

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

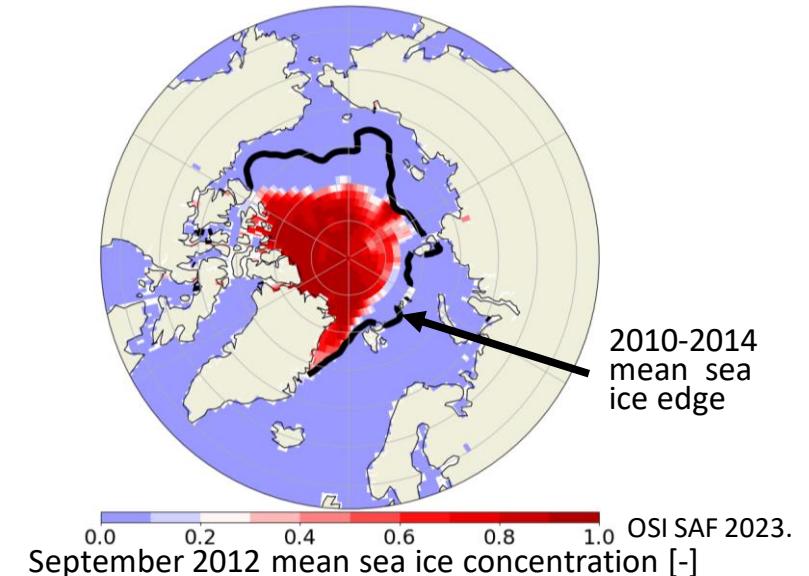
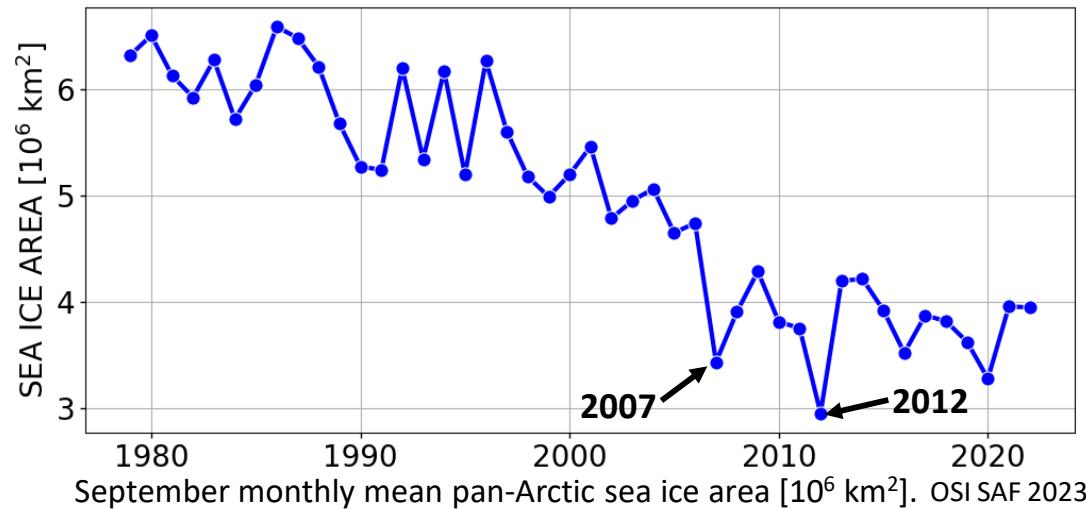
Jerome Sauer

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



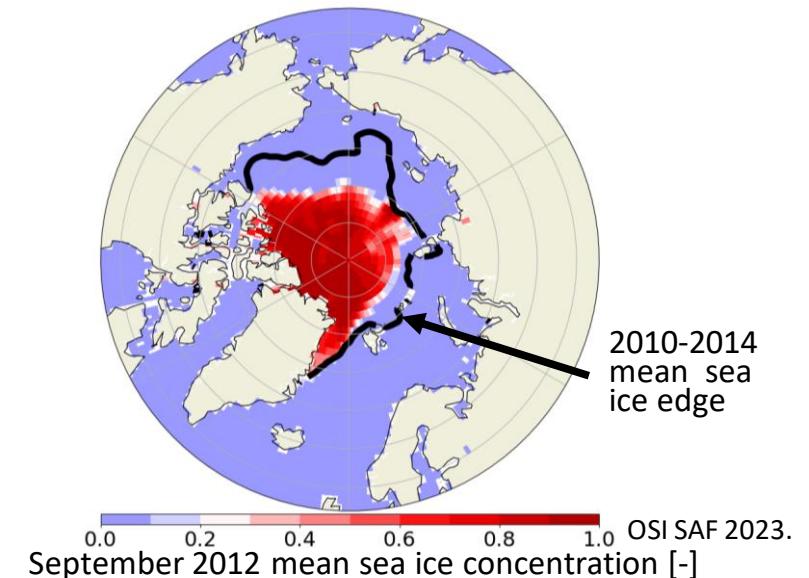
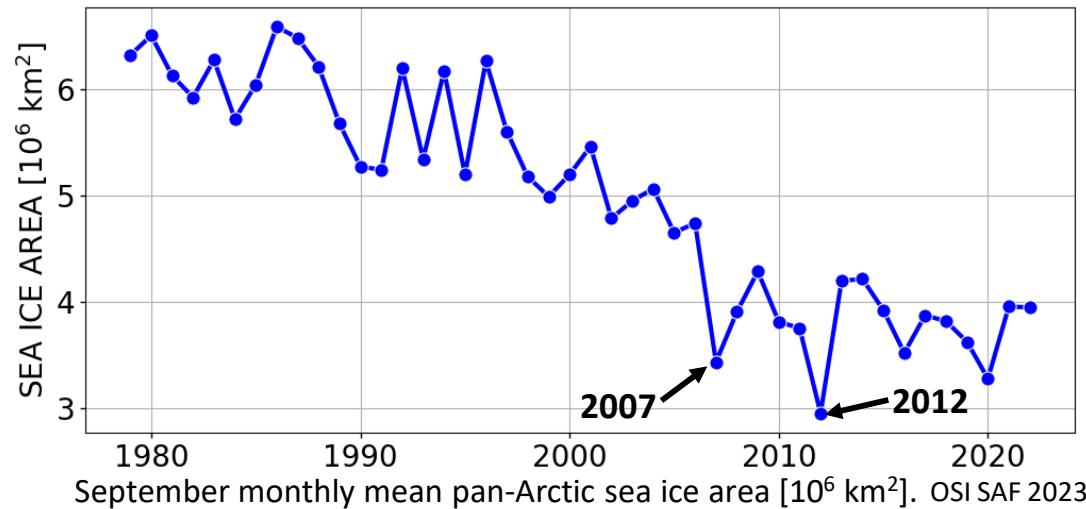
Extreme reductions in summer pan-Arctic sea ice area



Overarching goal: Understanding **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

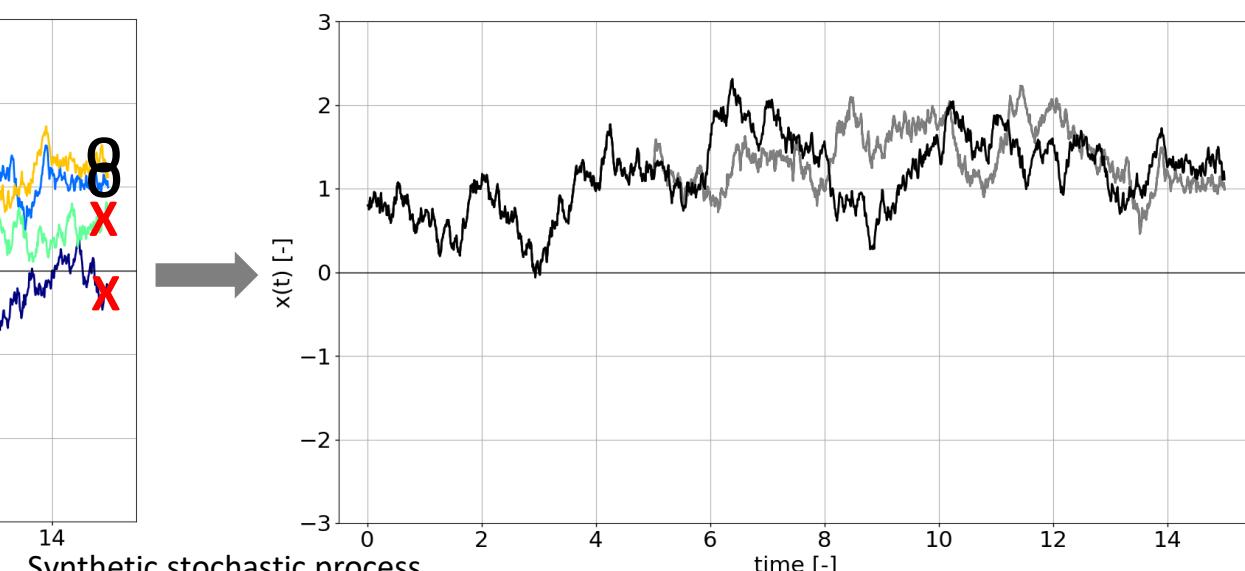
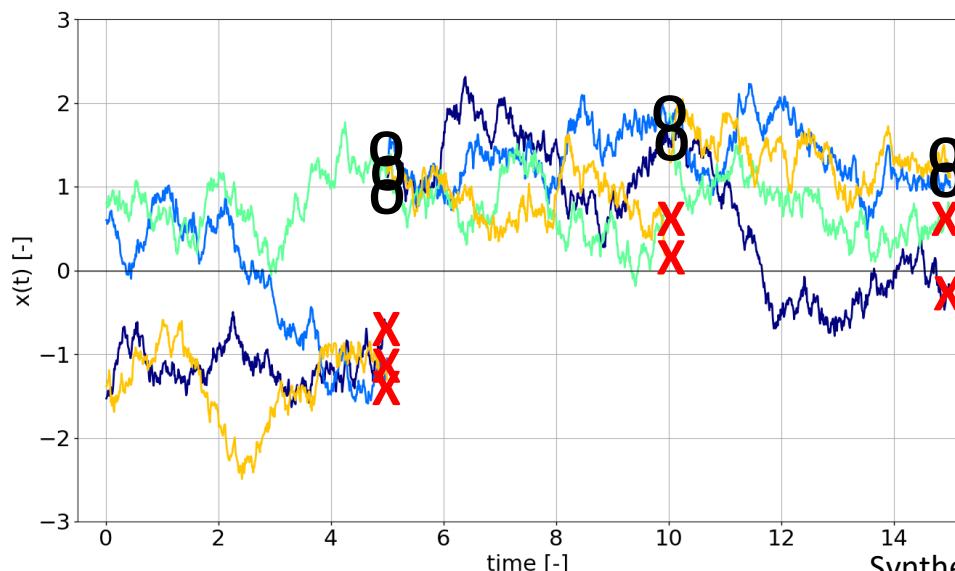


Problem: Quantitative statistical and dynamical studies of **climate extremes** are hindered by the **lack of data**

- 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**

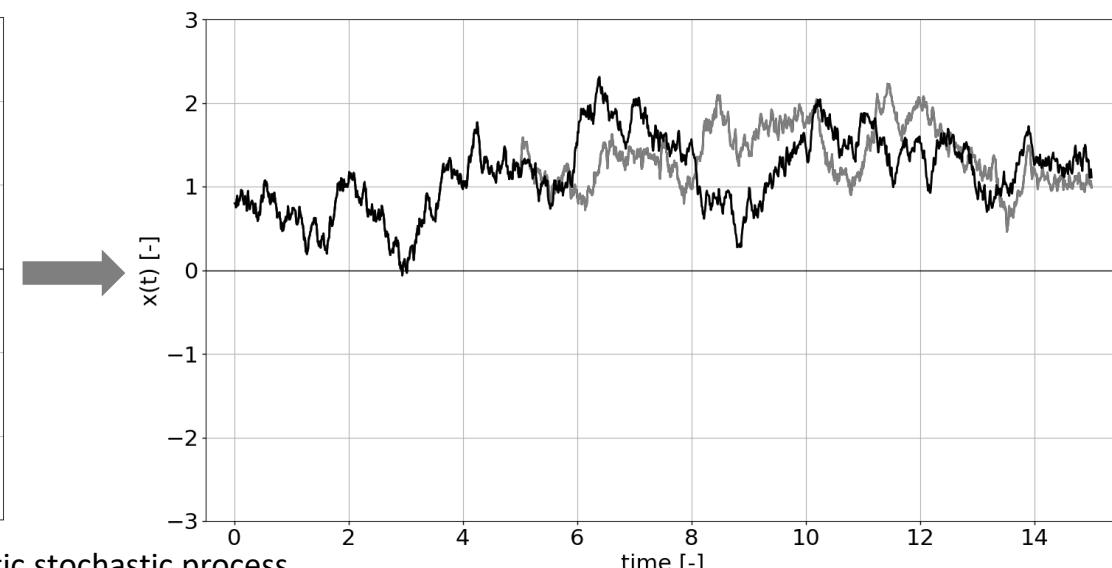
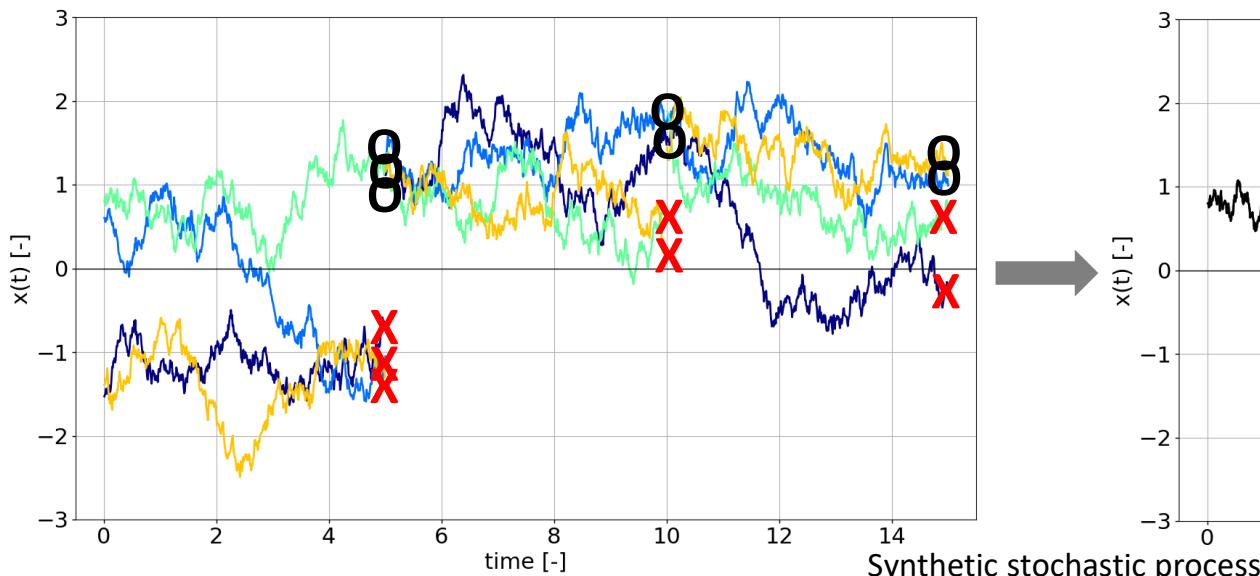


Methodology: Rare event algorithm

- **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 formula:** 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

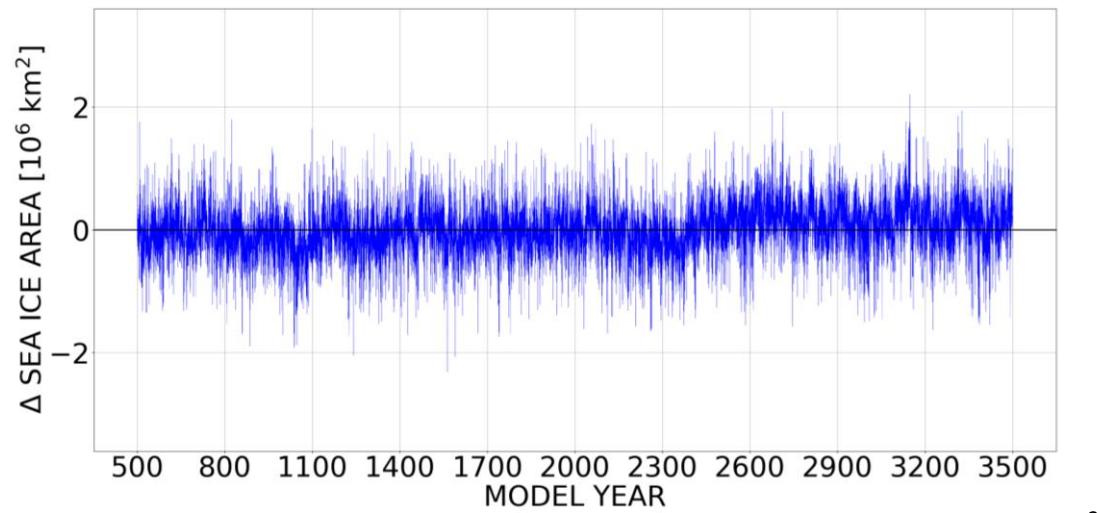
Coupled version: Large-Scale Geostrophic ocean and a zero-layer thermodynamic sea ice model

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

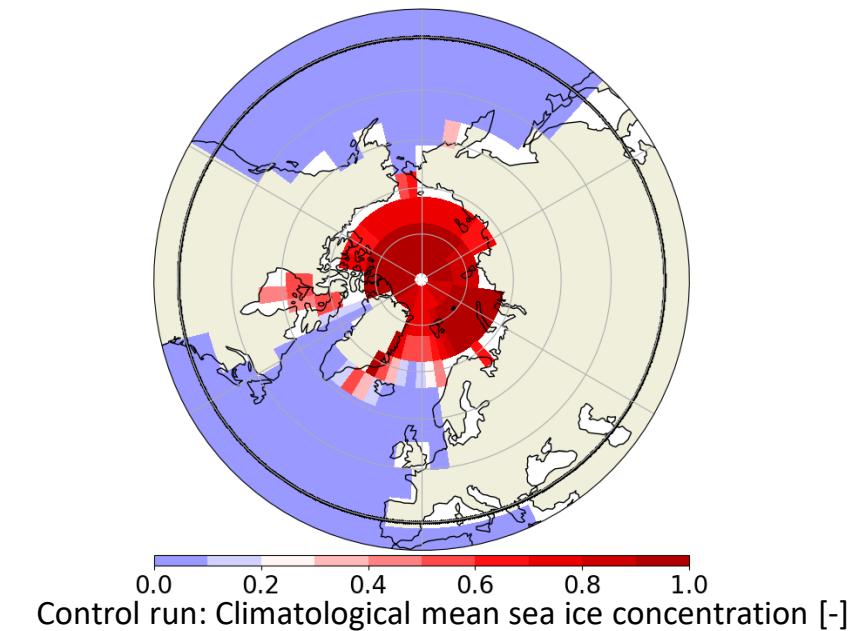
Forcing: constant pre-industrial greenhouse gas conditions

Observable: pan-Arctic sea ice area

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



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

PlaSim: Intermediate complexity general circulation model

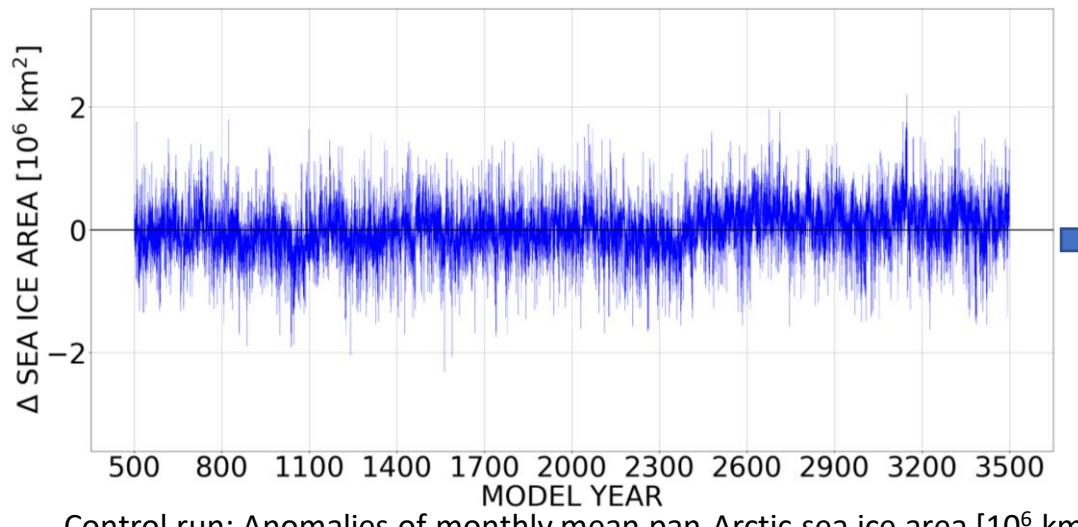
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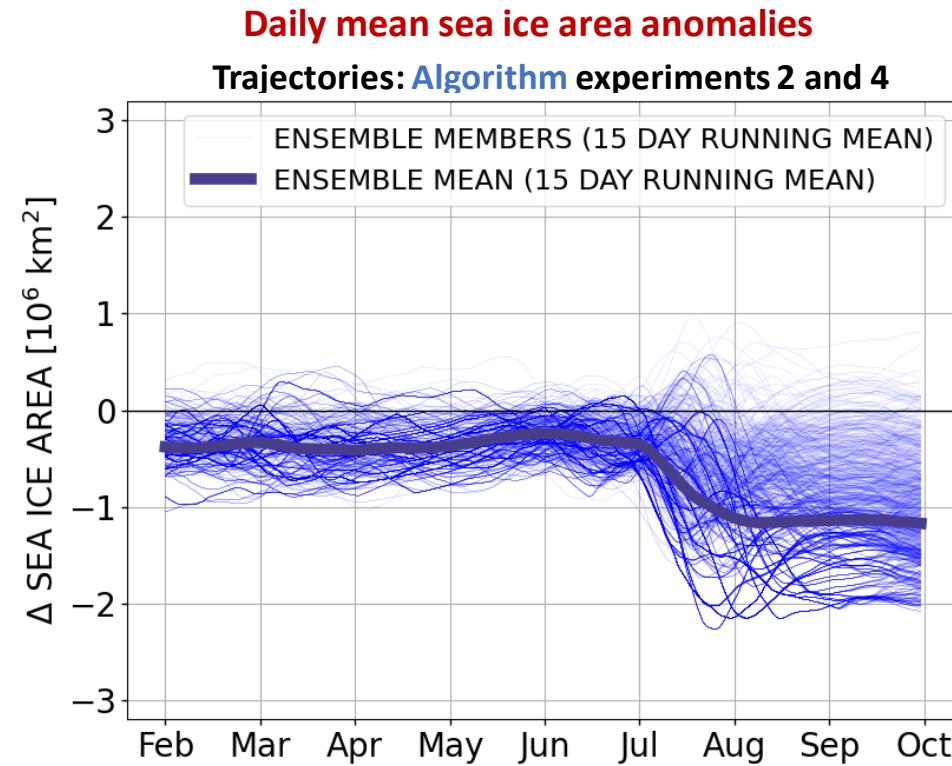
Rare event algorithm experiments

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

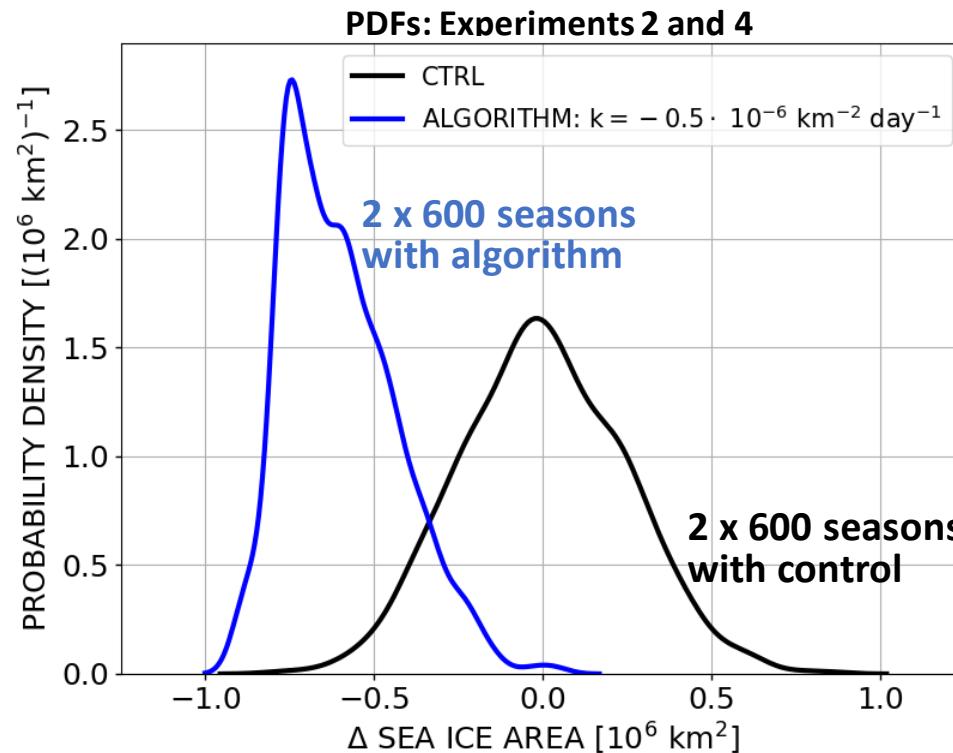
Seasons with extremely low pan-Arctic sea ice area in PlaSim



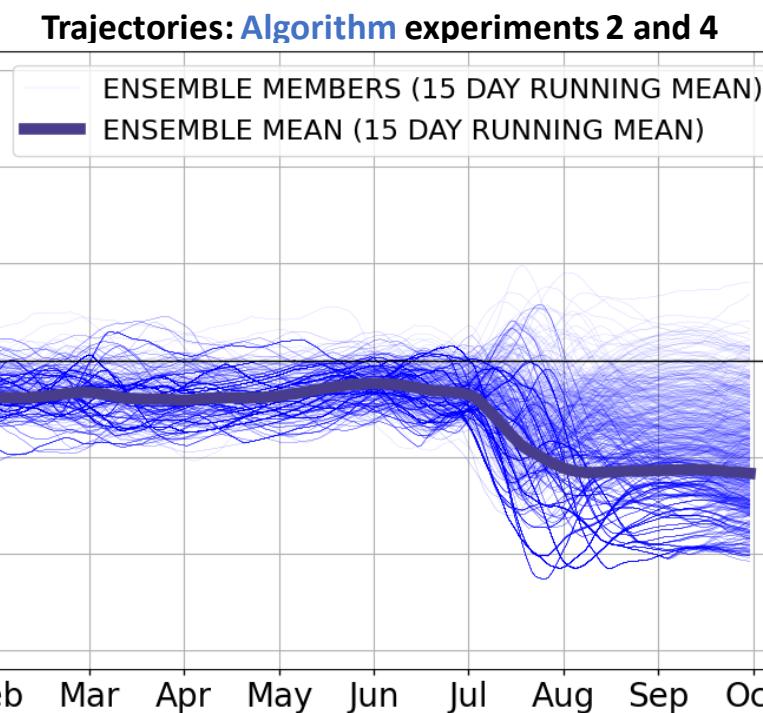
- Importance sampling of extreme negative February-September mean pan-Arctic sea ice area anomalies

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

February-September mean sea ice area anomalies

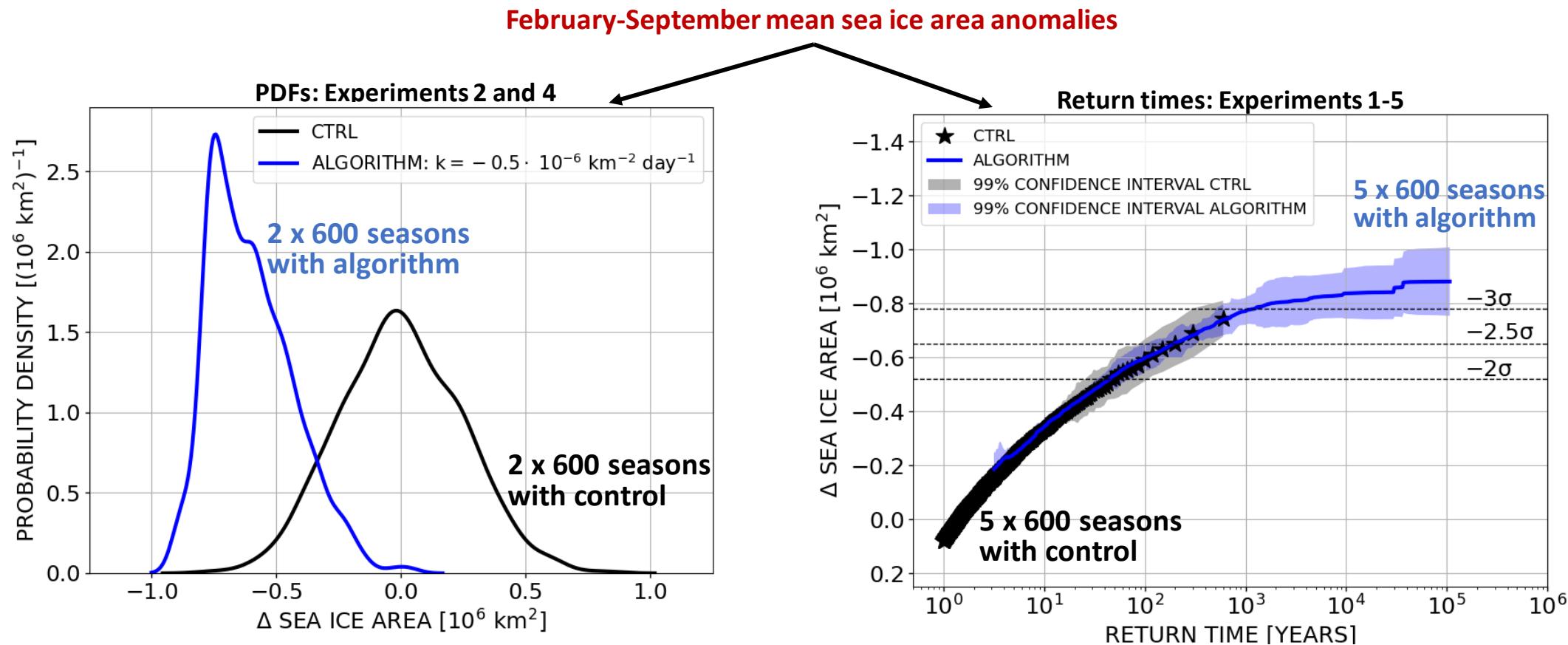


Daily mean sea ice area anomalies



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

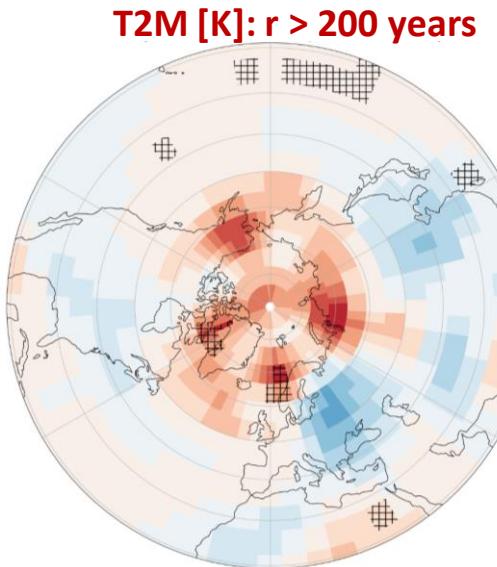
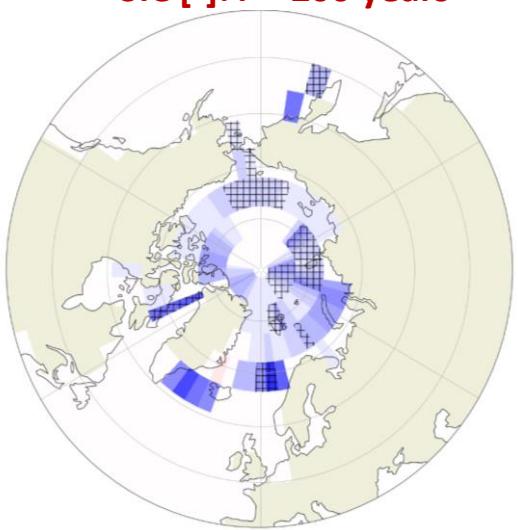
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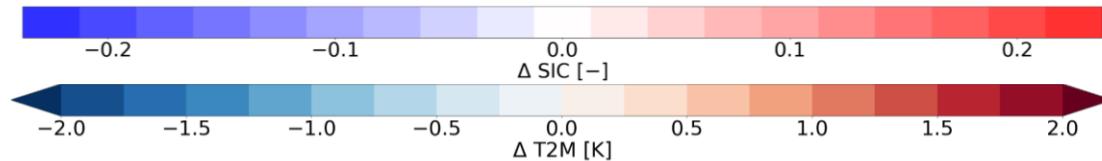
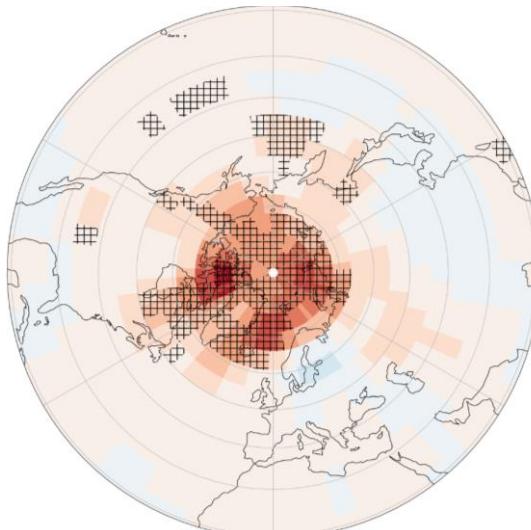
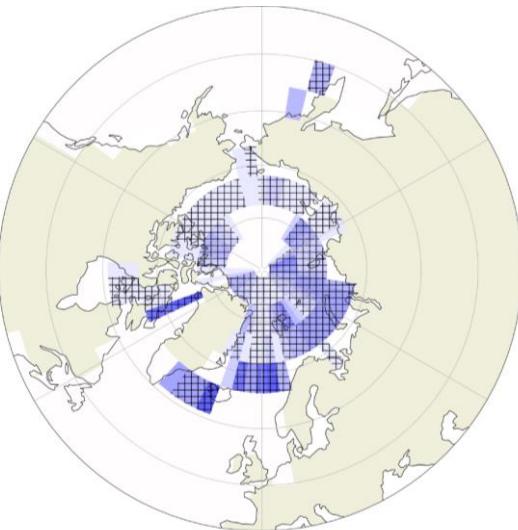
- Importance sampling of extreme negative February-September mean pan-Arctic sea ice area anomalies
- The algorithm allows to compute return times up to 10^5 years with computational cost of 3000 seasons

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

CONTROL



ALGORITHM



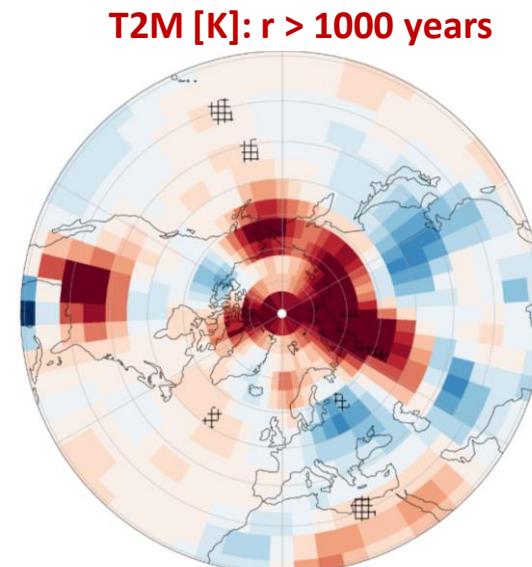
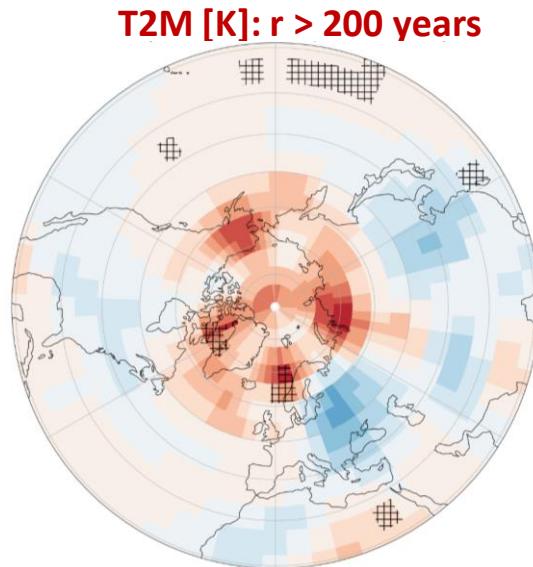
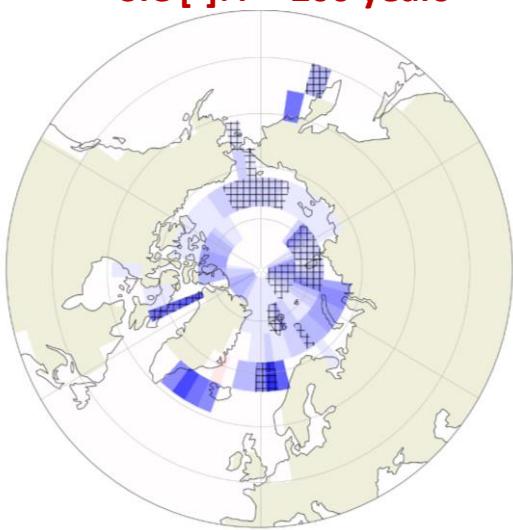
“Seasonal”/ “summer”: February-September average

Hatching: Significance on the 1% level

- Improved statistics with the algorithm compared to control

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

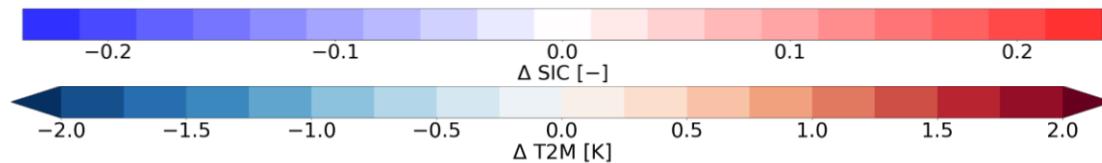
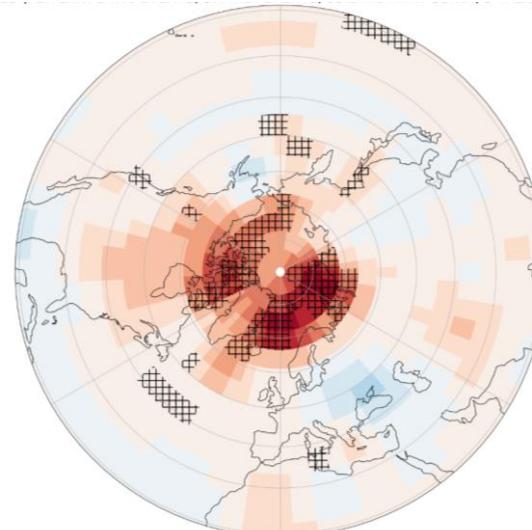
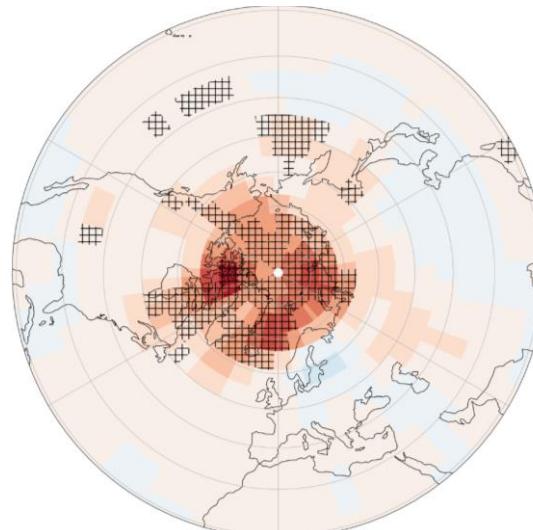
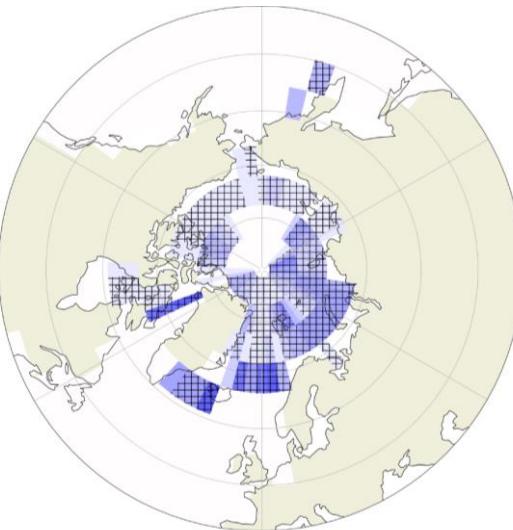
CONTROL



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

Hatching: Significance on the 1%
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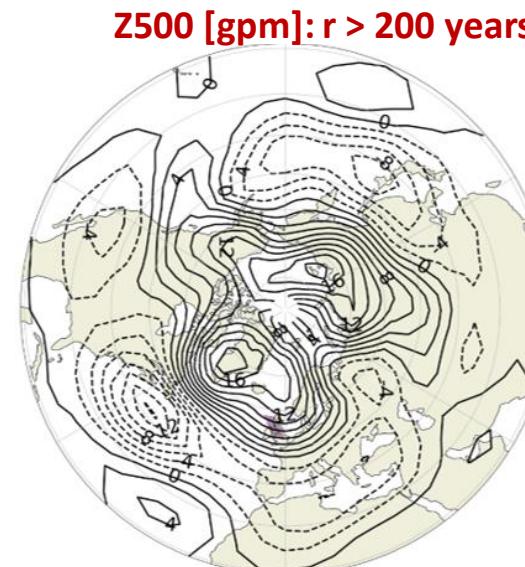
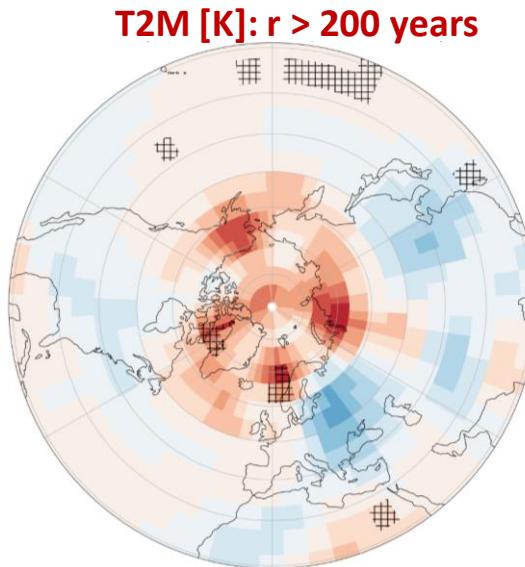
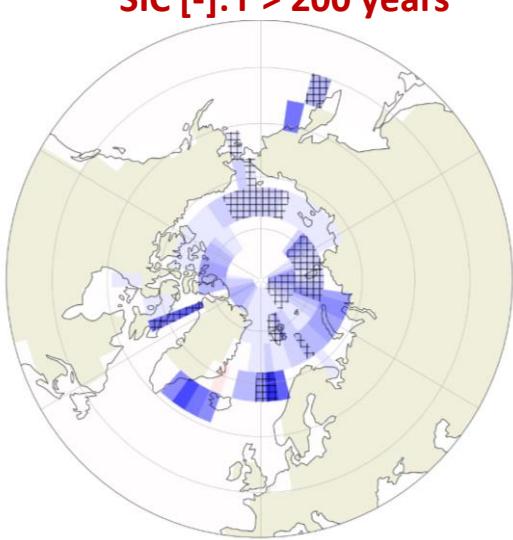
ALGORITHM



- Improved statistics with the algorithm compared to control

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

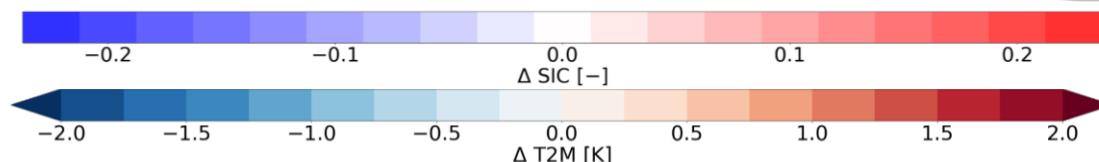
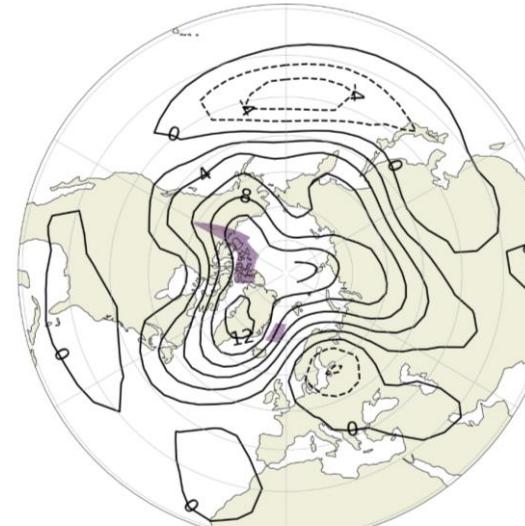
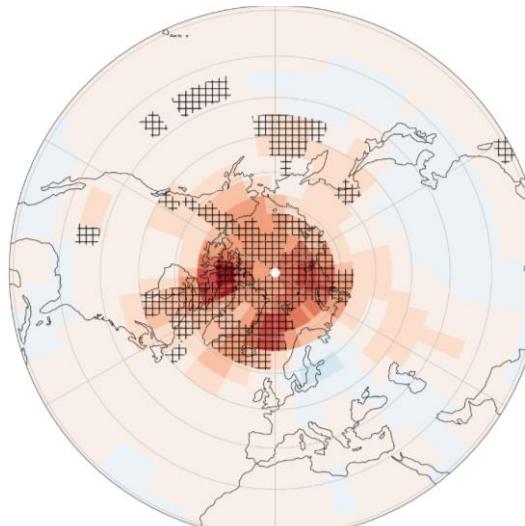
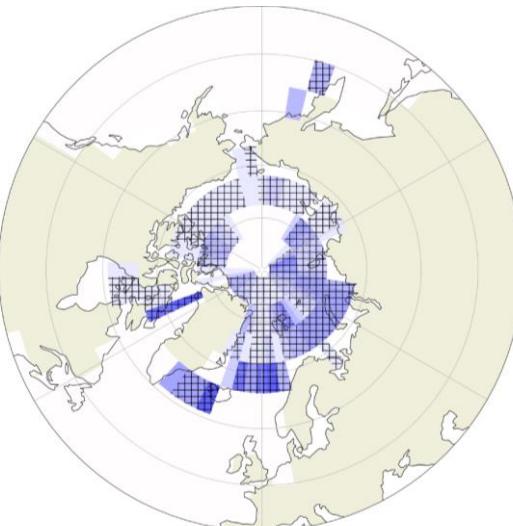
CONTROL



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

Hatching/Shading: Significance
on the 1% level

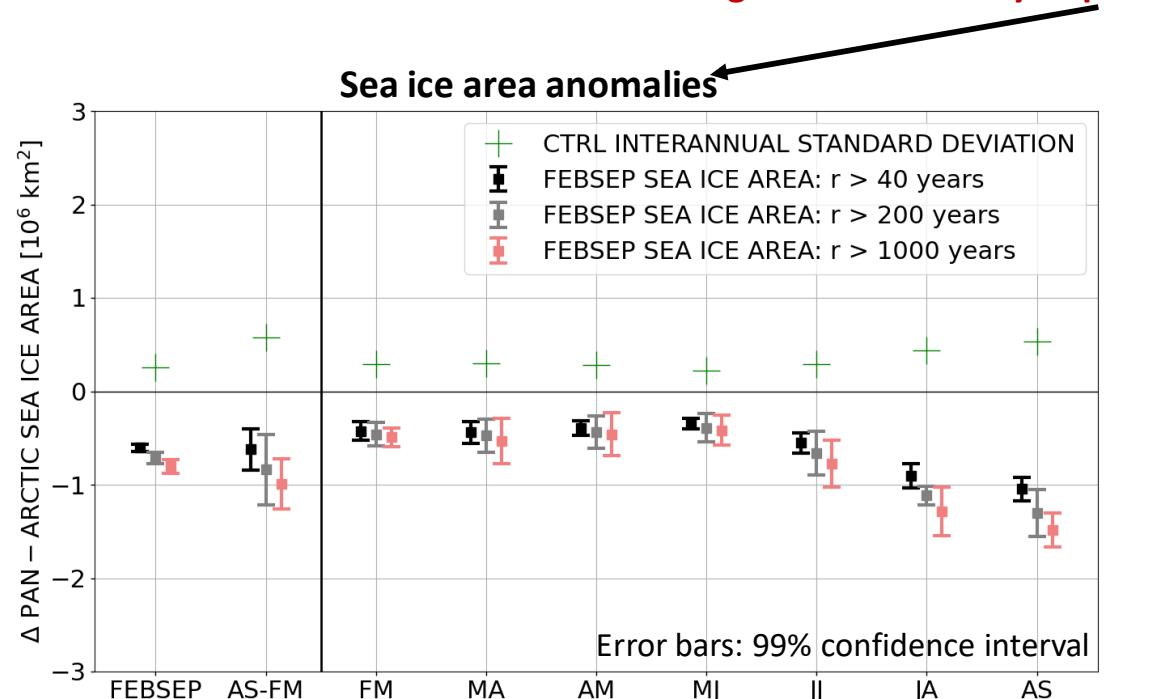
ALGORITHM



- Improved statistics with the algorithm compared to control
- What are the dominant drivers of the warm Arctic in PlaSim?

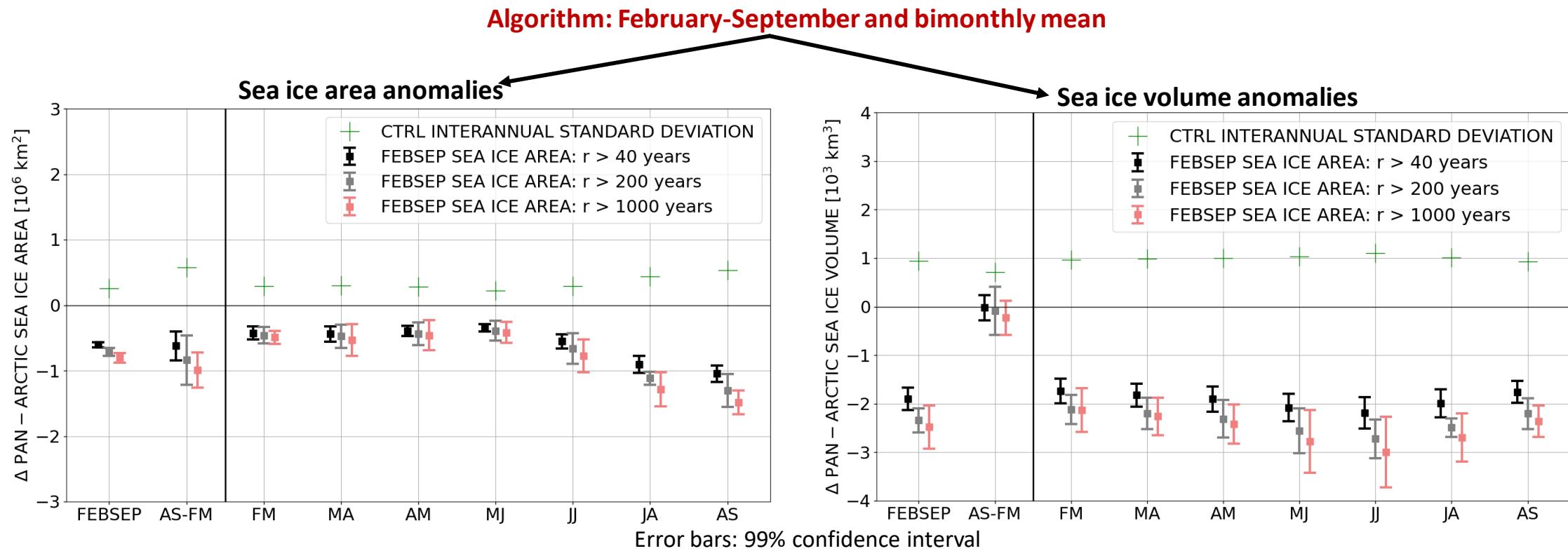
Preconditioning vs. intra-seasonal sea ice reduction

Algorithm: February-September and bimonthly mean



- 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

Preconditioning vs. intra-seasonal sea ice reduction

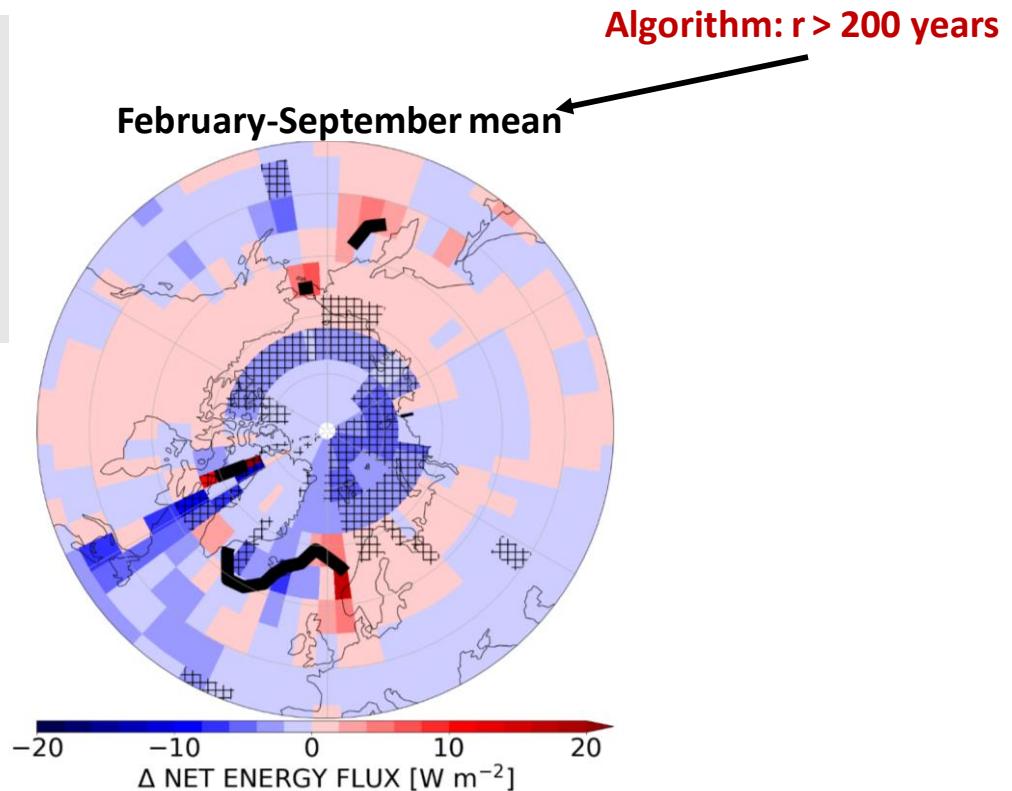


- Anomalously **low sea ice area** at the beginning of the simulation in late winter
- Anomalously **strong reduction of sea ice area** between May-June and August-September
- Anomalies of **sea ice volume** indicate a strong role of **preconditioning**

Surface energy fluxes during seasons with extremely low sea ice area

Hatching:
Significance at the
1% level

Downward fluxes
are negative

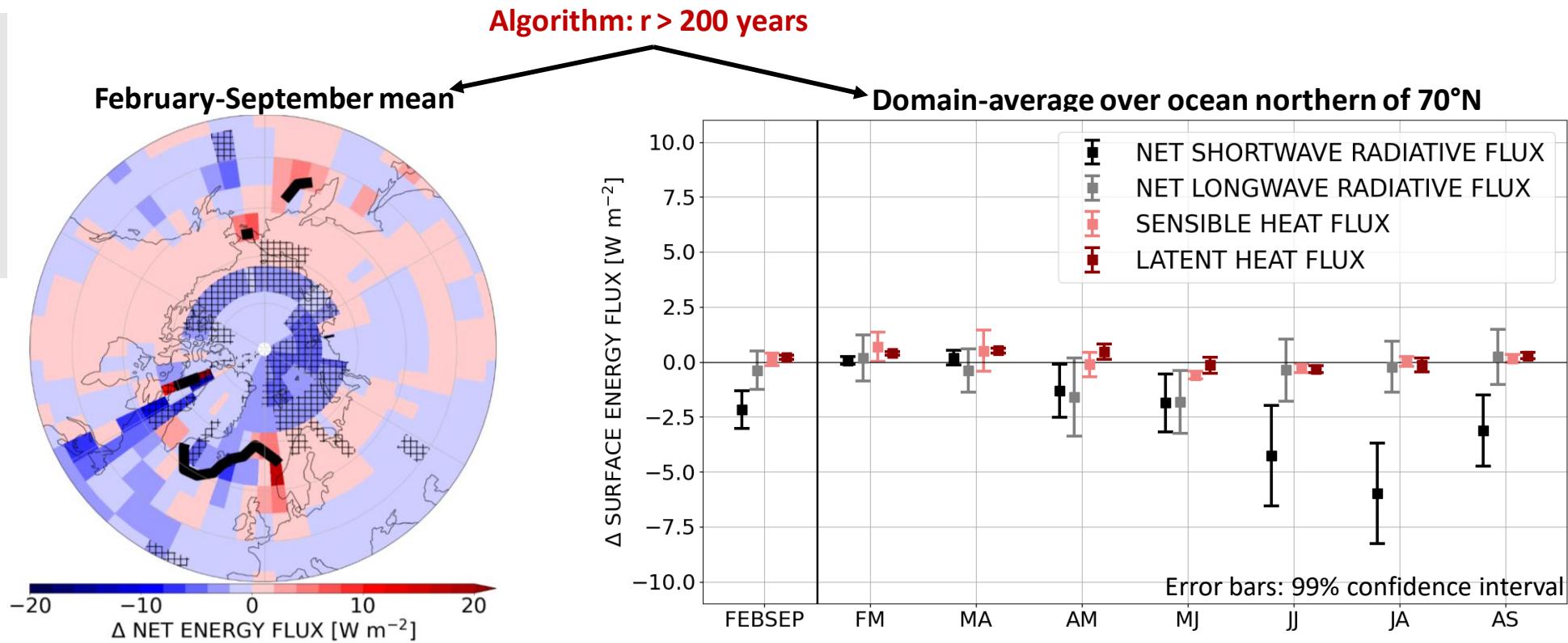


- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean

Surface energy fluxes during seasons with extremely low sea ice area

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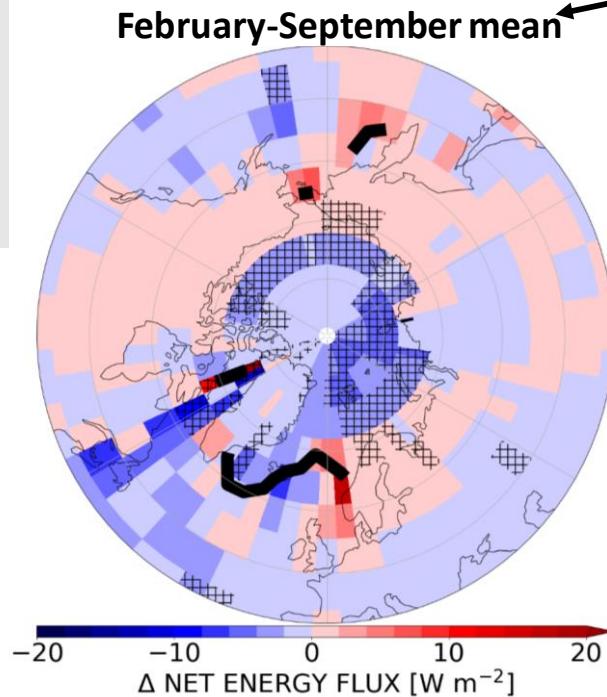


- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean
- Radiative fluxes** dominate net surface energy flux anomalies
- Dominant shortwave component** during summer and a weak contribution by the longwave flux in late spring

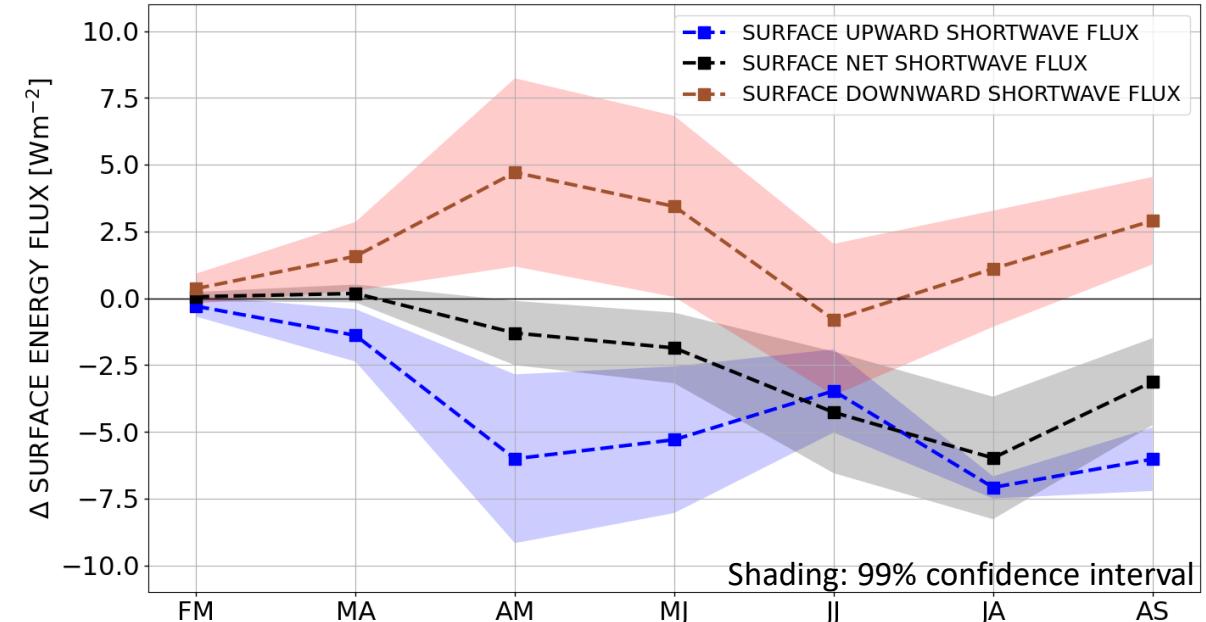
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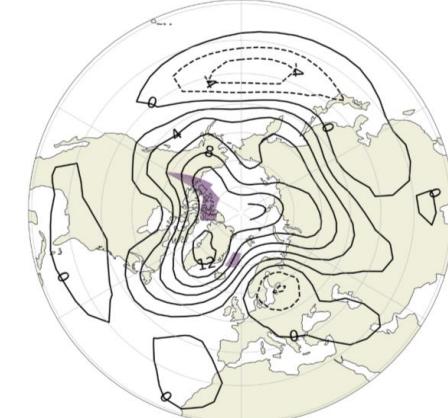
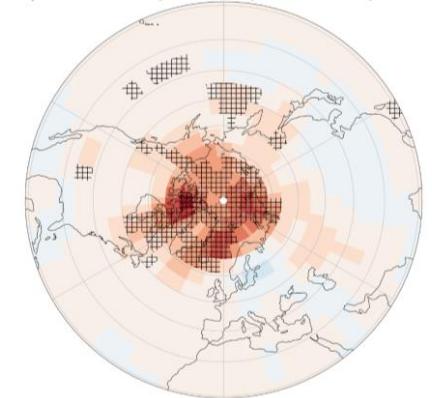
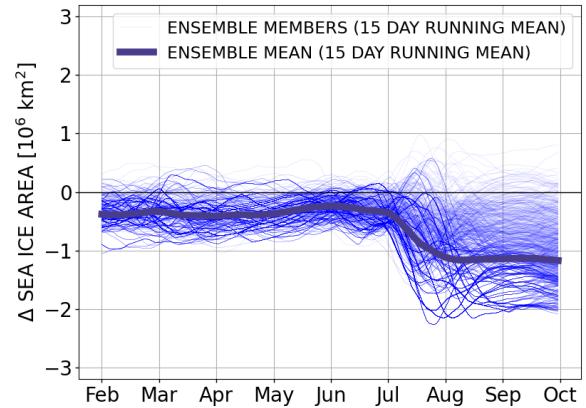
Domain-average over ocean northern of 70°N
Surface shortwave fluxes



- 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**

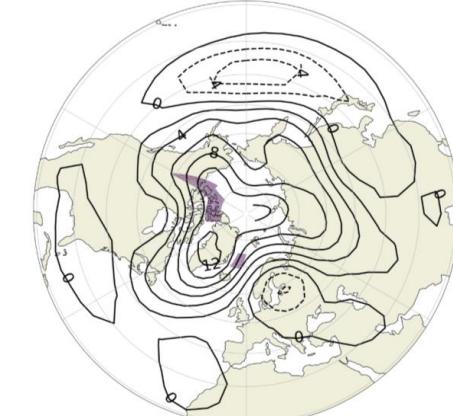
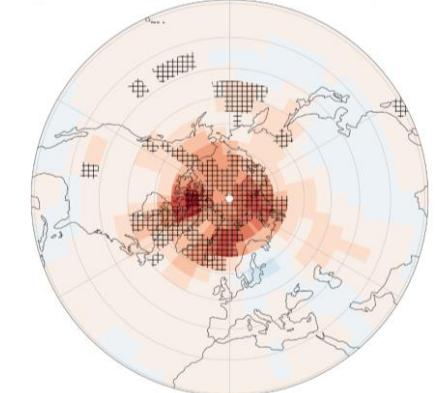
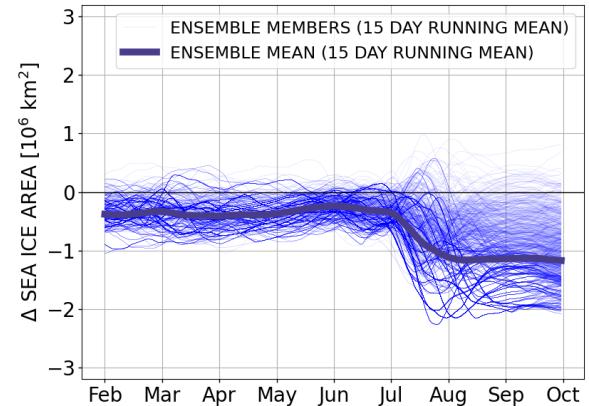
Summary and outlook

- 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



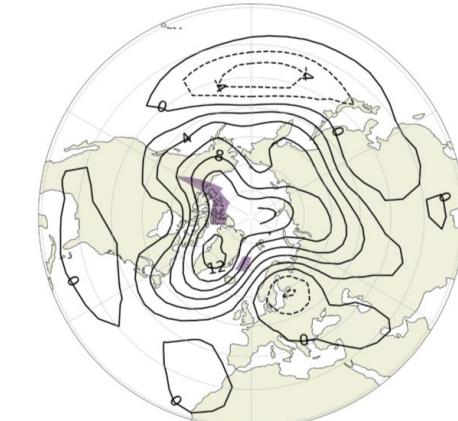
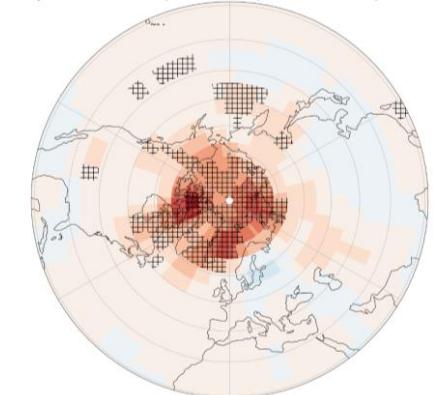
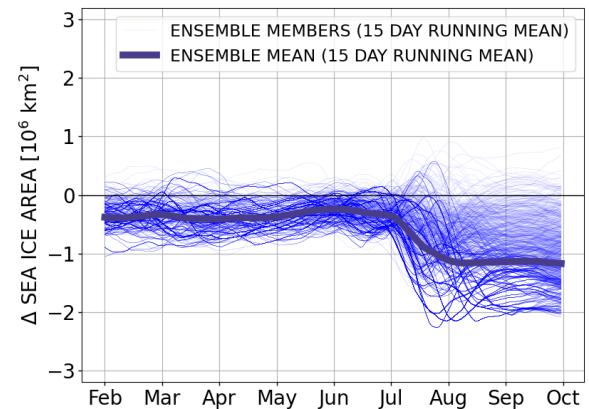
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- Evidence of strong contribution of preconditioning in the sea ice-ocean system and local feedback mechanisms to extremely low sea ice conditions in PlaSim



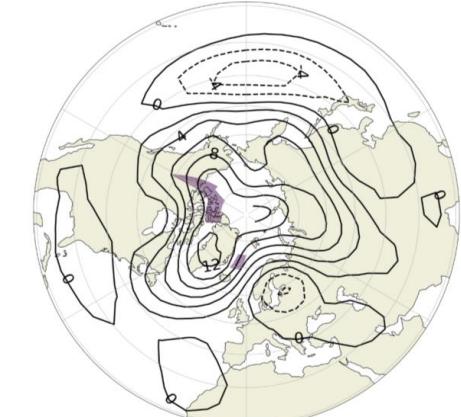
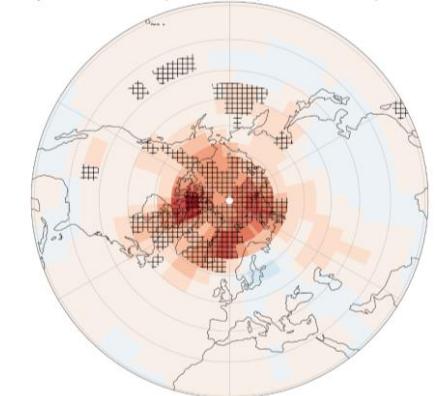
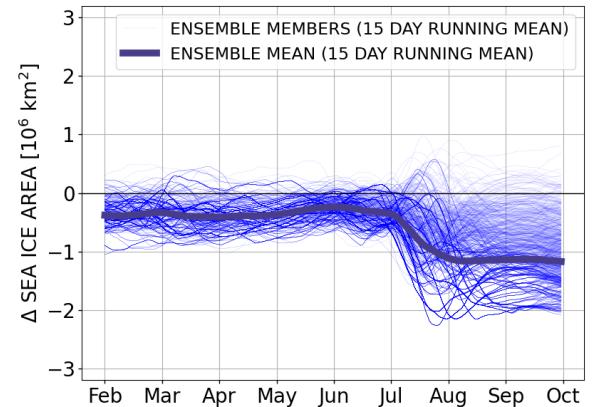
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- Analysis of the link between sea ice extremes and oceanic heat content and transport
- Atmospheric processes: Rare event algorithm experiments with five day resampling time
- Increase the model complexity: PlaSim-T42-LSG and EC-Earth4



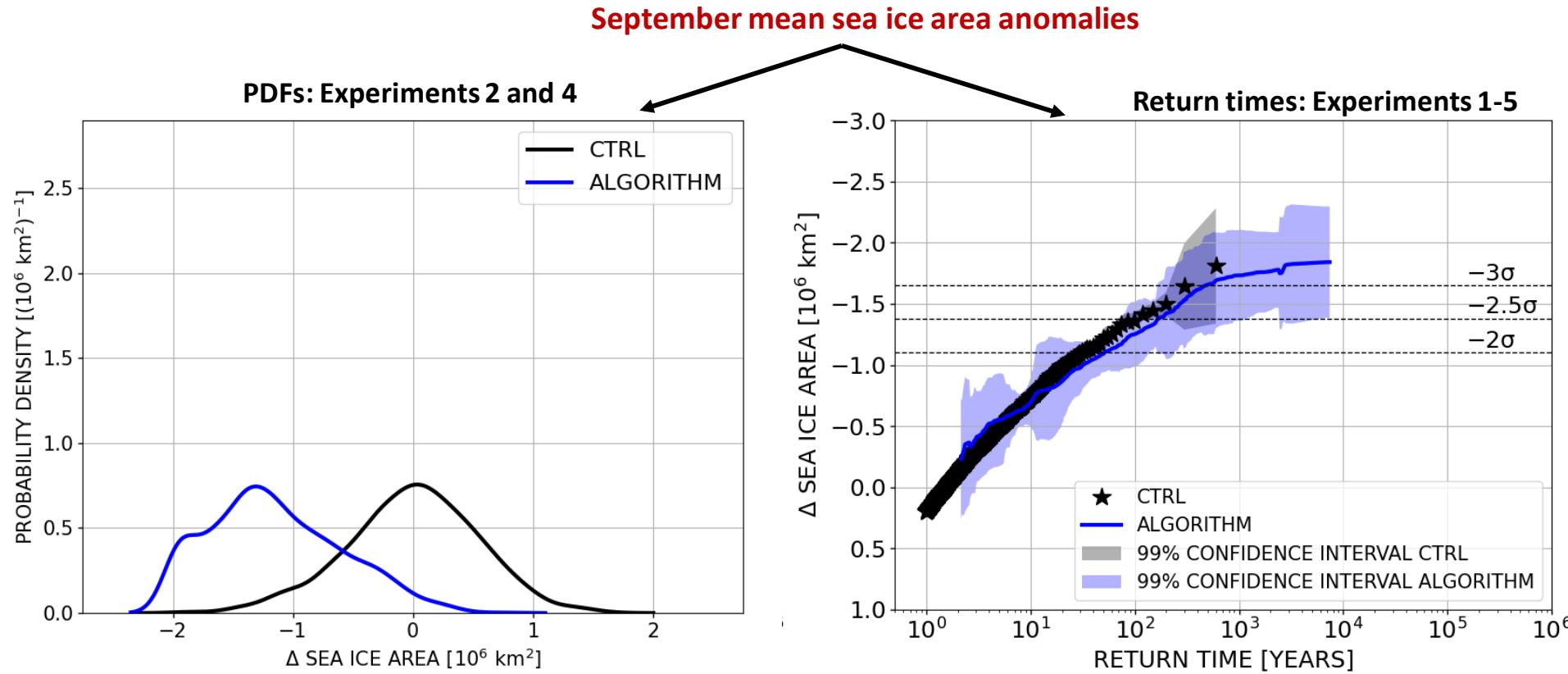
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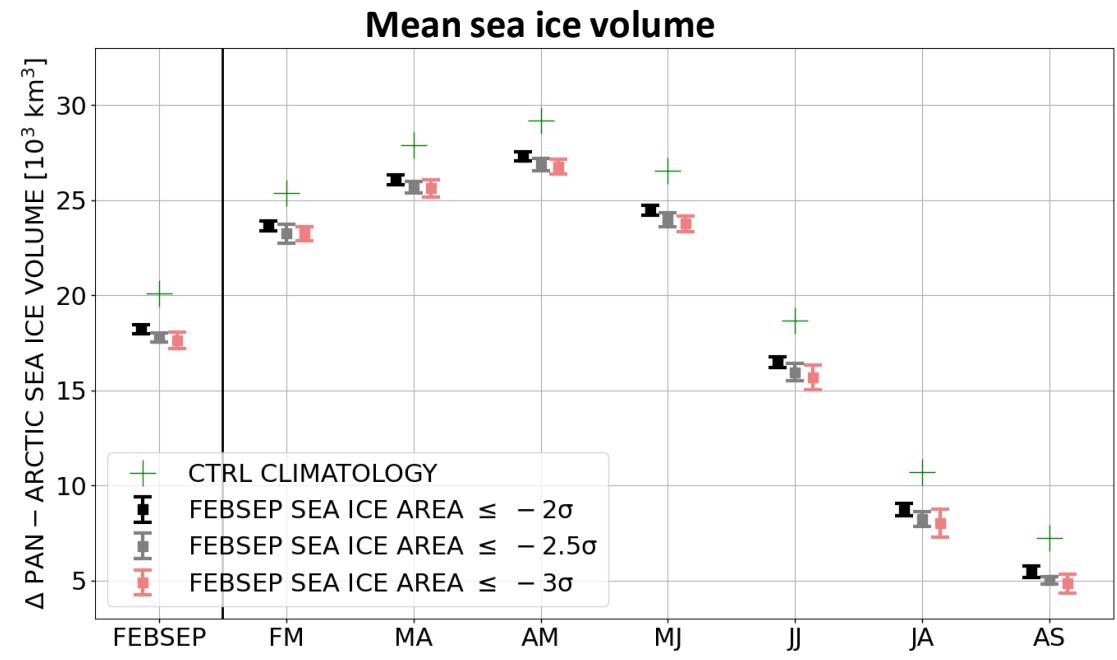
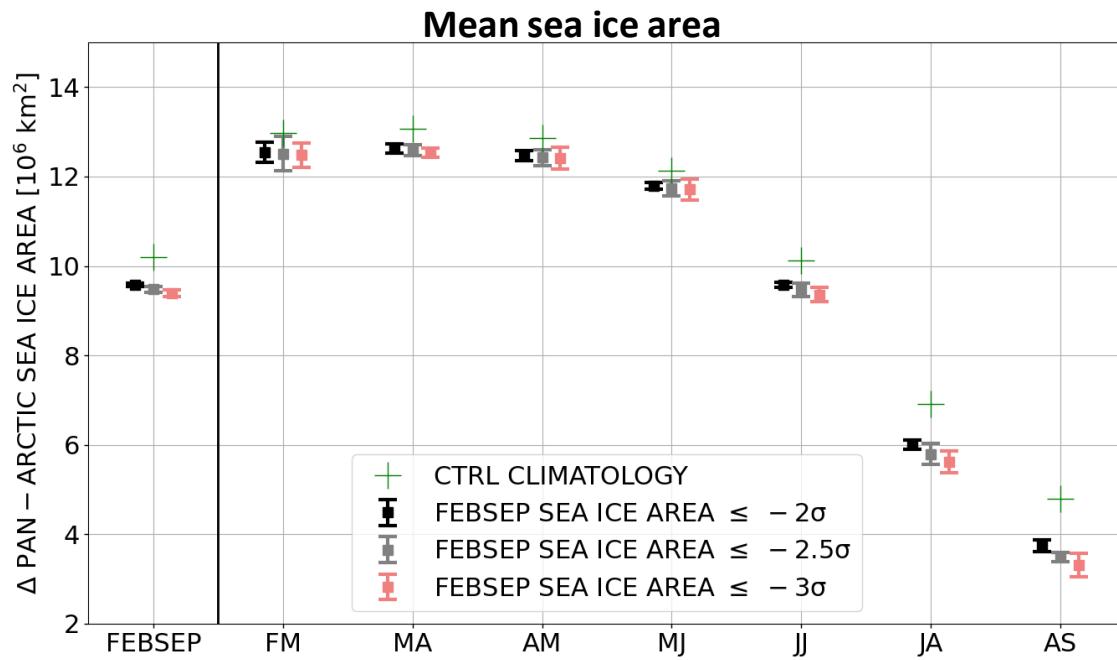
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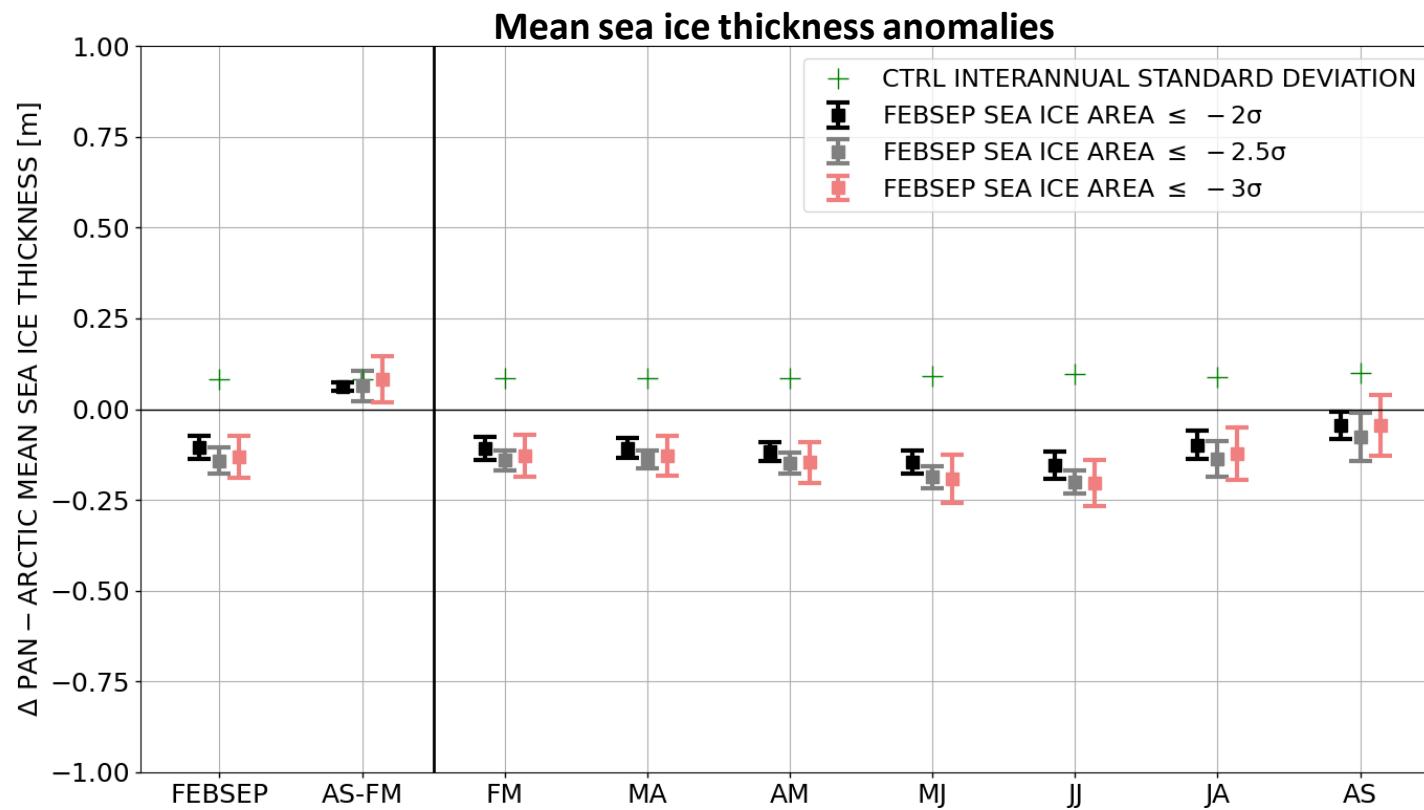


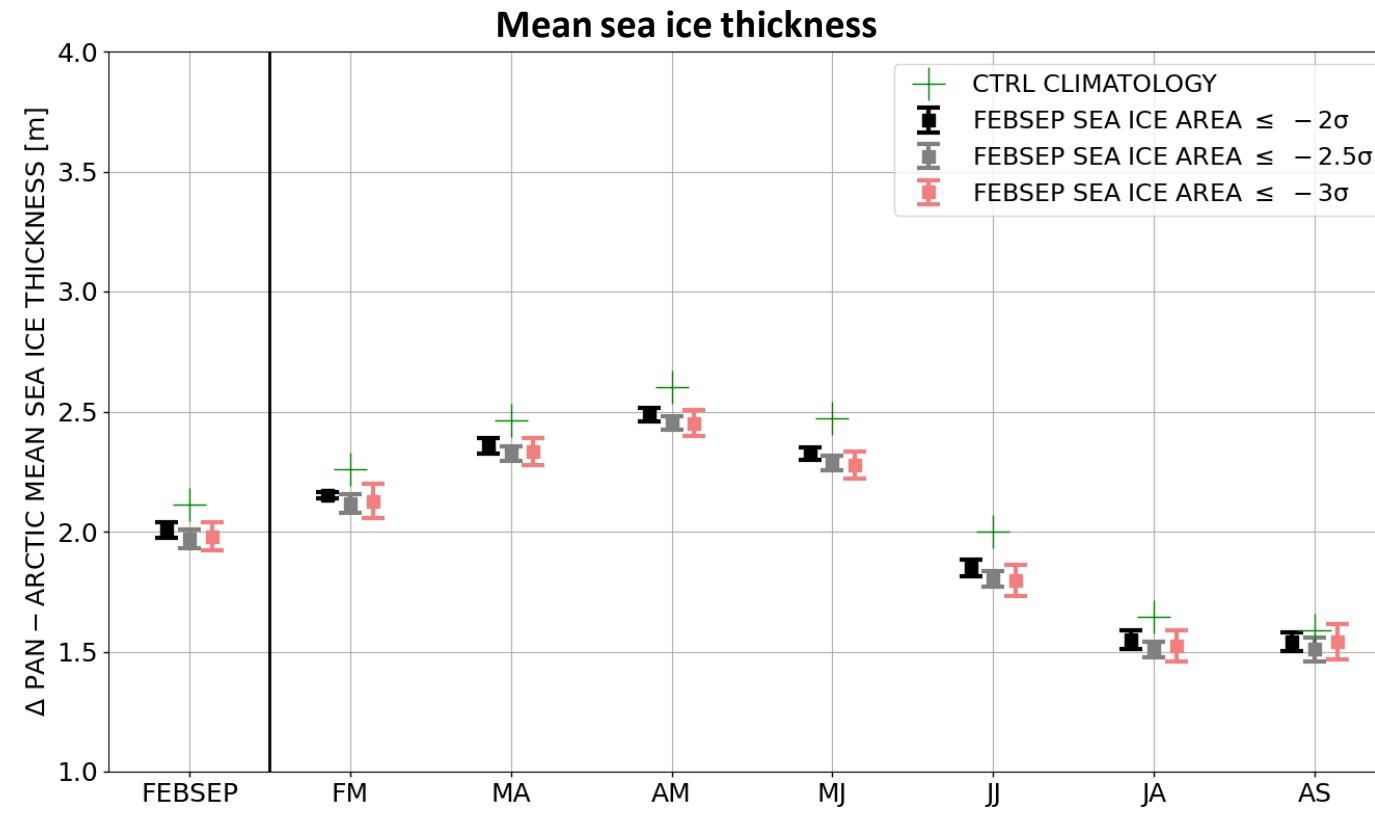
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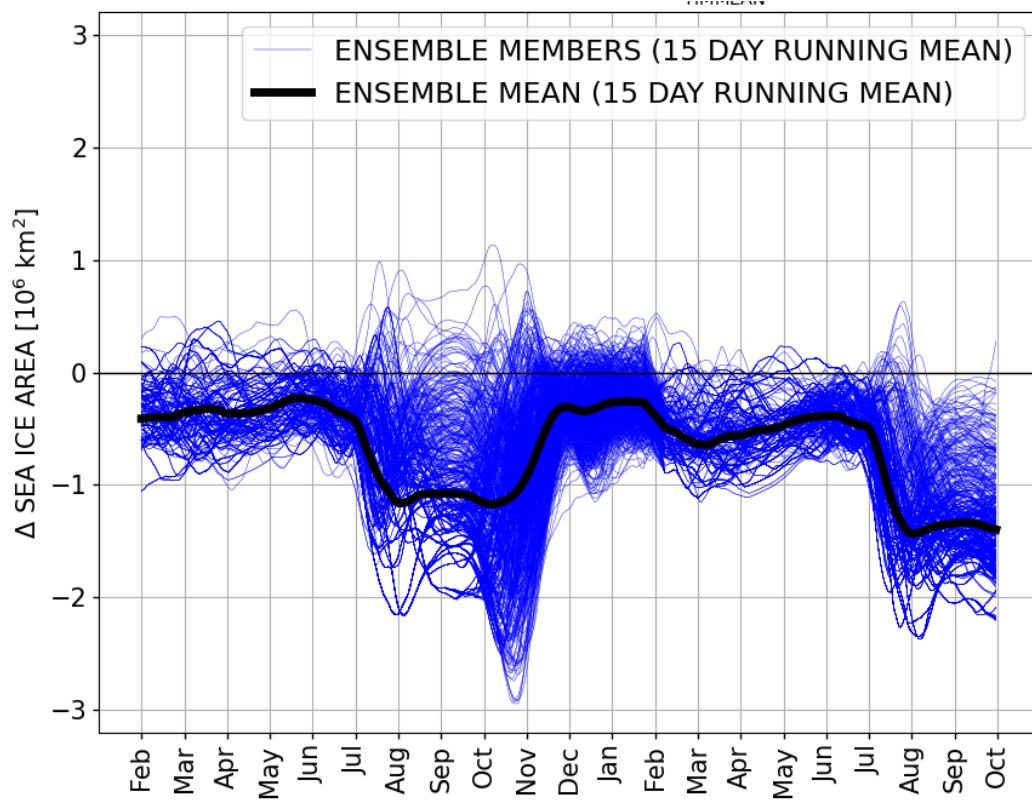
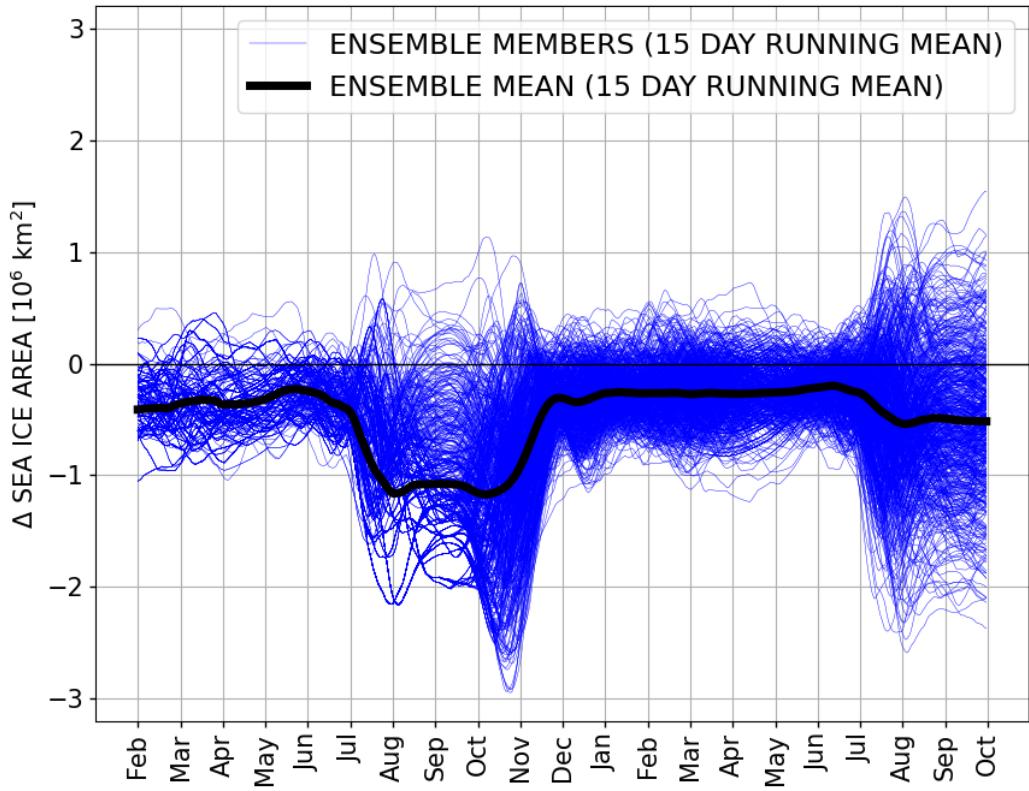
Appendix

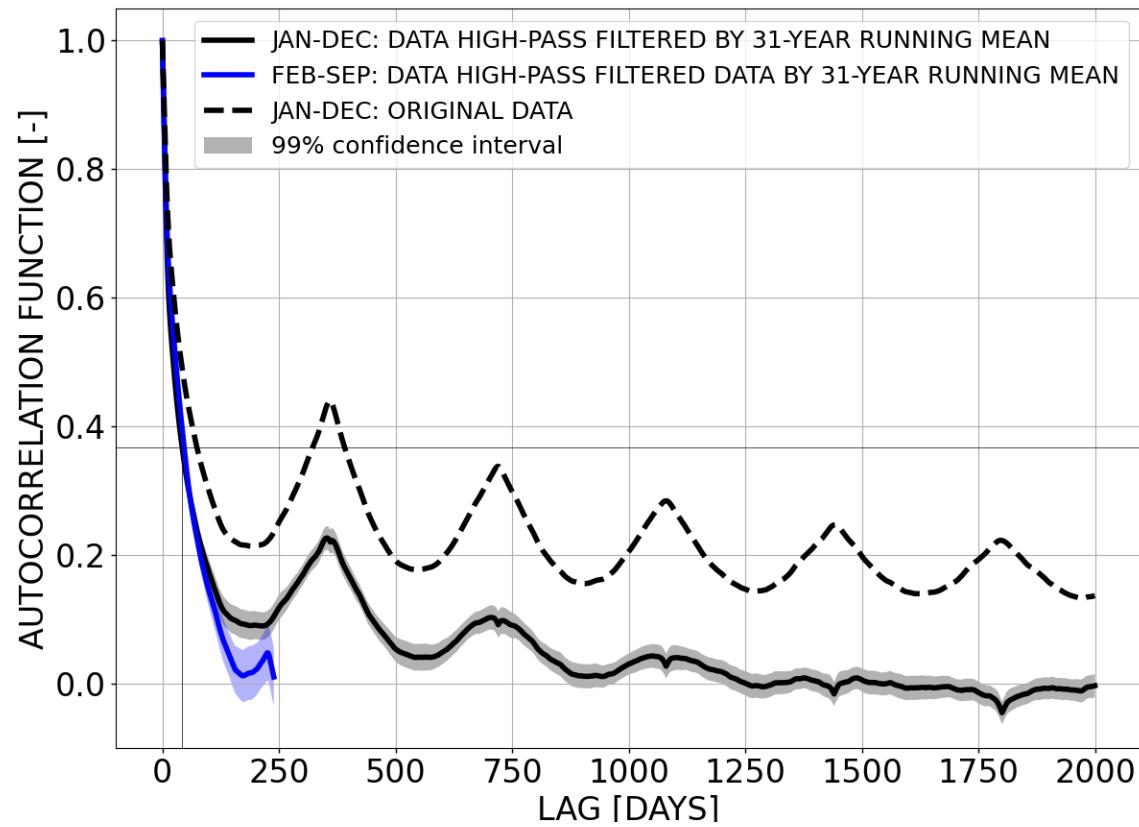


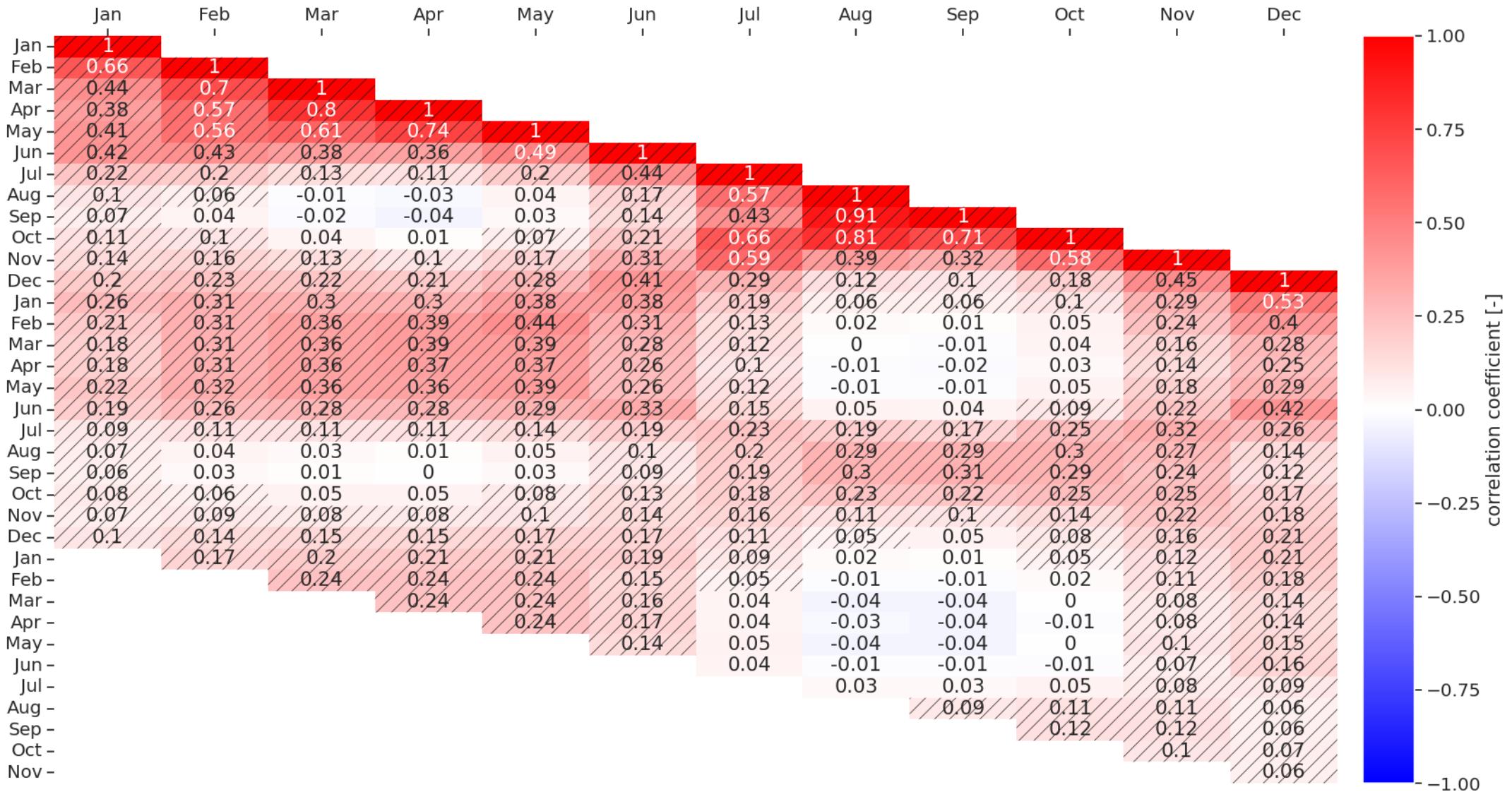


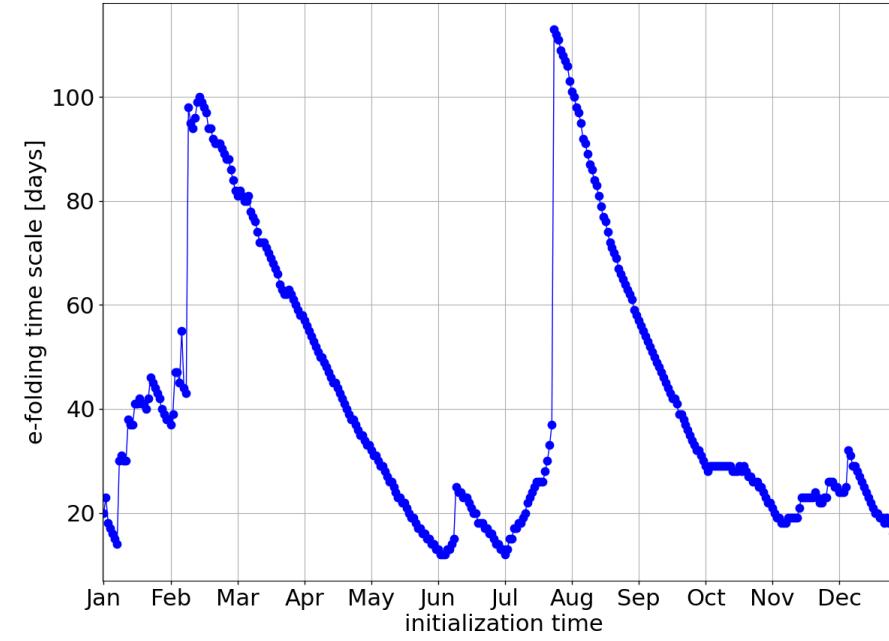
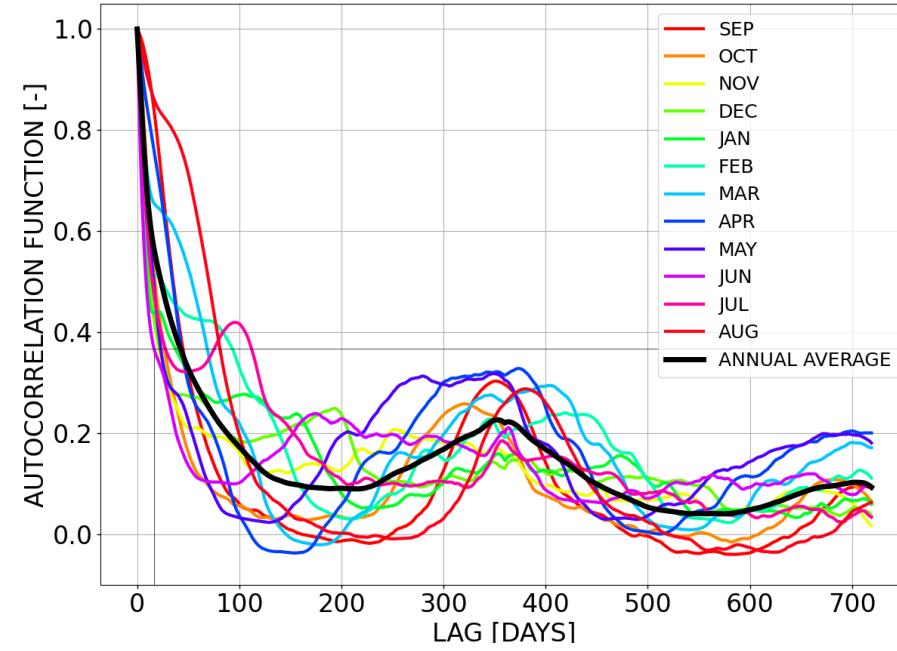


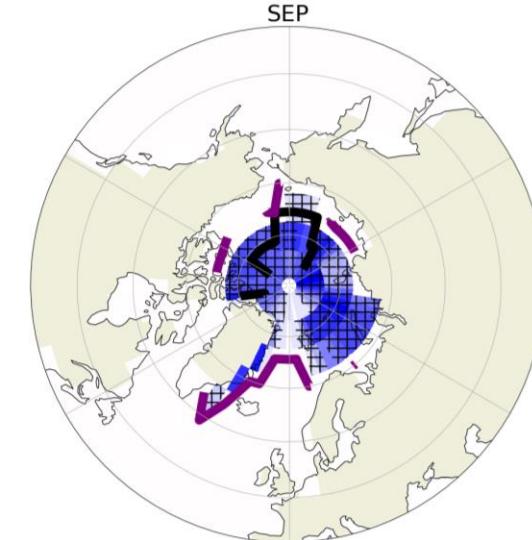
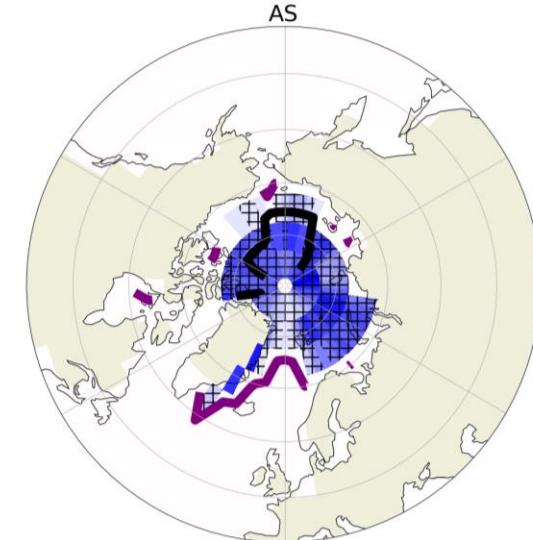
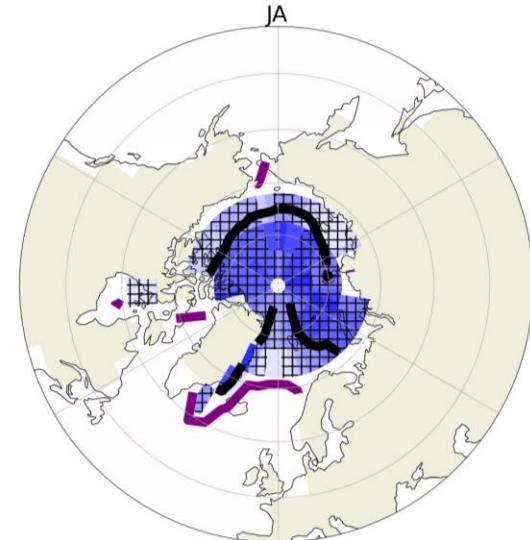
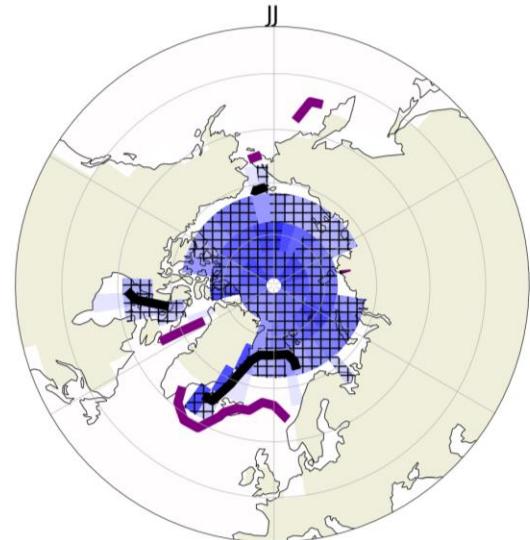
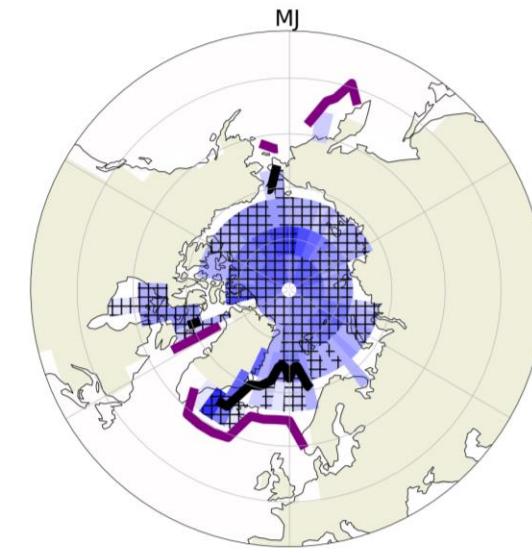
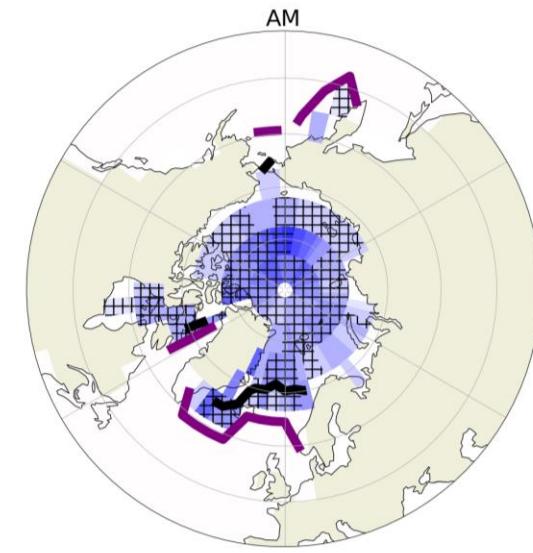
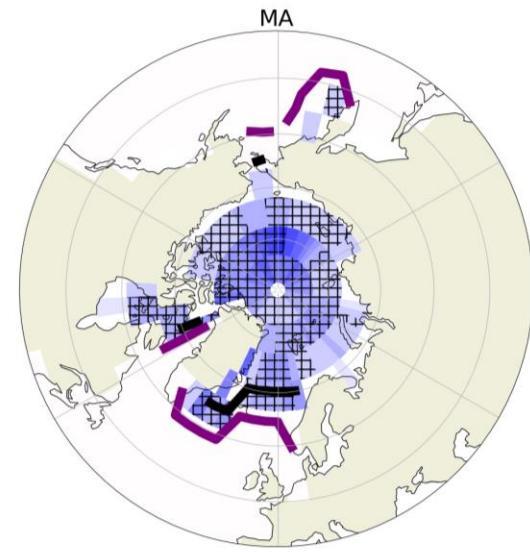
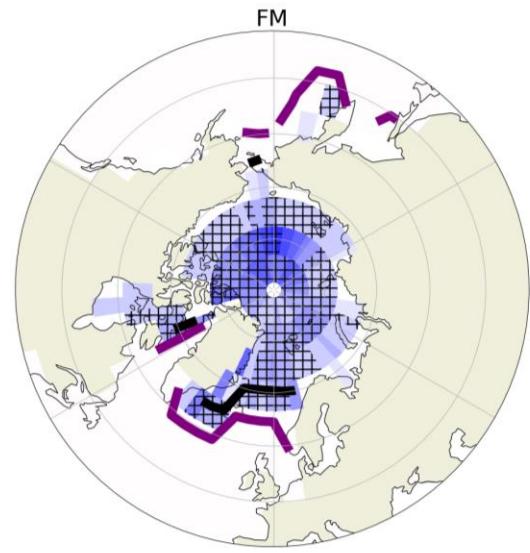


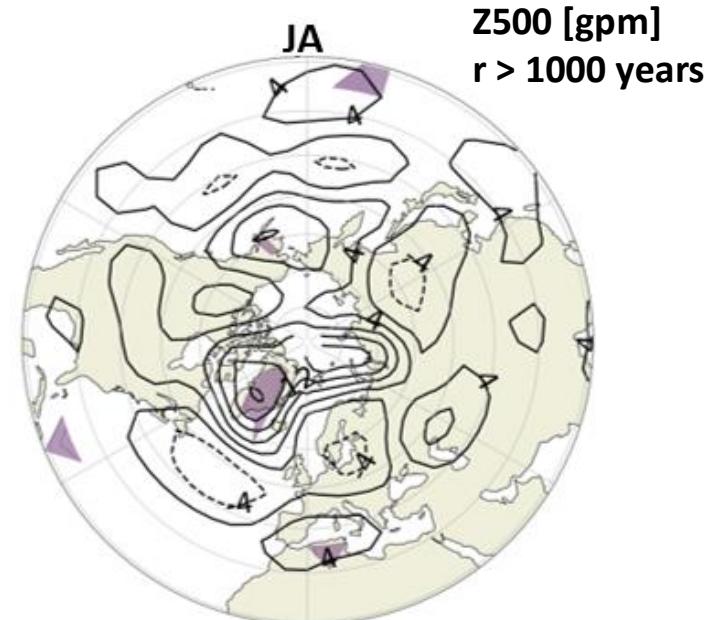
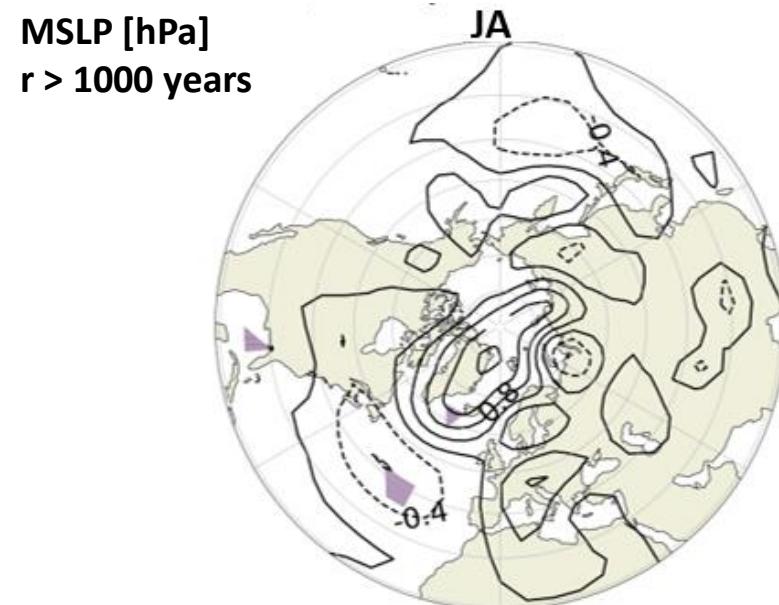
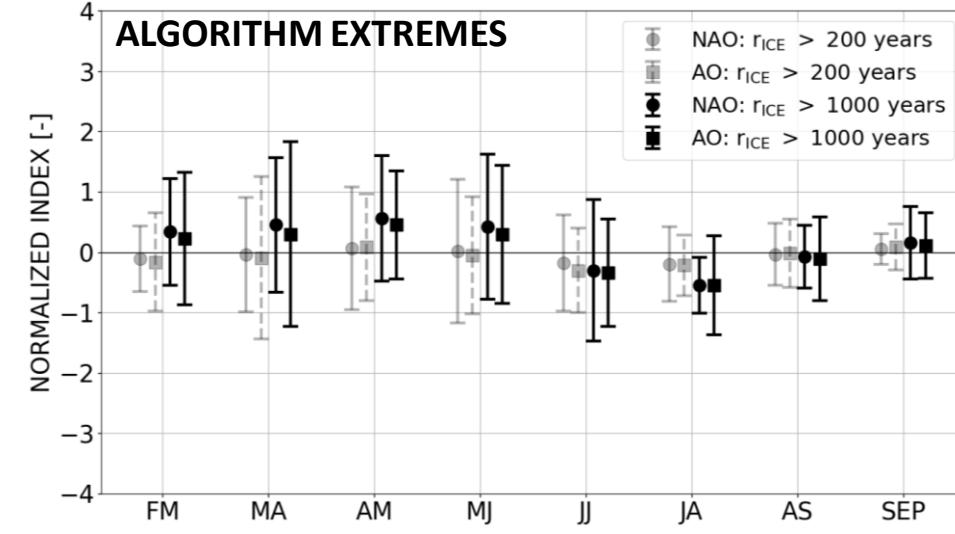
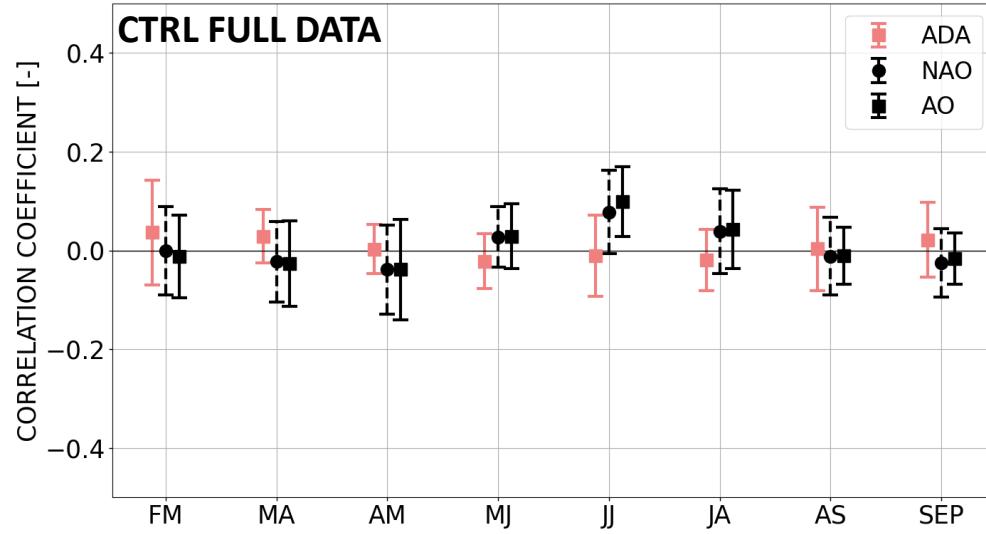






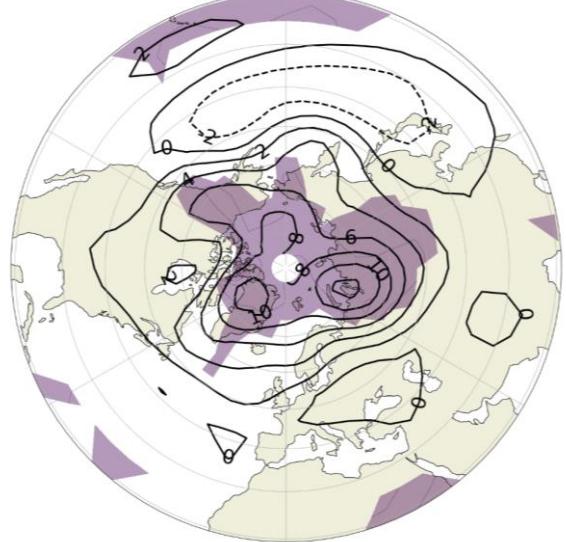




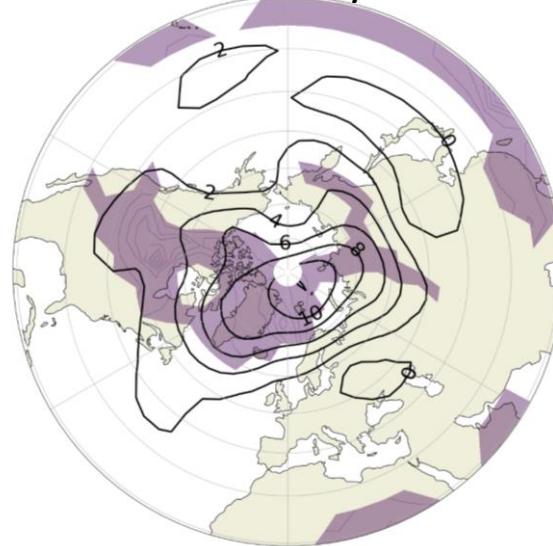


$Z500$ [gpm]

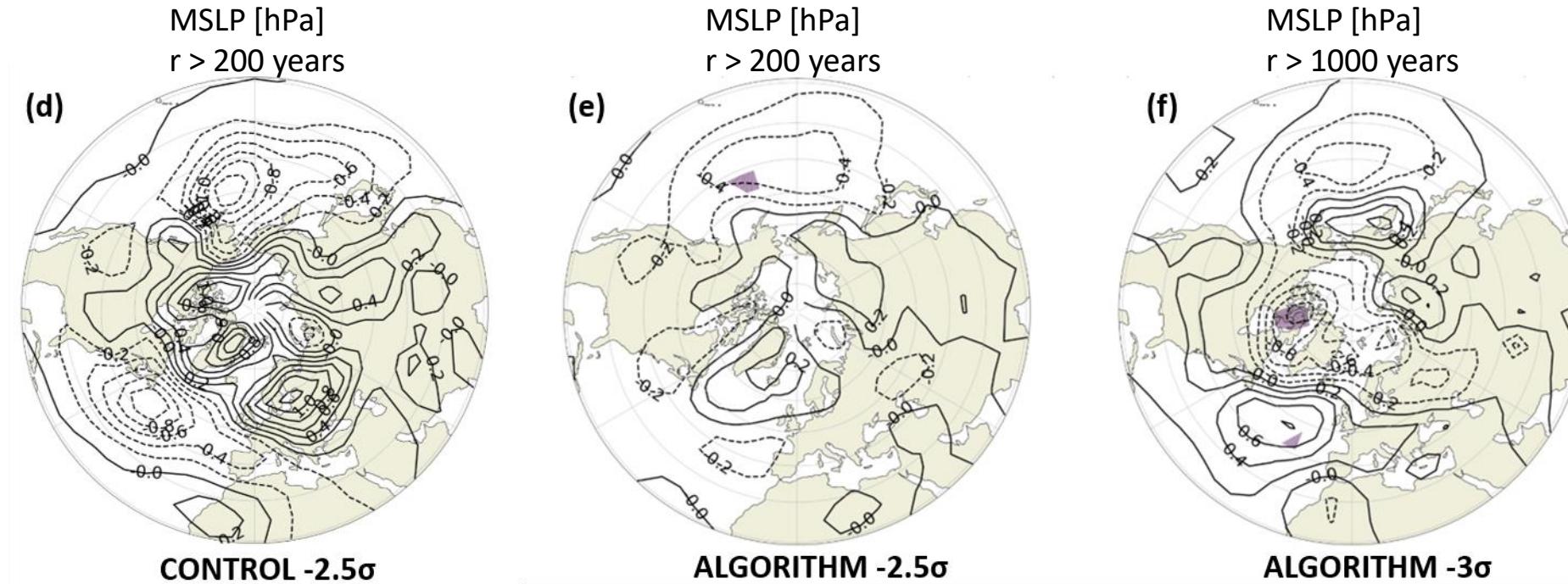
CTRL: $r > 40$ years



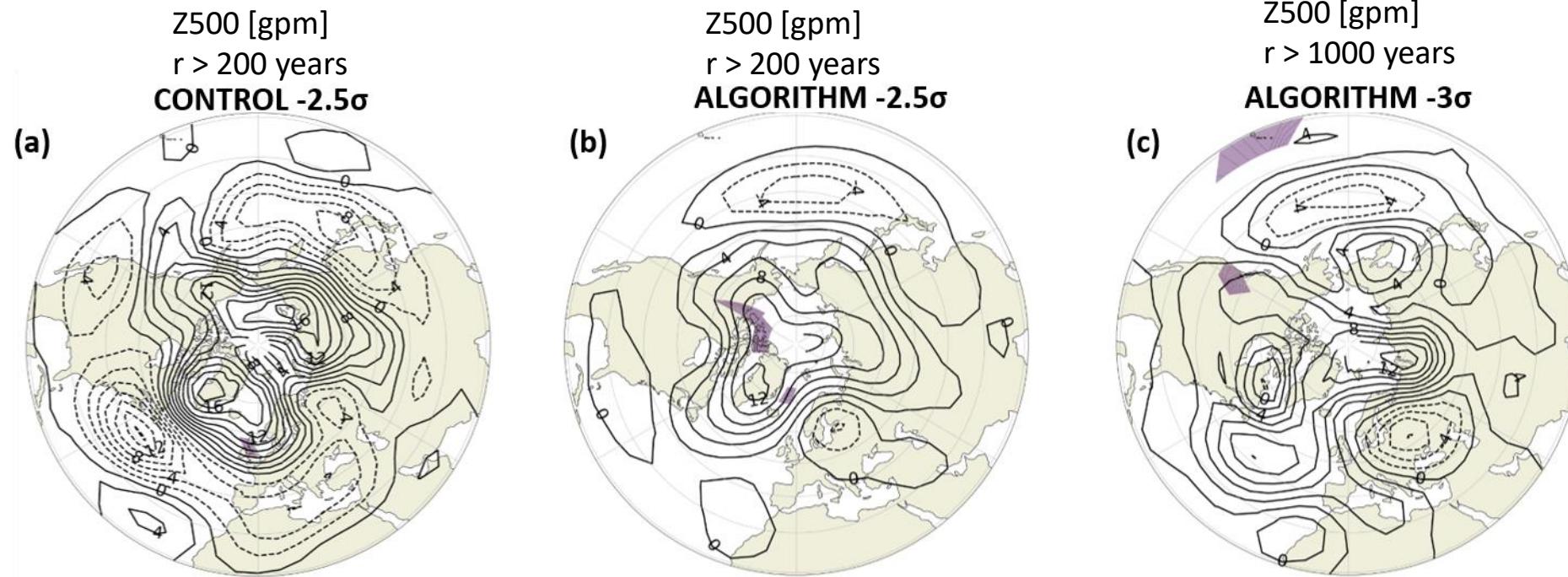
ALG: $r > 40$ years



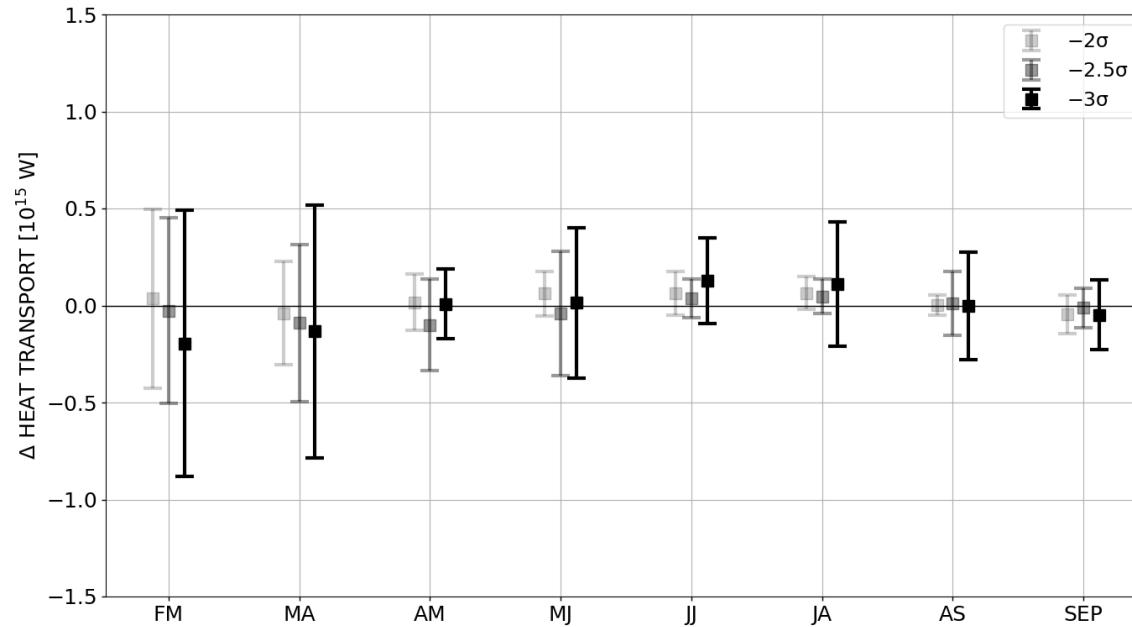
Atmospheric dynamics during extremes of sea ice reduction



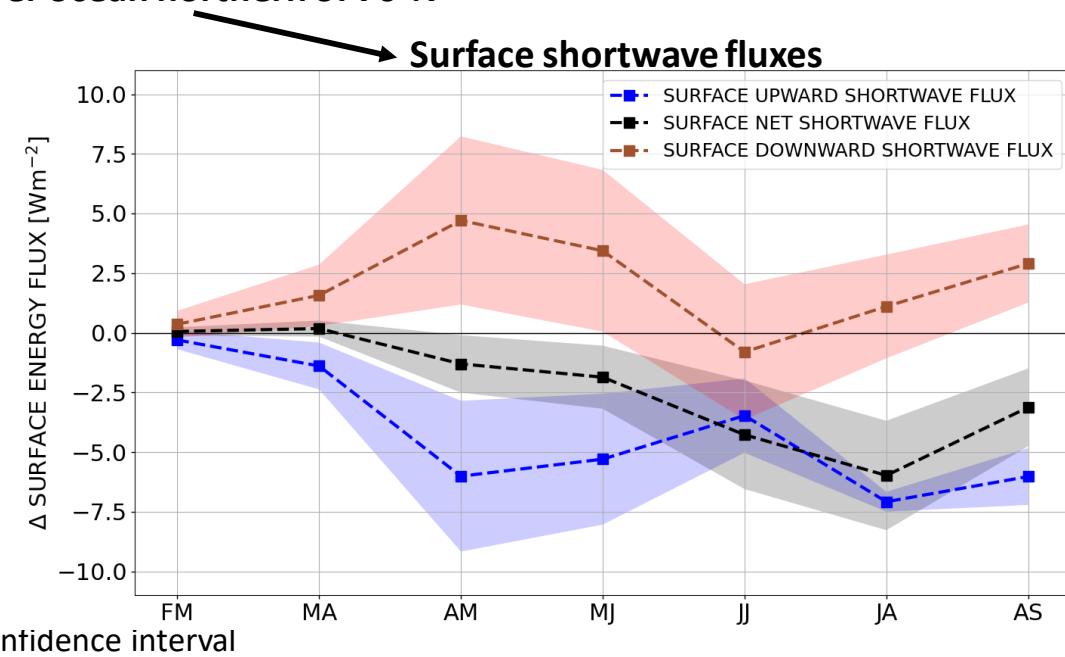
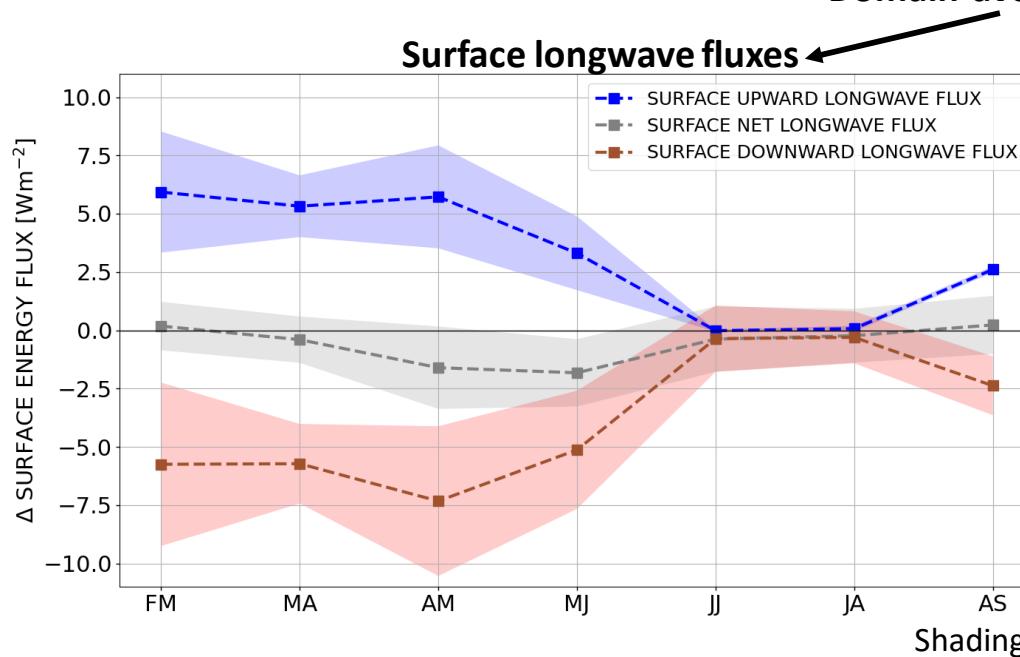
Atmospheric dynamics during extremes of sea ice reduction



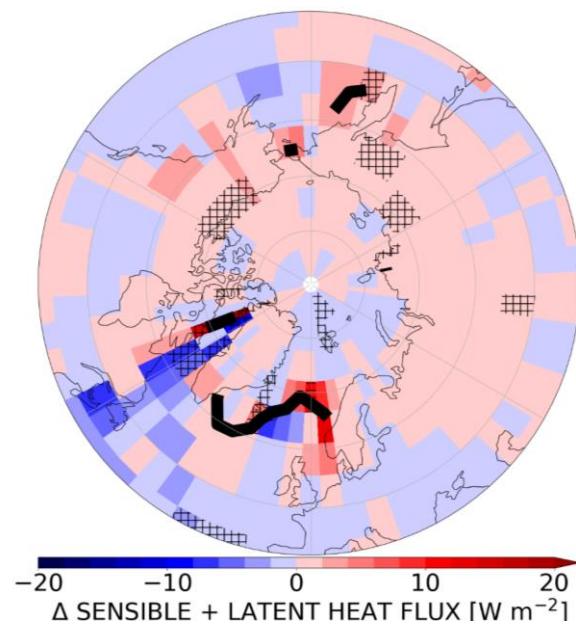
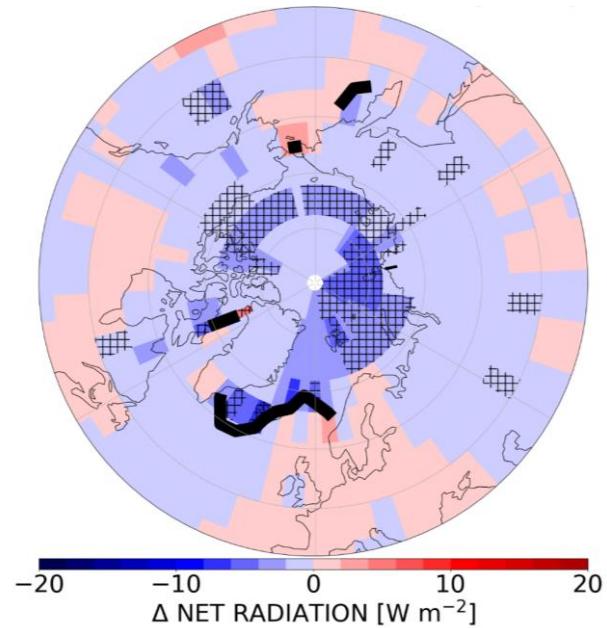
Atmospheric dynamics during extremes of sea ice reduction

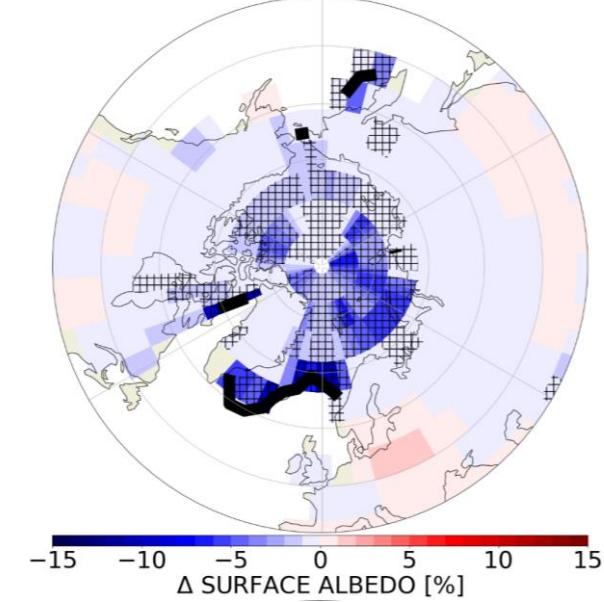
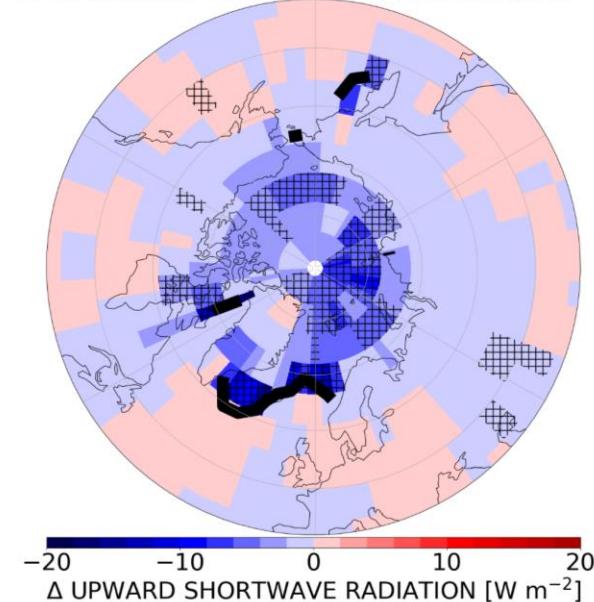
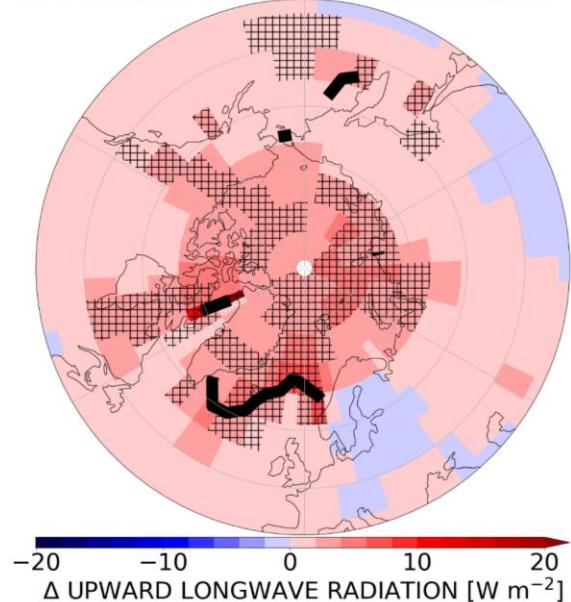
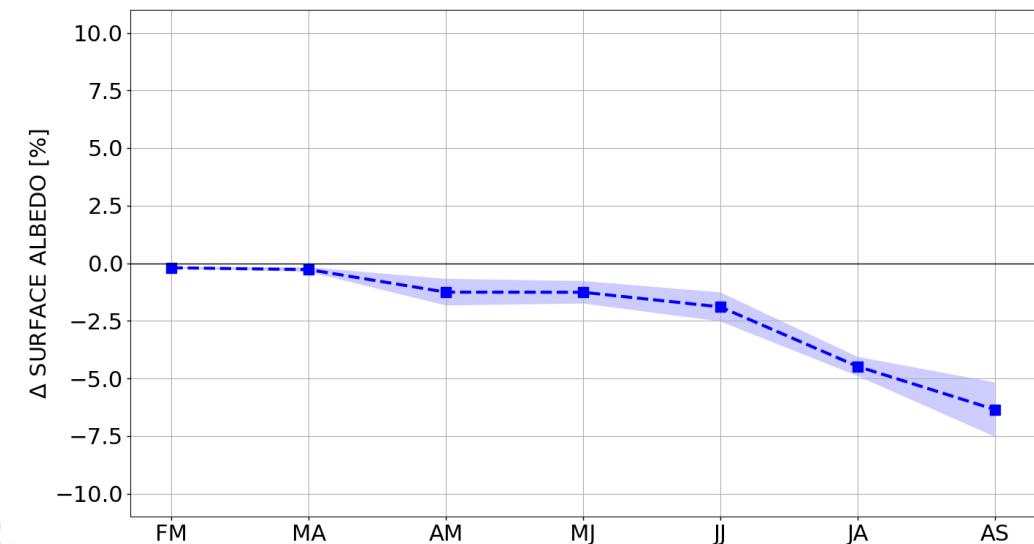
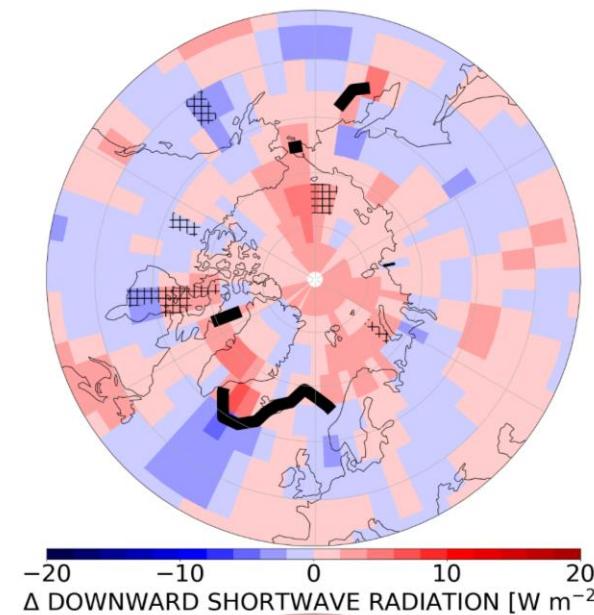
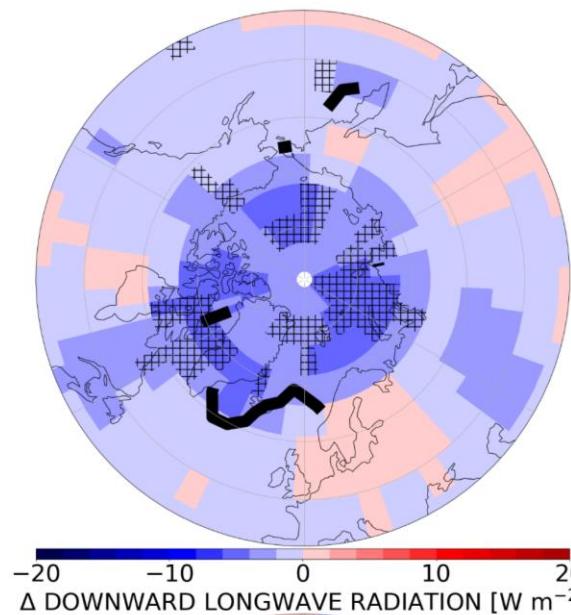


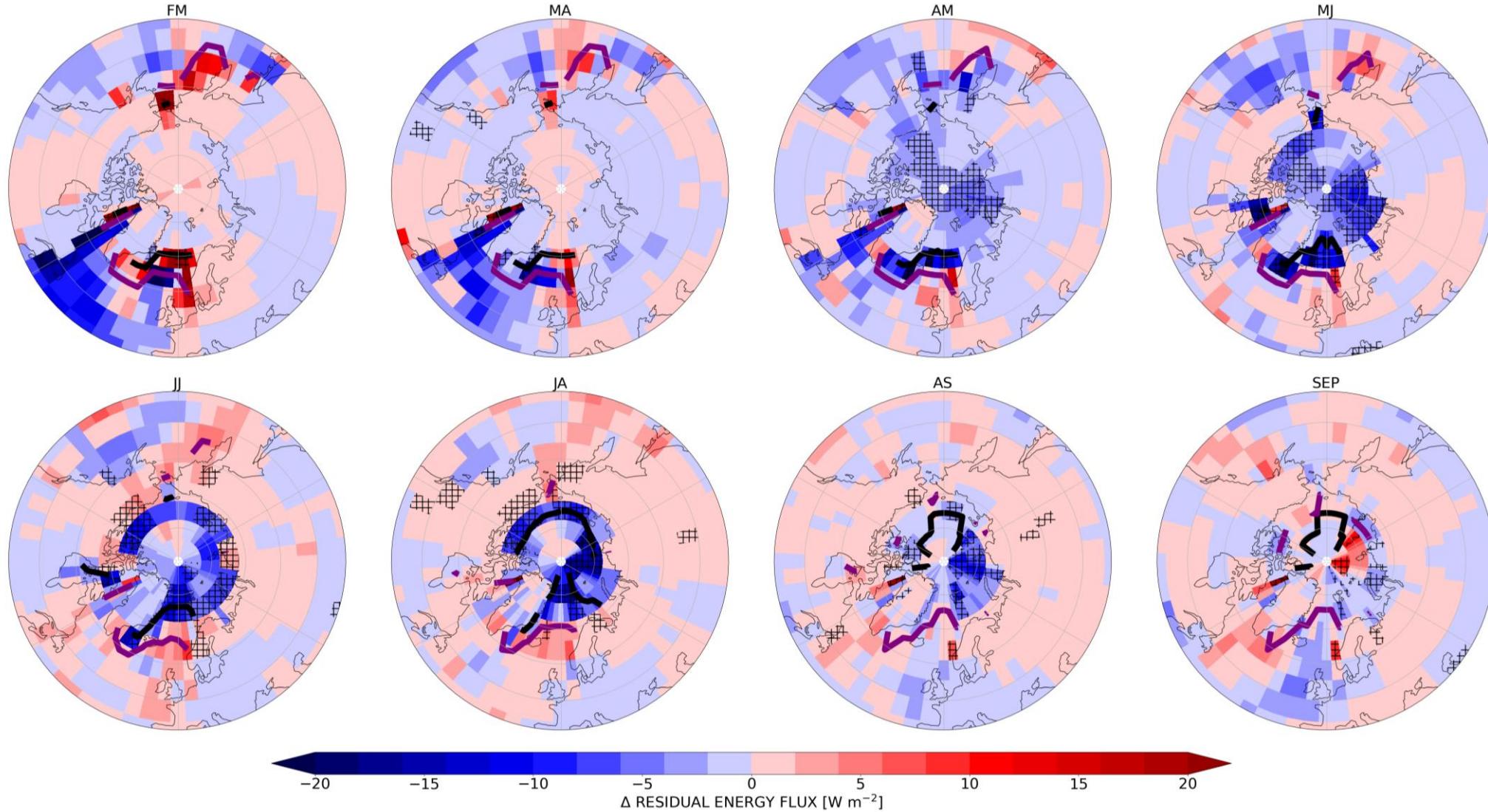
Algorithm: $r > 200$ years
February-September and bimonthly means
Domain-average over ocean northern of 70°N

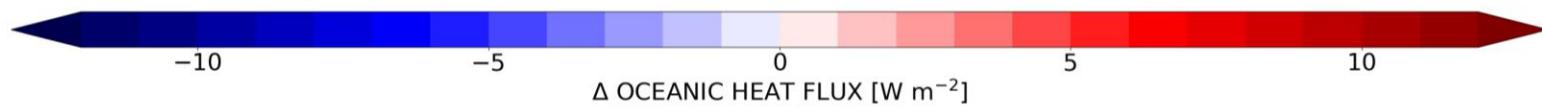
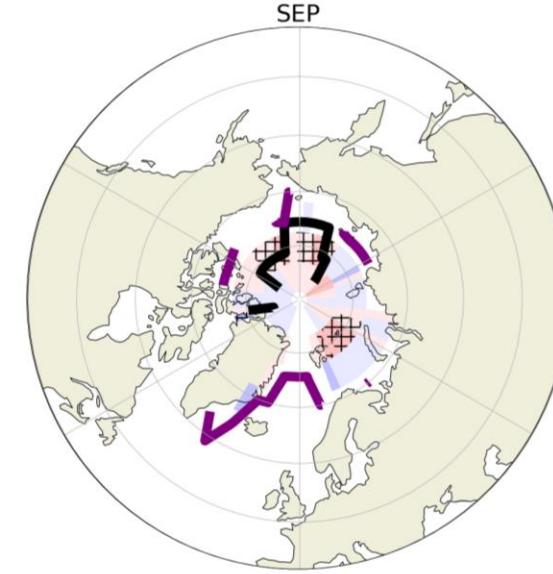
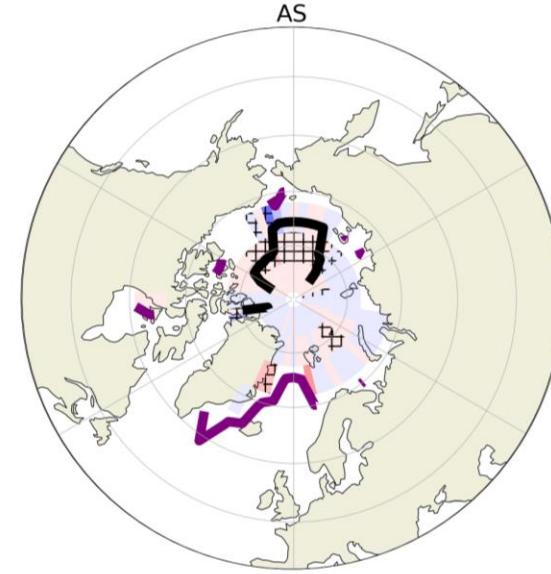
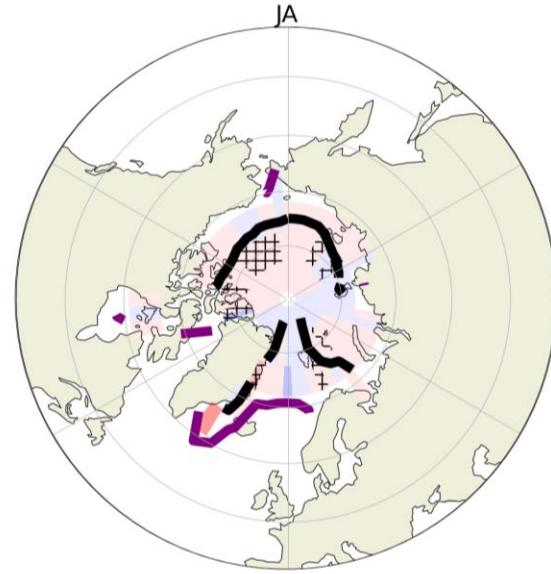
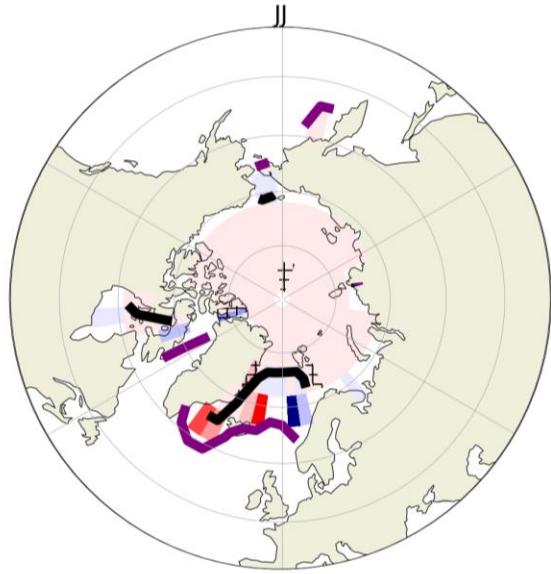
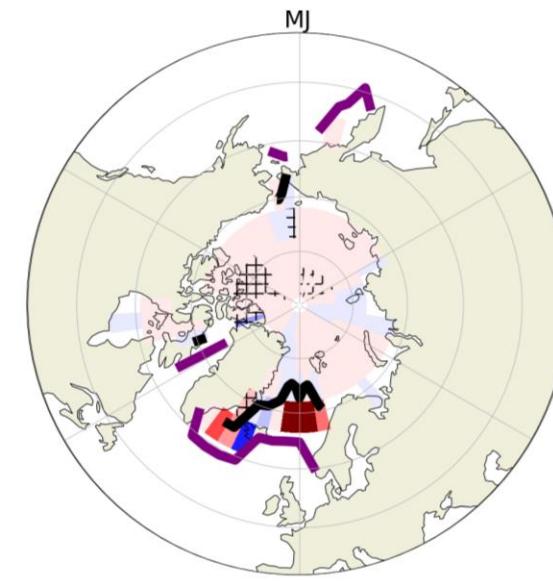
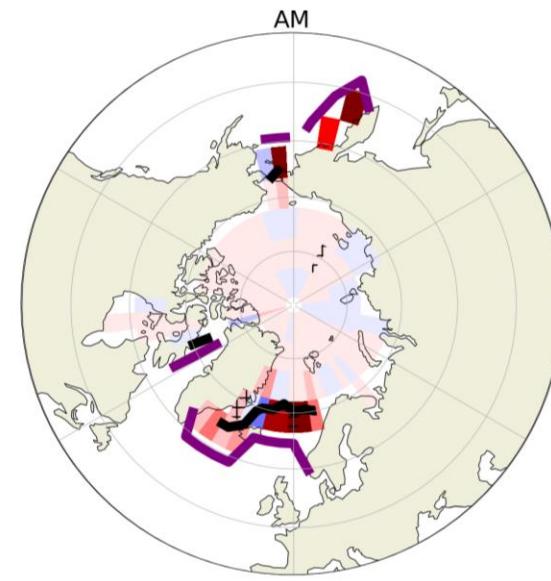
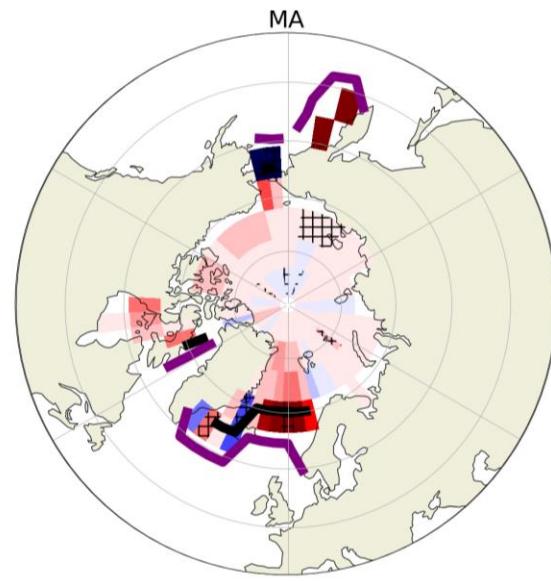
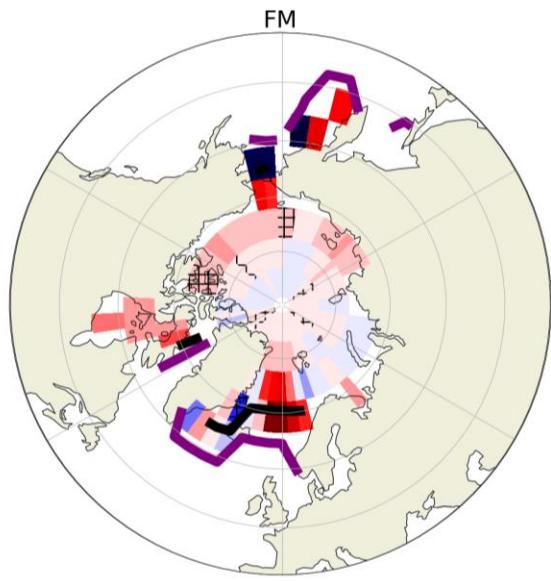


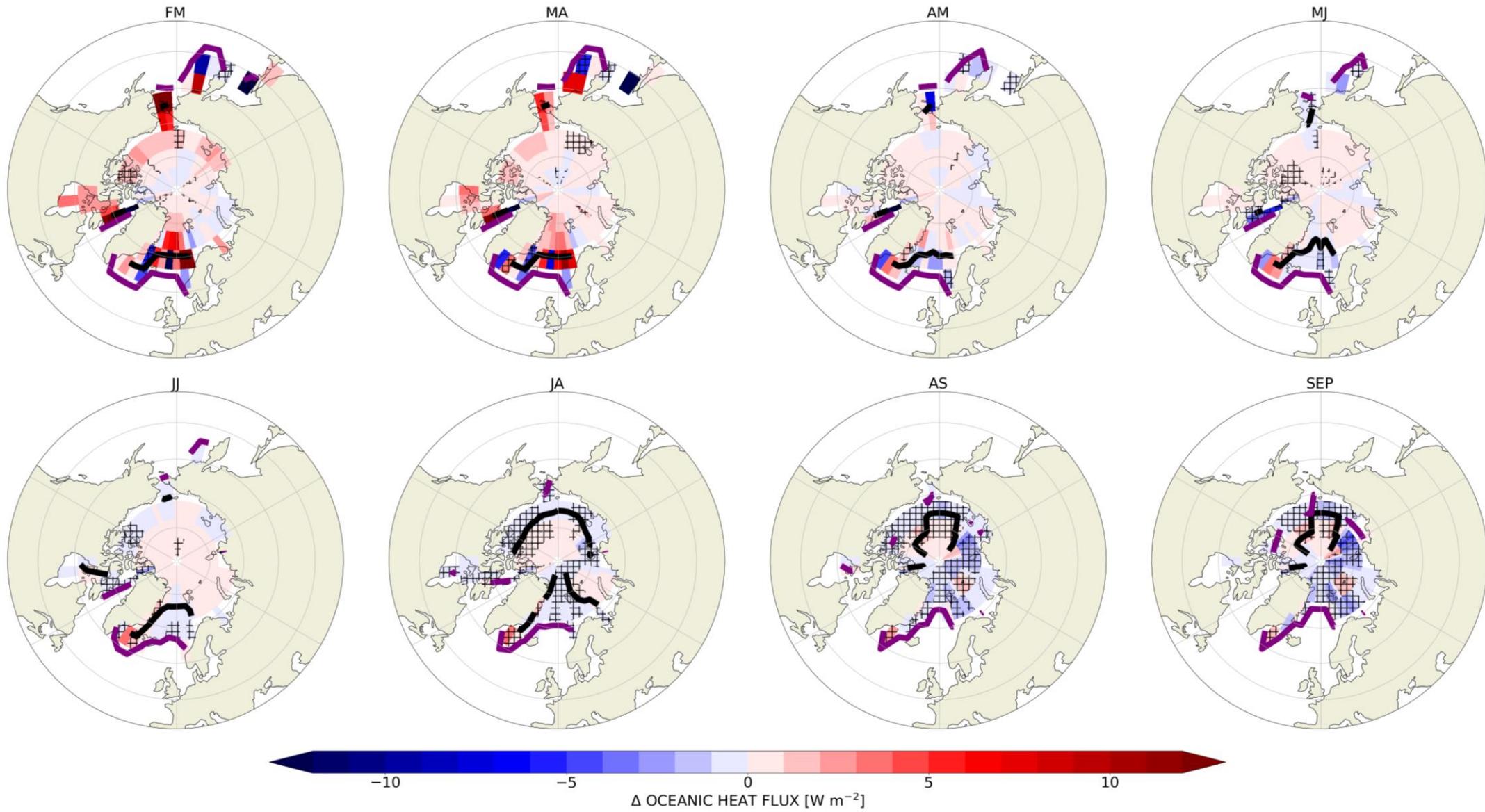
- Largely balance between enhanced upward and downward longwave radiation
- Reduced downward shortwave flux in spring and late summer suggests enhanced cloudiness
- Stronger reduction in upward than downward solar radiative flux: sea ice-albedo feedback

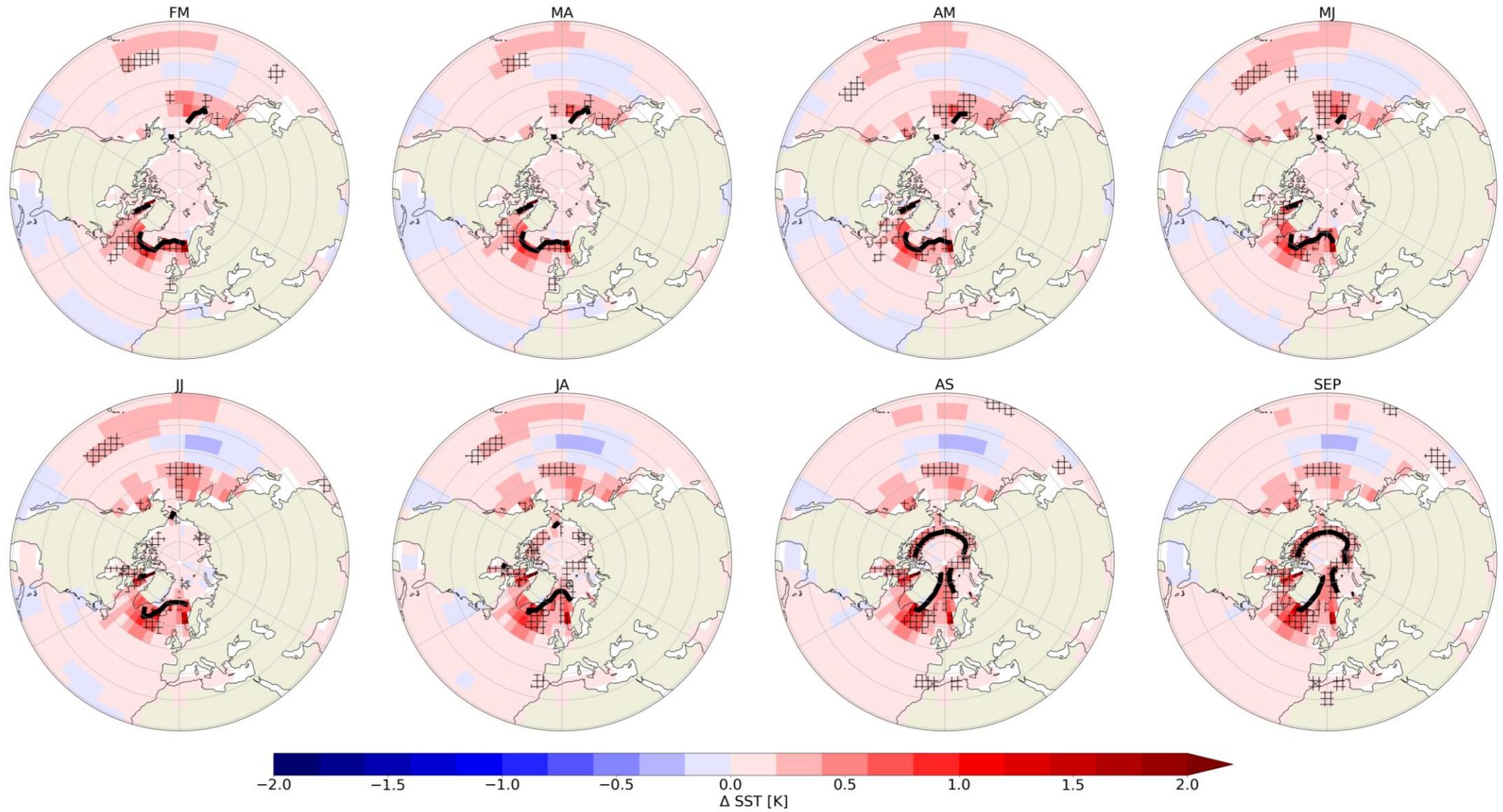


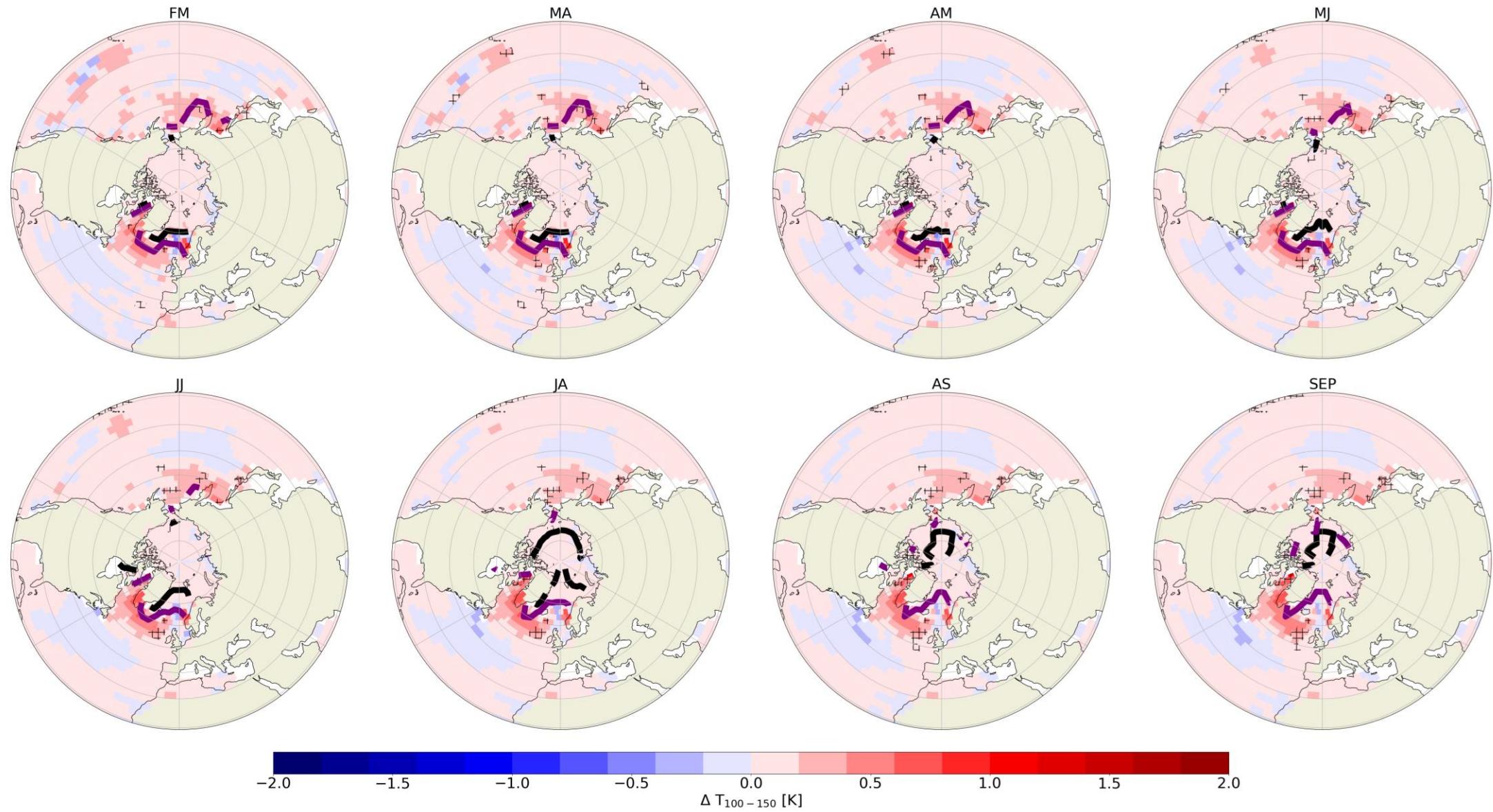










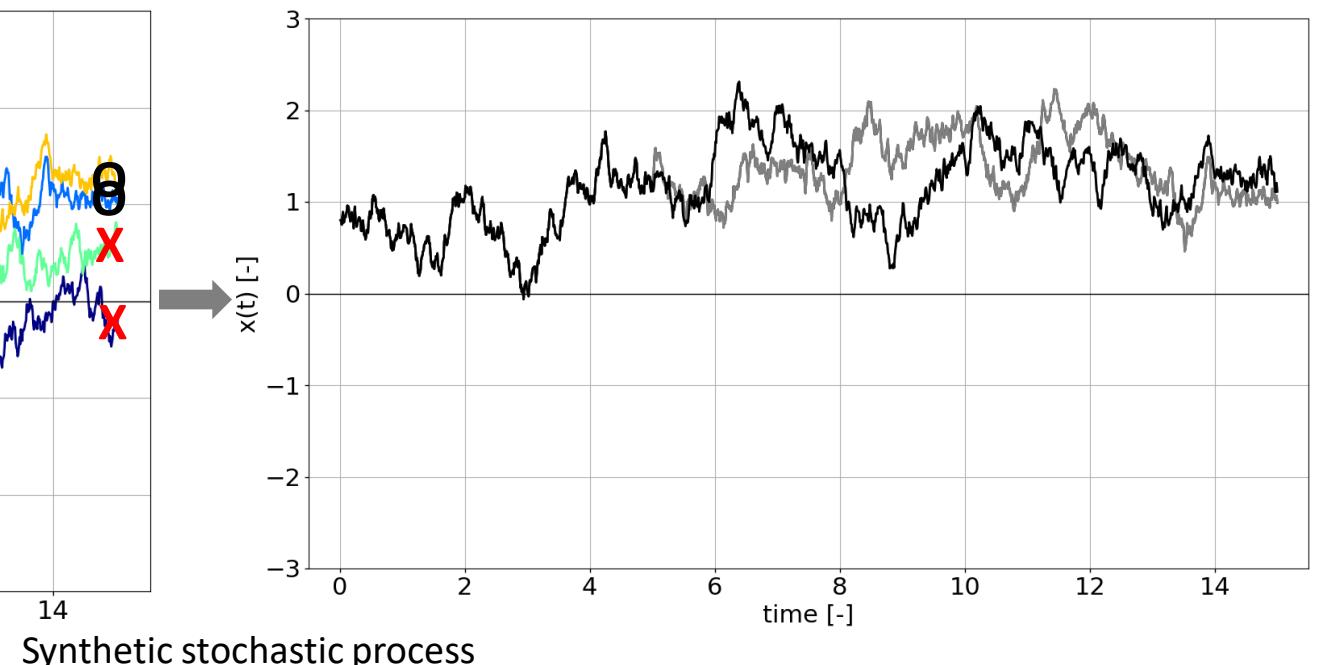
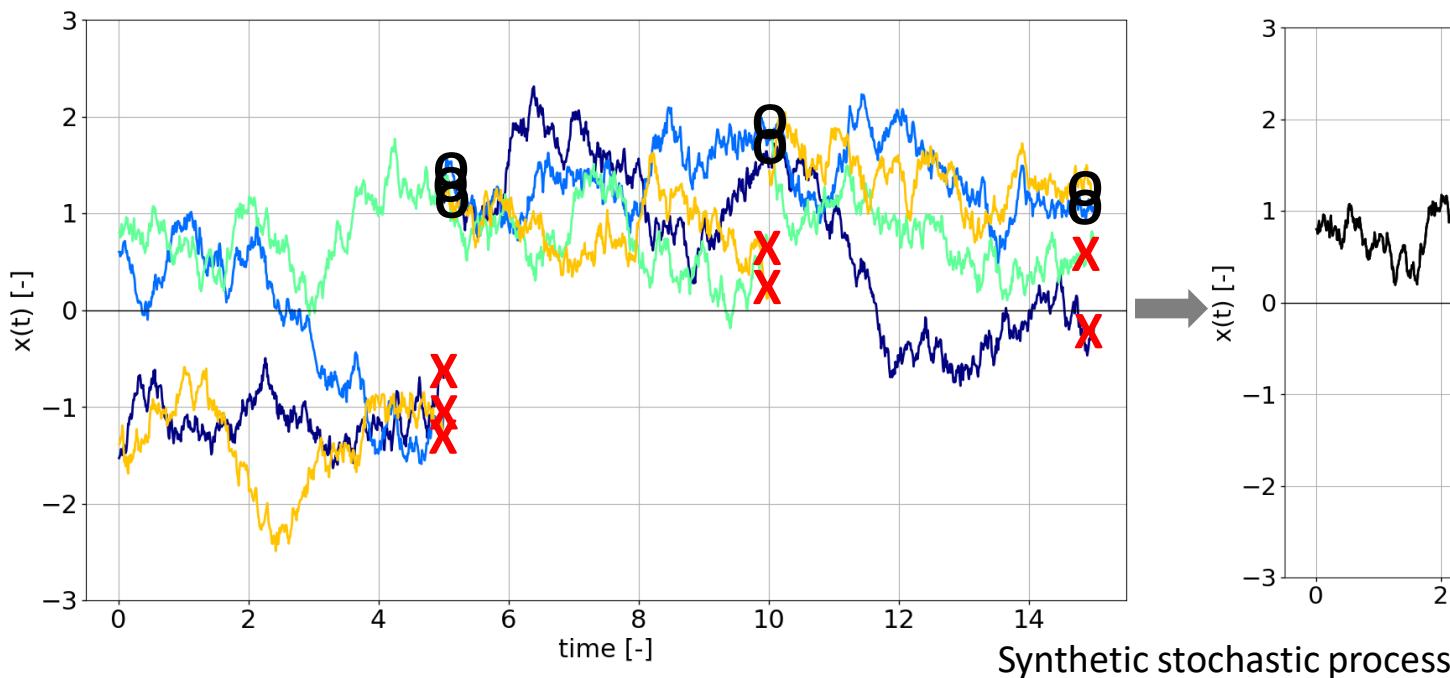


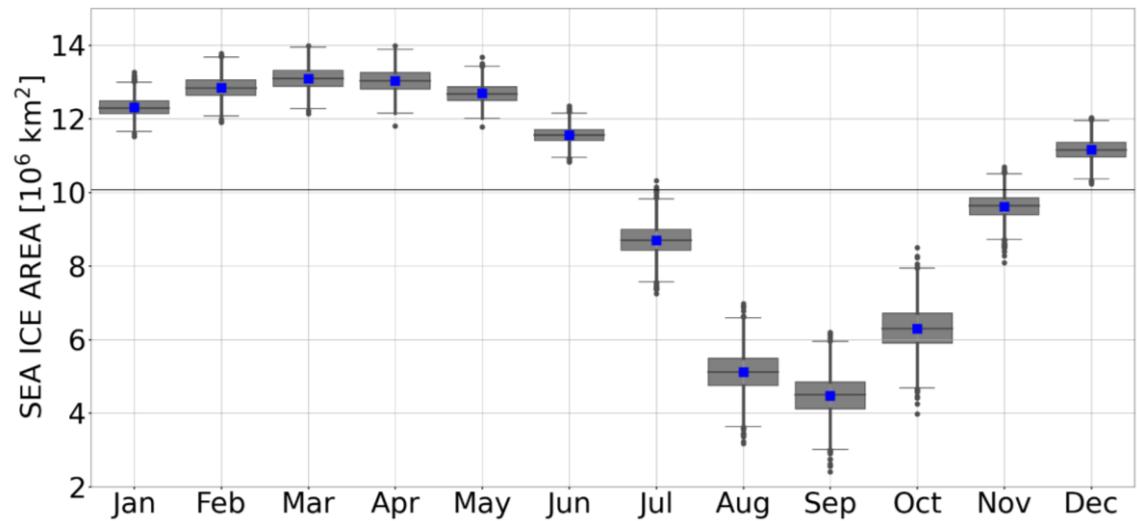
Methodology: Rare event algorithm

- Run N trajectories $\{X_n(t)\}$ ($n = 1, 2, \dots, N$) for total simulation time T_a and define **resampling time** τ_r
- At times $t_i = i\tau_r$ ($i = 1, \dots, \frac{T_a}{\tau_r}$), each trajectory generates a number of copies of itself given by **weights**:

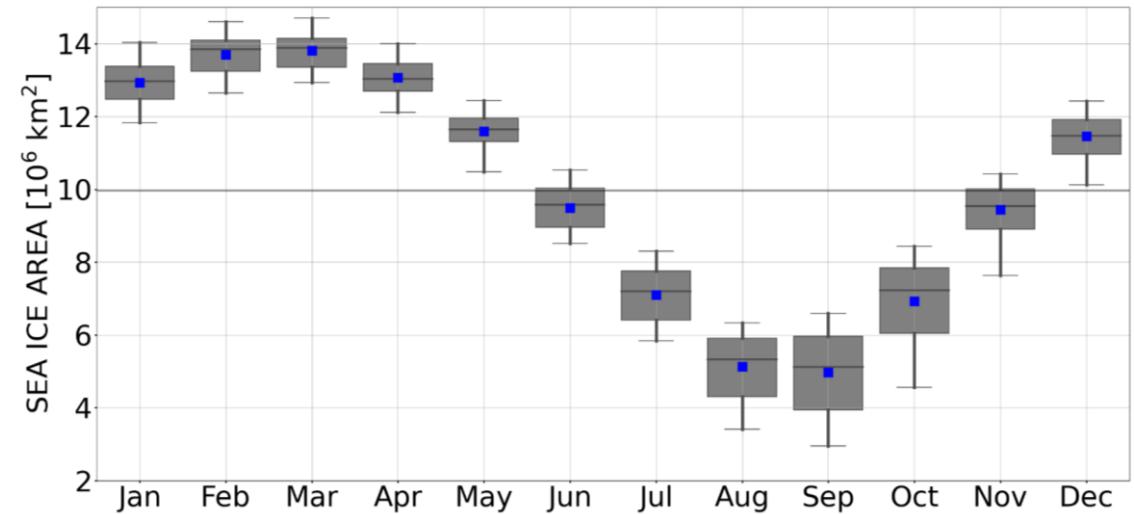
$$w_{n,i} = \frac{e^{k \int_{t_{i-1}}^{t_i} A(\{X_n(t)\}) dt}}{R_i}, \quad R_i = \frac{1}{N} \sum_{n=1}^N e^{k \int_{t_{i-1}}^{t_i} A(\{X_n(t)\}) dt}$$

with k **control parameter** and $A(\{X_n(t)\})$ **observable**

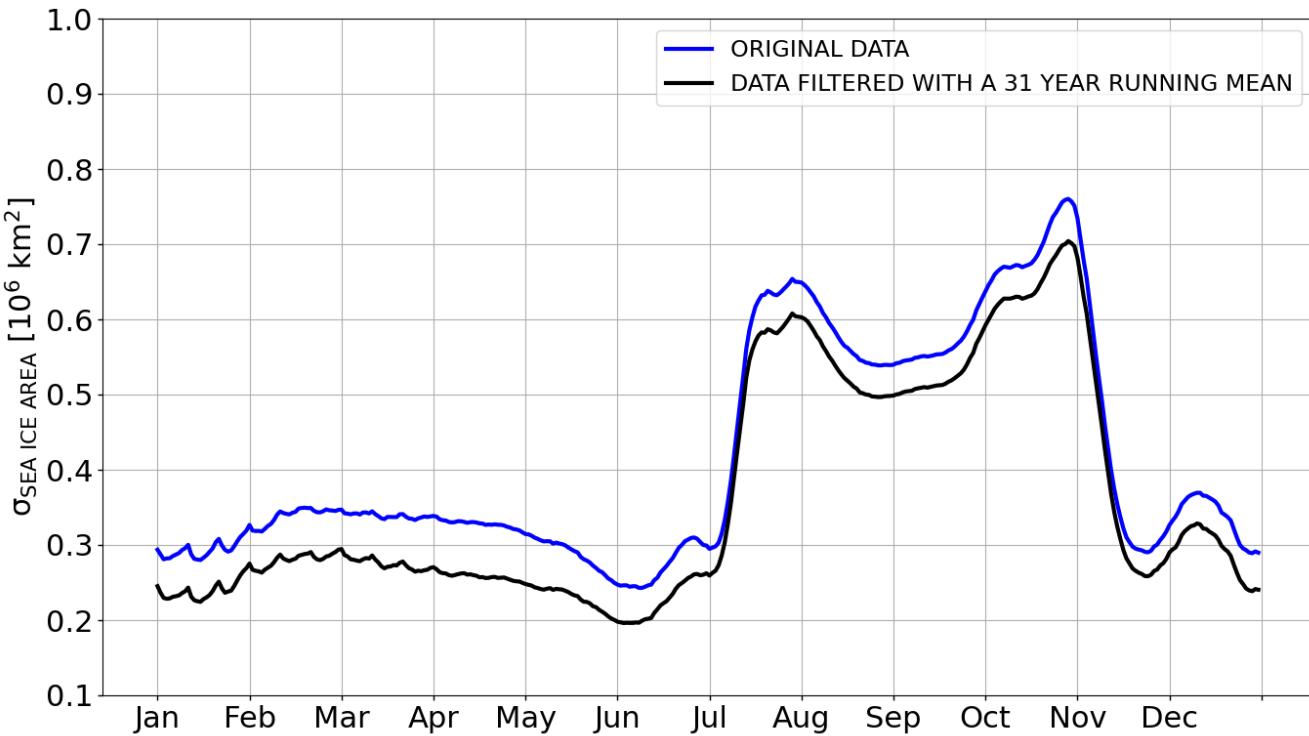


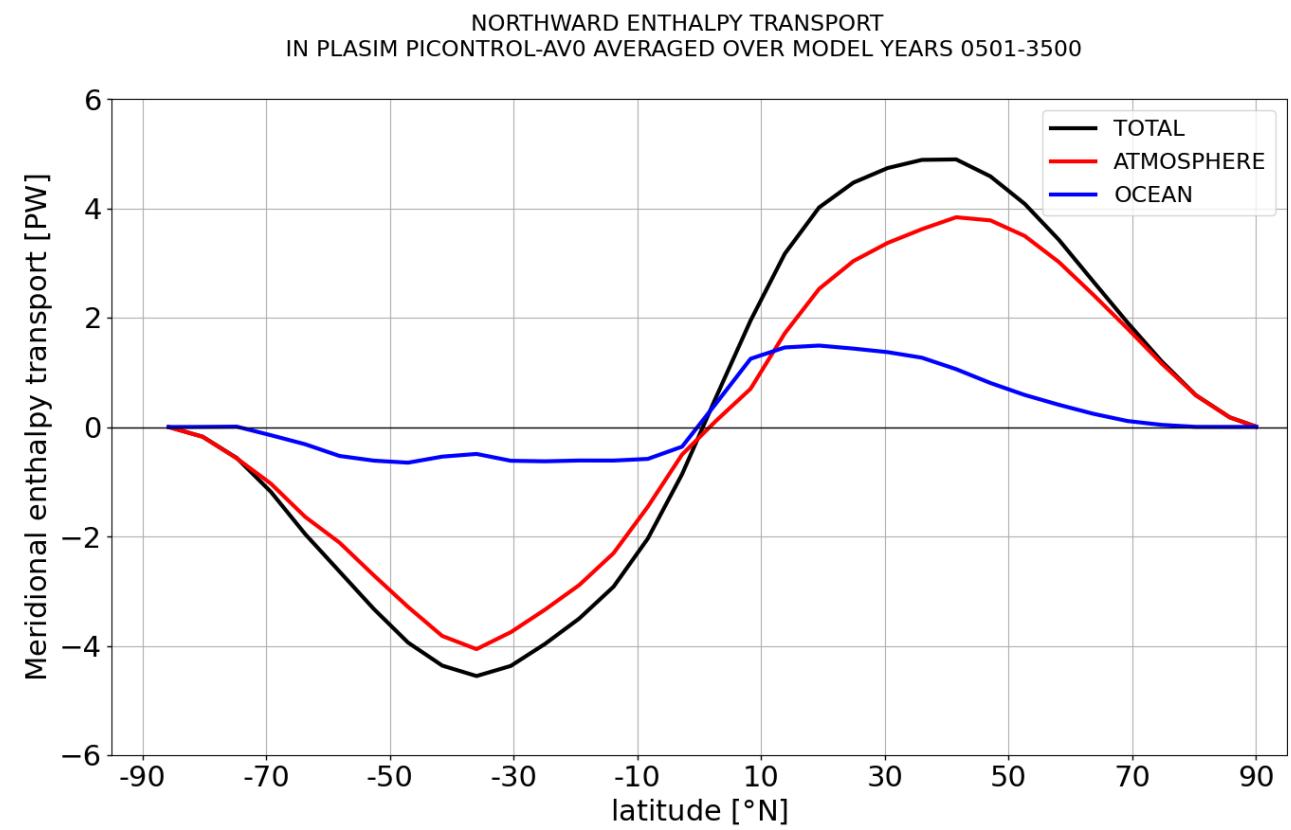
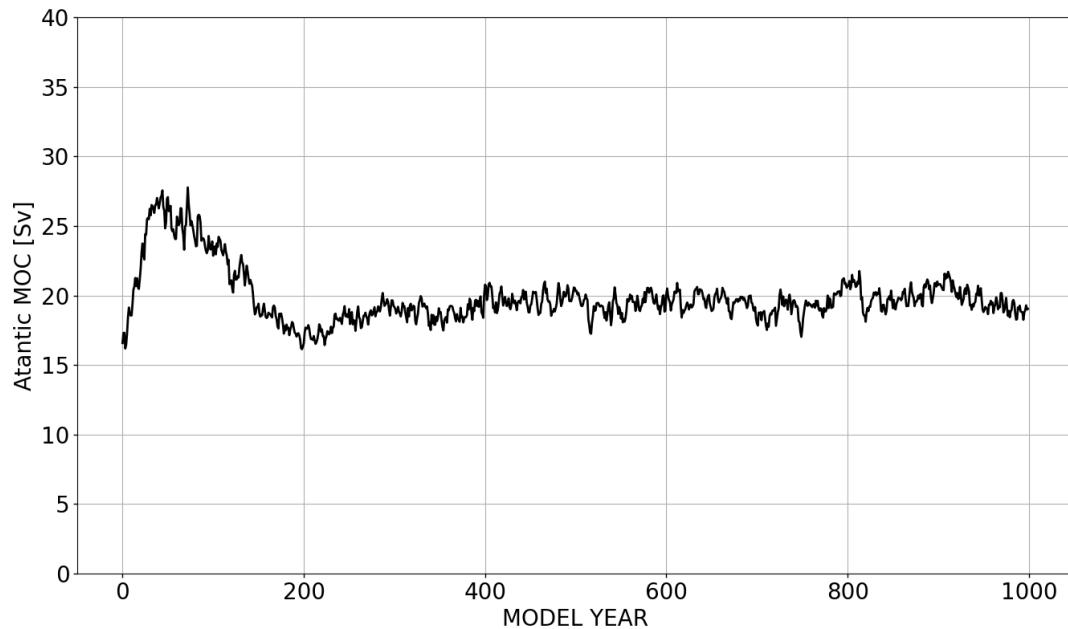


PlaSim-T21-LSG

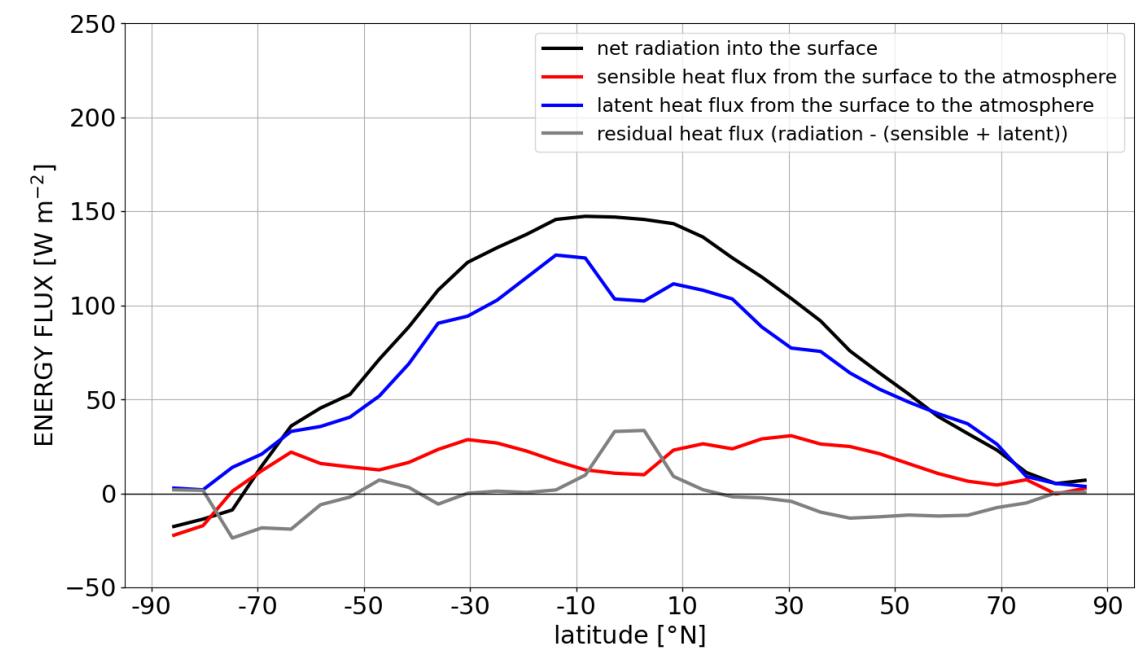
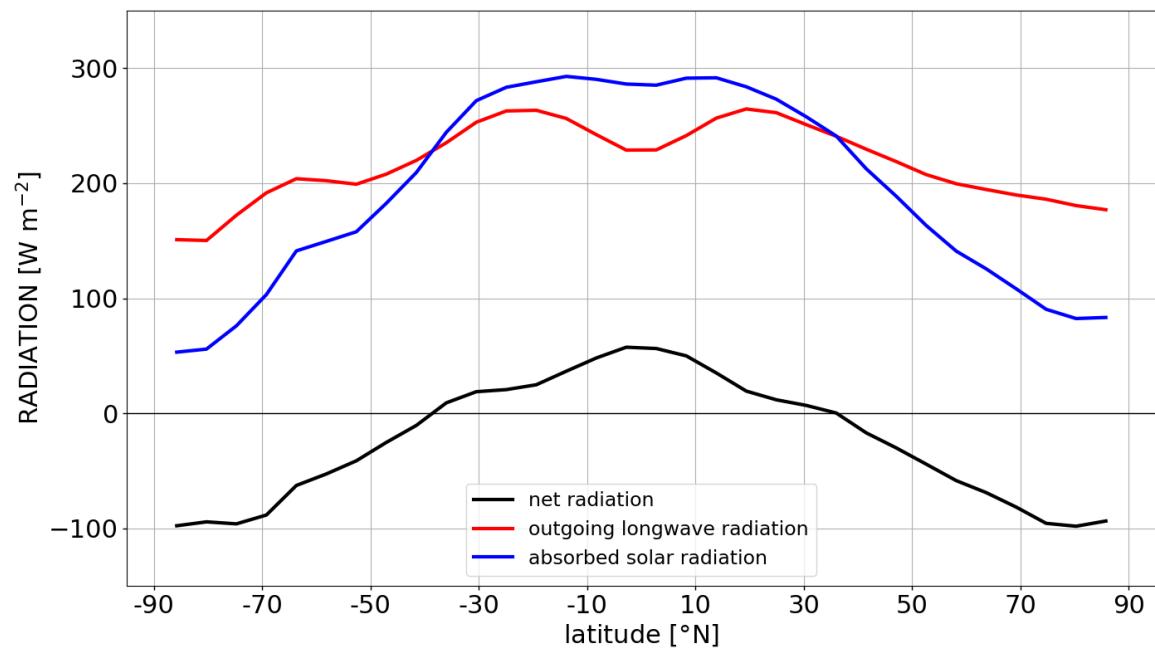


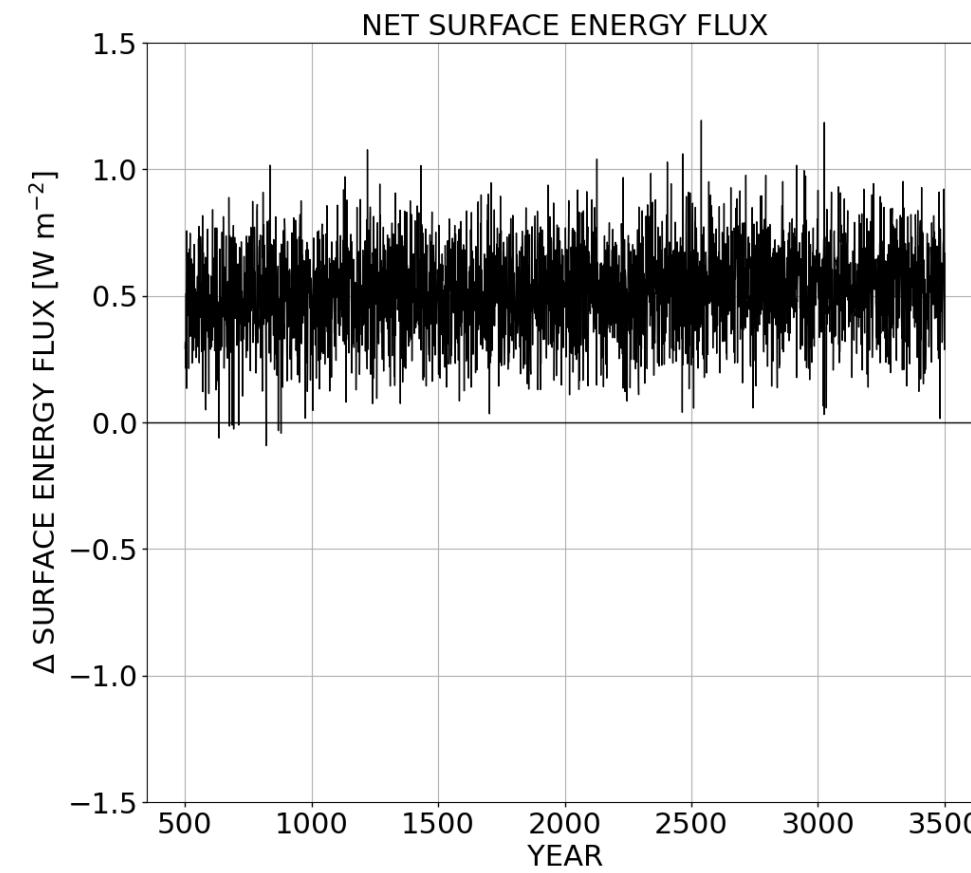
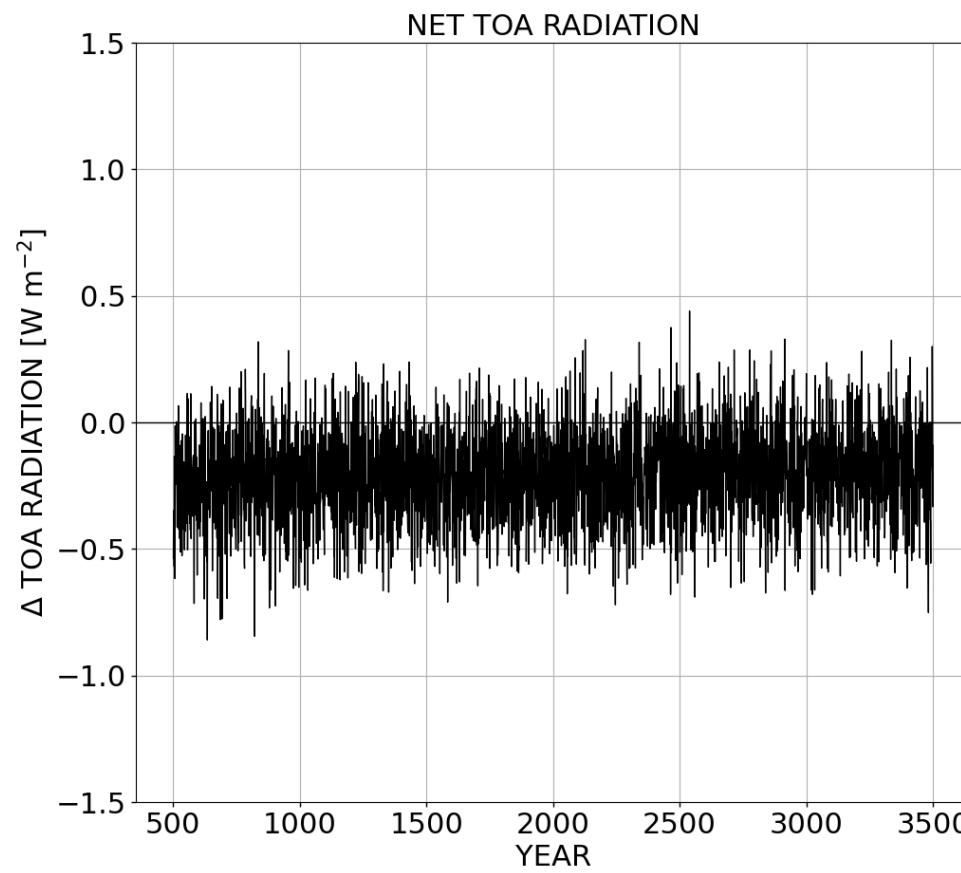
OSI SAF 1979-2022



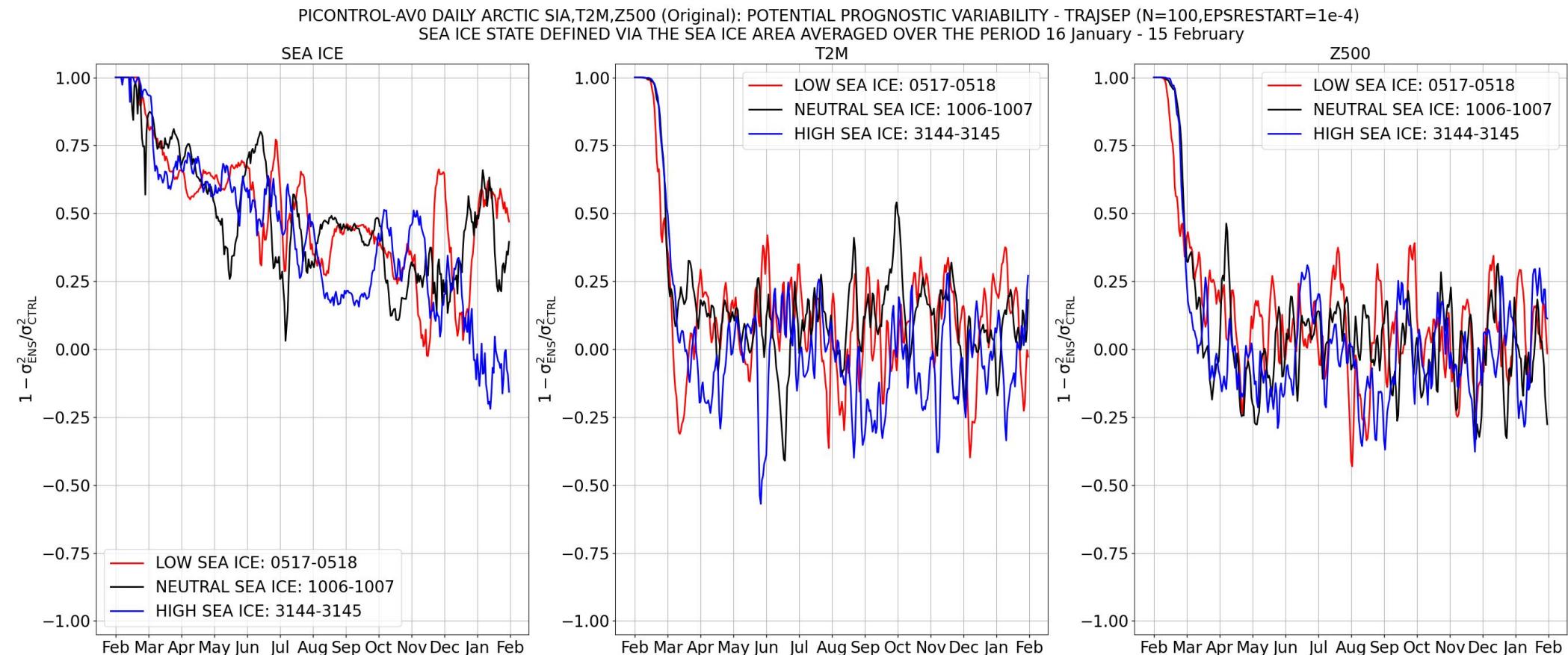


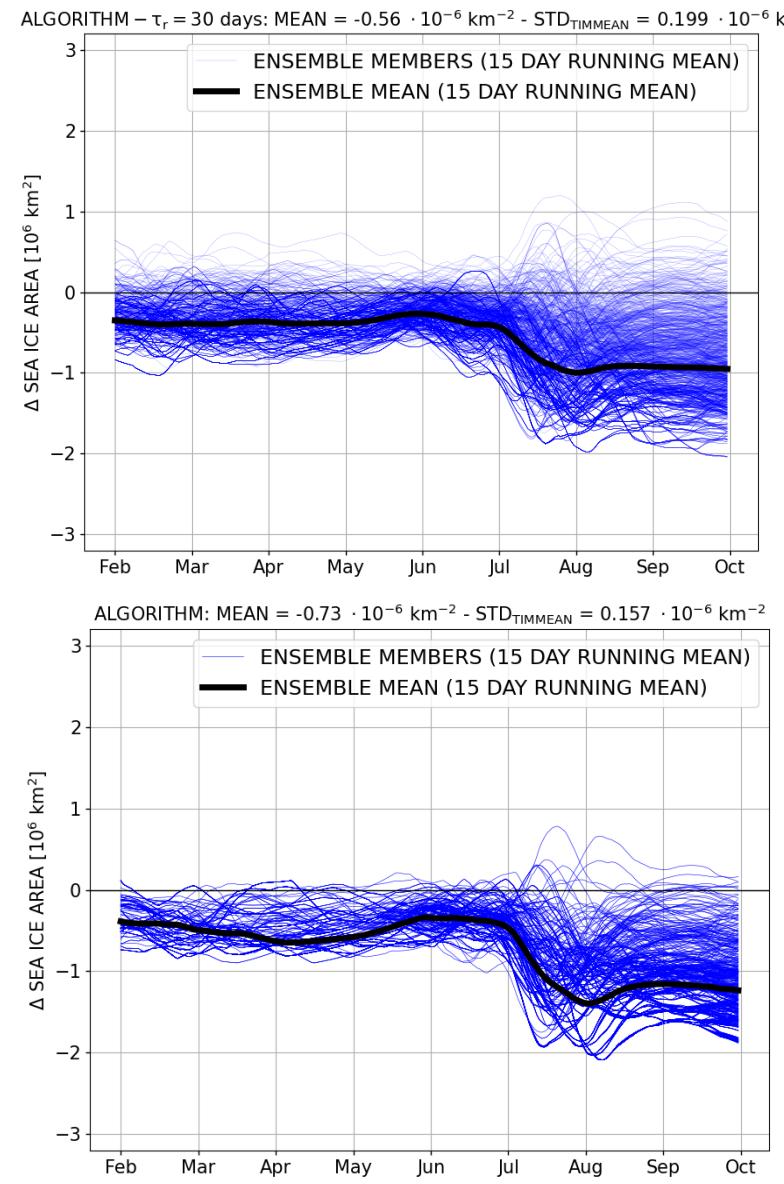
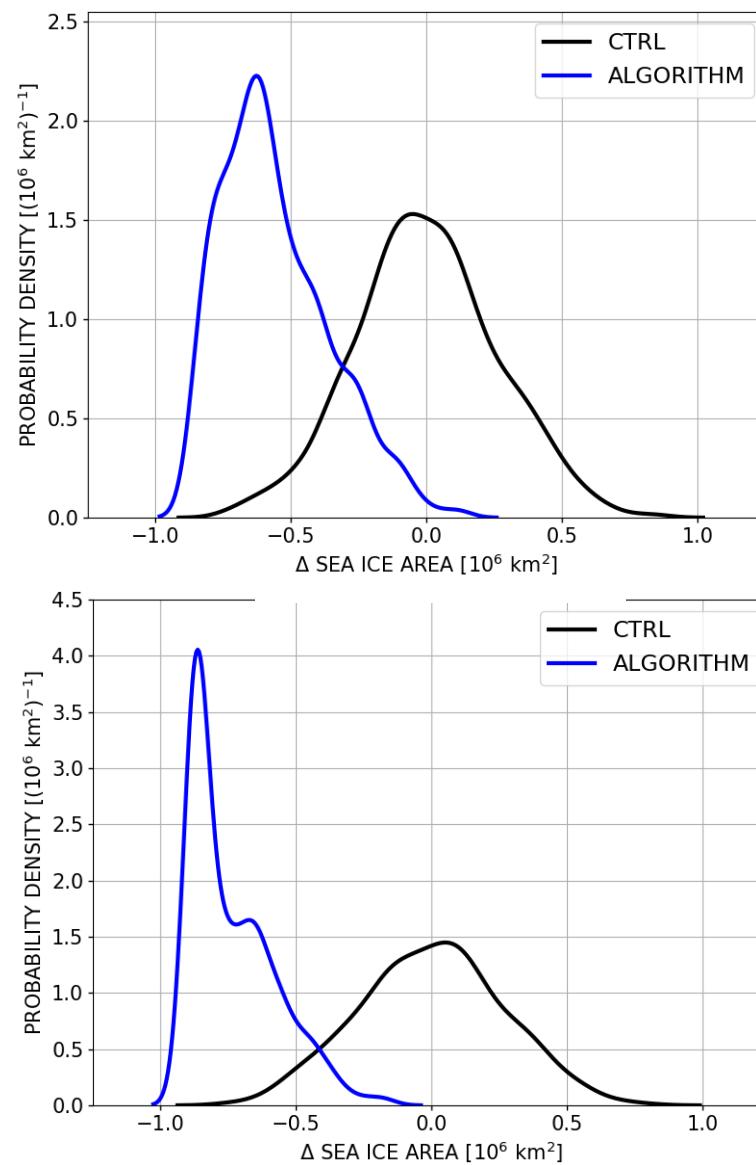
ZONAL MEAN TOA RADIATION IN PLASIM PICONTROL-AV0 AVERAGED OVER MODEL YEARS 0501-3500





General dynamical properties

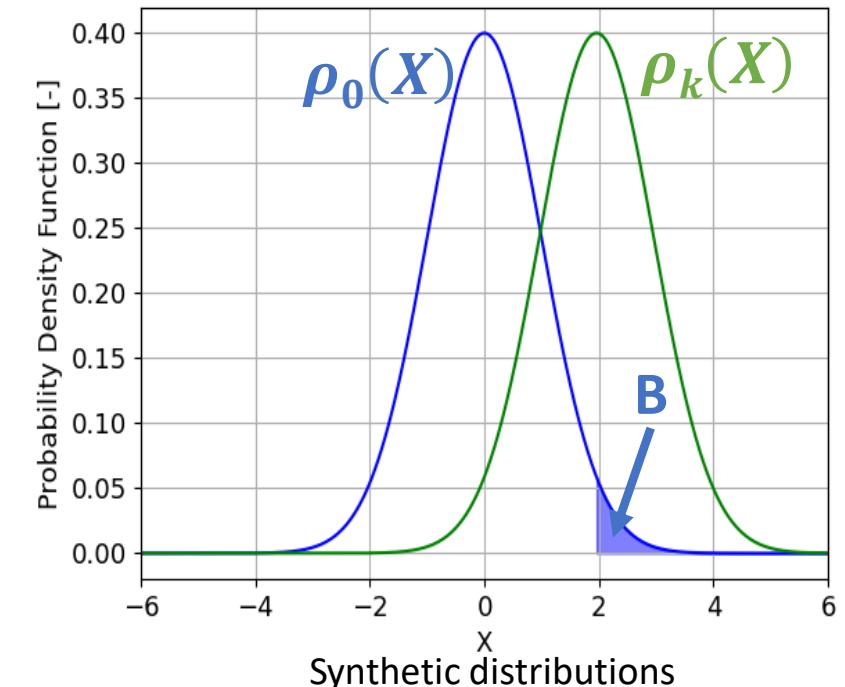




Importance sampling and rare event algorithm

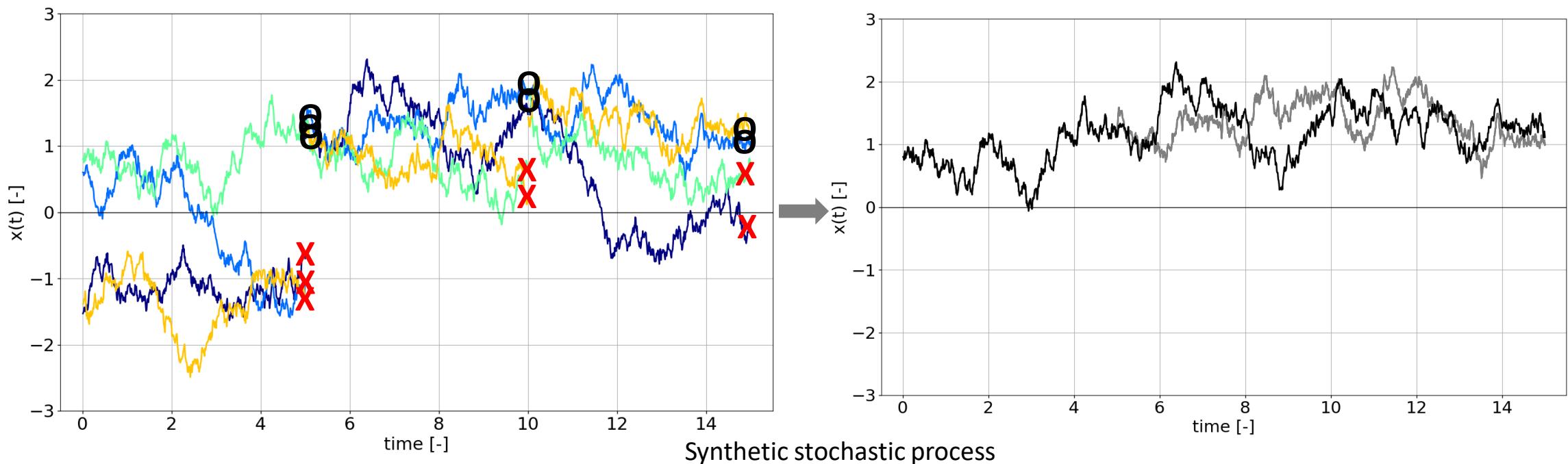
- **Importance sampling:** Make rare events more common to **reduce the statistical uncertainty** of an estimator
- **Synthetic example:** Estimate the **probability** of a **subset B** by sampling data from ρ_k instead of ρ_0

$$P(B) = \int \mathbf{1}_B(X) \cdot \frac{\rho_0(X)}{\rho_k(X)} \rho_k(X) dX \approx \frac{1}{n} \sum_{i=1}^n \mathbf{1}_B(X_{k,i}) \cdot \frac{\rho_0(X_{k,i})}{\rho_k(X_{k,i})}, \quad \mathbf{1}_B(X) = \begin{cases} 1, & \text{if } X \in B \\ 0, & \text{else} \end{cases}$$



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** that are very unlikely to be observed using conventional simulation strategies



Importance sampling and rare event algorithm

- Reconstruct **effective ensemble** by discarding all trajectories that did not survive until the end of the simulation
- **Importance sampling formula:** 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

→ Allows to compute **expectation values** with respect to the **real model statistics** (e.g. composites, return times etc.)

