

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

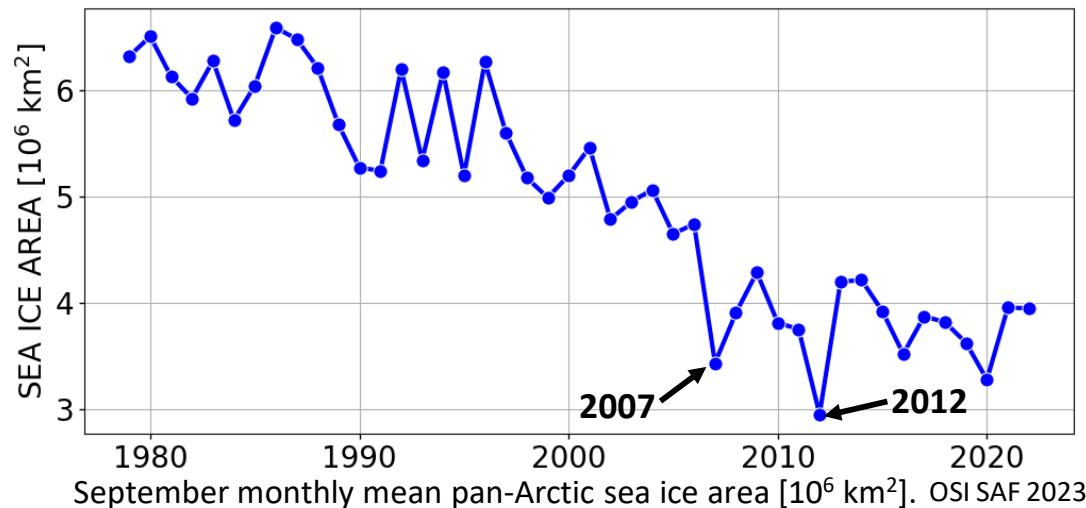
Jerome Sauer

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

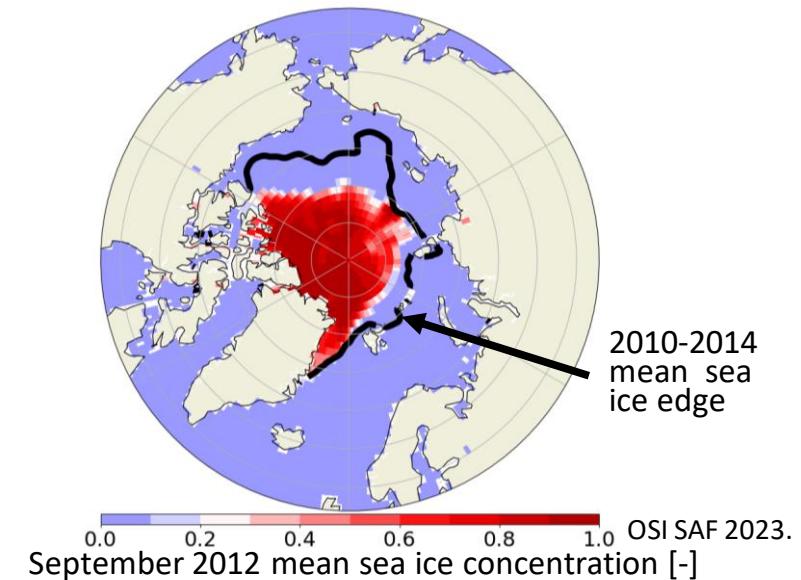
with Francesco Ragone, François Massonnet, Jonathan Demaeyer, Giuseppe Zappa



Extreme reductions in summer pan-Arctic sea ice area



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

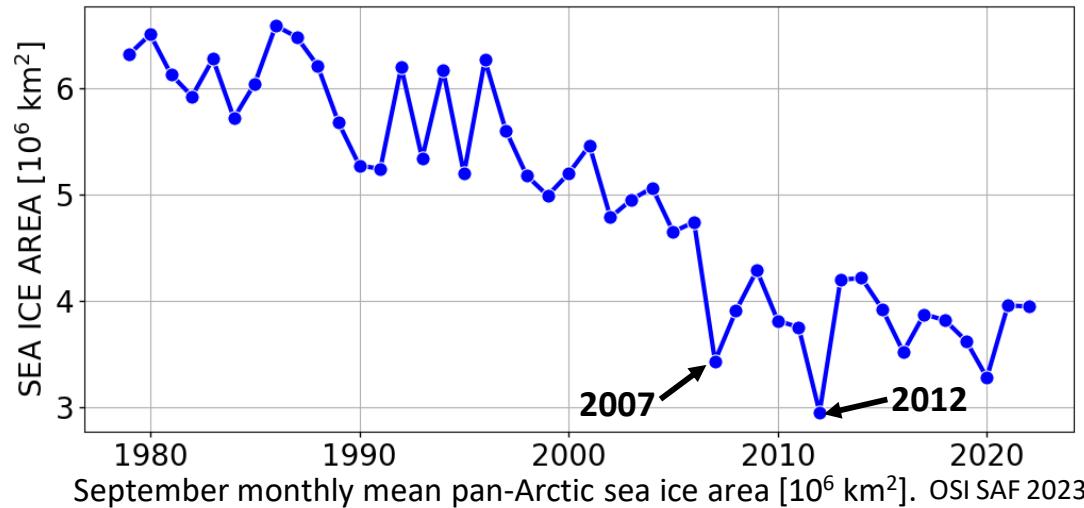


September 2012 mean sea ice concentration [-] OSI SAF 2023.

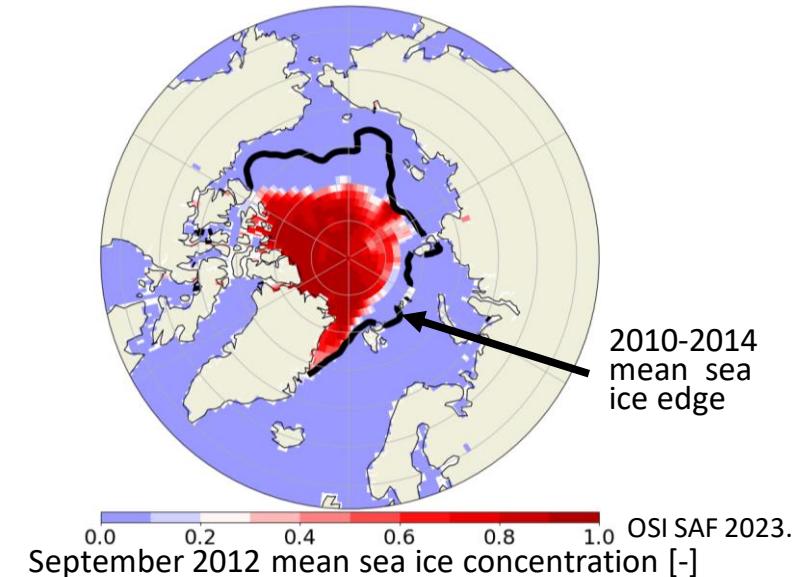
Overarching goal: Understanding the **atmospheric** and **oceanic drivers** of extremes of summer Arctic sea ice reduction

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



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

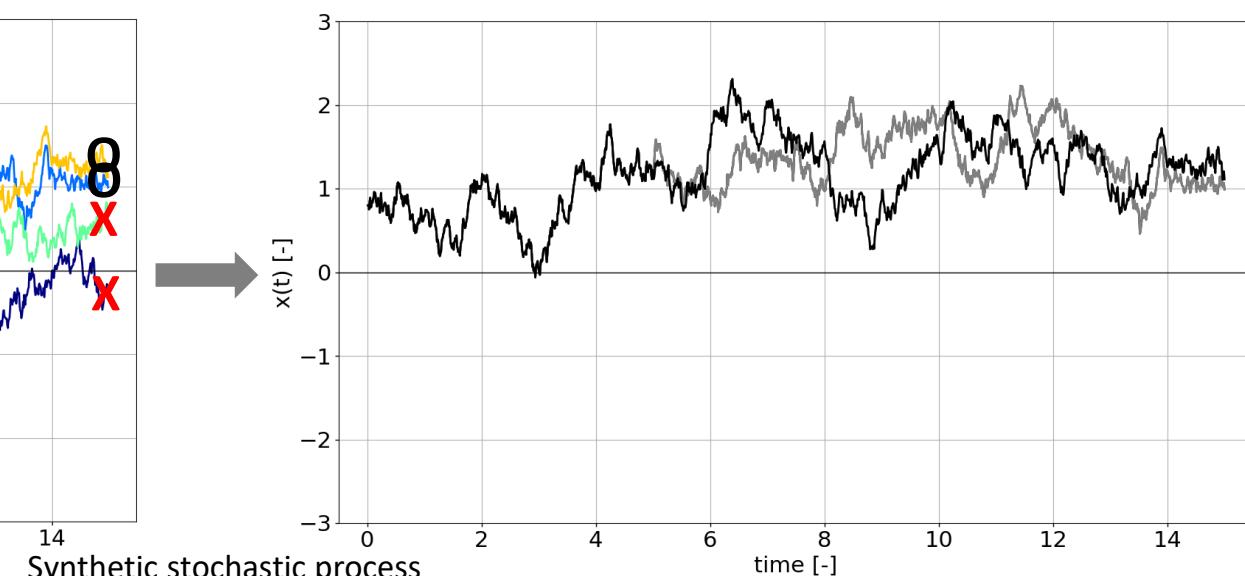
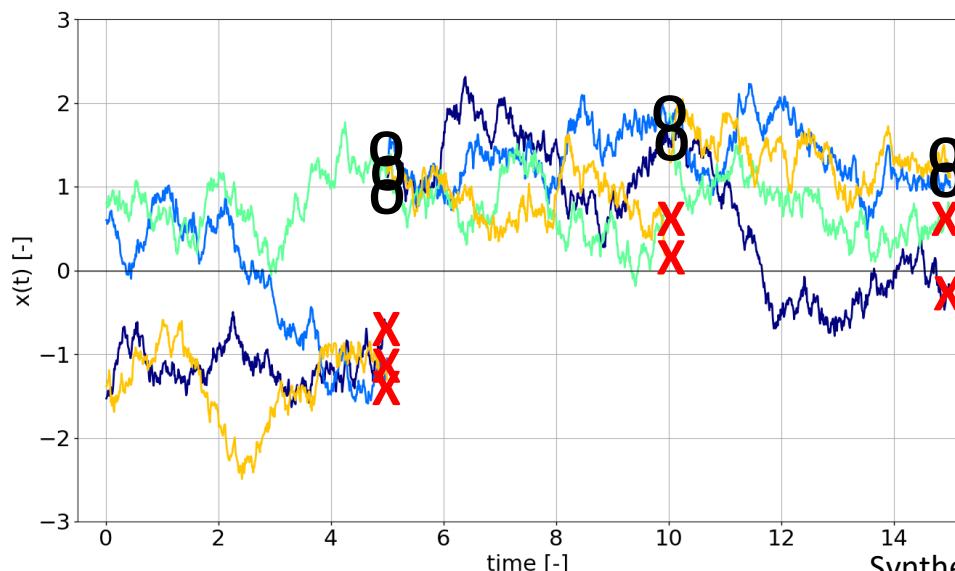


Problem: Quantitative statistical and dynamical studies of **climate extremes** are hindered by the **lack of data**

- 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**

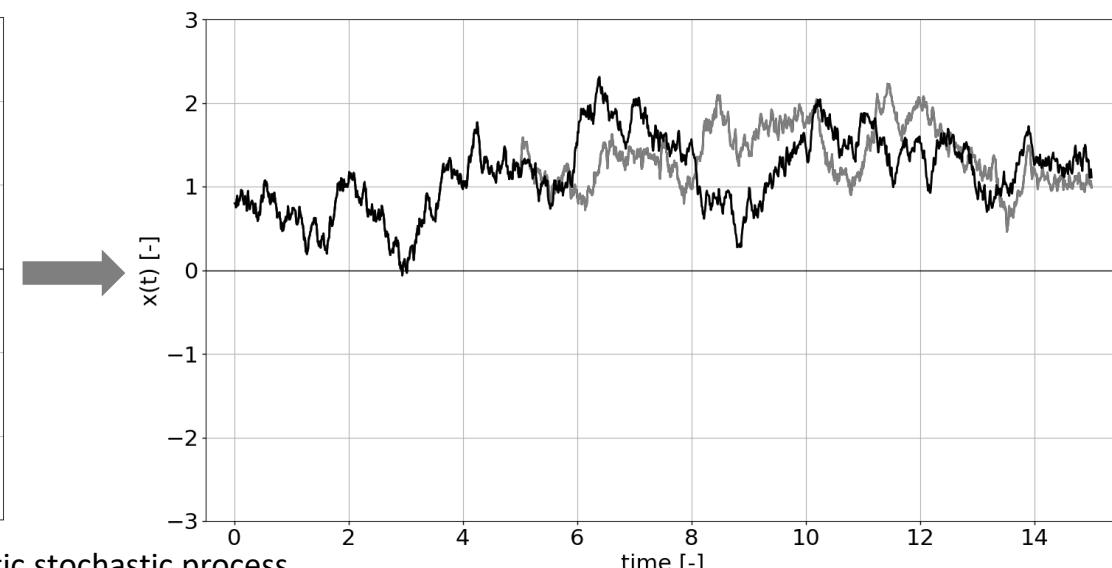
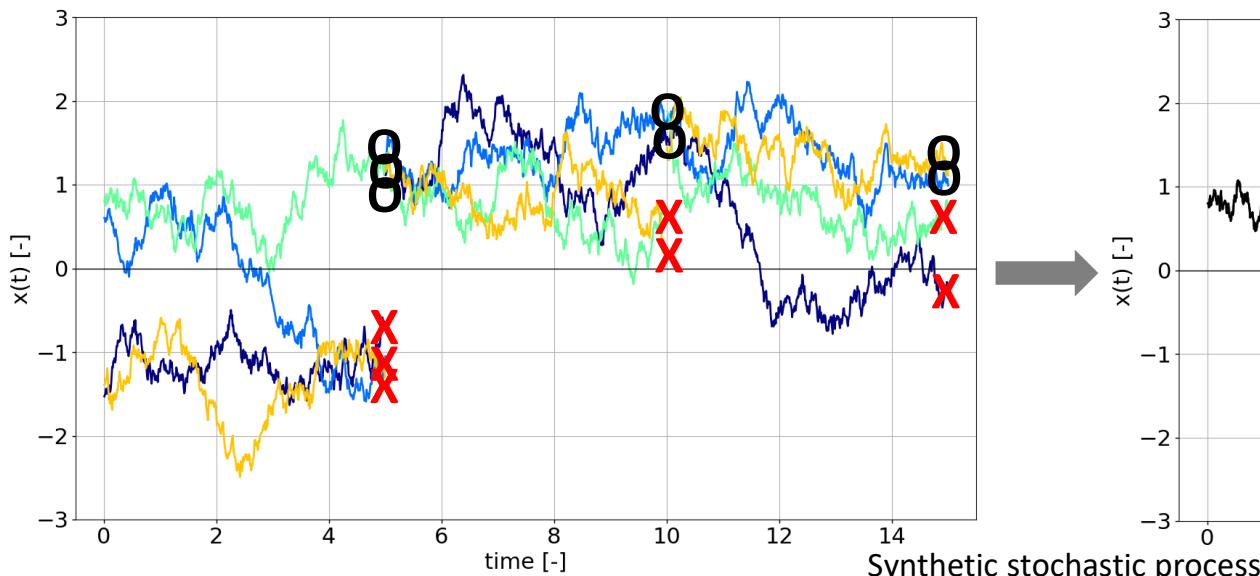


Methodology: Rare event algorithm

- **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

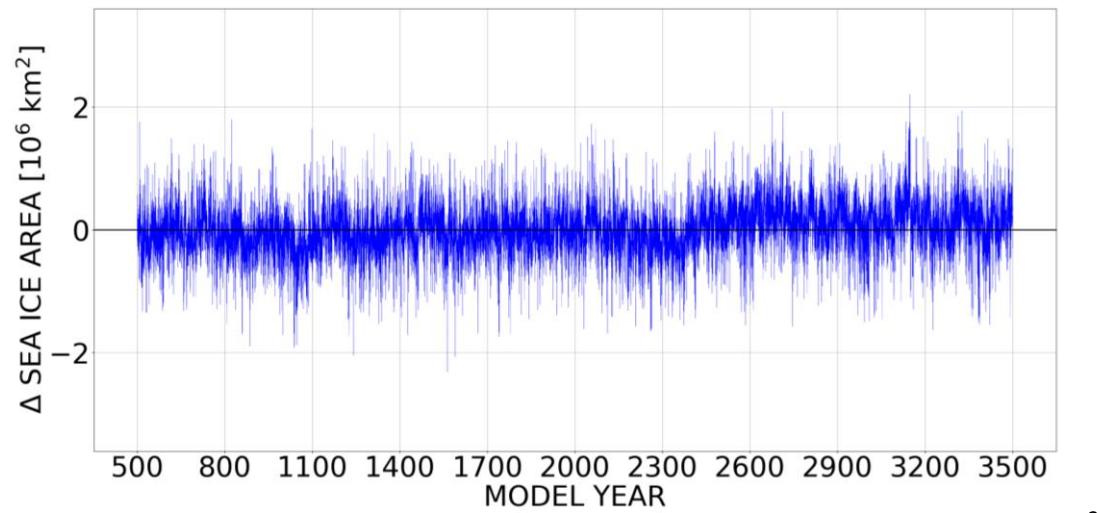
Coupled version: Large-Scale Geostrophic ocean and a zero-layer thermodynamic sea ice model

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

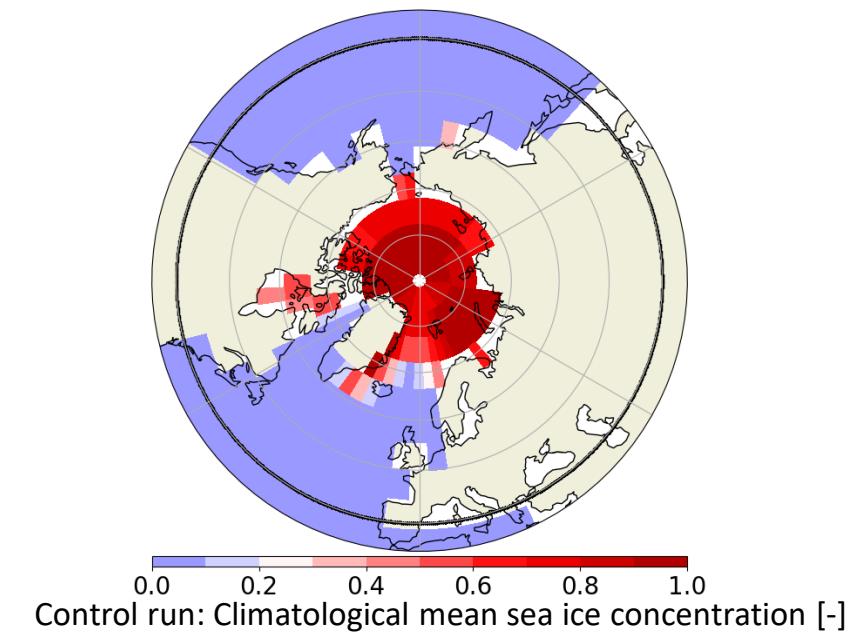
Forcing: constant pre-industrial greenhouse gas conditions

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

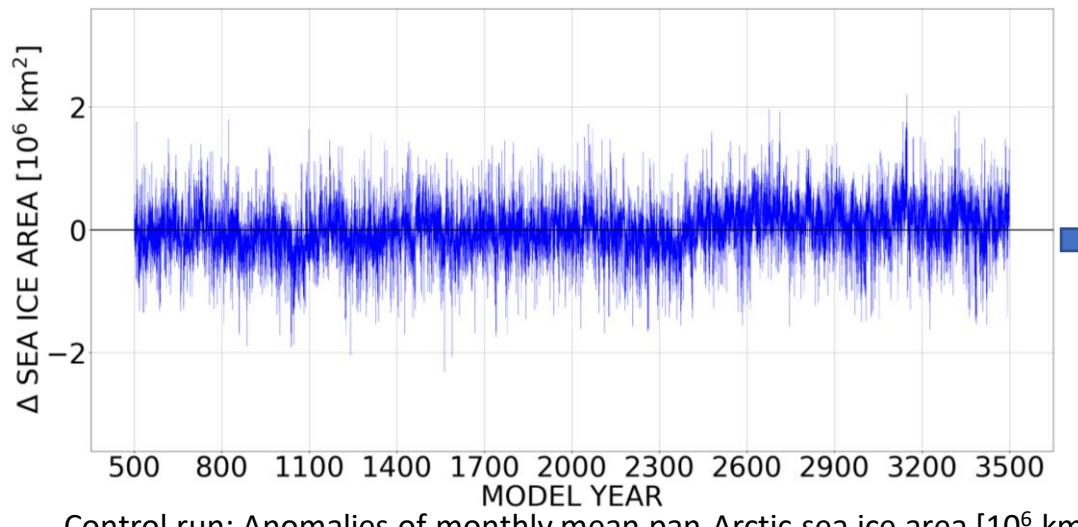
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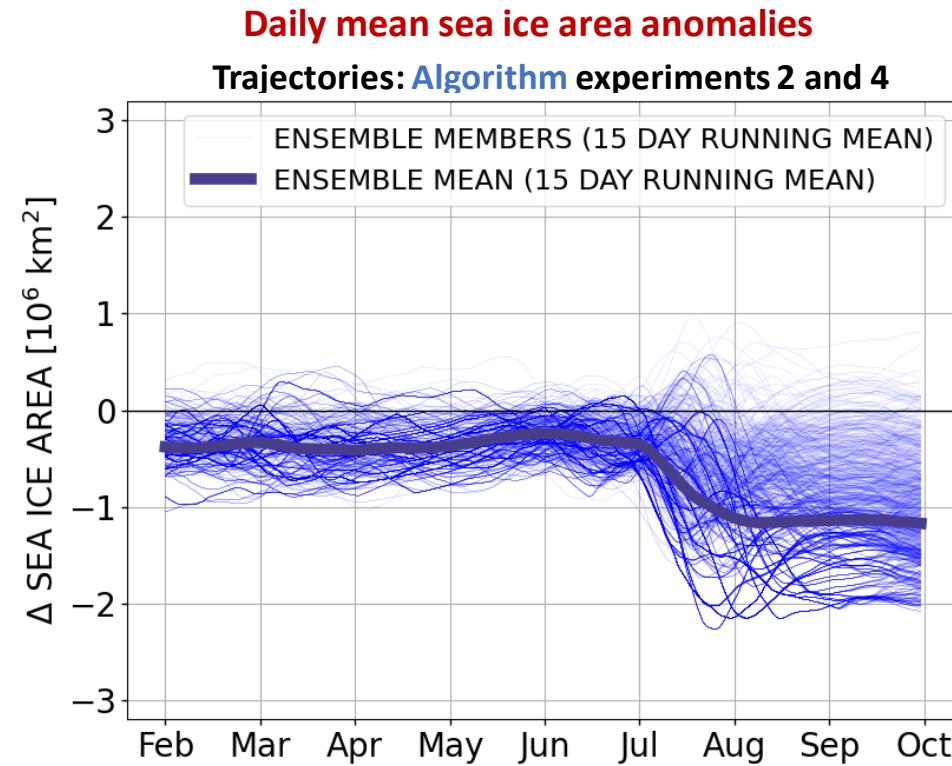
Rare event algorithm experiments

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

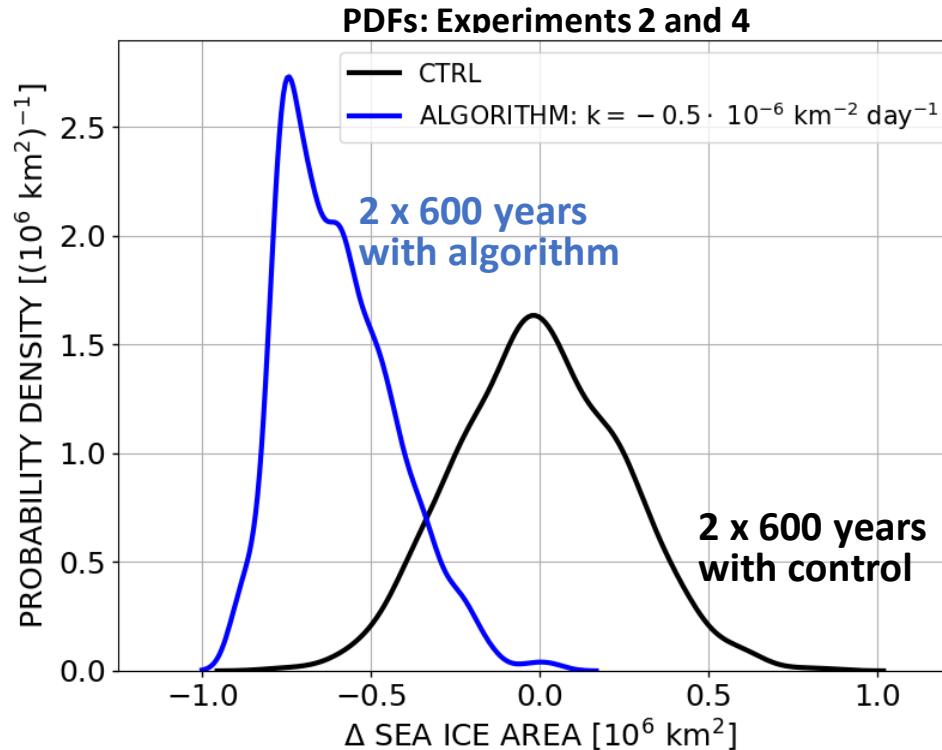
Seasons with extremely low pan-Arctic sea ice area in PlaSim



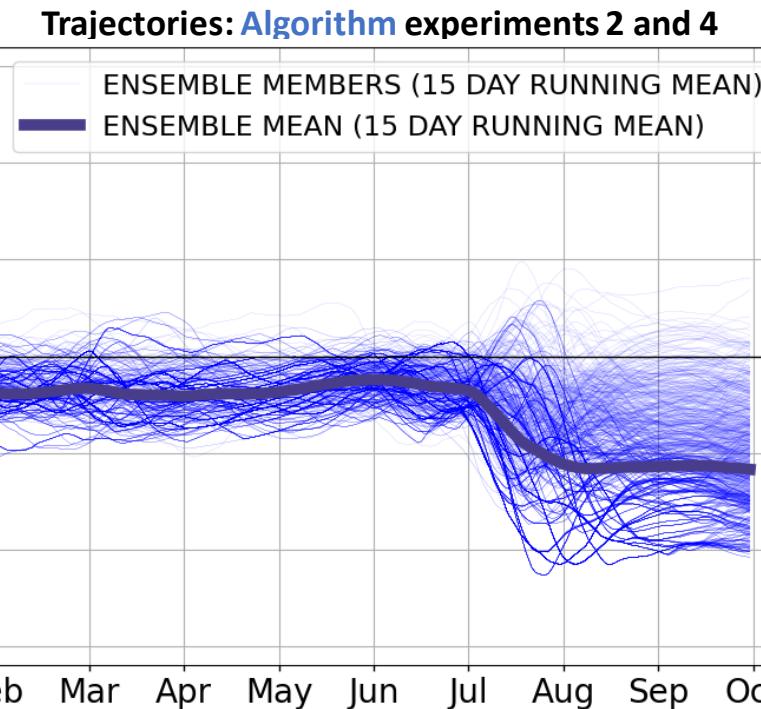
- Importance sampling of extreme negative February-September mean pan-Arctic sea ice area anomalies

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

February-September mean sea ice area anomalies

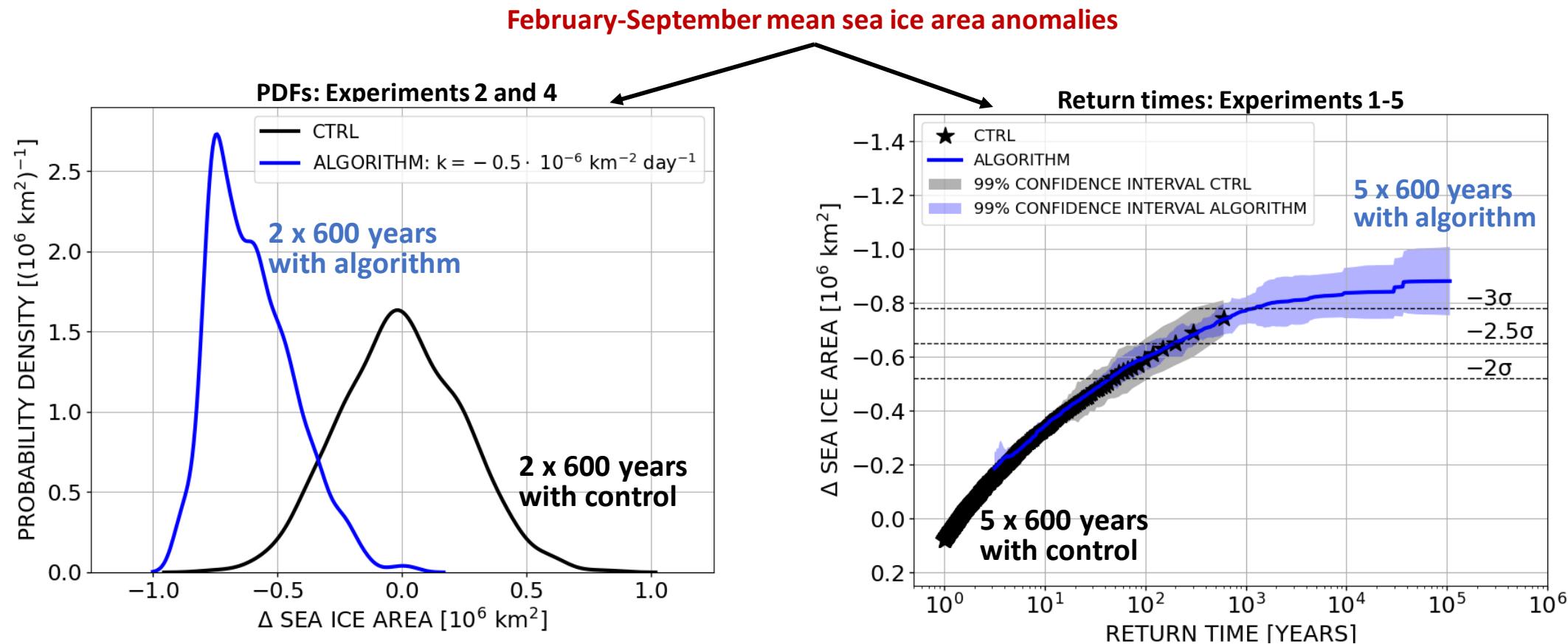


Daily mean sea ice area anomalies



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

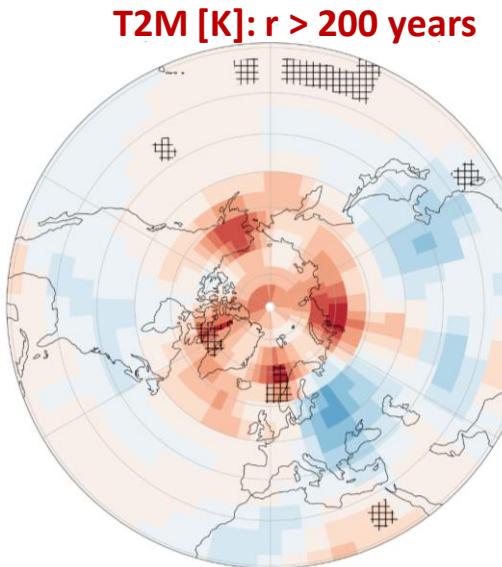
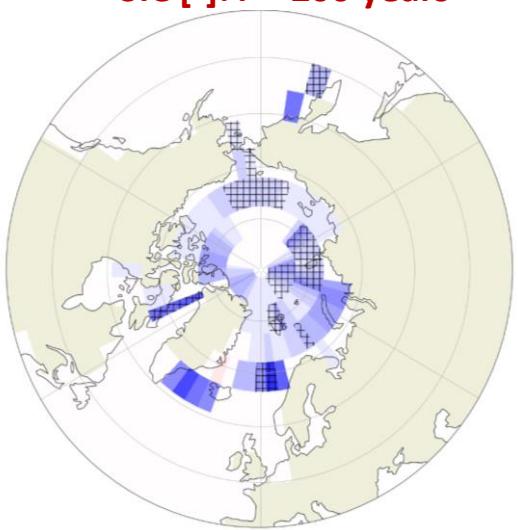
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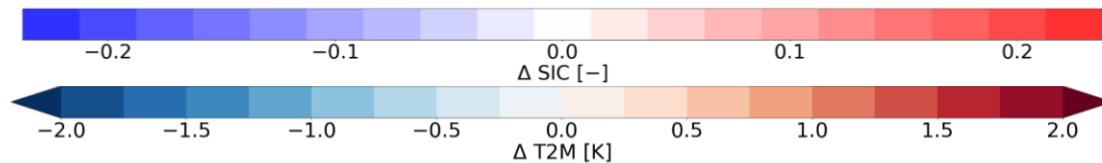
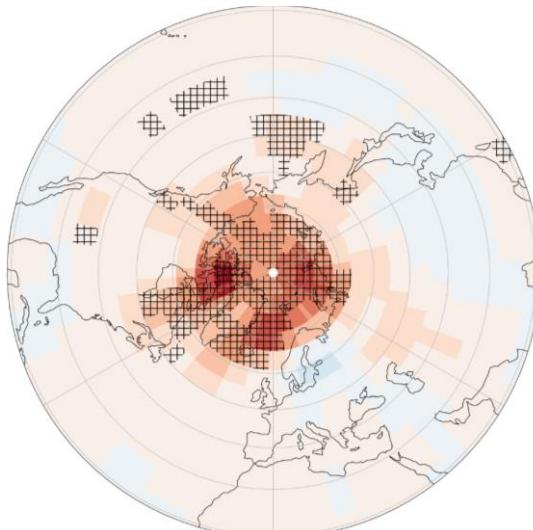
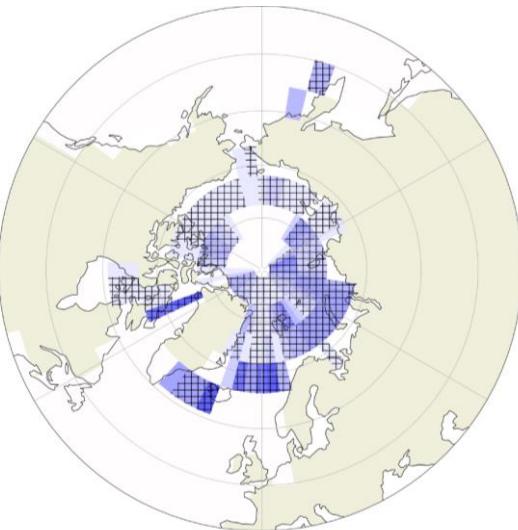
- Importance sampling of extreme negative February-September mean pan-Arctic sea ice area anomalies
- The algorithm allows to compute return times up to 10^5 years with computational cost of 3000 years

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

CONTROL



ALGORITHM



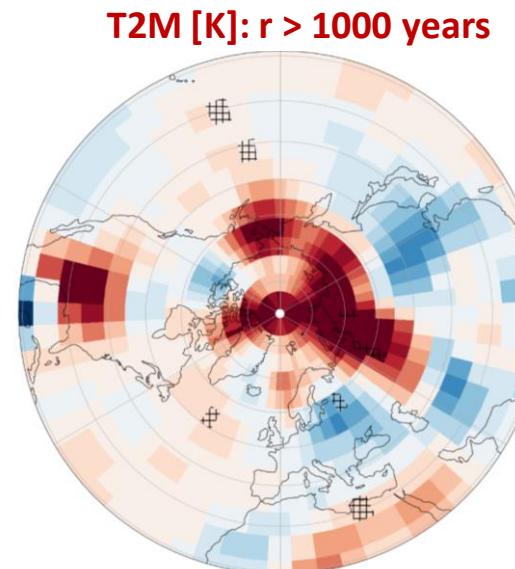
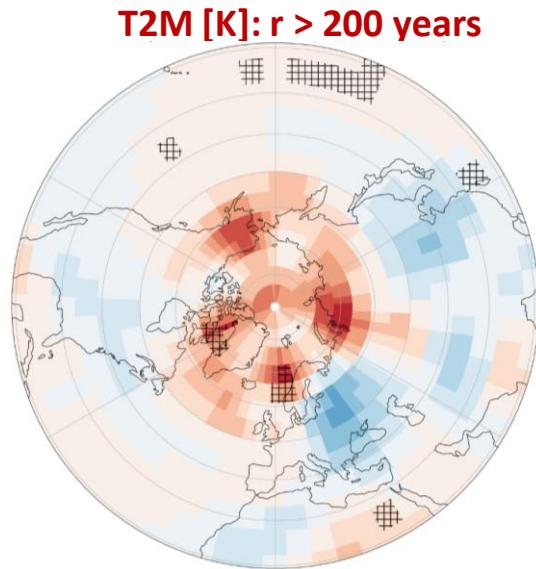
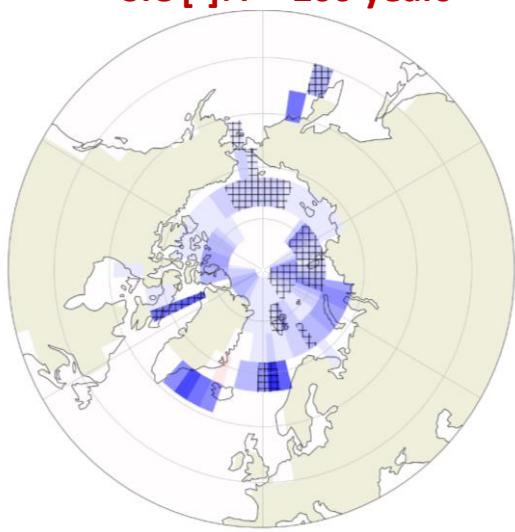
"Seasonal"/ "summer":
February-September average

Hatching: Significance on the 1%
level

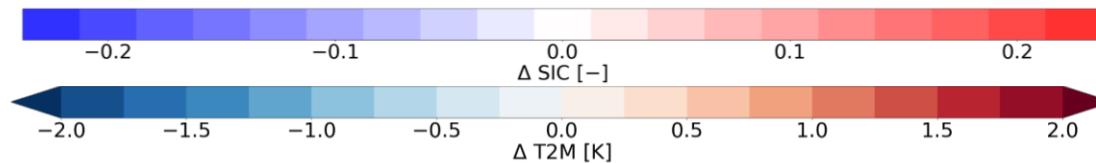
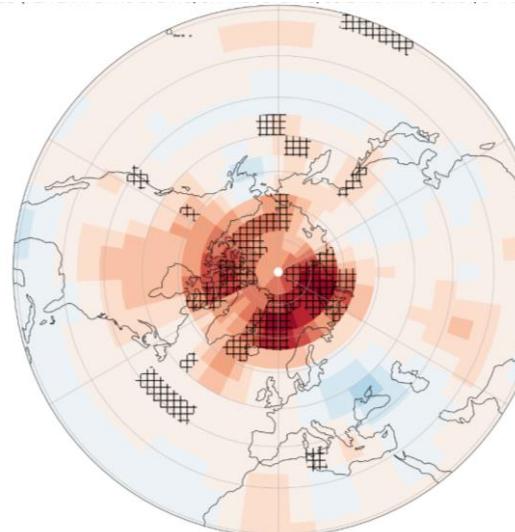
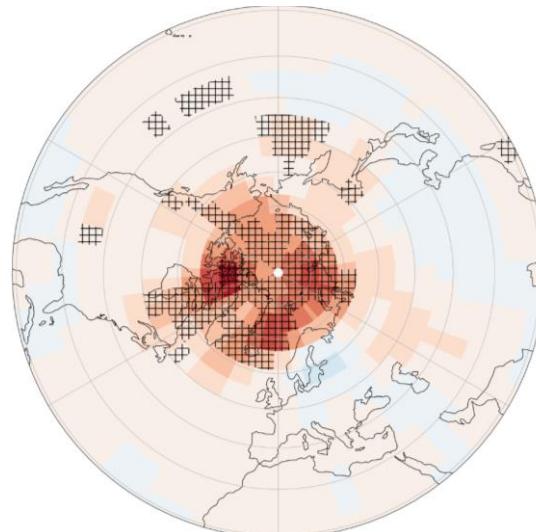
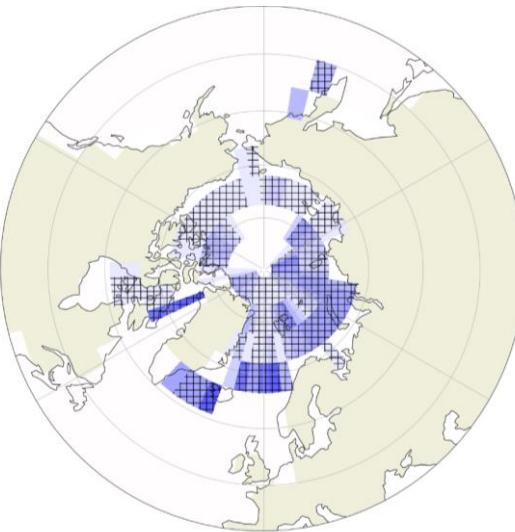
- Algorithm: Increase of statistical significance compared to control run

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

CONTROL



ALGORITHM



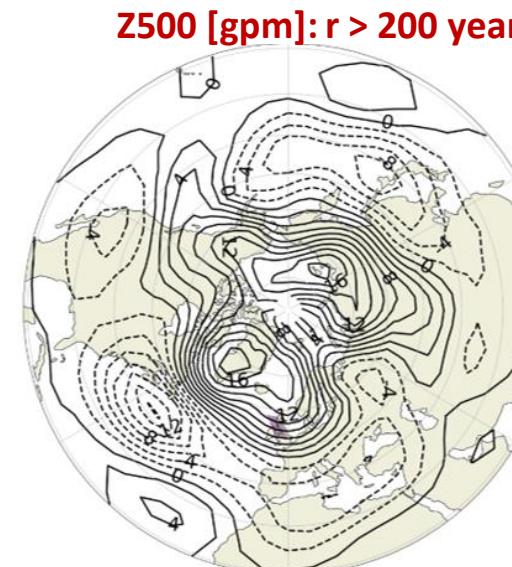
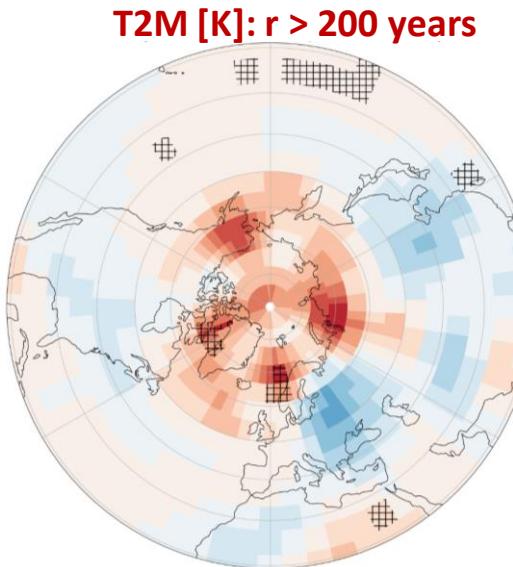
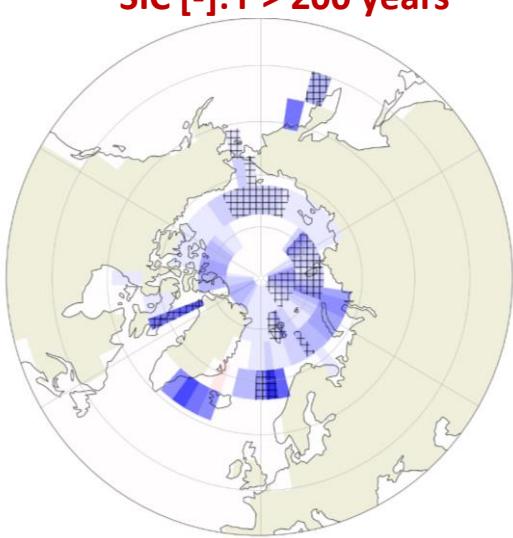
“Seasonal”/ “summer”: February-September average

Hatching: Significance on the 1% level

- Algorithm: Increase of statistical significance compared to control run

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

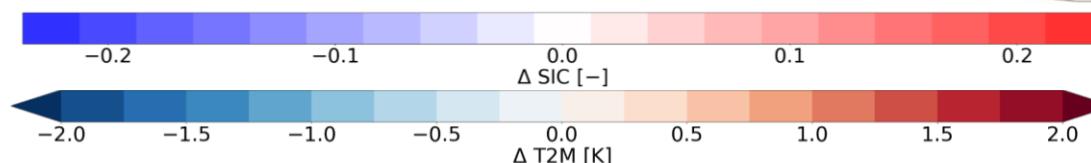
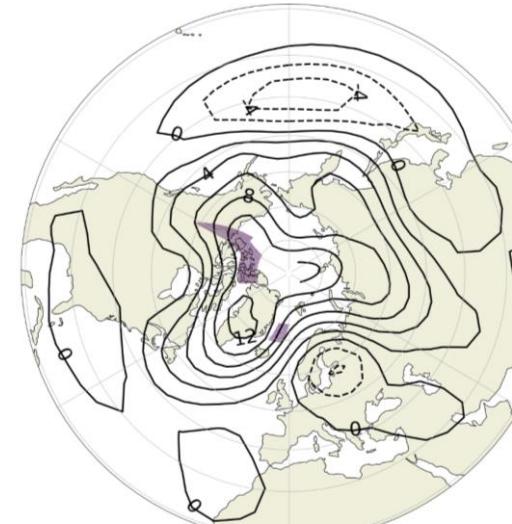
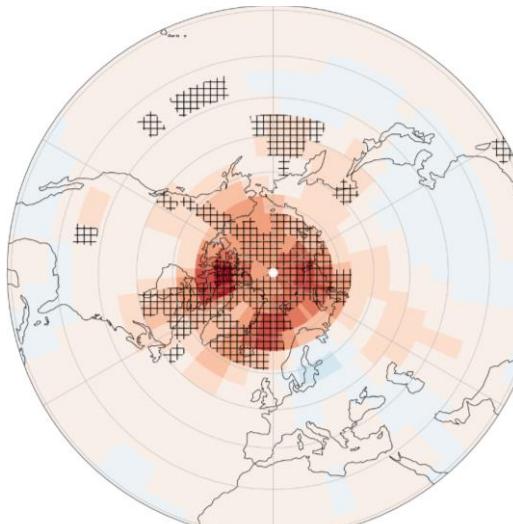
CONTROL



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

Hatching/Shading: Significance
on the 1% level

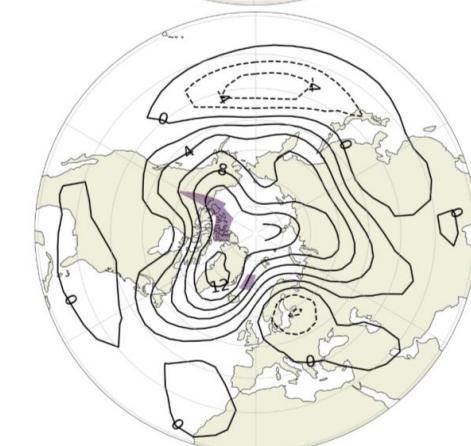
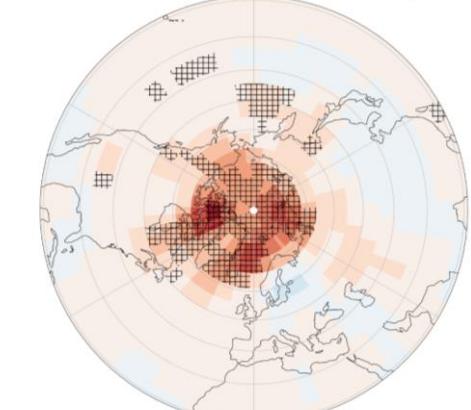
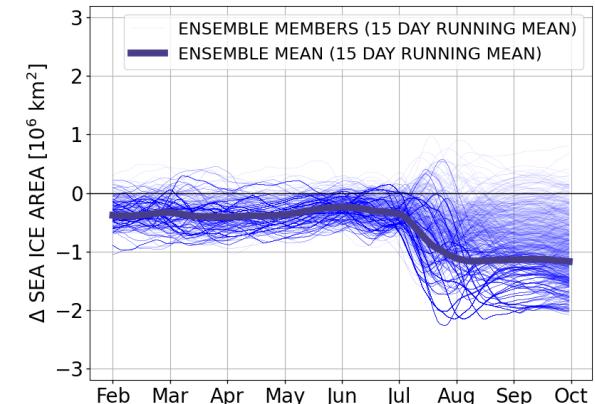
ALGORITHM



- Algorithm: Increase of statistical significance compared to control run
- What are the dominant drivers of the warm Arctic in PlaSim?

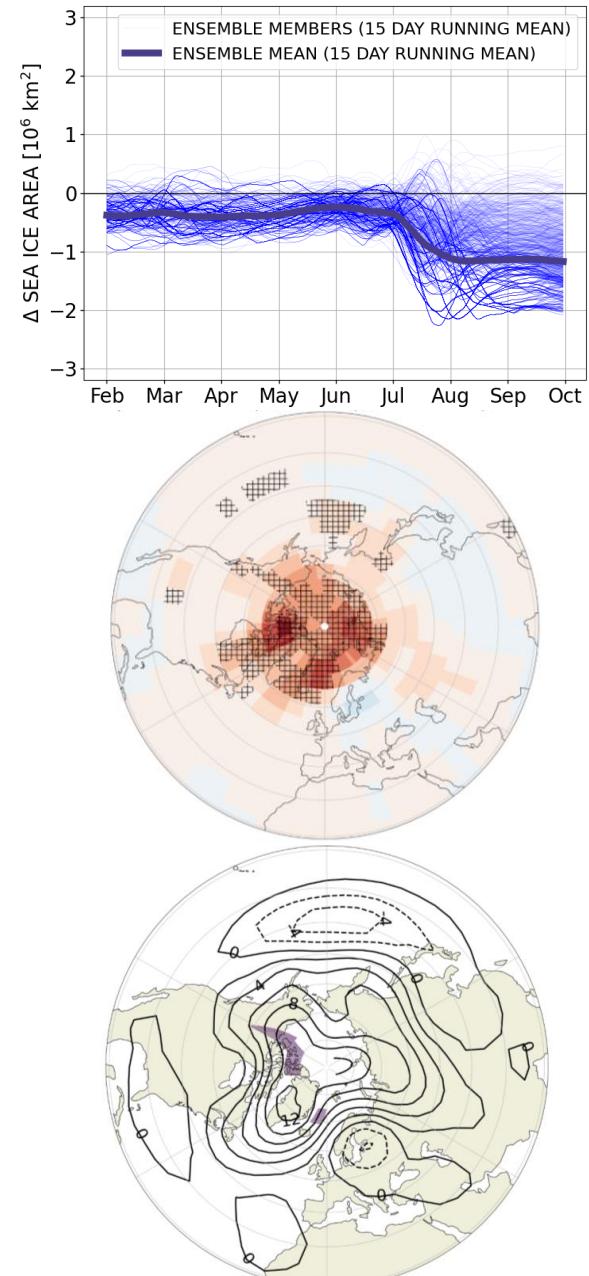
Summary and ongoing work

- 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



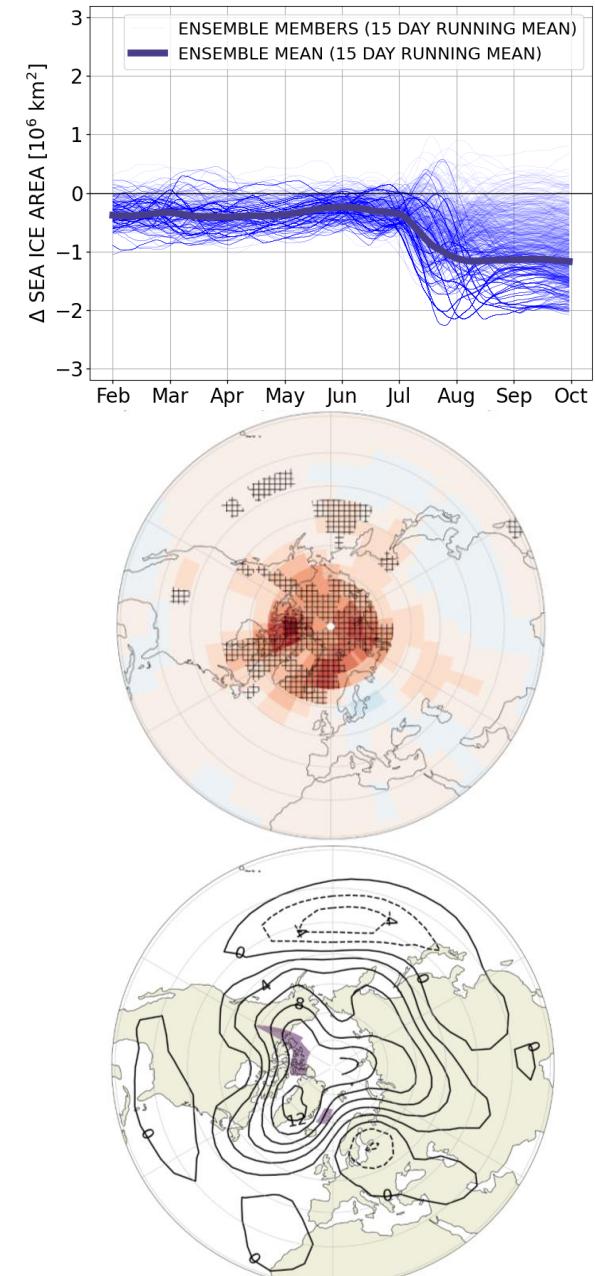
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- What is driving the warm Arctic in PlaSim?
 - Analysis of the energetics: surface energy budget and meridional heat transports
 - Dominant modes of atmospheric circulation variability
 - Preconditioning and state of the ocean
- Extending the analysis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



Summary and ongoing work

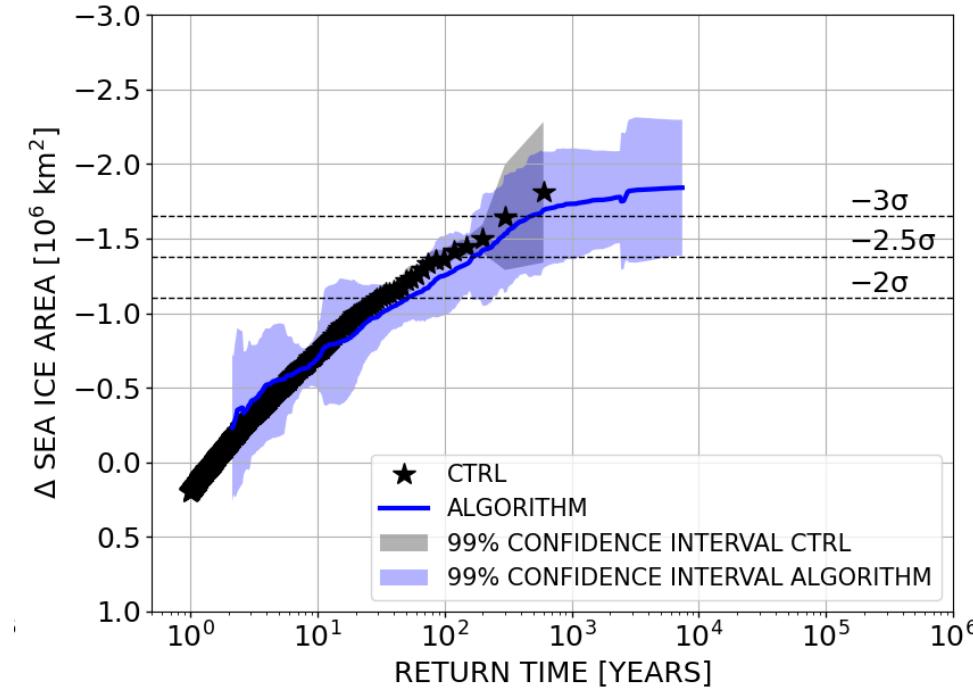
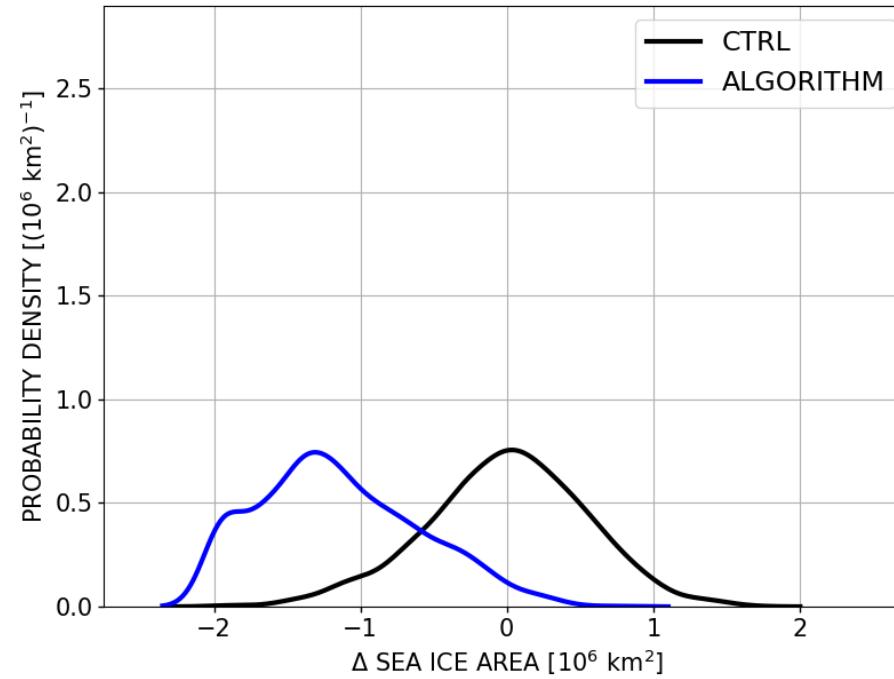
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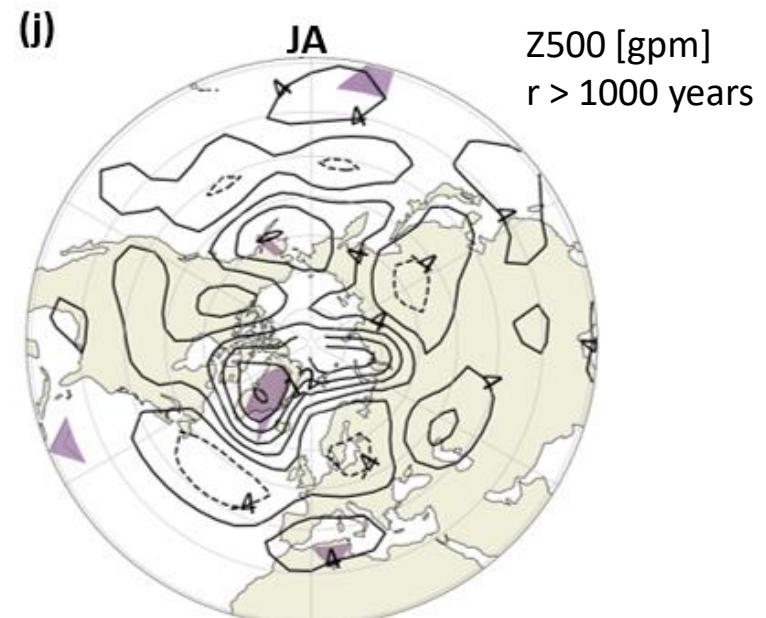
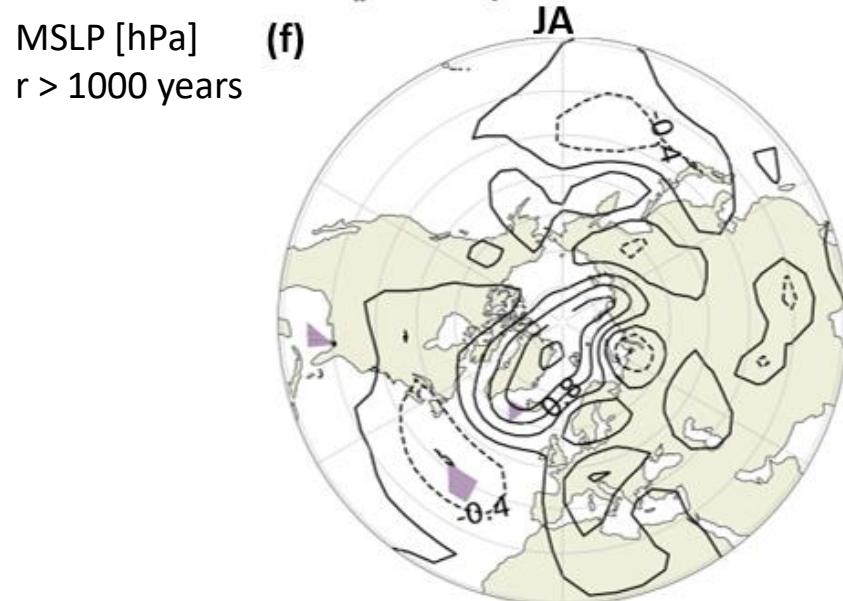
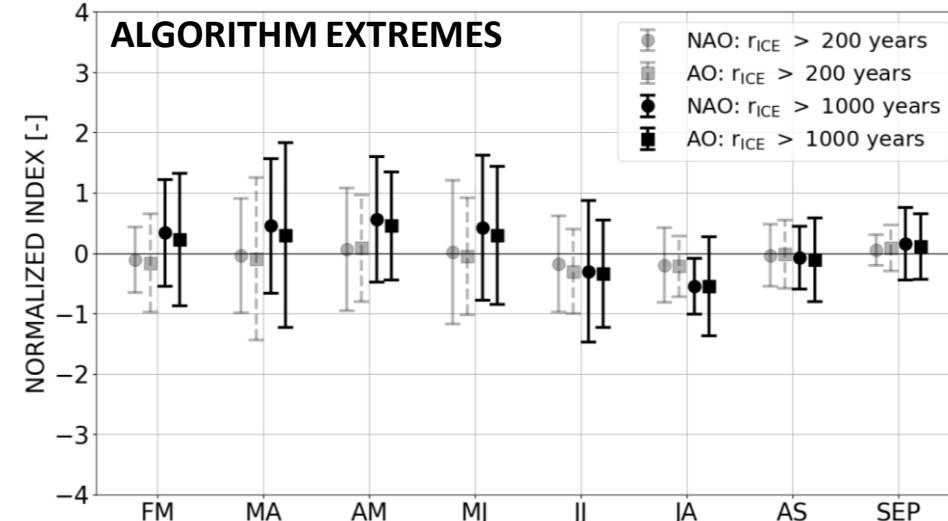
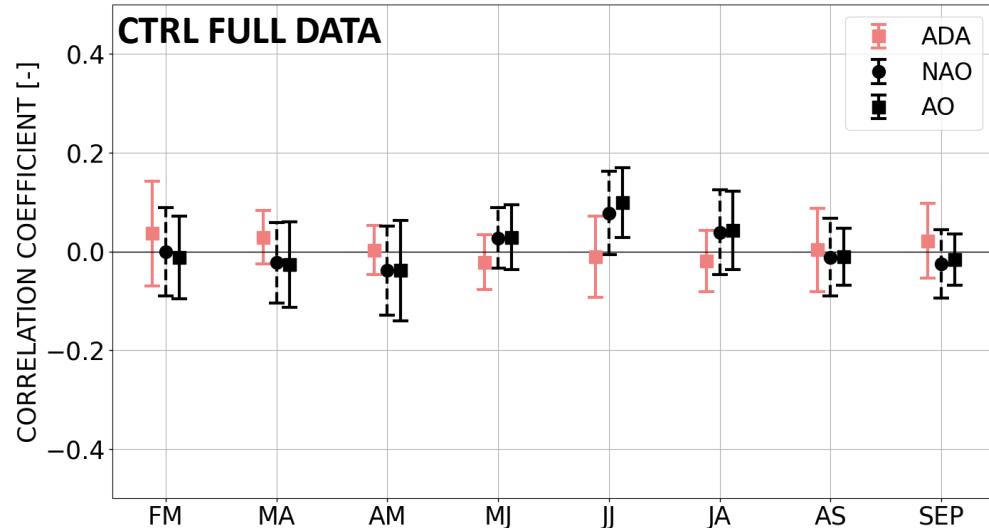
Thank you for your attention

Appendix

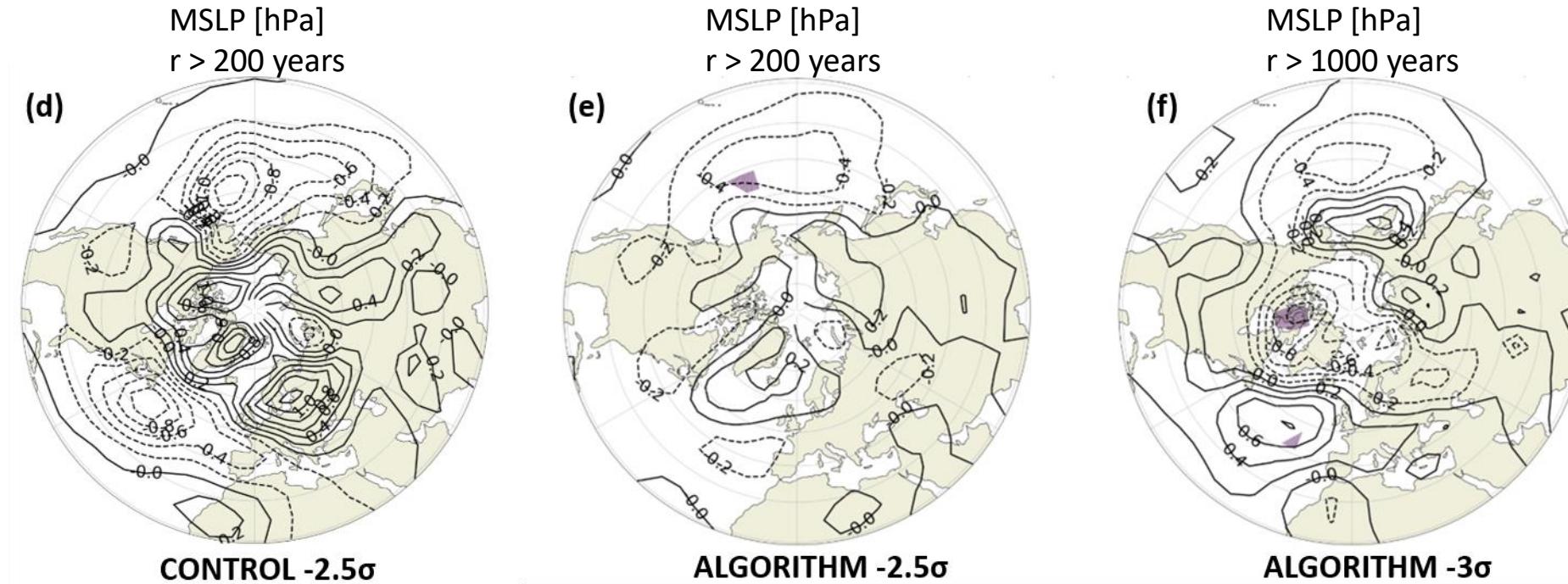
Septembers with extremely low pan-Arctic sea ice area in PlaSim



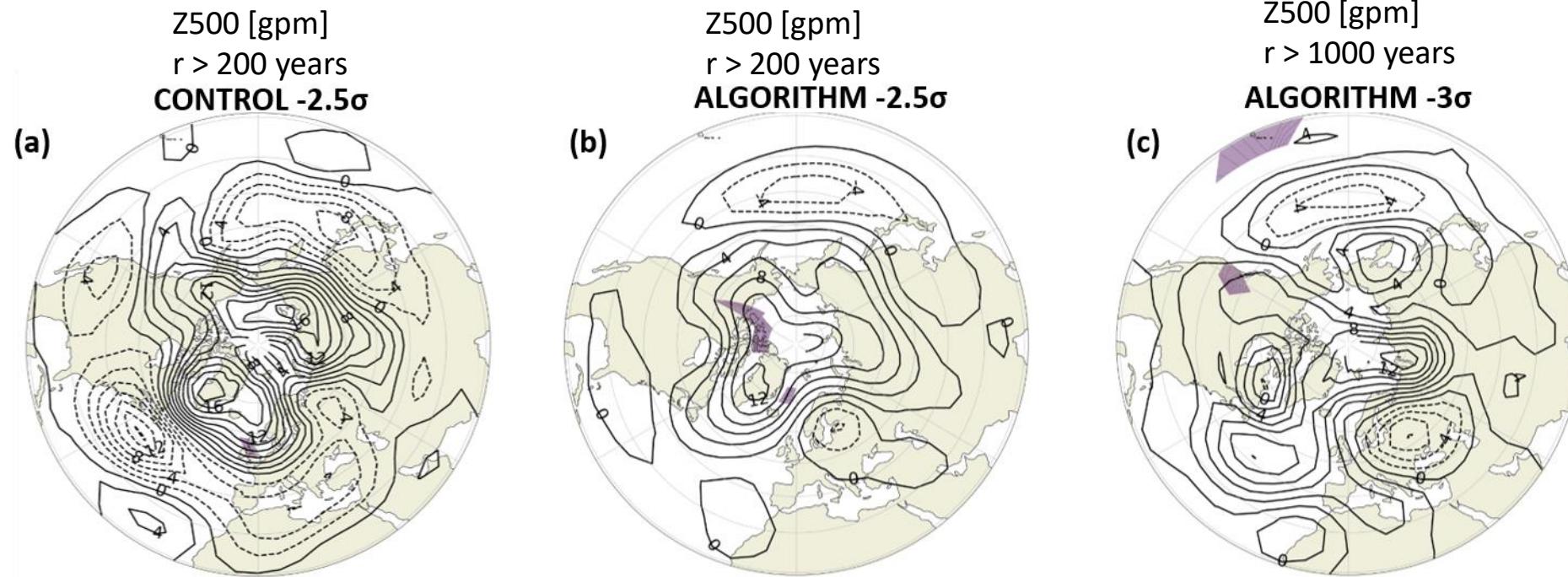
Atmospheric dynamics during extremes of sea ice reduction



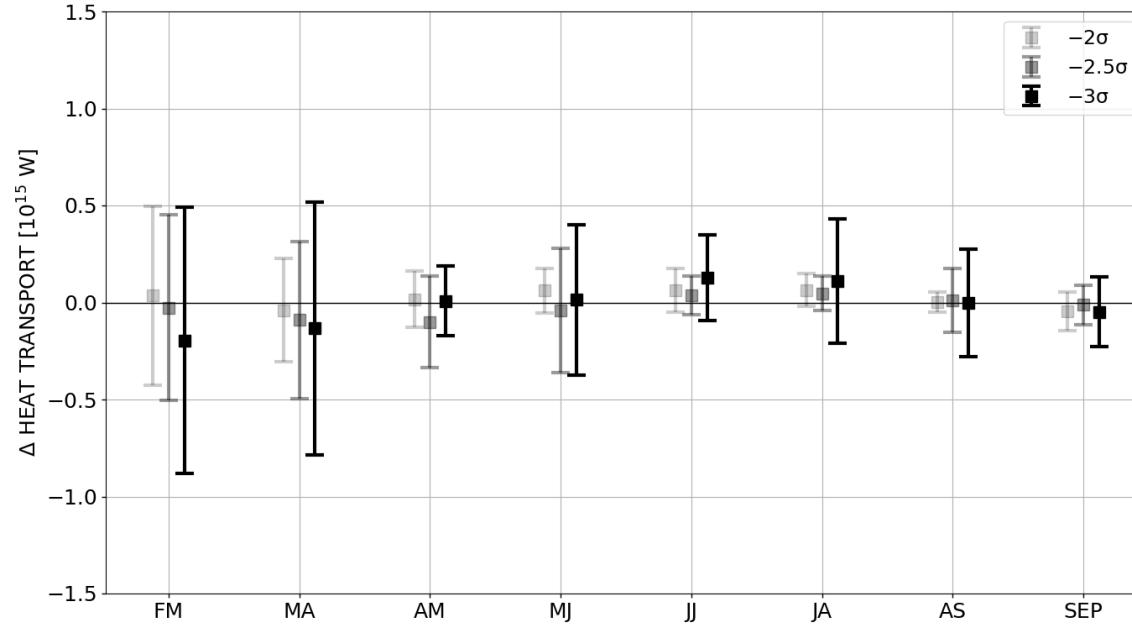
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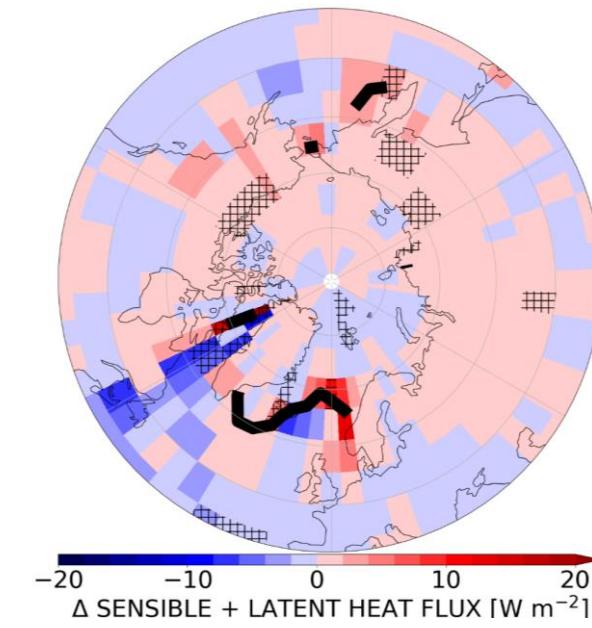
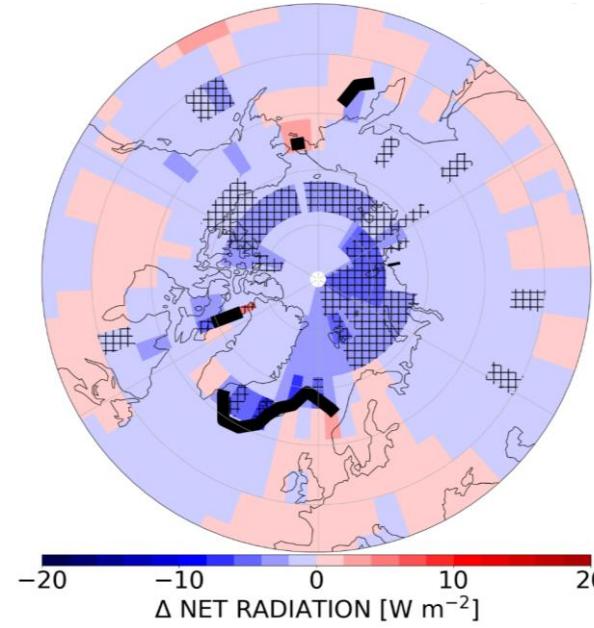
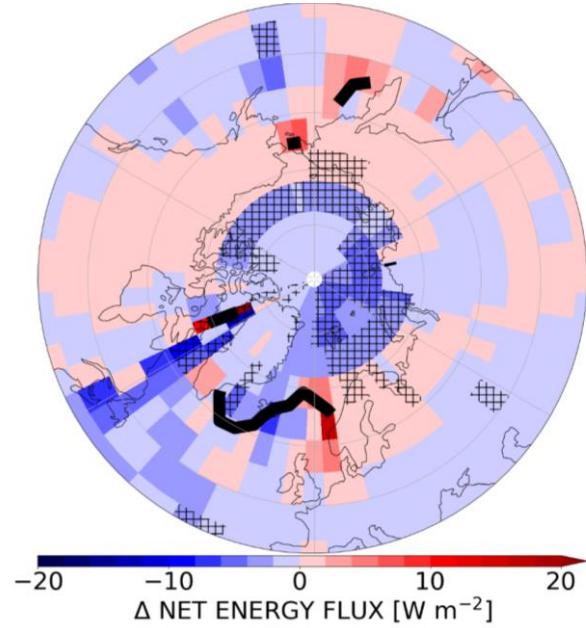
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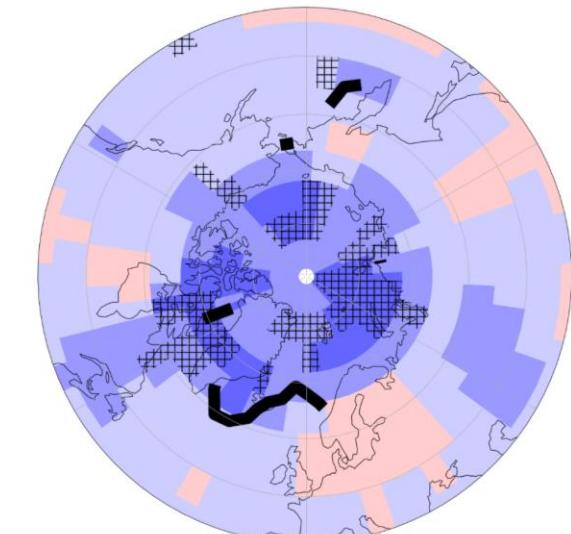
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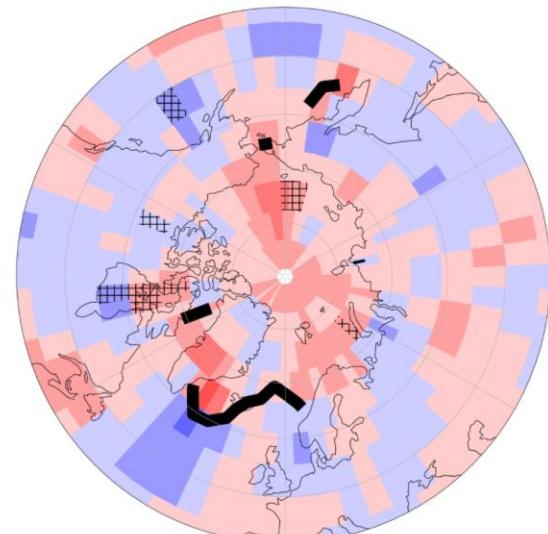
Seasonal surface energy fluxes during extremes of sea ice reduction



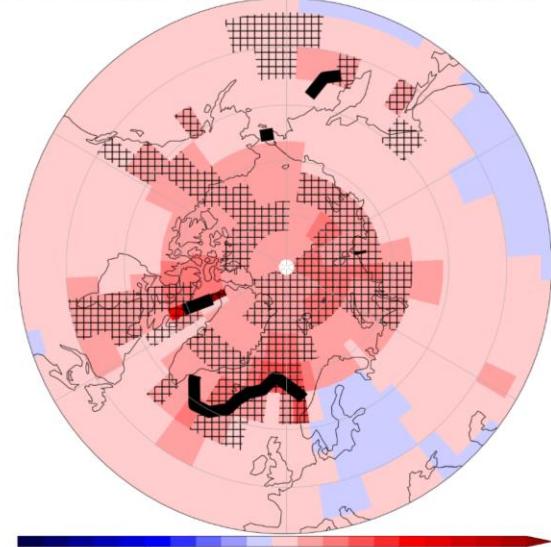
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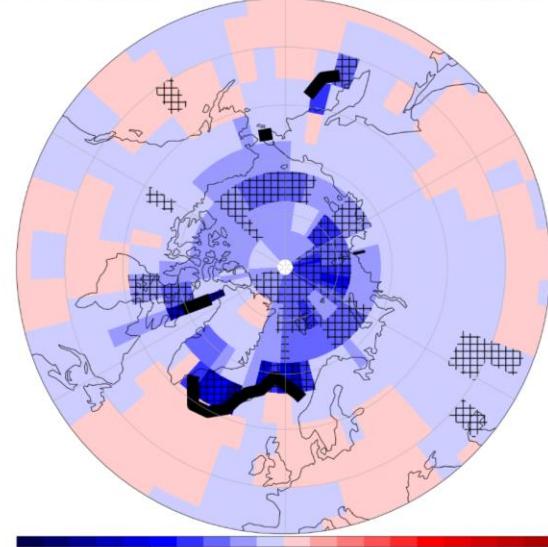
-20 -10 0 10 20
Δ DOWNWARD LONGWAVE RADIATION [W m^{-2}]



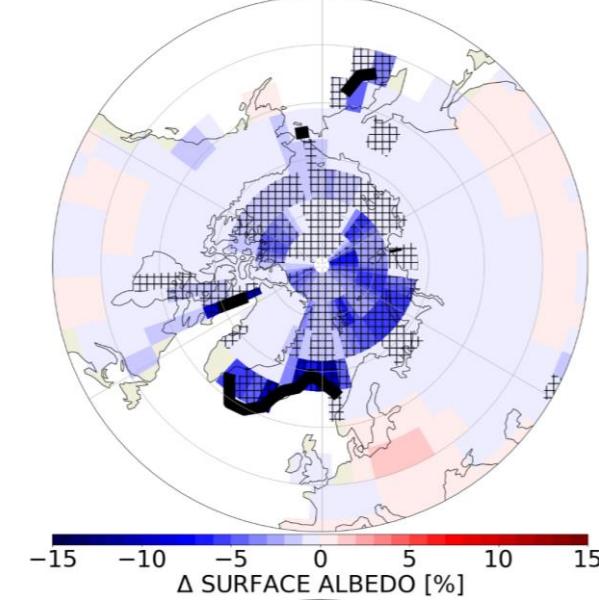
-20 -10 0 10 20
Δ DOWNWARD SHORTWAVE RADIATION [W m^{-2}]



-20 -10 0 10 20
Δ UPWARD LONGWAVE RADIATION [W m^{-2}]

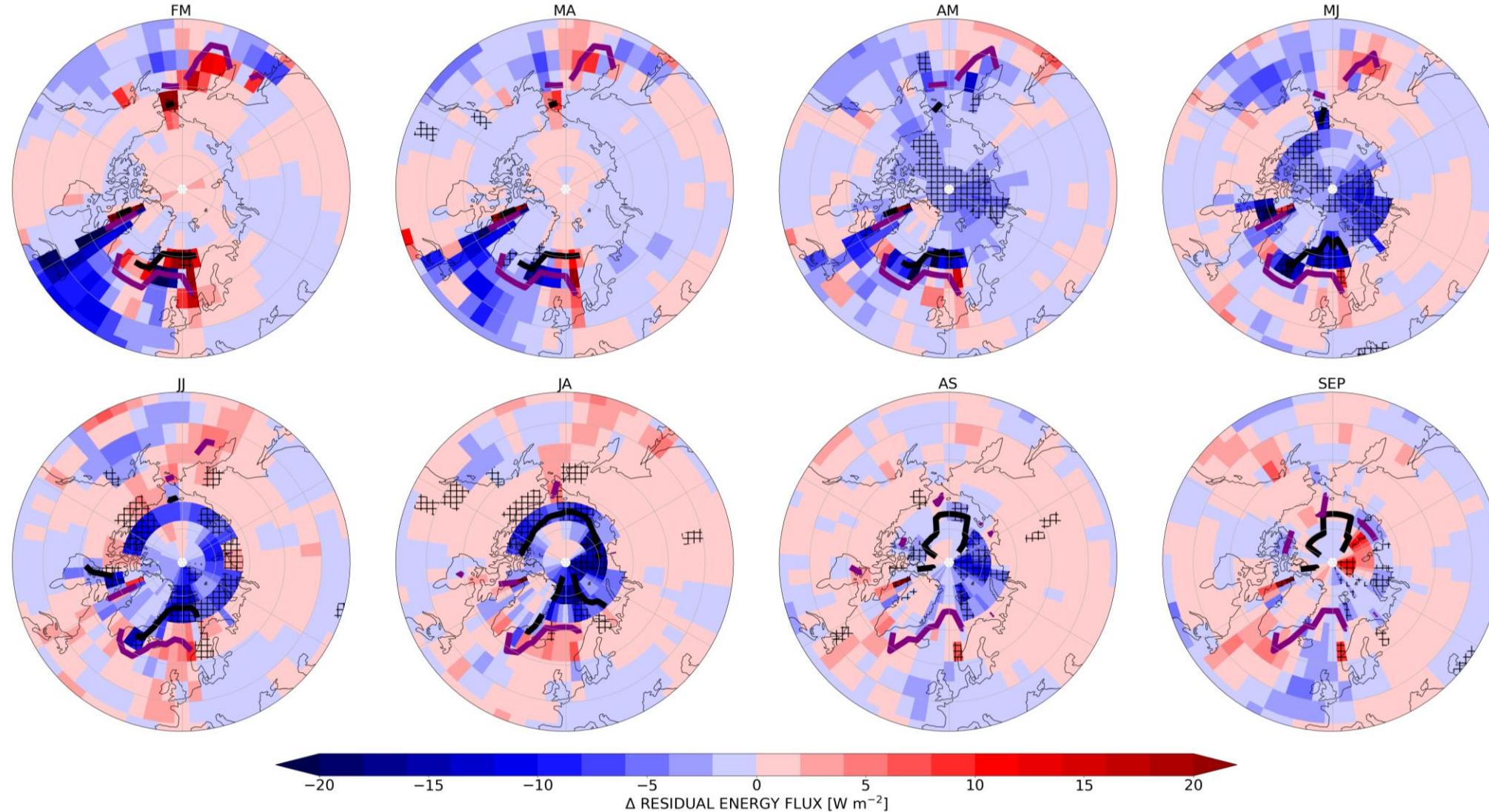


-20 -10 0 10 20
Δ UPWARD SHORTWAVE RADIATION [W m^{-2}]

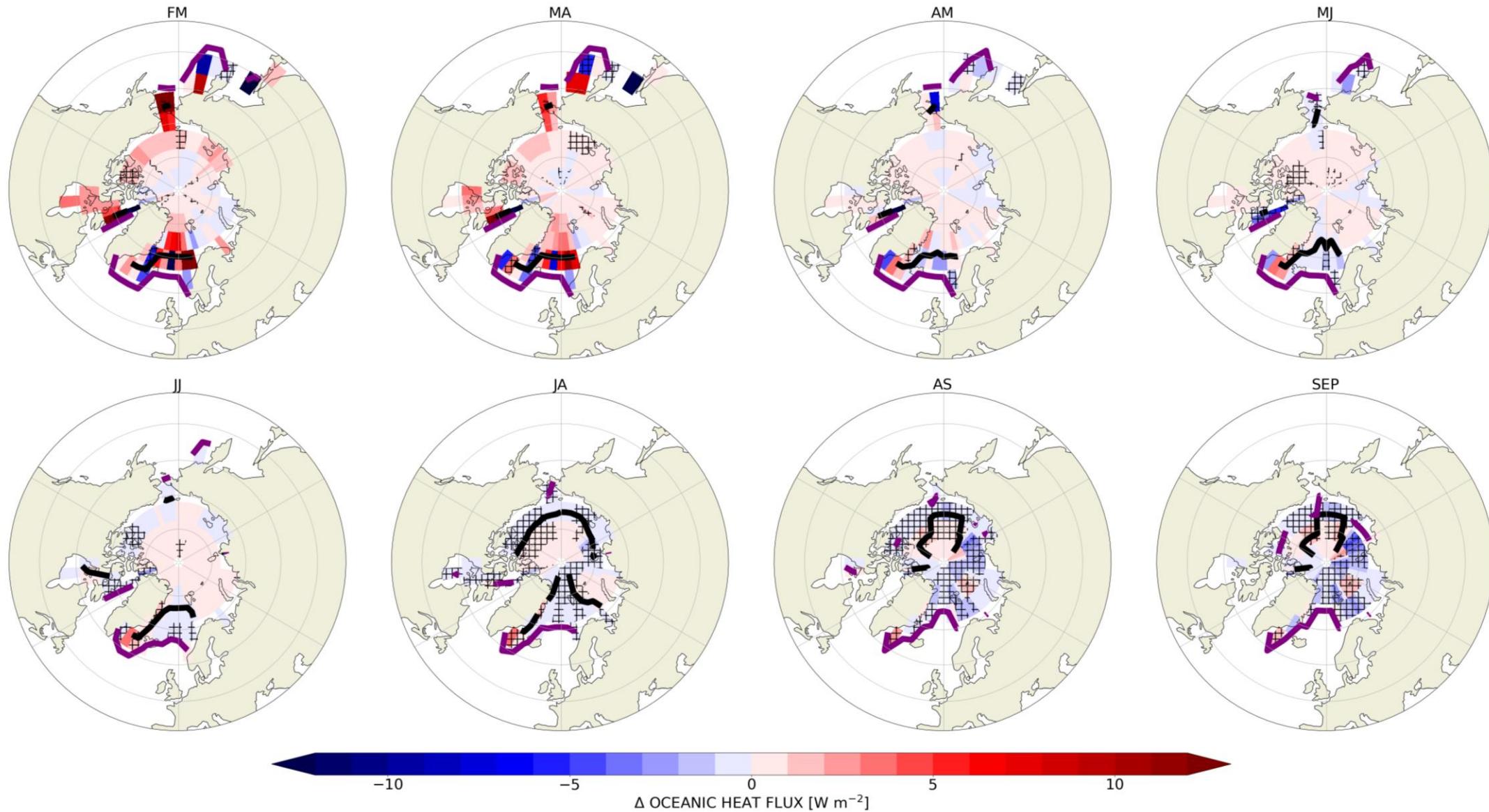


-15 -10 -5 0 5 10 15
Δ SURFACE ALBEDO [%]

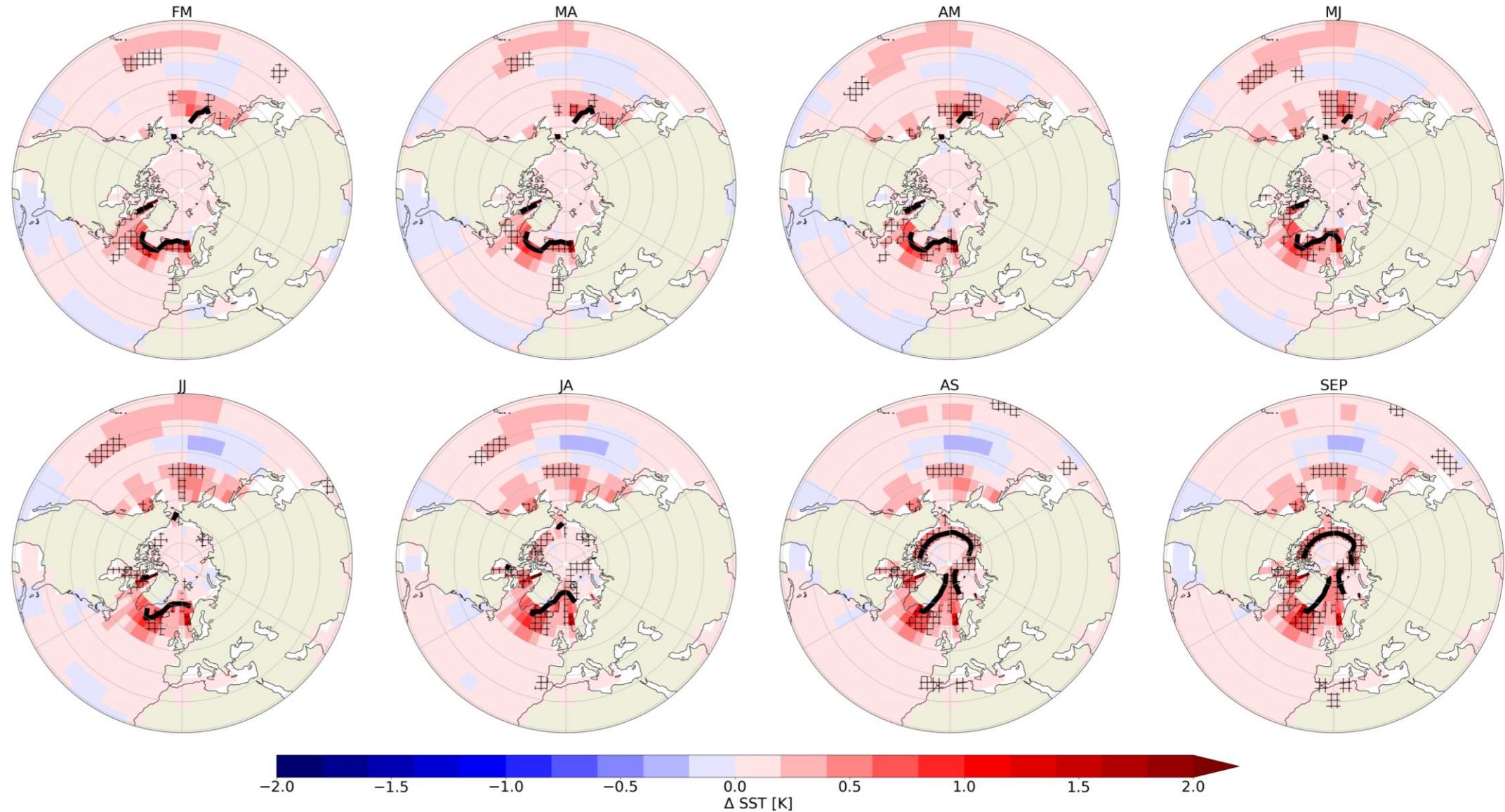
Surface energy fluxes during extremes of sea ice reduction



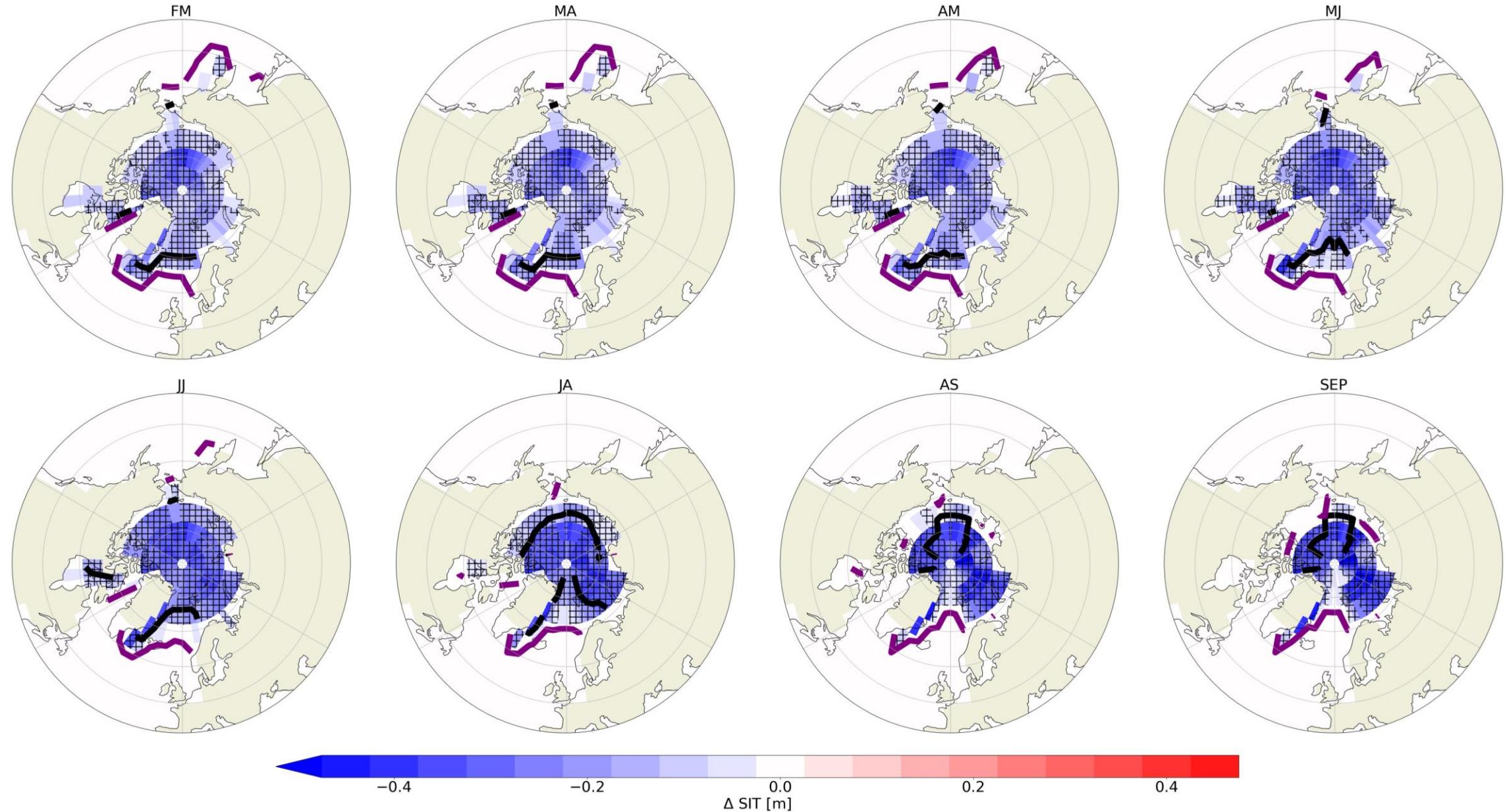
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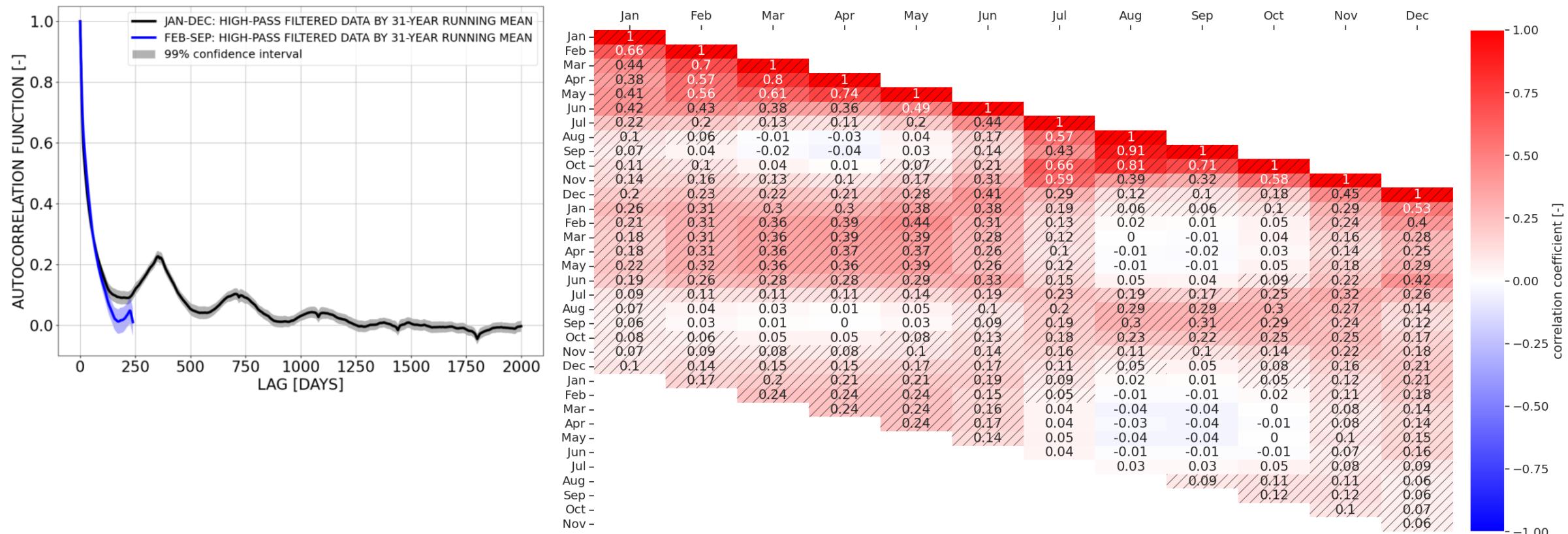
State of sea ice-ocean during extremes of sea ice reduction



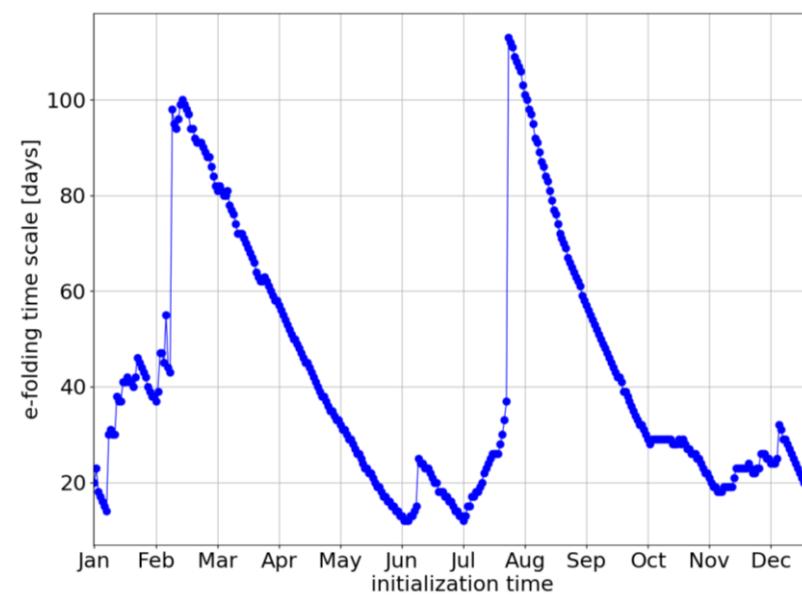
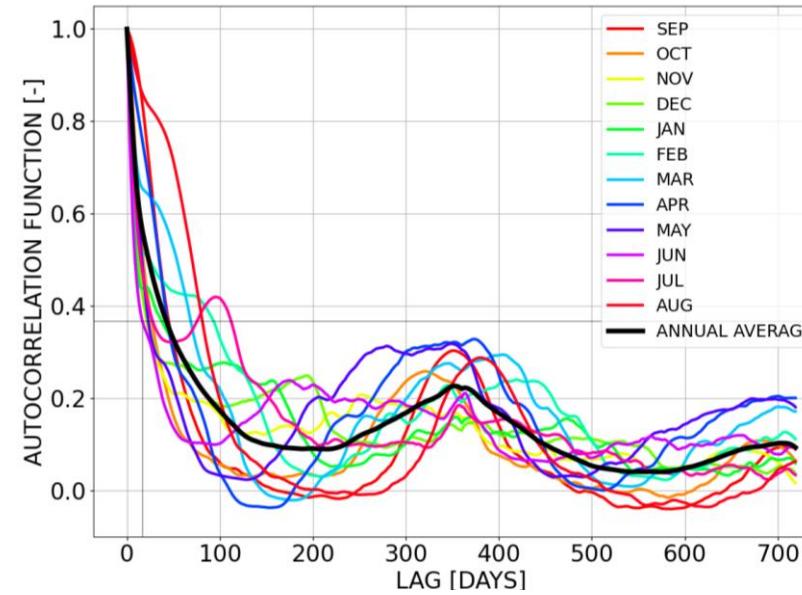
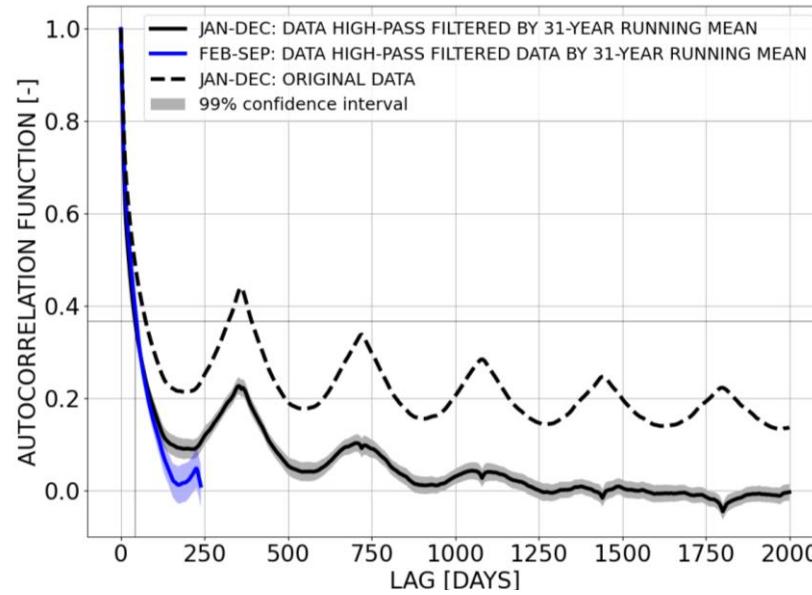
State of sea ice-ocean during extremes of sea ice reduction



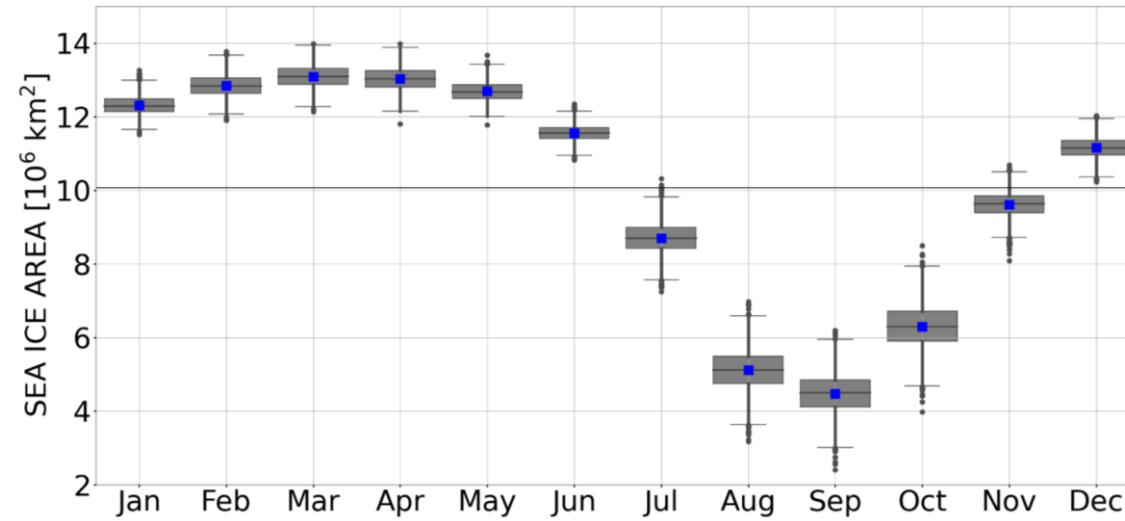
Climatological properties of pan-Arctic sea ice area in PlaSim-T21



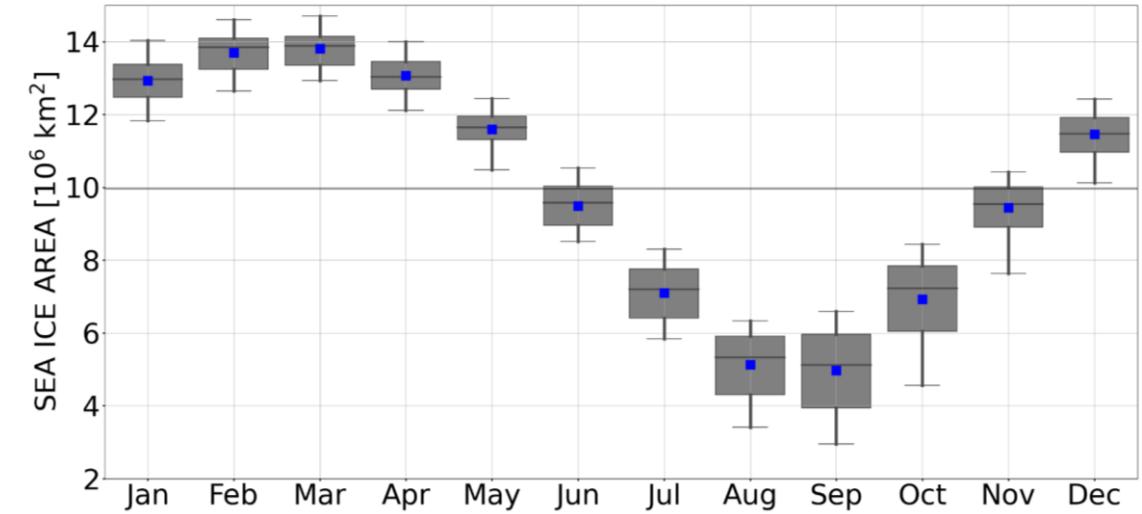
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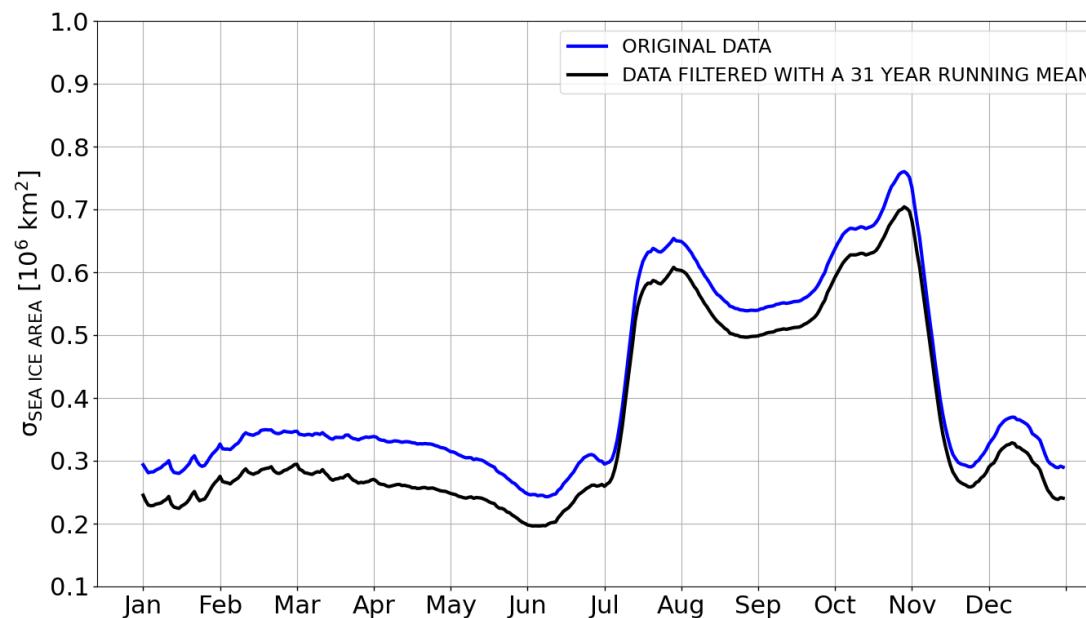


PlaSim-T21-LSG

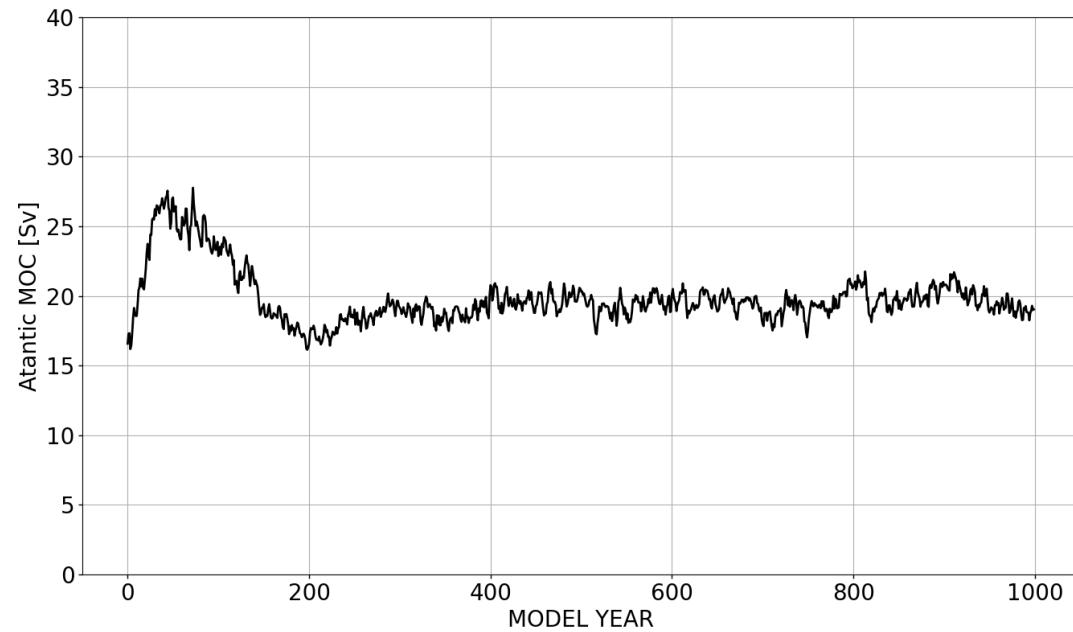


OSI SAF 1979-2022

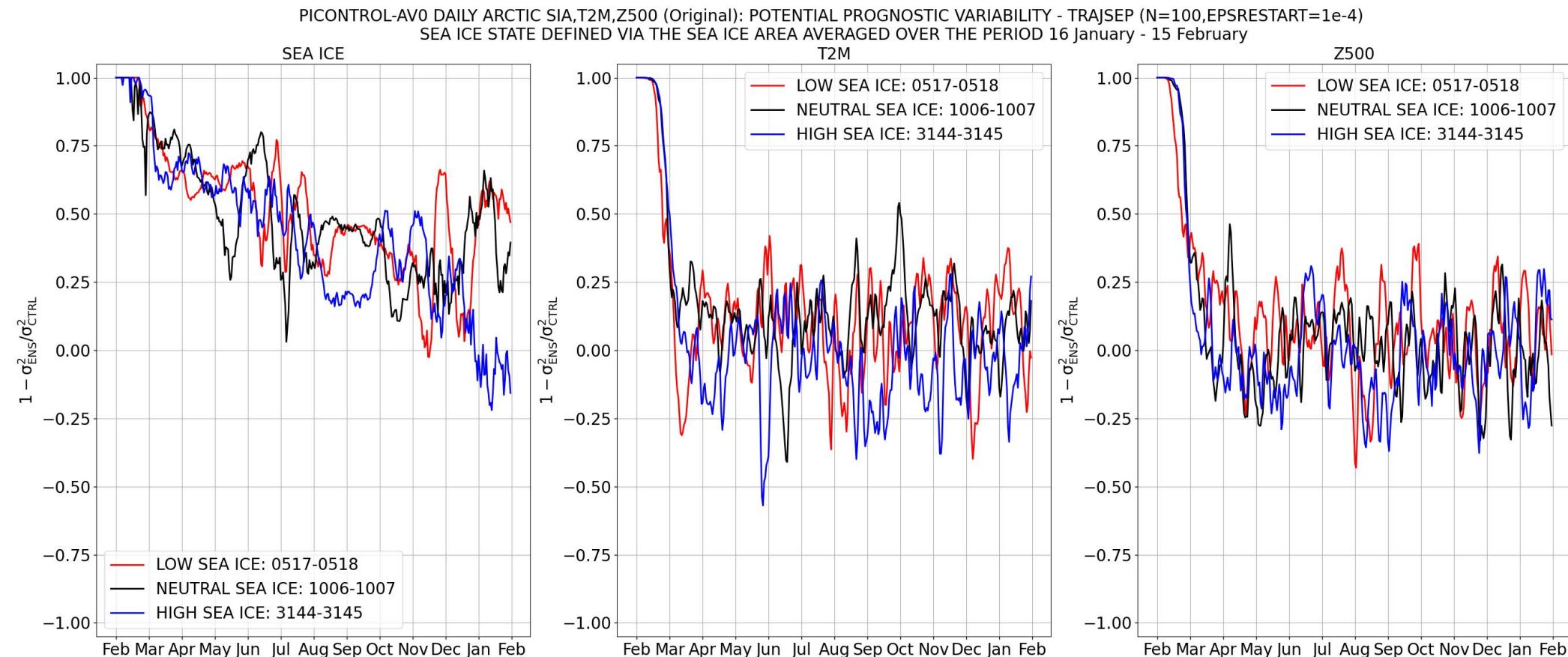
Climatological properties of pan-Arctic sea ice area in PlaSim-T21



Climatological properties of pan-Arctic sea ice area in PlaSim-T21



General dynamical properties



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

