Drivers and predictability of extreme summer Arctic sea ice conditions with rare event simulation methods

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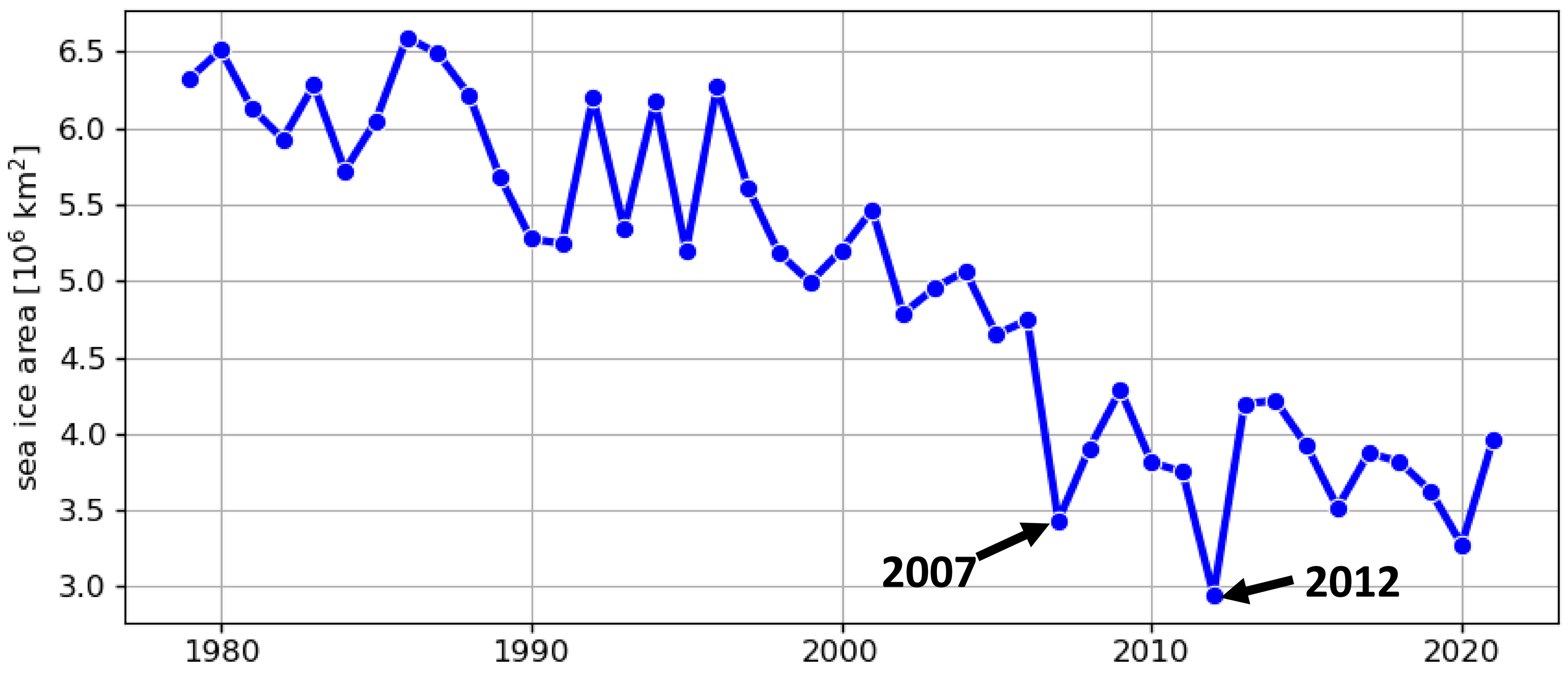
Extreme events in summer Arctic sea ice cover



September monthly mean pan-Arctic sea ice area [10^6 km^2]. Data: OSI SAF 2022.

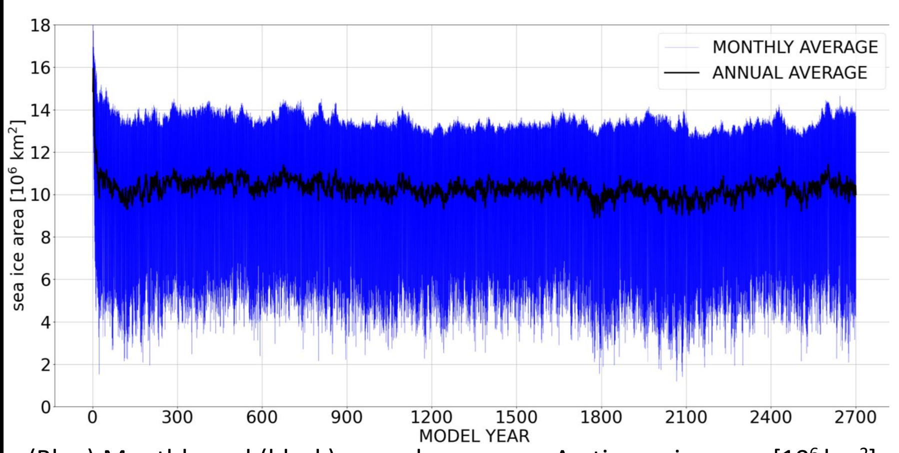
- Due to **climate change, summer Arctic sea ice cover** is **decreasing**
- On top of the **downward trend, internal climate variability** contributes to the **year-to-year variations** and **associated extremes** of the **annual Arctic sea ice minimum**
- **Three problems** complicate **robust statistical** and **dynamical studies** about **extreme events** in **summer Arctic sea ice cover:**

  1) lack of observational data
  2) poor sampling of rare events in **computationally expensive climate models**
  3) reliability of climate models

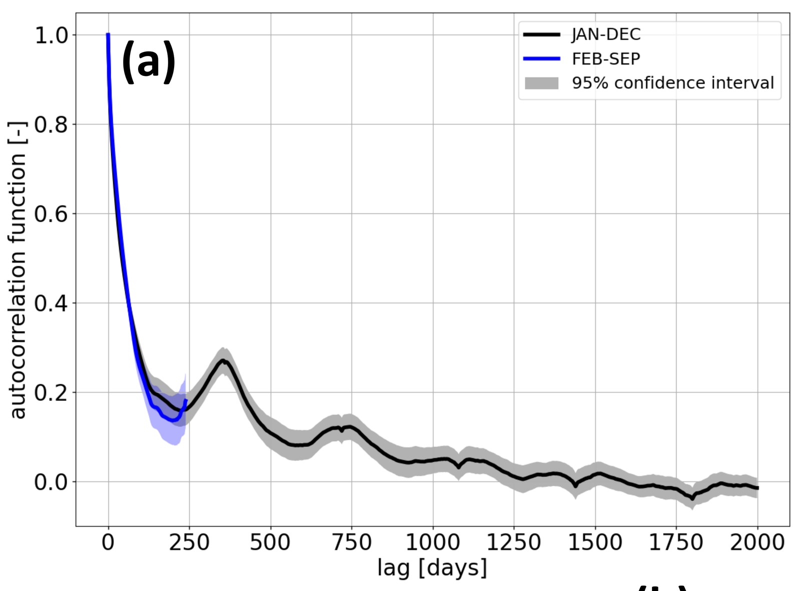
➡ What is the **relative contribution** of different **atmospheric** and **oceanic drivers** and of **natural** and **forced variability** to **extremes in summer Arctic sea ice cover?**

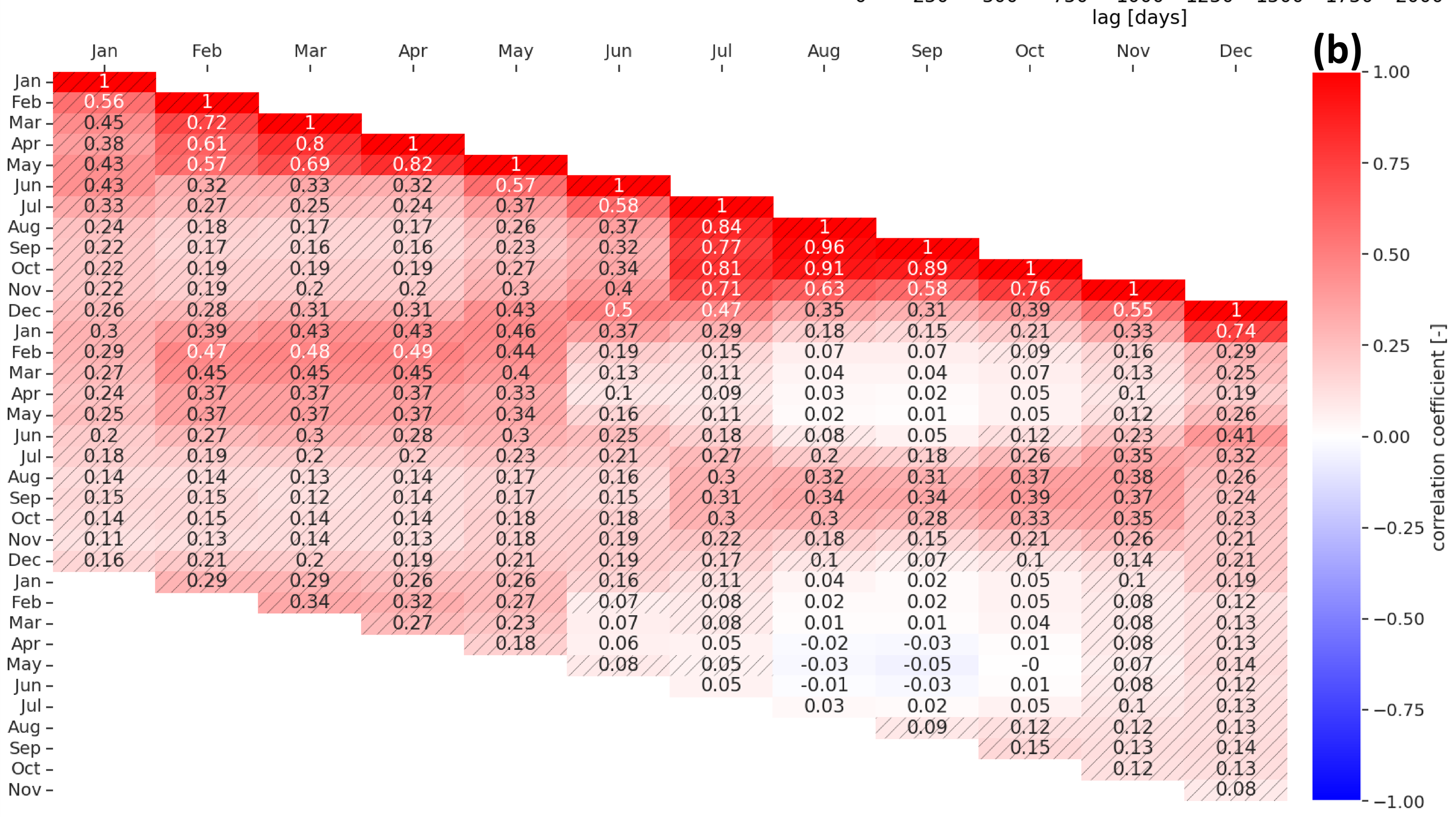
➡ Can we **improve seasonal predictions of extreme summer Arctic sea ice cover** by exploiting a **better understanding of the physical drivers of these events?**

Persistence of pan-Arctic sea ice area anomalies



(Blue) Monthly and (black) annual mean pan-Arctic sea ice area [10^6 km^2] simulated with a coupled atmosphere-ocean configuration of the "Planet Simulator"(PlaSim) with constant pre-industrial greenhouse gas forcing.





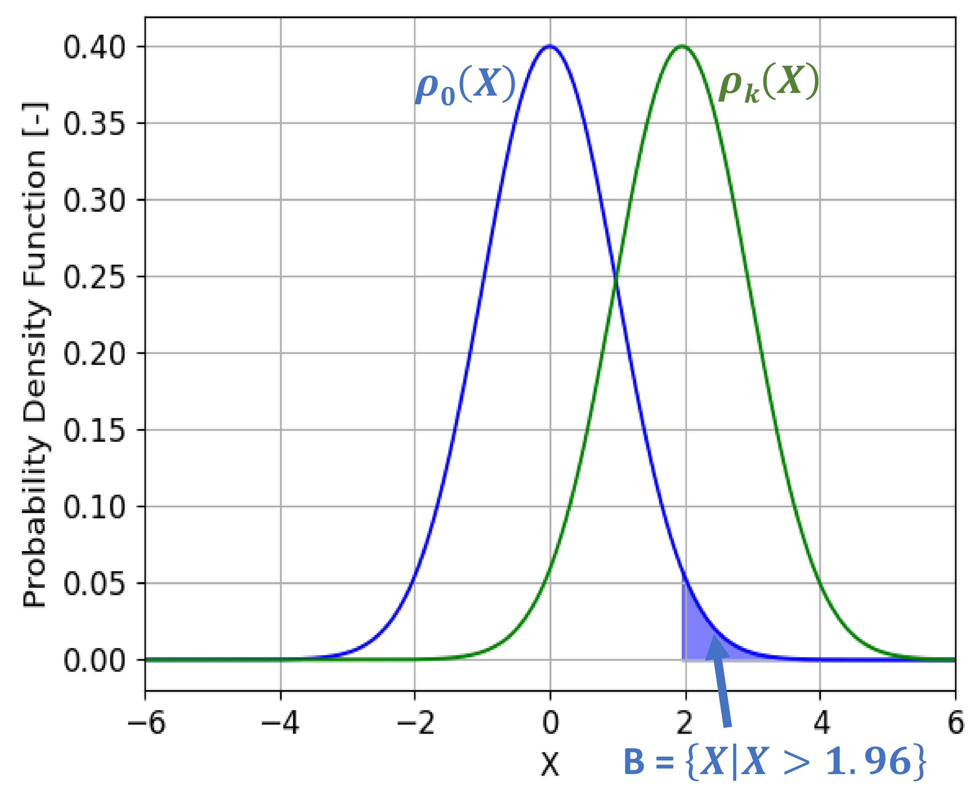
(a) Autocorrelation function applied to high-pass filtered daily pan-Arctic sea ice area anomalies and (b) lagged correlations applied to high-pass filtered monthly mean pan-Arctic sea ice area anomalies with increasing lag from top to bottom up to a lag of 23 months. Hatching denotes statistical significance according to the 95% confidence interval. Both (a) and (b) are based on the PlaSim model years 1201-2700.

- The **persistence** of the **sea ice area anomalies** is one important criterion for the set-up of the **rare event algorithm experiments**
- Up to a **lag of three months, the autocorrelation function** of **pan-Arctic sea ice area anomalies decays exponentially** with an **e-folding time scale** of about **70 days**
- The **memory of sea ice area anomalies** has a strong **seasonality**, shows **melt-to-growth** and **growth-to-melt season reemergence** and **vanishes completely after 3 to 5 years**

Coupling climate model ensembles to a rare event algorithm

Importance sampling

Goal: Make **rare events more common** to reduce the **statistical uncertainty of an estimator**



- **Synthetic example:** Estimate

$$P(B) = \int \mathbf{1}_B(X) \cdot \rho_0(X) dX$$

by drawing data from ρ_k instead of ρ_0 with

$$P(B) = \int \mathbf{1}_B(X) \cdot \frac{\rho_0(X)}{\rho_k(X)} \rho_k(X) dX$$

$$\approx \frac{1}{n} \sum_{k=1}^{n} \mathbf{1}_B(X_k) \cdot \frac{\rho_0(X_k)}{\rho_k(X_k)}$$

Methodology of the rare event algorithm

Genealogical rare event algorithm to perform **importance sampling** at **the level of model trajectories**

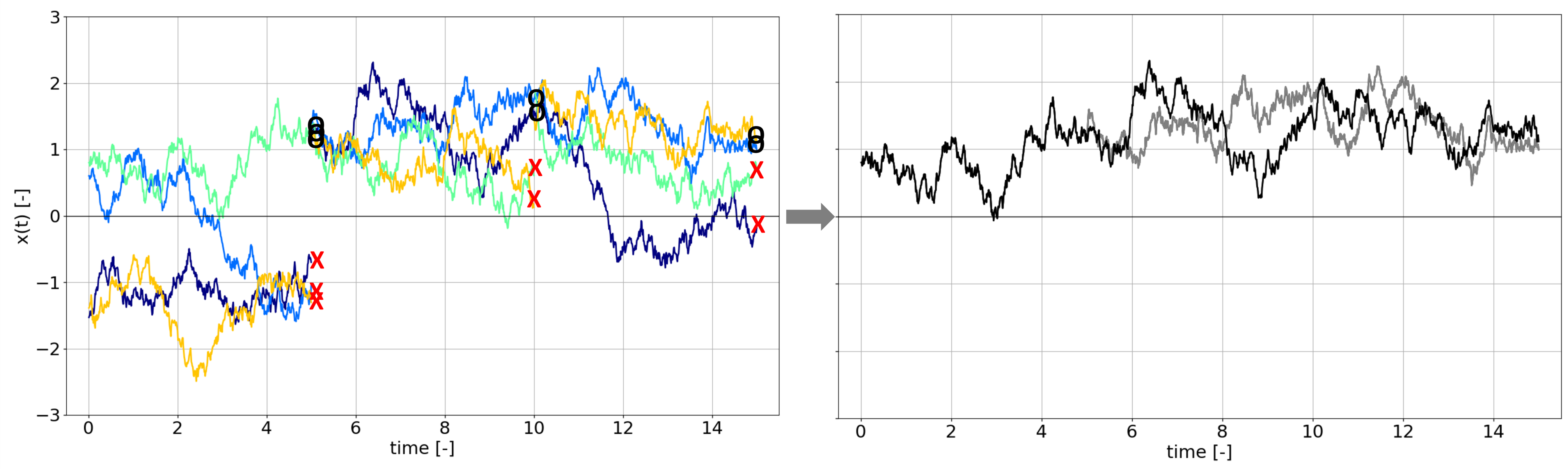
- Run N **trajectories** $\{X_n(t)\}$ $(n = 1, 2, \dots, N)$ for **total simulation time** T_a and define **observable** $A(\{X_n(t)\})$
- At **resampling times** $t_i = i\tau$ $\left(i = 1, \dots, \frac{T_a}{\tau}\right)$, the **trajectories generate a number of copies of itself** given by the **weights**

$$w_{n,i} = \frac{e^{k \int_{t_{i-1}}^{t_i} A(\{X_n(t)\}) dt}}{R_i}, \quad R_i = \frac{1}{N} \sum_{n=1}^{N} e^{k \int_{t_{i-1}}^{t_i} A(\{X_n(t)\}) dt}$$

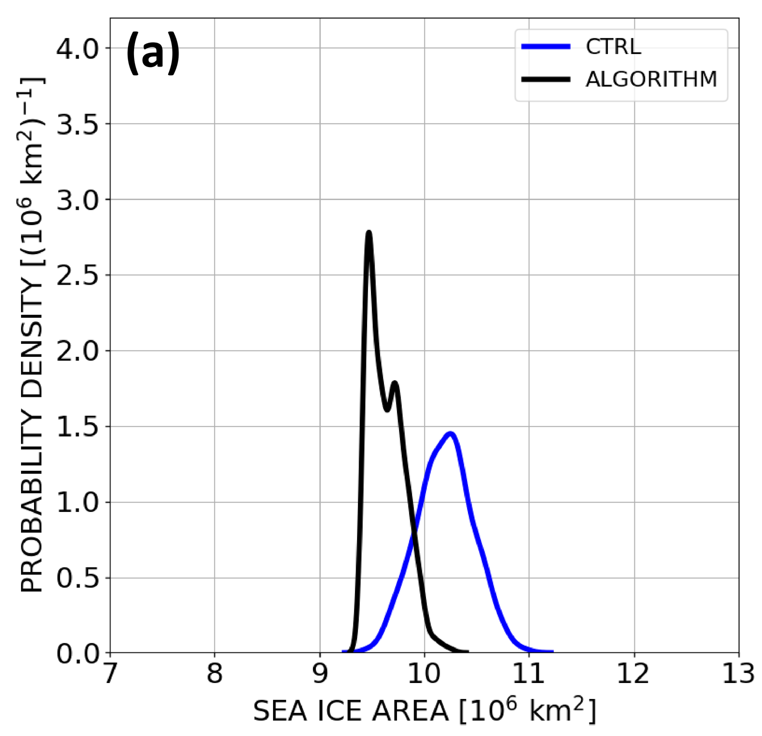
, with k **parameter of the algorithm**

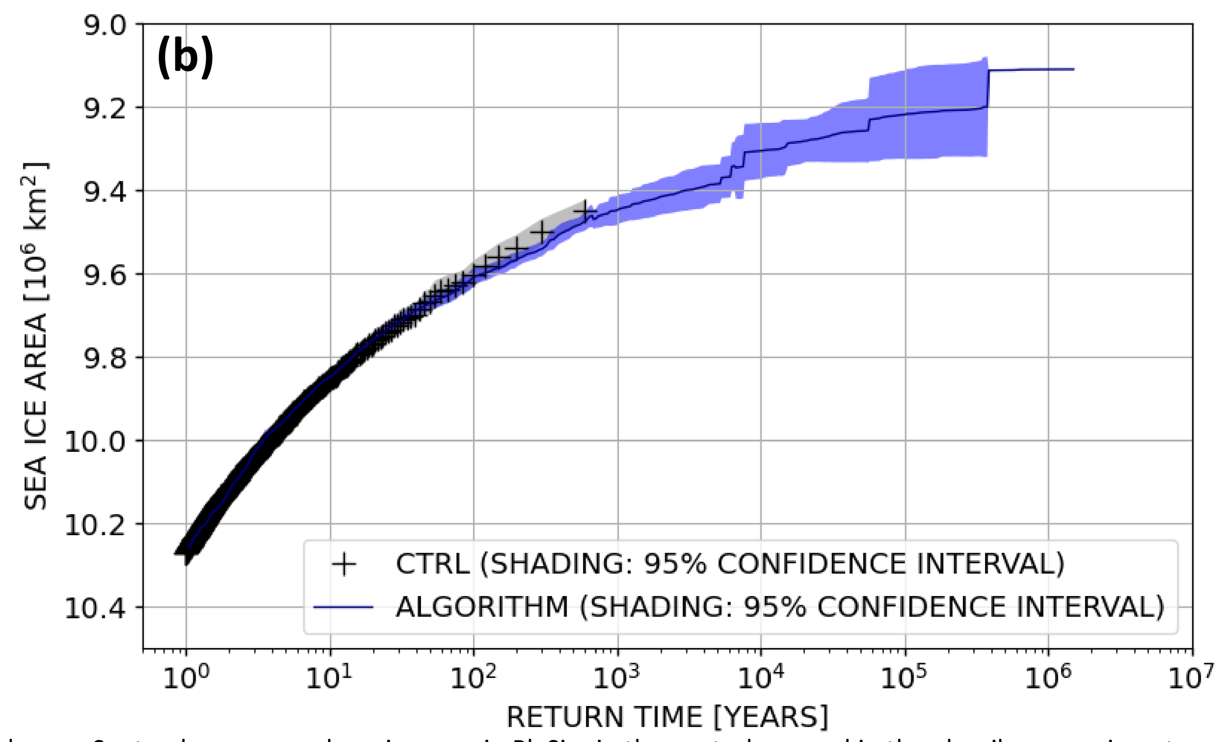
- The **algorithm** shifts the **original trajectory distribution** P_0 towards a **new distribution** P_k such that **trajectories** with **large values of the time-averaged observable become common:**

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



Results from the experiments with the rare event algorithm





Probability distributions (a) and return curves (b) of pan-Arctic February-September averaged sea ice area in PlaSim in the control run and in the algorihm experiment using a resampling time of 30 days. (a) One algorithm experiment with k = -0.05 $\cdot 10^{-6}$ km^{-2} day^{-1} and (b) eight algorithm experiments with different k are used.

- The **algorithm** enables to **efficiently sample rare events with very low Arctic sea ice area** and to **compute return times up to more than 10^5 years** from a **total computational cost of a few 1000 years**

References

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