

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

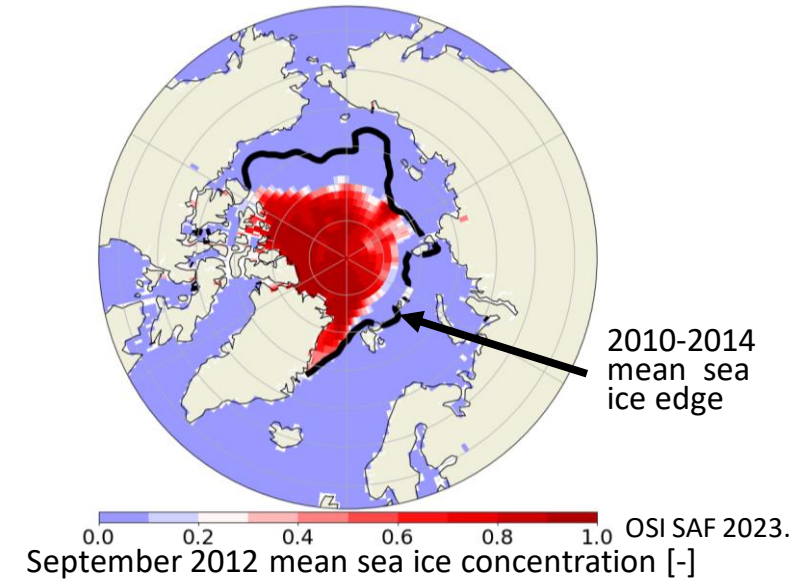
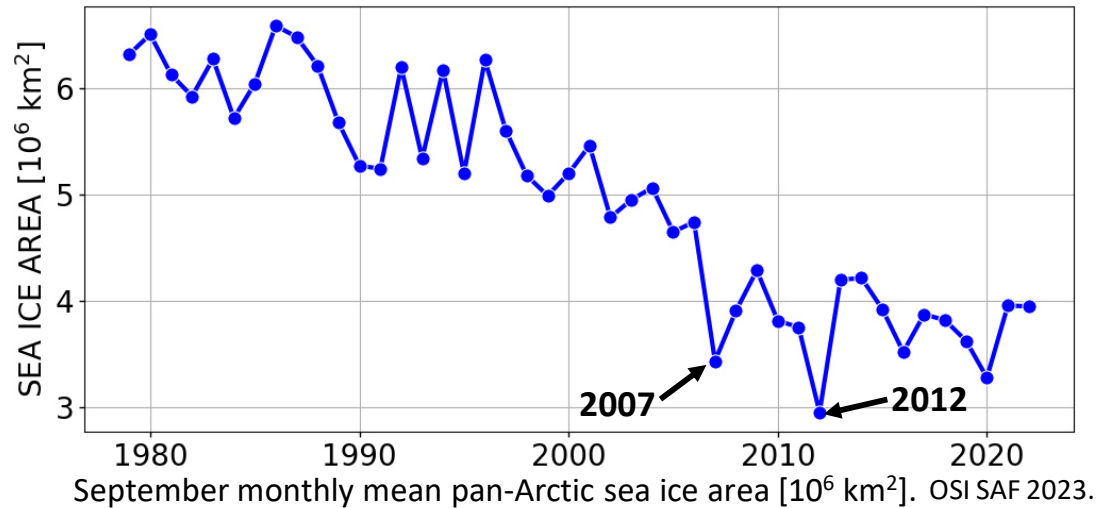
Jerome Sauer

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



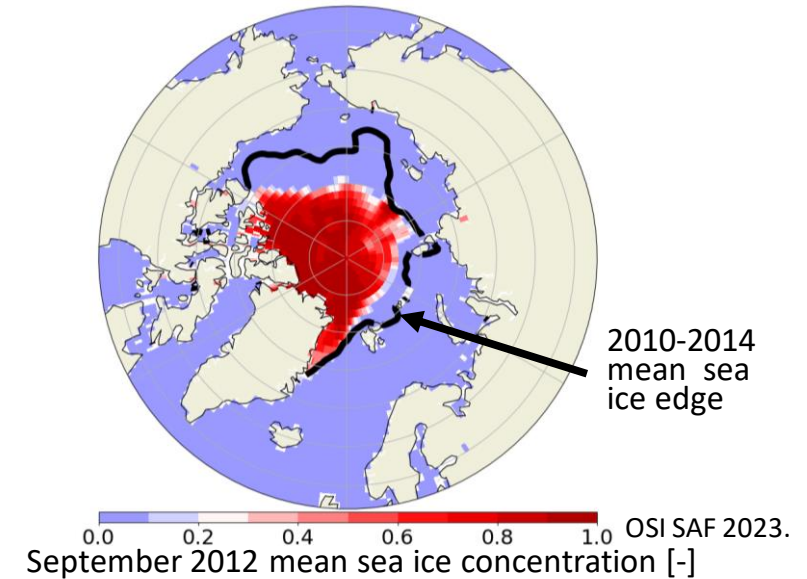
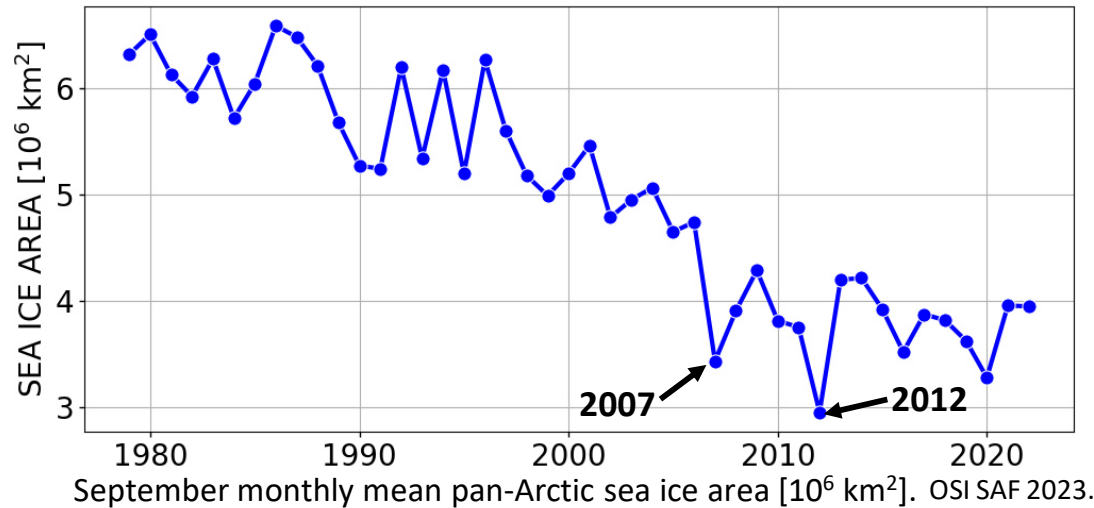
Extreme reductions in summer pan-Arctic sea ice area



Overarching goal: Understanding the **atmospheric** and **oceanic drivers** of extremes of summer Arctic sea ice reduction

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



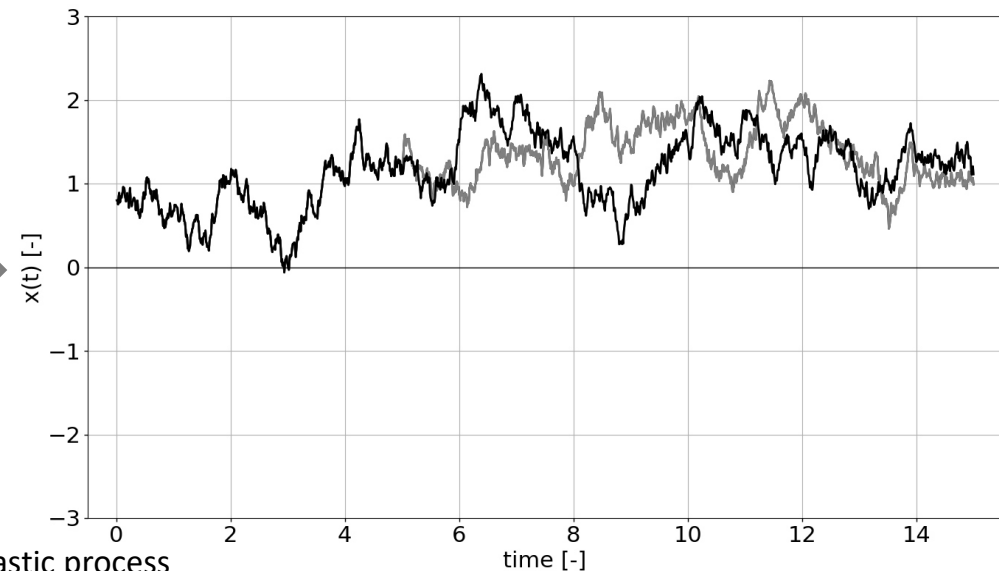
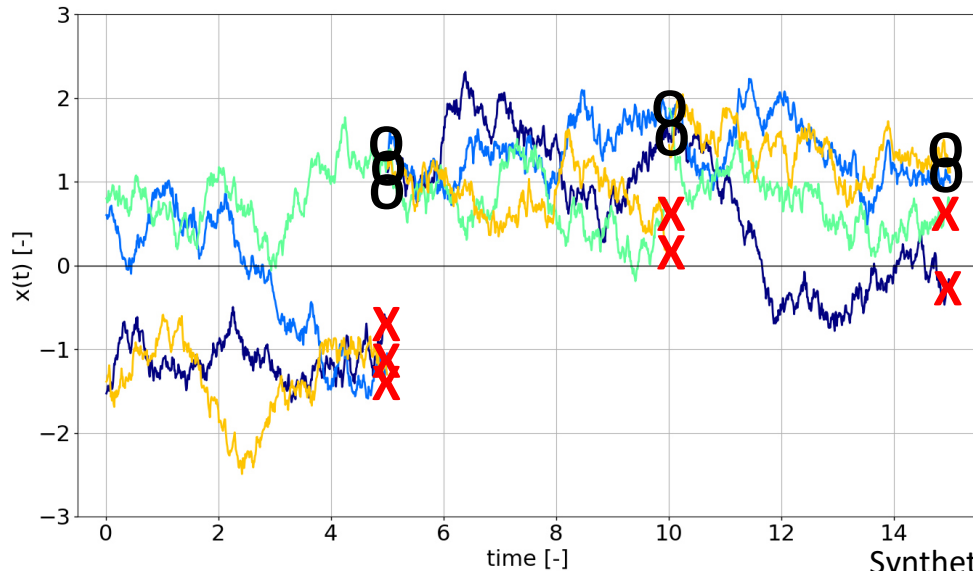
Problem: Quantitative statistical and dynamical studies of **climate extremes** are hindered by the **lack of data**

→ 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**

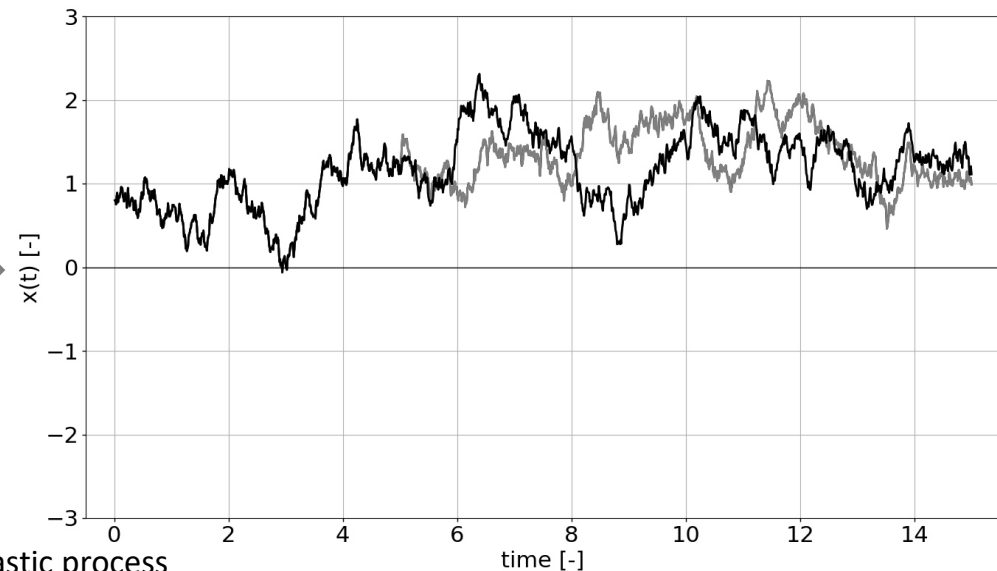
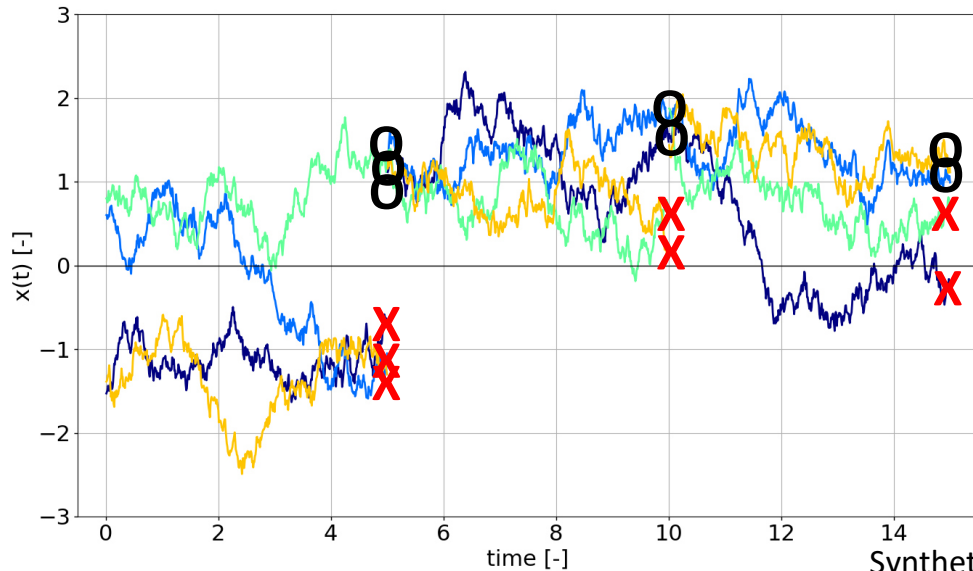


Methodology: Rare event algorithm

- **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

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

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



Experiments with coupled climate model PlaSim

PlaSim: Intermediate complexity general circulation model

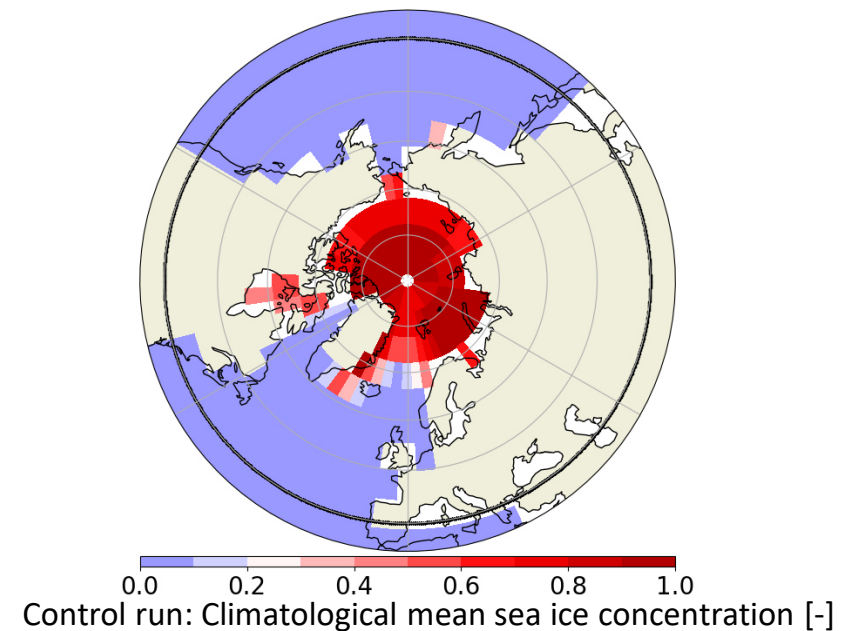
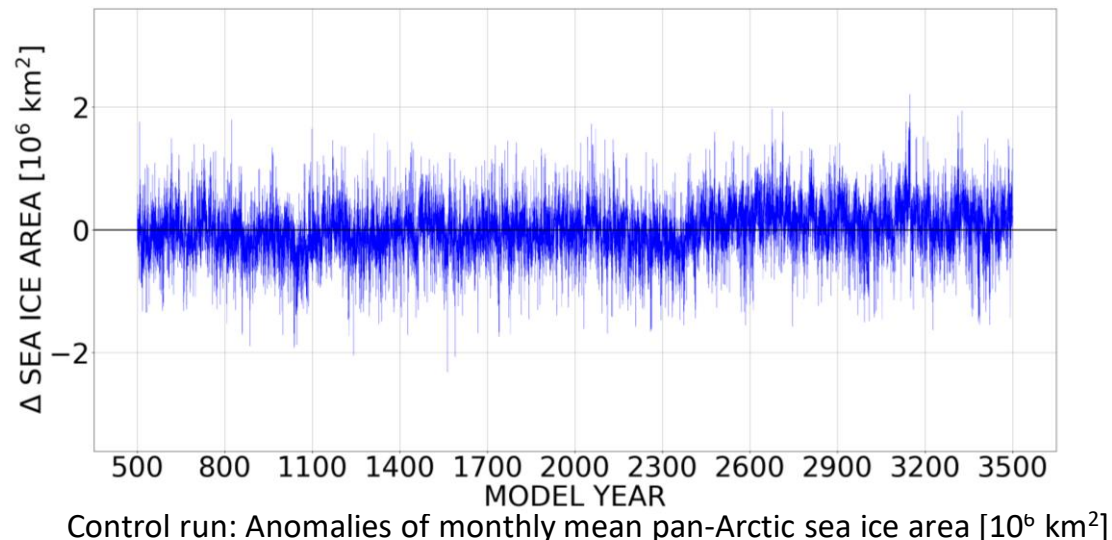
Coupled version: Large-Scale Geostrophic ocean and a zero-layer thermodynamic sea ice model

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**



Experiments with coupled climate model PlaSim

PlaSim: Intermediate complexity general circulation model

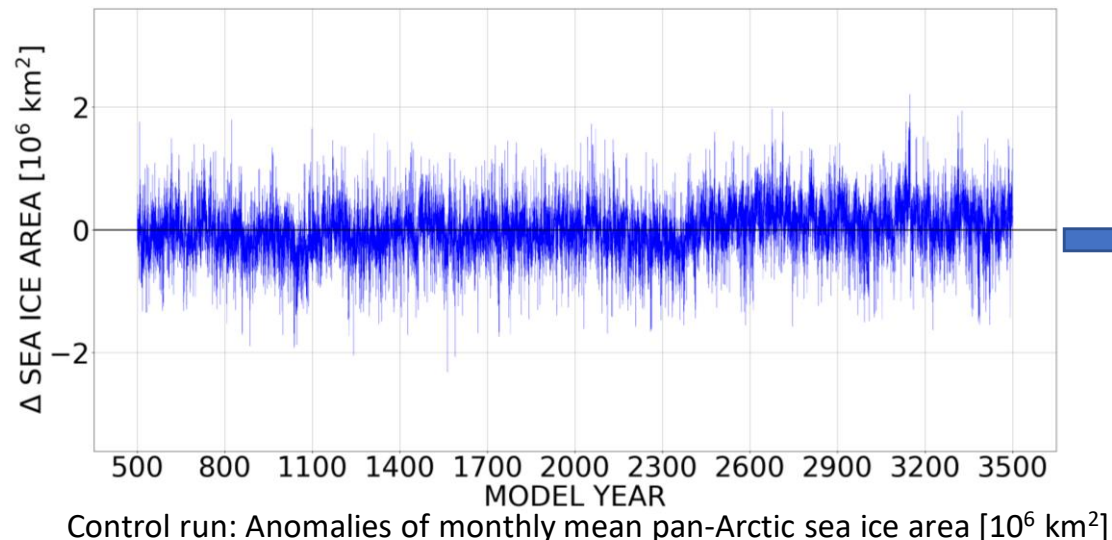
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3000-year control run: independent initial conditions for **five 600-member ensemble simulations with the algorithm**



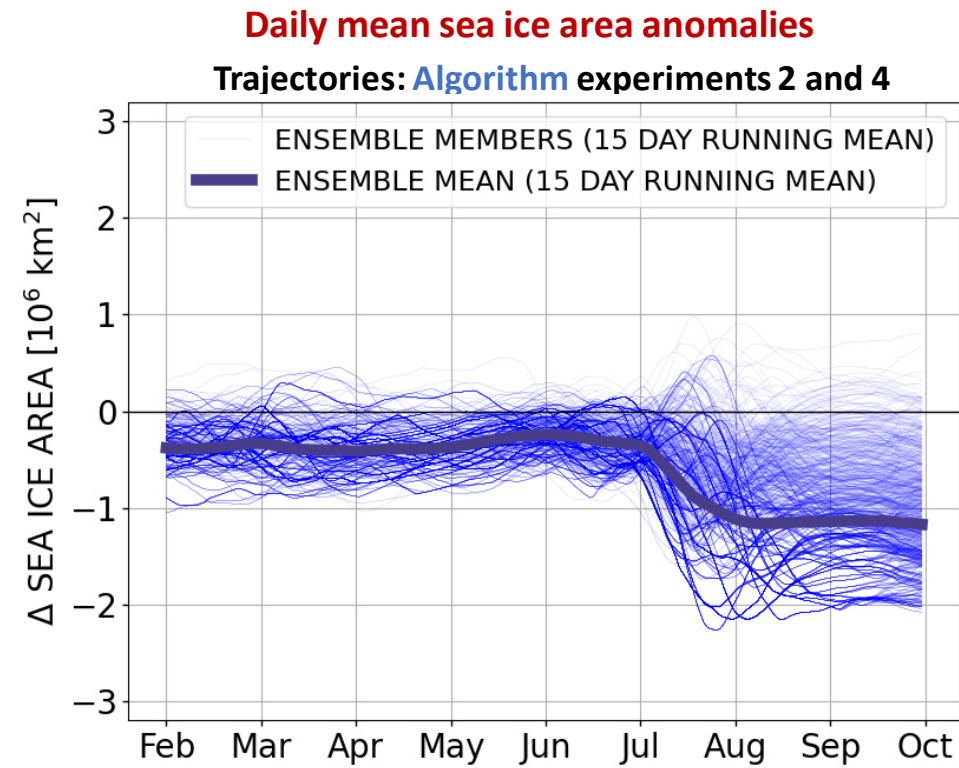
Rare event algorithm experiments

| Exp. | Model years for initial conditions | k [$10^{-6} \text{ km}^{-2} \text{ day}^{-1}$] |
|------|------------------------------------|--|
| 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

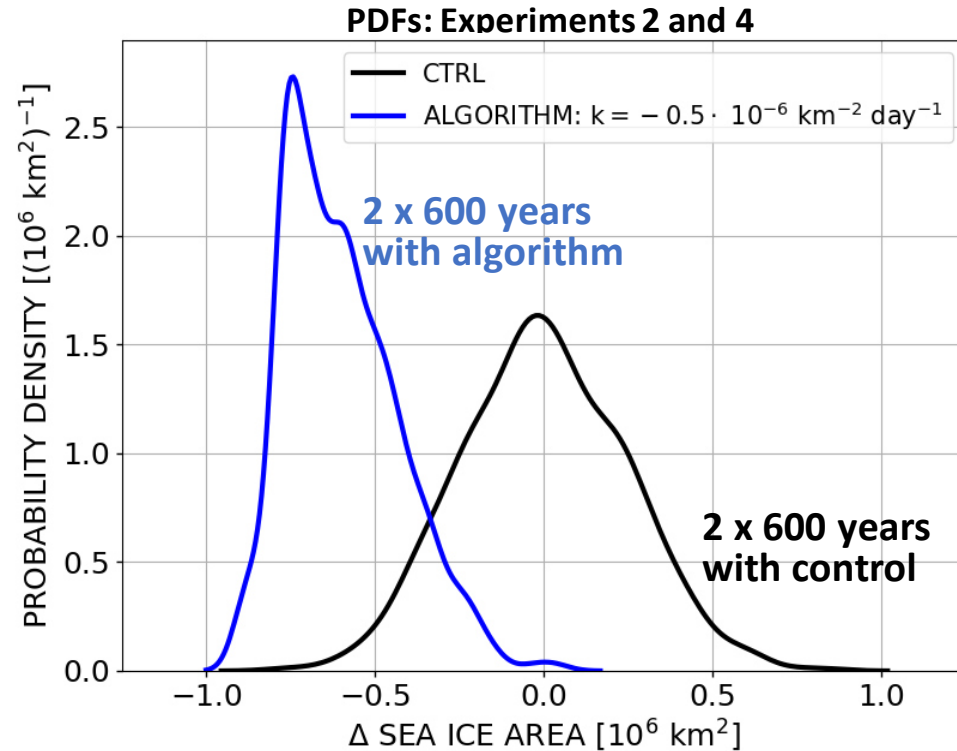
Seasons with extremely low pan-Arctic sea ice area in PlaSim



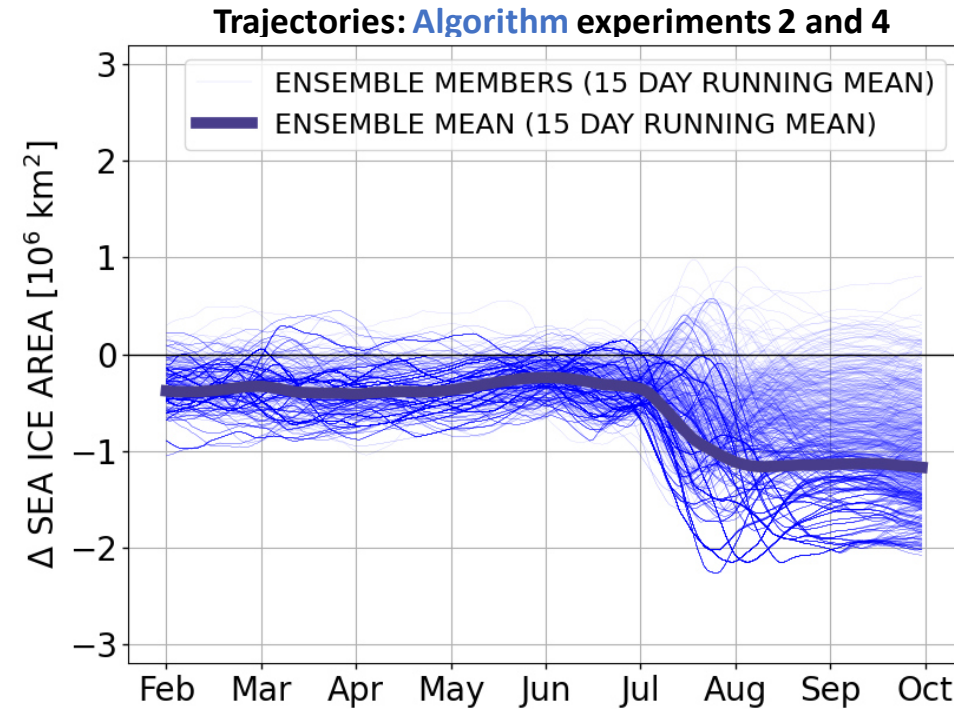
- Importance sampling of extreme negative February-September mean pan-Arctic sea ice area anomalies

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

February-September mean sea ice area anomalies



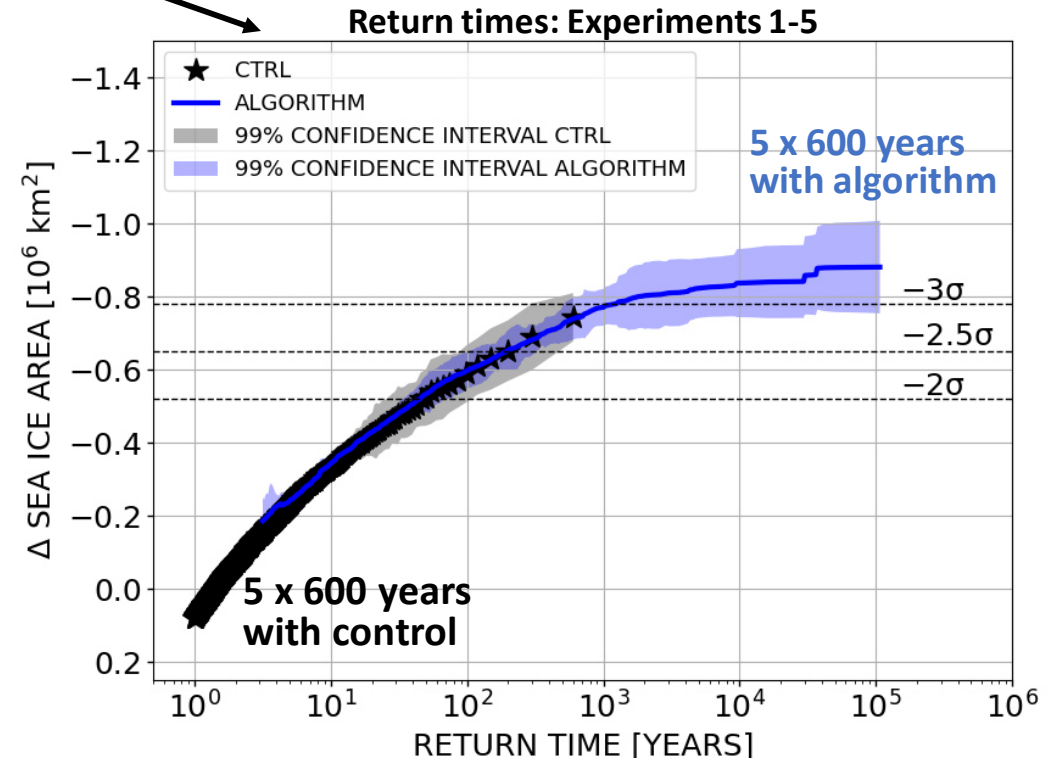
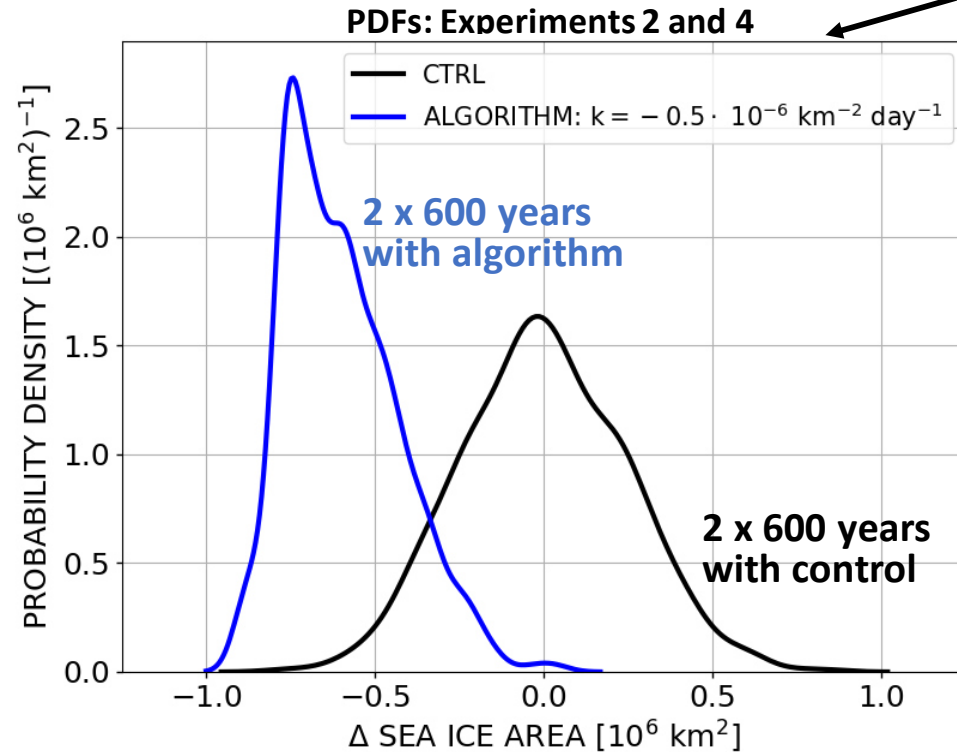
Daily mean sea ice area anomalies



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

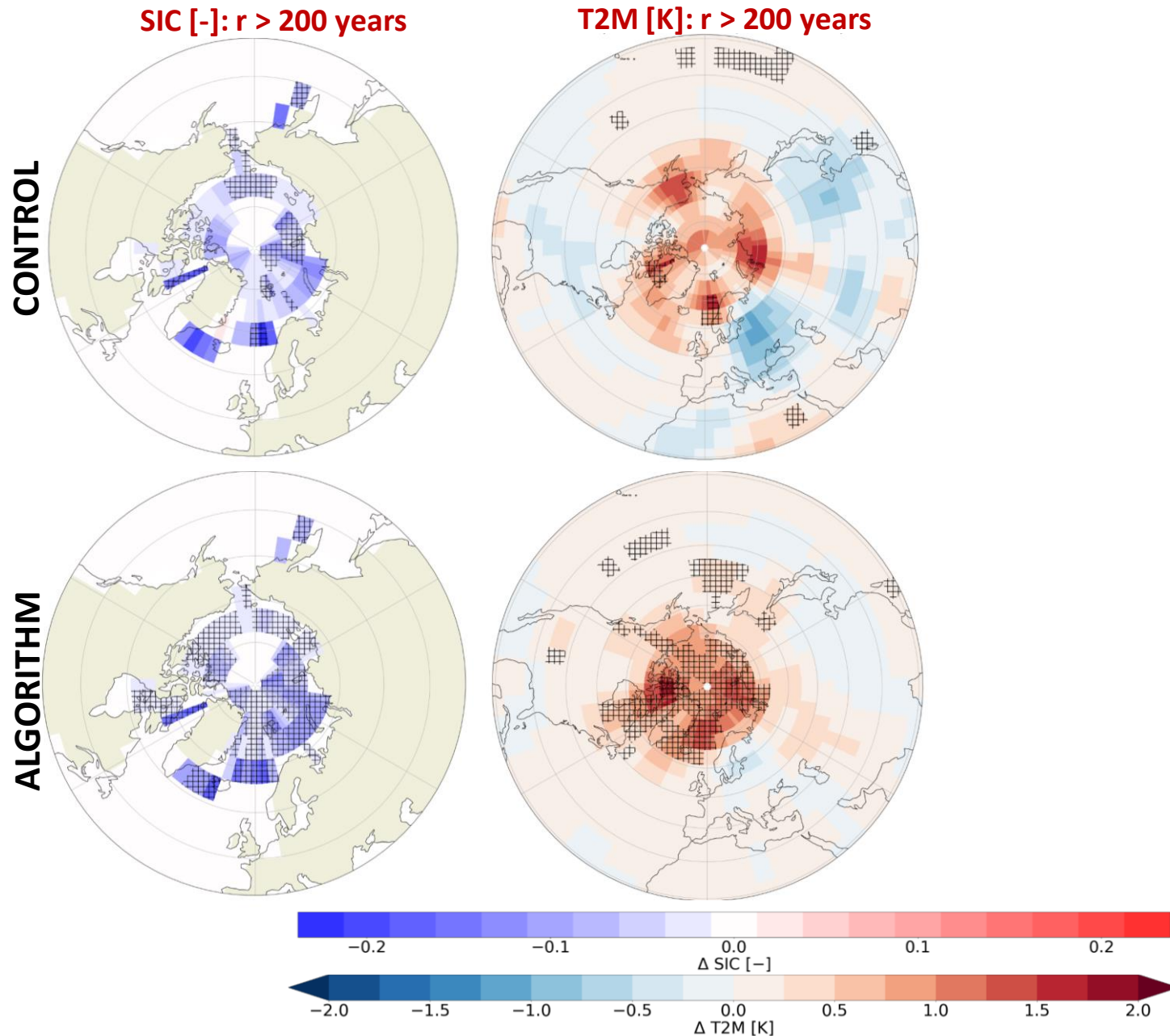
Seasons with extremely low pan-Arctic sea ice area in PlaSim

February-September mean sea ice area anomalies



- 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 years

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

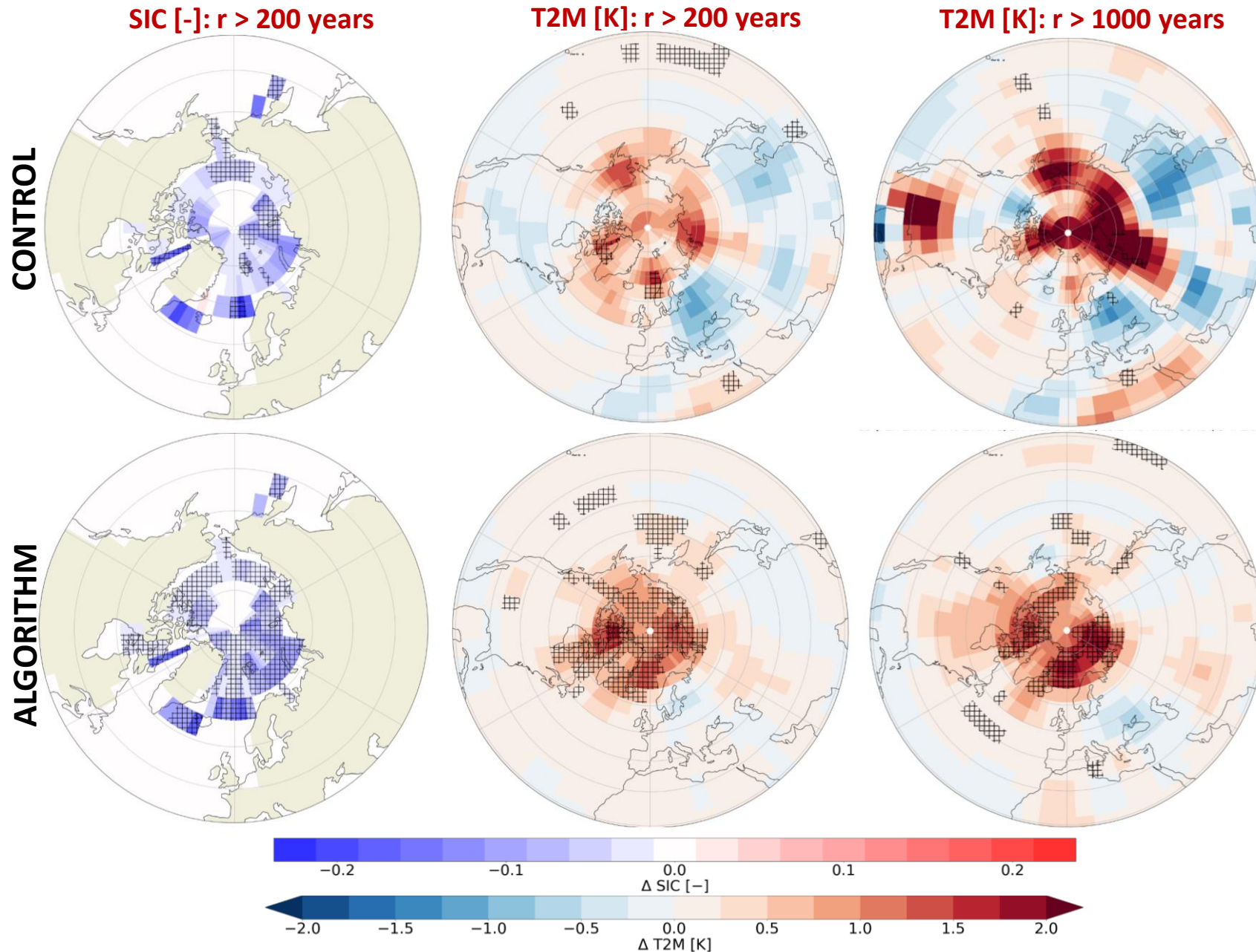


“Seasonal” / “summer”:
February-September average

Hatching: Significance on the 1%
level

- **Algorithm: Increase of statistical significance compared to control run**

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

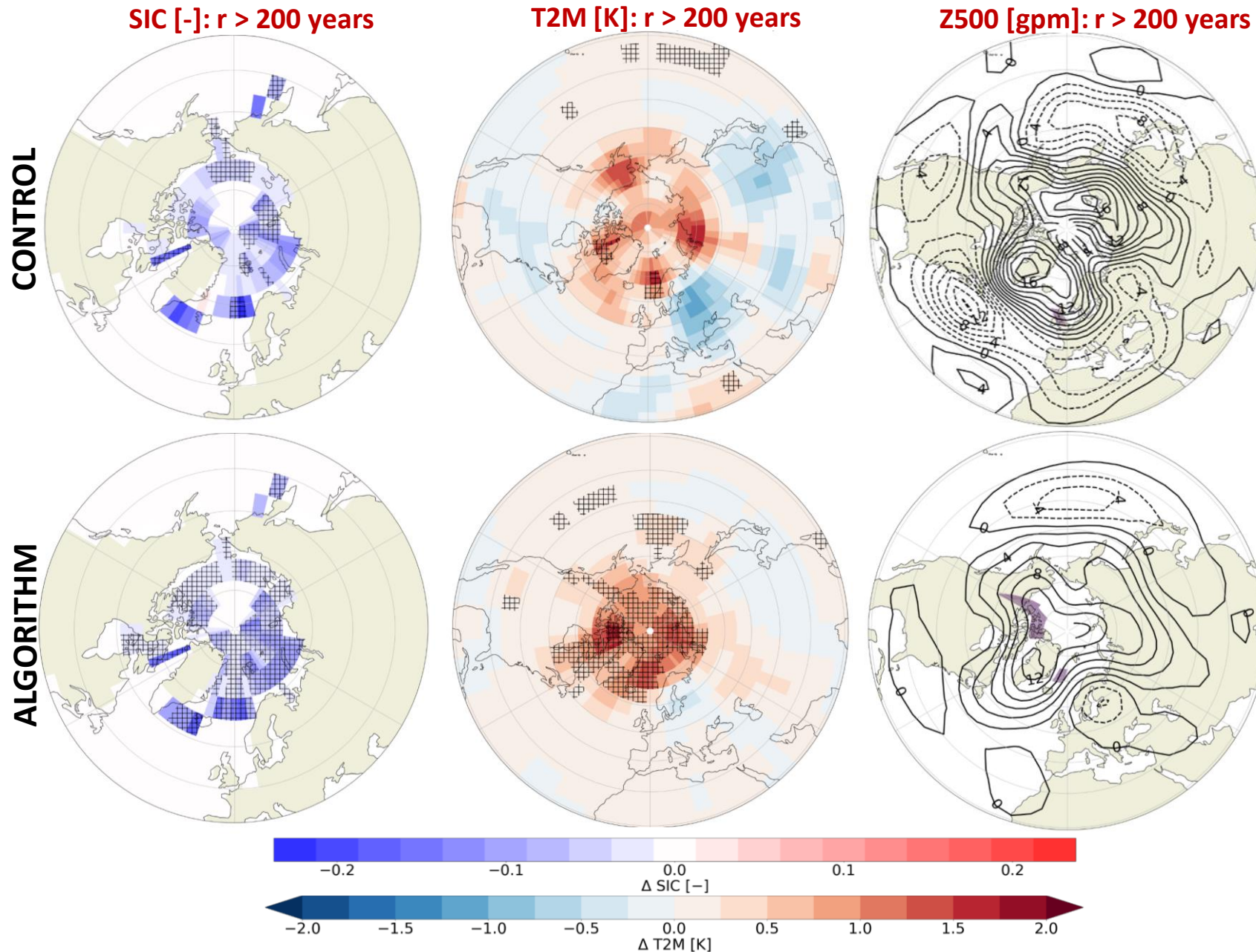


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- **Algorithm: Increase of statistical significance compared to control run**

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



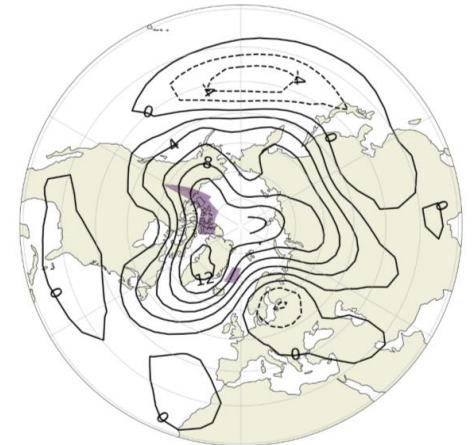
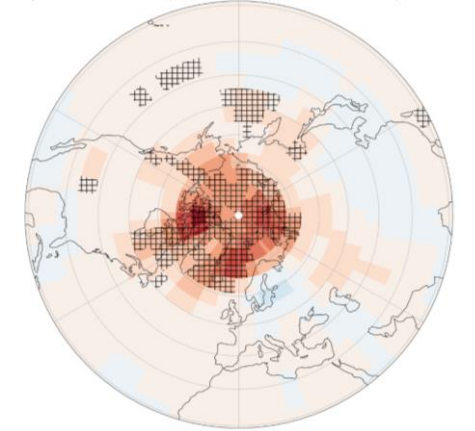
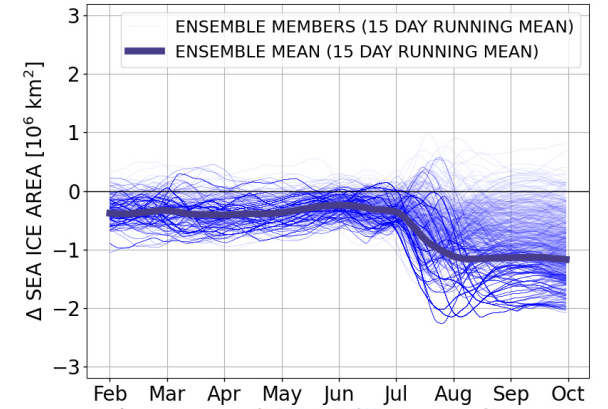
“Seasonal” / “summer”:
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Hatching/Shading: Significance
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- **Algorithm: Increase of statistical significance compared to control run**
- What are the dominant **drivers** of the **warm Arctic** in PlaSim?

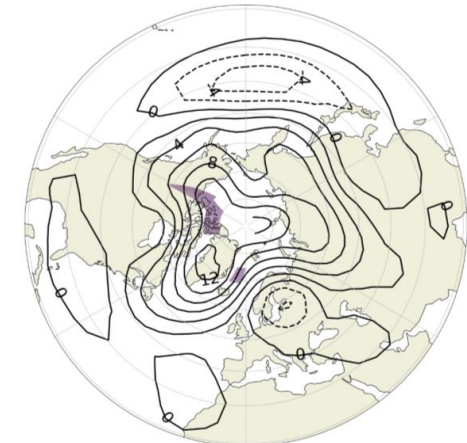
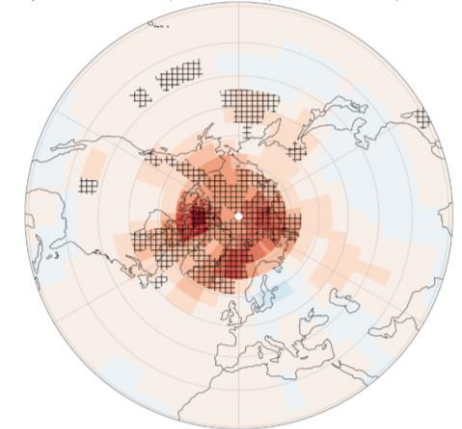
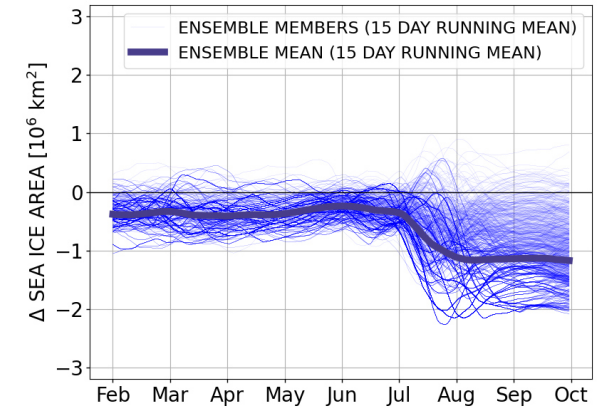
Summary and ongoing work

- Application of a rare event algorithm to PlaSim: Improved sampling efficiency of extreme negative pan-Arctic sea ice area anomalies
- More precise composite maps conditional on the extremes and access to the statistics of ultra-rare events
- Warm Arctic state during low sea ice years with signature in the 500 hPa geopotential height field



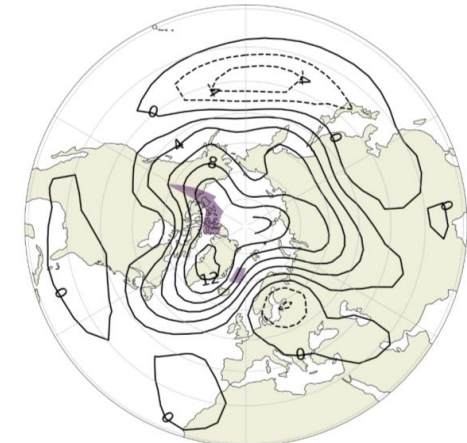
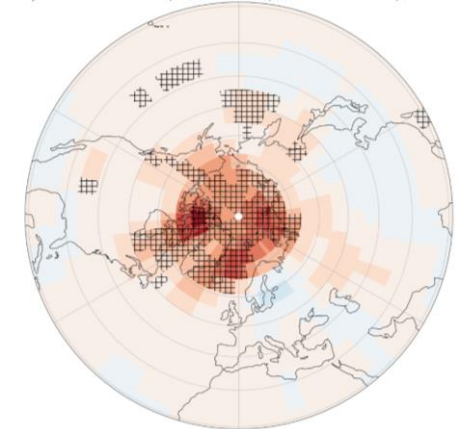
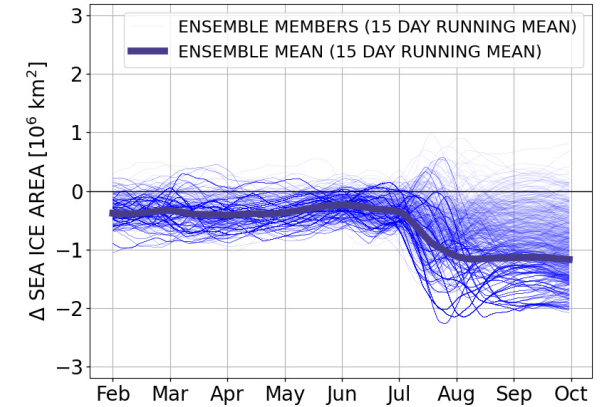
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- What is driving the warm Arctic in PlaSim?
 - Analysis of the energetics: surface energy budget and meridional heat transports
 - Dominant modes of atmospheric circulation variability
 - Preconditioning and state of the ocean
- Extending the analysis to the annual sea ice minimum in September



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Thank you for your attention