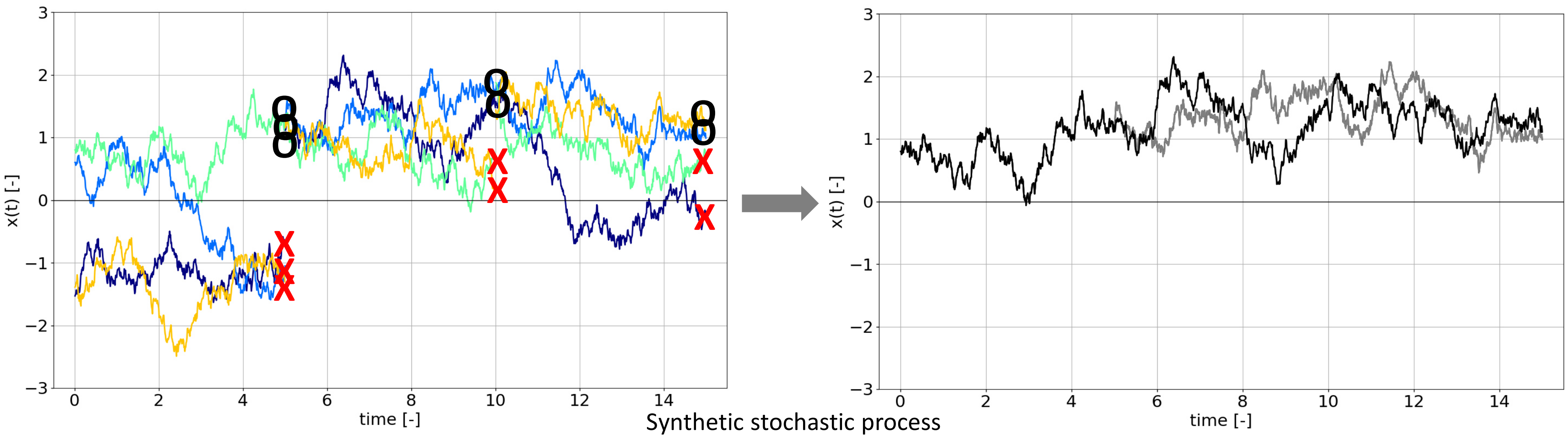
- **Importance sampling** of trajectories in **ensemble simulation with numerical model**
  → make trajectories with **large anomalies** of a **time-averaged observable** common

- **Resampling** at constant time intervals: **trajectories are killed or cloned** depending on **weights** measuring the likelihood to lead to an **extreme** of the **time-averaged observable**

- **Importance sampling formular:** Relates probabilities of trajectories between biased and unbiased statistics

$$P_k(\{X_n(t)\}_{0\le t\le T_a}) = \frac{e^{k\int_0^{T_a} A(\{X_n(t)\})\,dt}}{R} P_0(\{X_n(t)\}_{0\le t\le T_a})$$

P_k, P_0: Prob. dens. in biased and unbiased statistics
k, R: Controling parameter and normalization term
t, T_a: Time and simulation length
$A, \{X_n(t)\}$: Observable and model trajectories



Synthetic stochastic process

Experiments with coupled climate model PlaSim

PlaSim: Intermediate complexity general circulation model

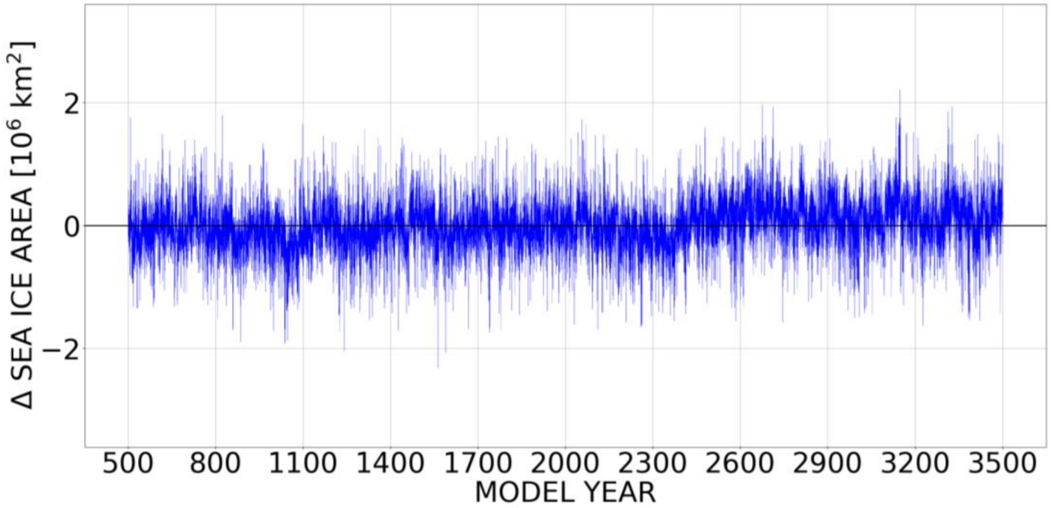
Coupled version: Large-Scale Geostrophic ocean and a zero-layer thermodynamic sea ice model

Resolution: T21 horizontal (32x64), 10 vertical layers

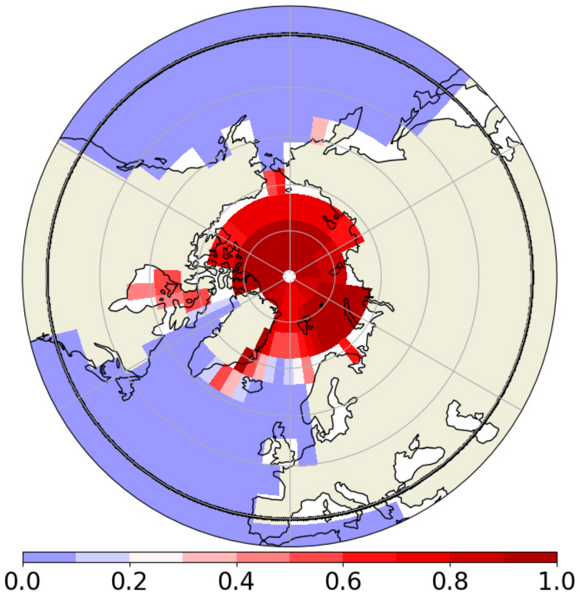
Forcing: constant pre-industrial greenhouse gas conditions

Observable: pan-Arctic sea ice area

3000-year control run: independent initial conditions for five 600-member ensemble simulations with the algorithm



Control run: Anomalies of monthly mean pan-Arctic sea ice area [10^6 km^2]



Control run: Climatological mean sea ice concentration [-]

Experiments with coupled climate model PlaSim

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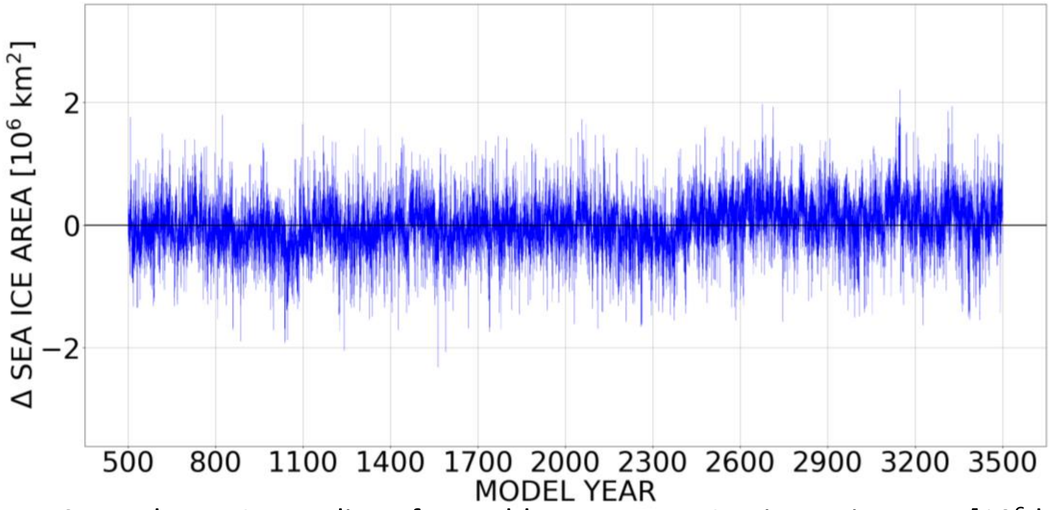


Control run: Anomalies of monthly mean pan-Arctic sea ice area [10^6 km^2]

Rare event algorithm experiments

Exp.	Model years for initial conditions	k [10^{-6} km^{-2} day^{-1}]
1	501,506,...,3496	-0.06
2	502,507,...,3497	-0.05
3	503,508,...,3498	-0.04
4	504,509,...,3499	-0.05
5	505,510,...,3500	-0.04

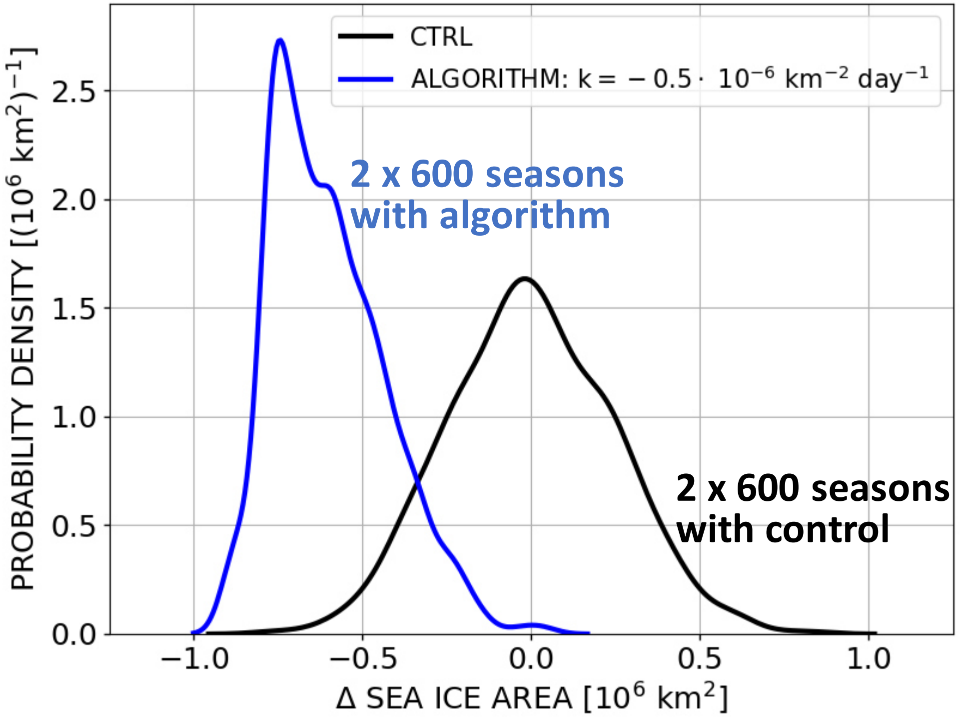
Resampling time: 30 days

Simulation period: February-September

Seasons with extremely low pan-Arctic sea ice area in PlaSim

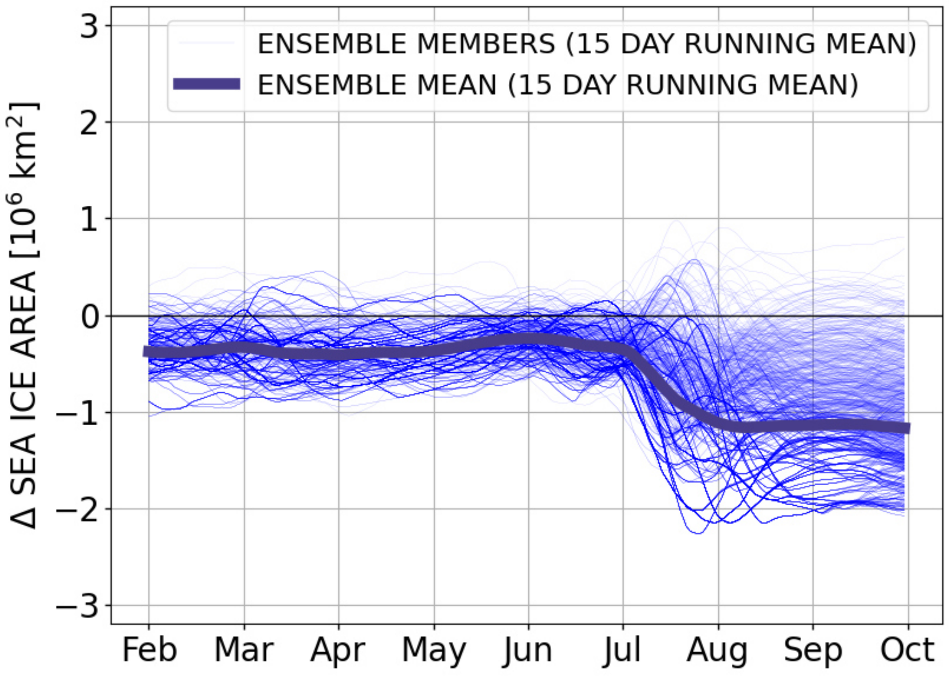
February-September mean sea ice area anomalies

PDFs: Experiments 2 and 4



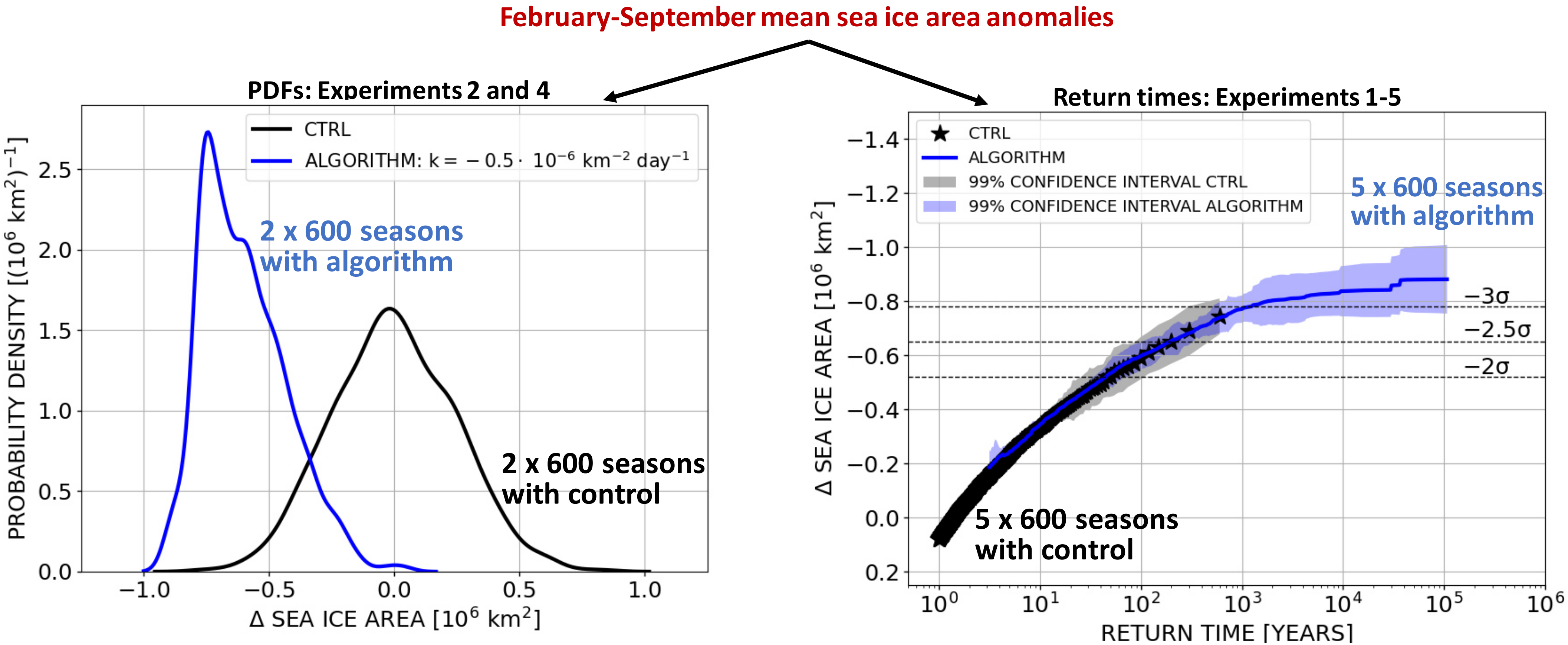
Daily mean sea ice area anomalies

Trajectories: Algorithm experiments 2 and 4



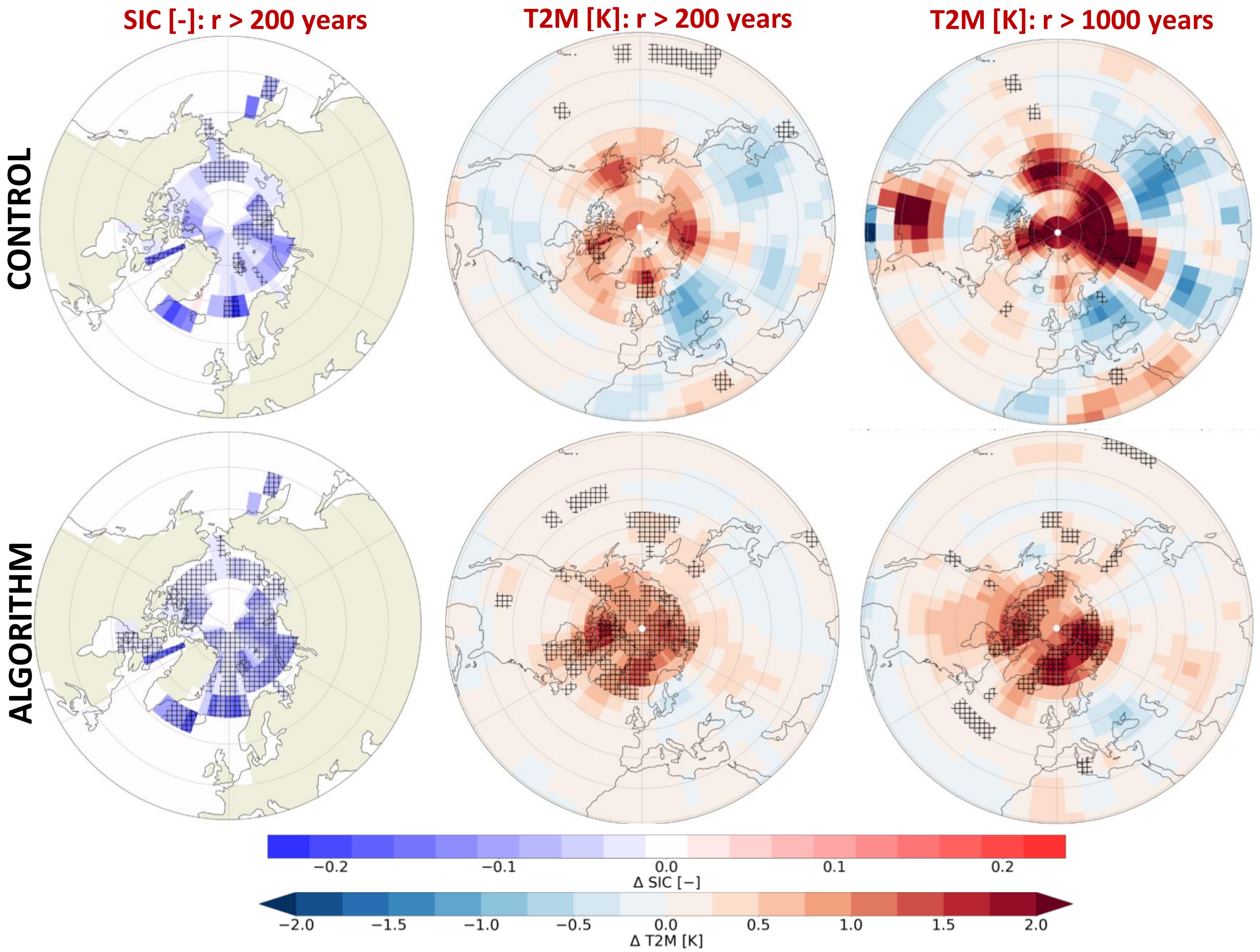
- Importance sampling of extreme negative February-September mean pan-Arctic sea ice area anomalies

Seasons with extremely low pan-Arctic sea ice area in PlaSim



- Importance sampling of extreme negative February-September mean pan-Arctic sea ice area anomalies
- The algorithm allows to compute return times up to 10^5 years with computational cost of 3000 seasons

Seasonal anomalies of SIC and T2M during extremes of sea ice reduction

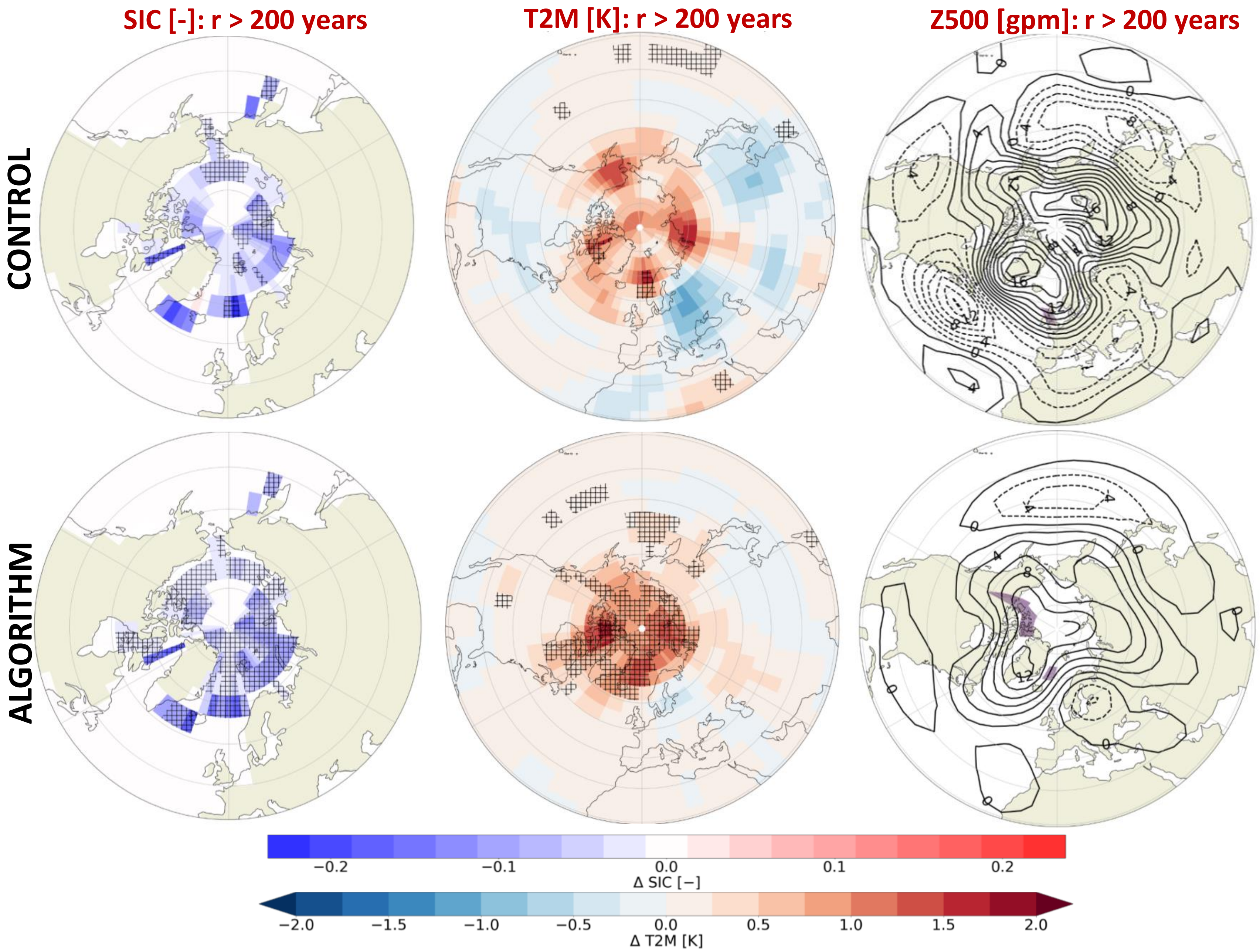


"Seasonal"/ "summer": February-September average

Hatching: Significance on the 1% level

- **Improved statistics** with the algorithm compared to control

Seasonal anomalies of SIC, T2M, Z500 during extremes of sea ice reduction



"Seasonal"/ "summer": February-September average

Hatching/Shading: Significance on the 1% level

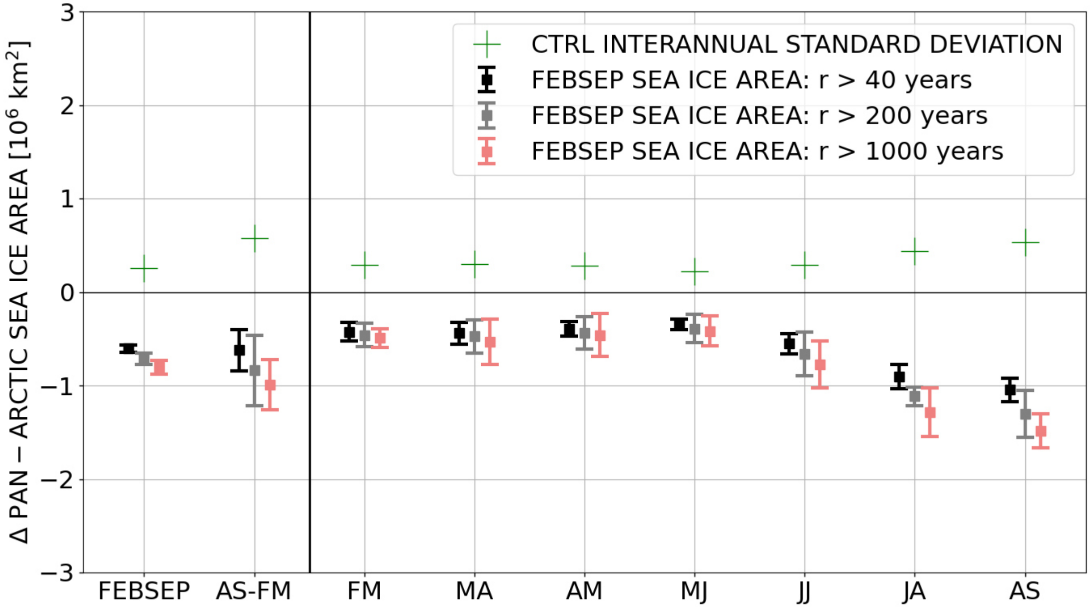
- **Improved statistics** with the algorithm compared to control

- **What are the dominant drivers of the warm Arctic in PlaSim?**

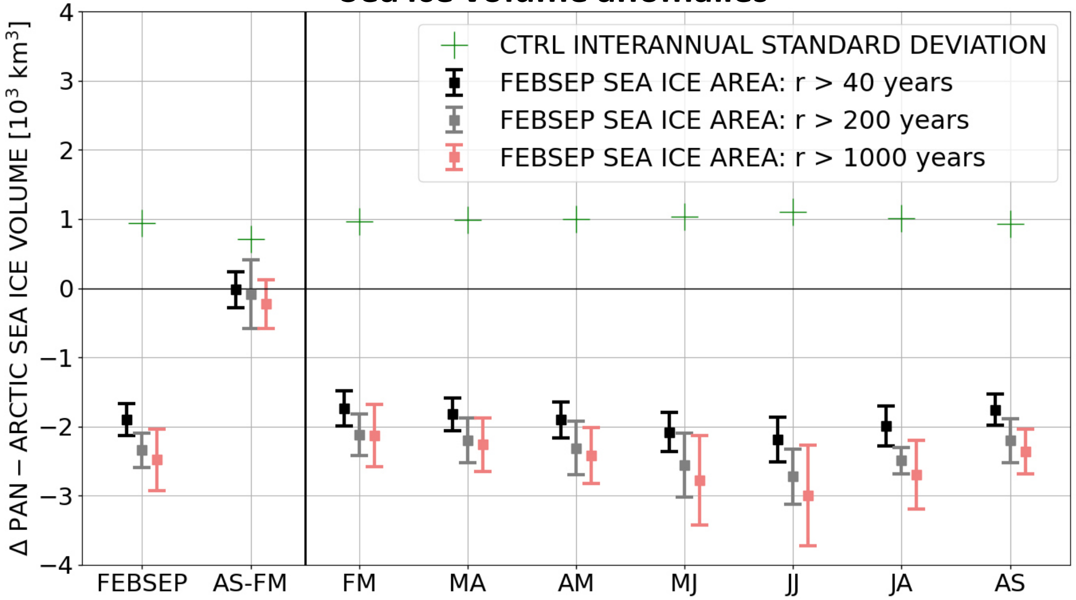
Preconditioning *vs.* intra-seasonal sea ice reduction

Algorithm: February-September and bimonthly mean

Sea ice area anomalies



Sea ice volume anomalies



Error bars: 99% confidence interval

- Anomalously **low sea ice area** at the beginning of the simulation in late winter
- Anomalously **strong reduction of sea ice area** between May-June and August-September
- Anomalies of **sea ice volume** indicate a strong role of **preconditioning**

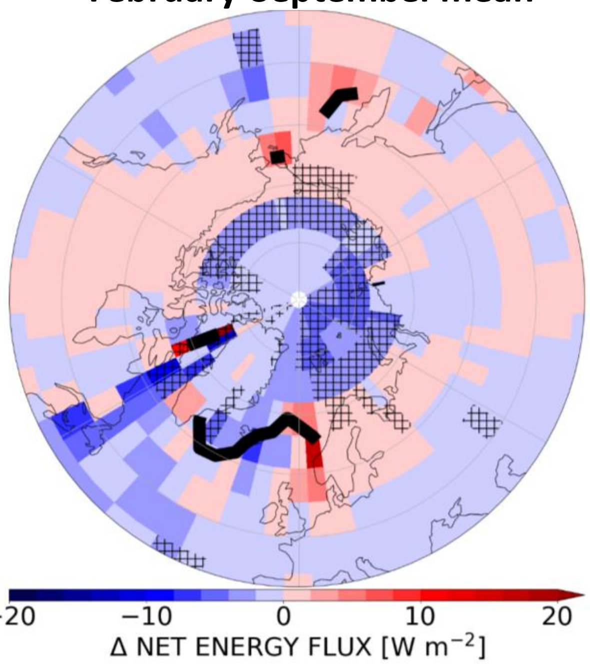
Surface energy fluxes during seasons with extremely low sea ice area

Hatching: Significance at the 1% level

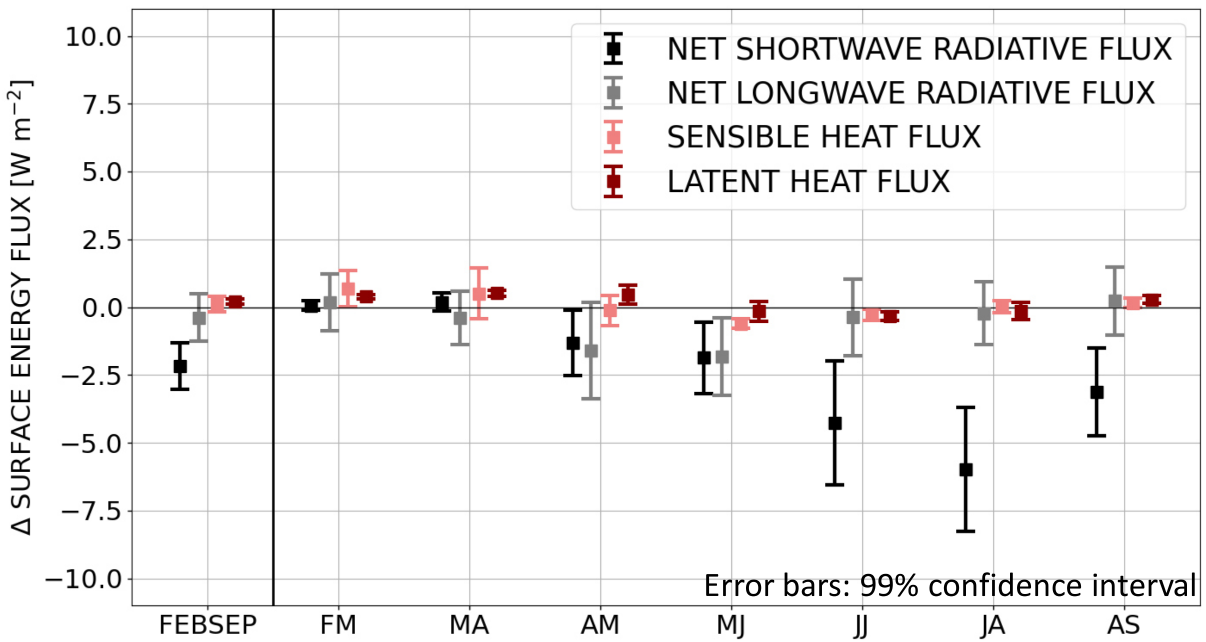
Downward fluxes are negative

Algorithm: r > 200 years

February-September mean



Domain-average over ocean northern of 70°N



- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean
- **Radiative fluxes** dominate net surface energy flux anomalies
- **Dominant shortwave component** during summer and a weak contribution by the longwave flux in late spring

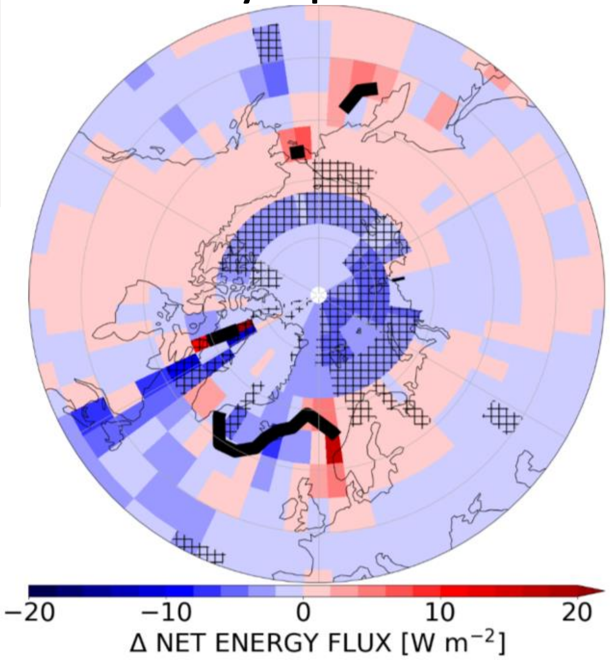
Surface energy fluxes during seasons with extremely low sea ice area

Hatching:
Significance at the 1% level

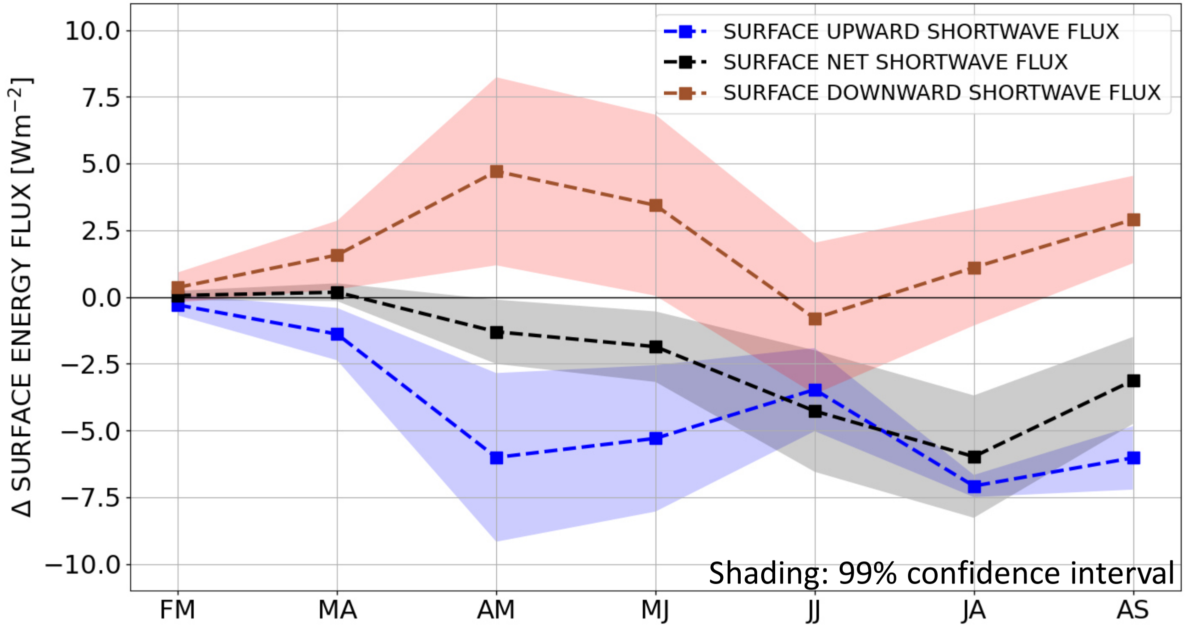
Downward fluxes are negative

Algorithm: r > 200 years

February-September mean



Domain-average over ocean northern of 70°N
Surface shortwave fluxes



- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean
- **Reduced downward shortwave flux** in spring and late summer suggests enhanced cloudiness
- **Reduced upward shortwave flux** due to reduced downward shortwave flux and due to **reduced surface albedo**

Summary and outlook

- Application of a rare event algorithm to PlaSim:

  Improved conditional statistics on extreme negative seasonal pan-Arctic sea ice area anomalies + access to ultra-rare events

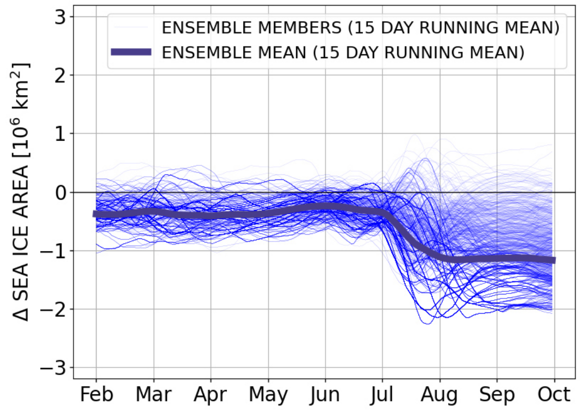
- Warm Arctic state during extremely low sea ice years with imprint on the 500 hPa geopotential height field

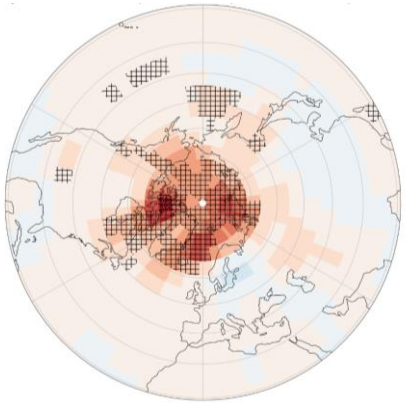
- Evidence of strong contribution of preconditioning in the sea ice-ocean system and local feedback mechanisms to extremely low sea ice conditions in PlaSim

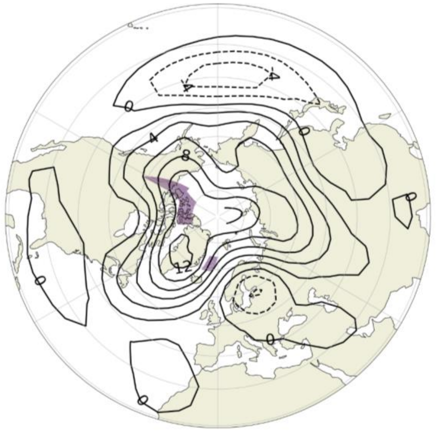
- Analysis of the link between sea ice extremes and oceanic heat content and transport

- Atmospheric processes: Rare event algorithm experiments with five day resampling time

- Increase the model complexity: PlaSim-T42-LSG and EC-Earth4







Thank you for your attention