Extreme Arctic sea ice lows investigated with a rare event algorithm

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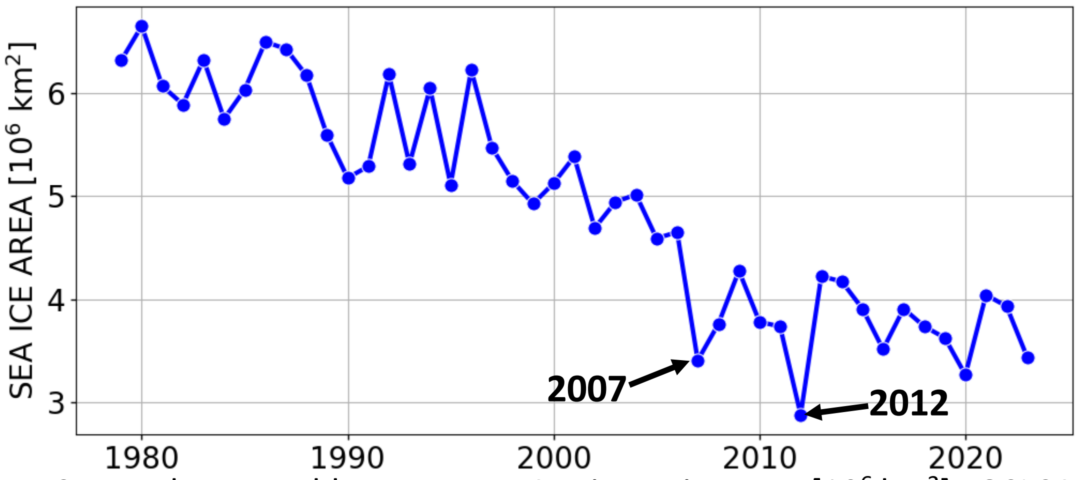
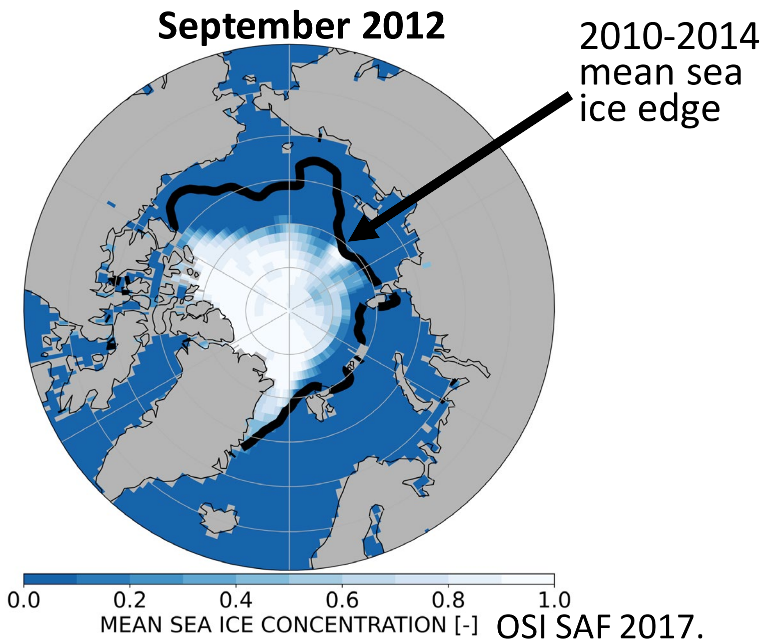
Extreme reductions in the summer pan-Arctic sea ice area



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

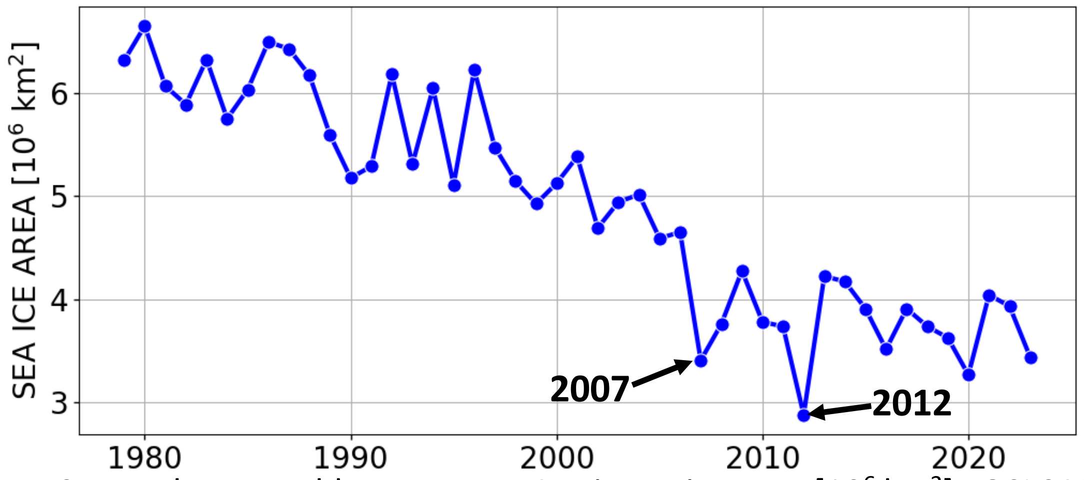


OSI SAF 2017.

- Goal: understanding physical drivers and quantifying probabilities of extremes of Arctic sea ice reduction

- Problem: quantitative statistical and dynamical studies of climate extremes hindered by lack of data
  -> lack of observations, poor sampling with numerical models due to large computational cost

Extreme reductions in the summer pan-Arctic sea ice area



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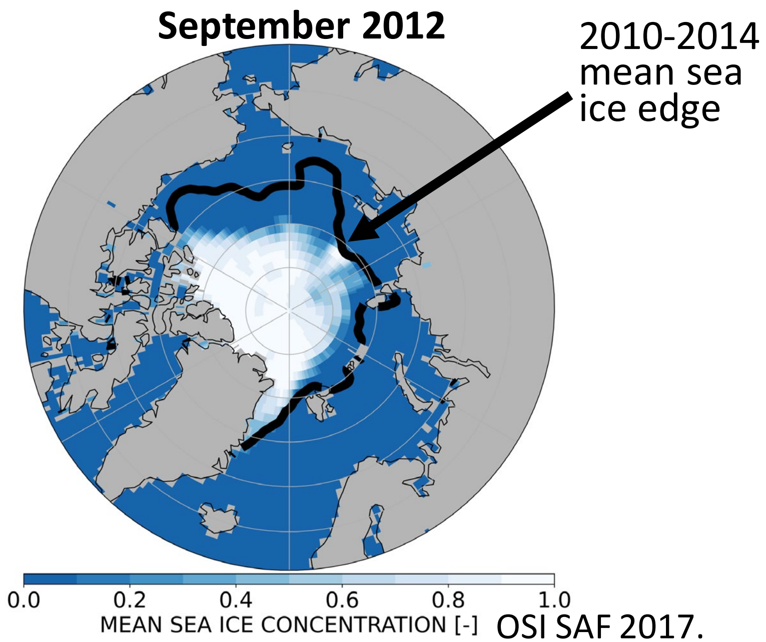

OSI SAF 2017.

- Problem: quantitative statistical and dynamical studies of climate extremes hindered by lack of data

→ From statistical physics: improve the sampling efficiency of extreme events 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 dynamical trajectories in ensemble simulation with numerical model
  -> make trajectories leading to large anomalies of a time-averaged observable (e.g. sea ice area) common
  -> reduces statistical errors (e.g. composites and return times) and generates ultra-rare events

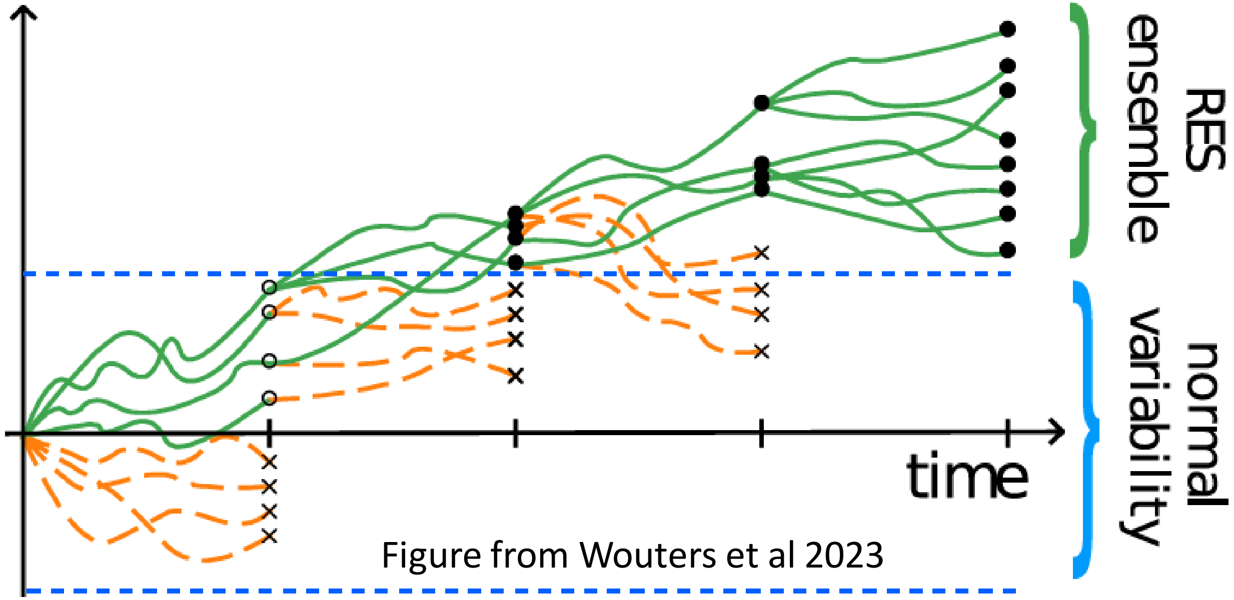

Figure from Wouters et al 2023

Methodology: Rare event algorithm

- Importance sampling of dynamical trajectories in ensemble simulation with numerical model
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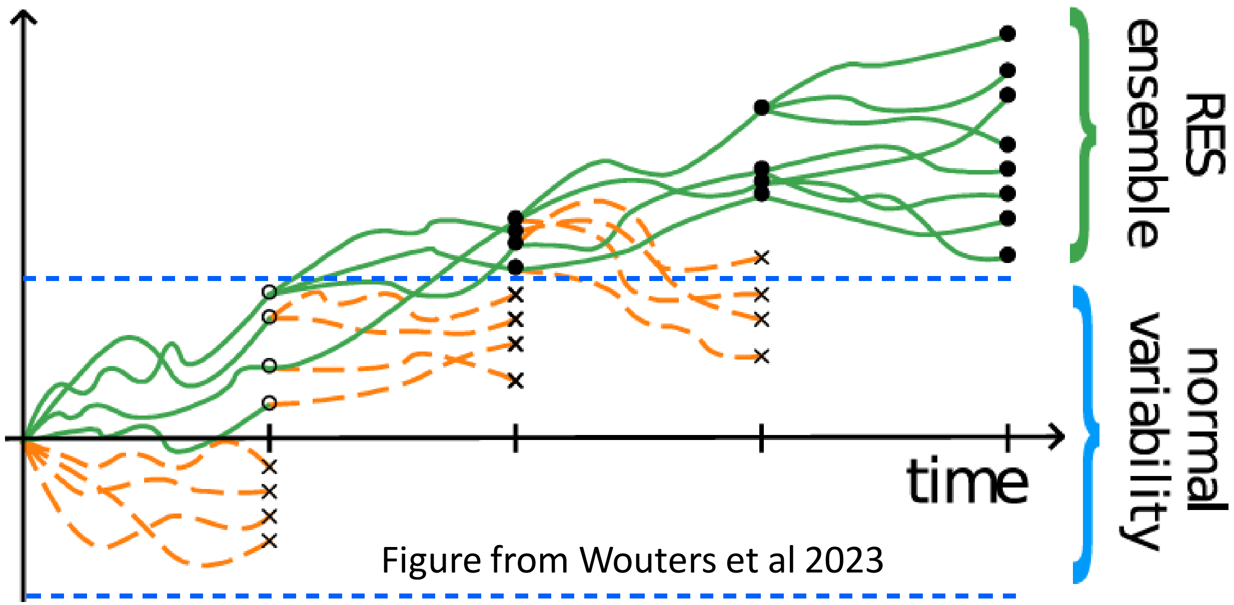
- Resampling at constant time intervals: trajectories are killed or cloned depending on weights measuring the likelihood to lead to an extreme event



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Methodology: Rare event algorithm

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  -> make trajectories leading to large anomalies of a time-averaged observable (e.g. sea ice area) common

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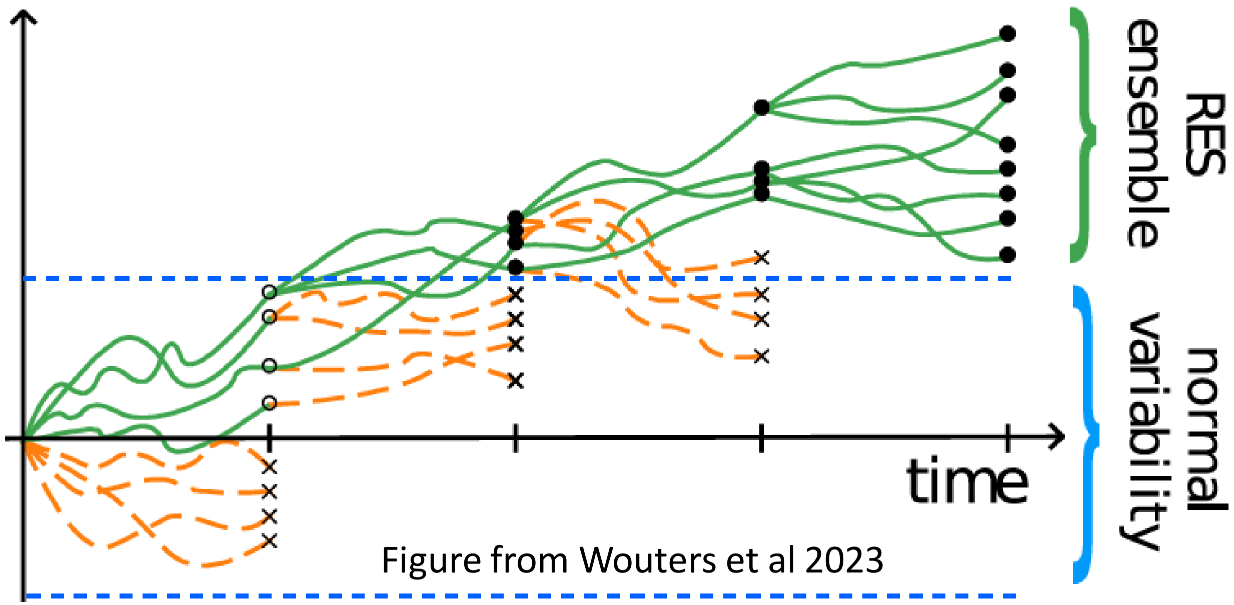
- Importance sampling formula: relates probabilities of trajectories between biased and unbiased statistics

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

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



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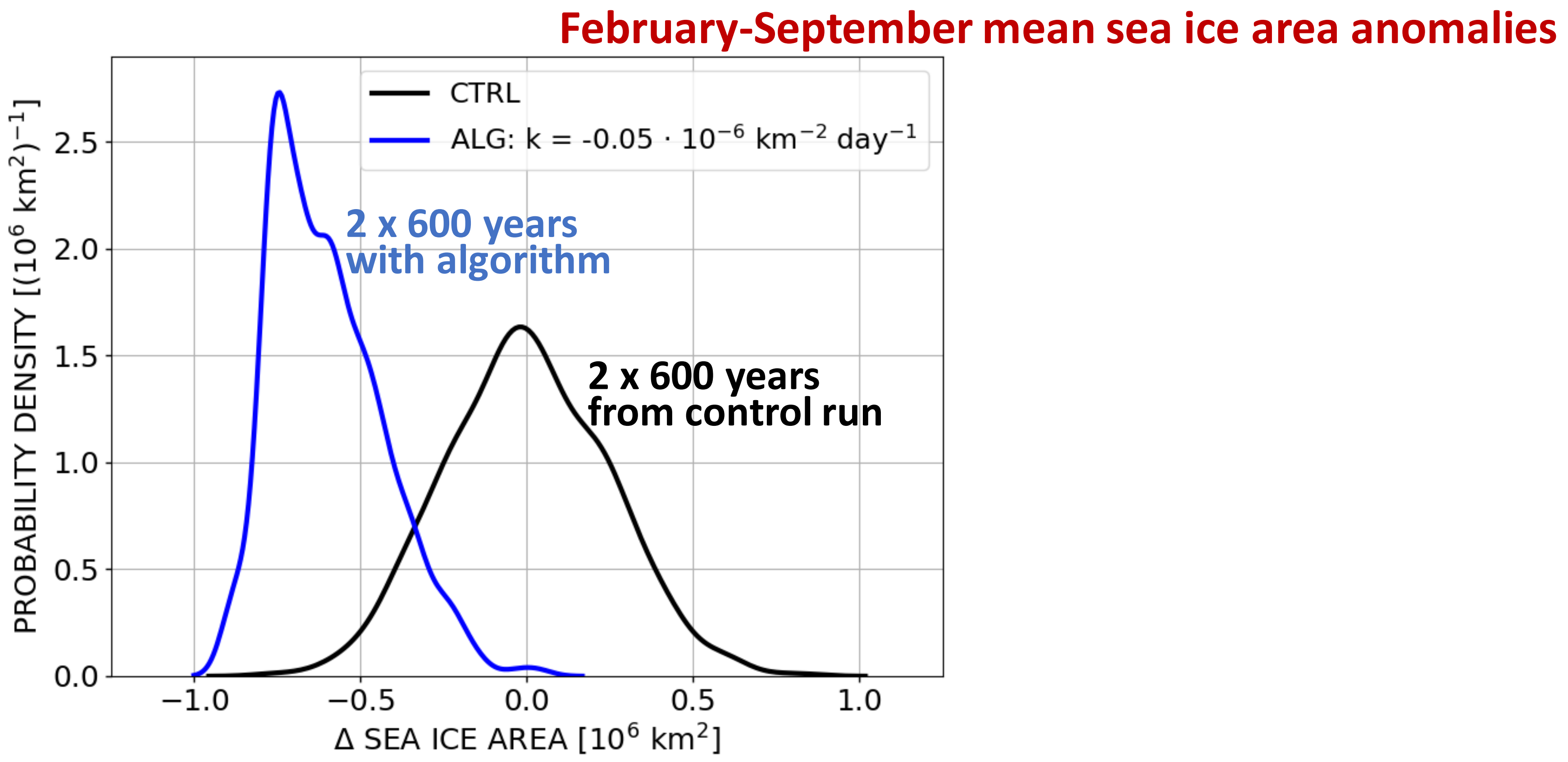
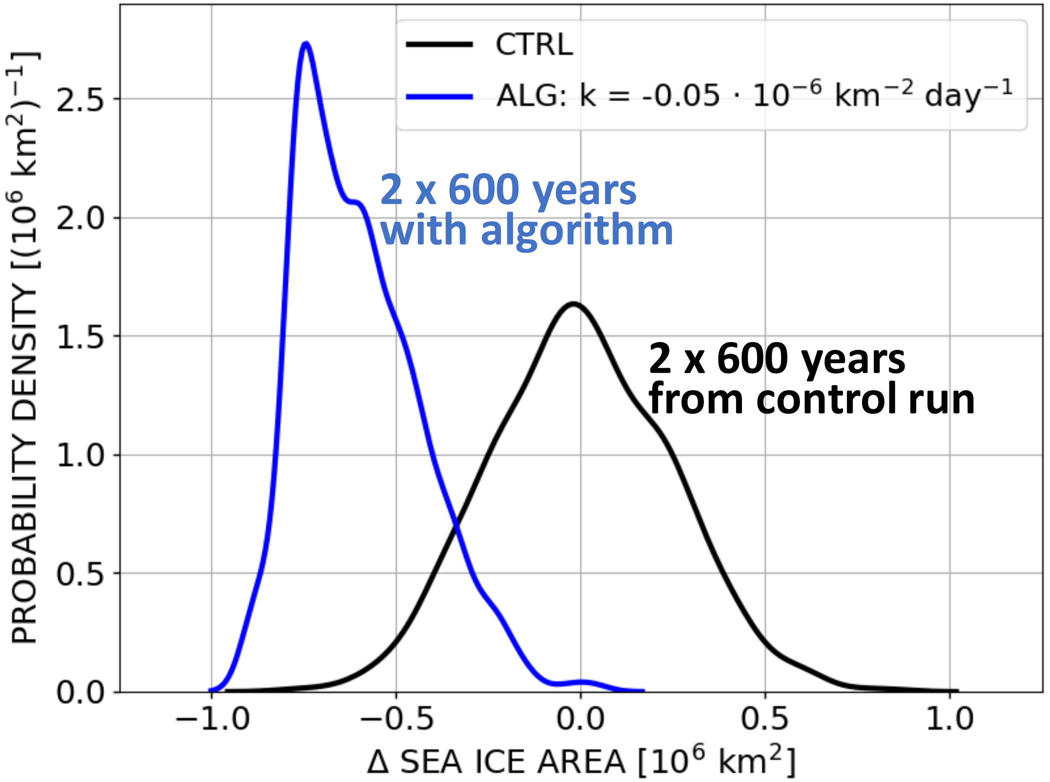
Results: Application of the rare event algorithm to PlaSim-T21-LSG



- Independent initial conditions sampled from long control run (stationary pre-industrial climate)

Results: Application of the rare event algorithm to PlaSim-T21-LSG

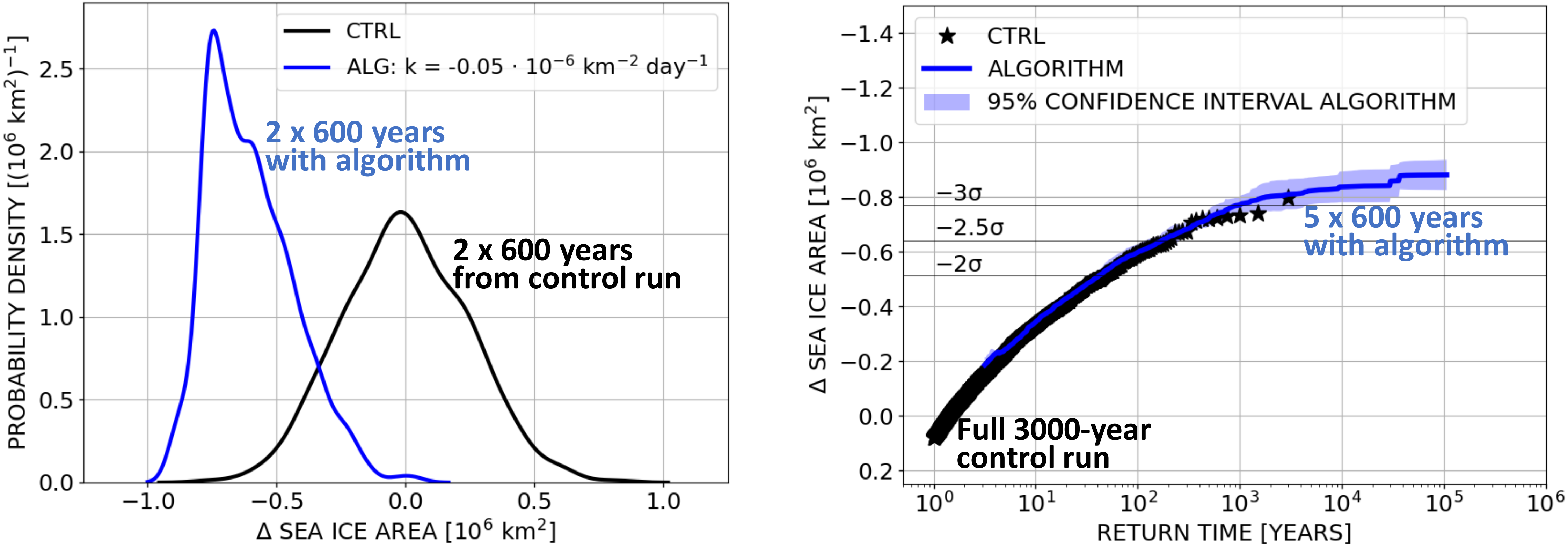
February-September mean sea ice area anomalies



- Independent initial conditions sampled from long control run (stationary pre-industrial climate)
- Importance sampling of extreme negative February-September mean pan-Arctic sea ice area anomalies

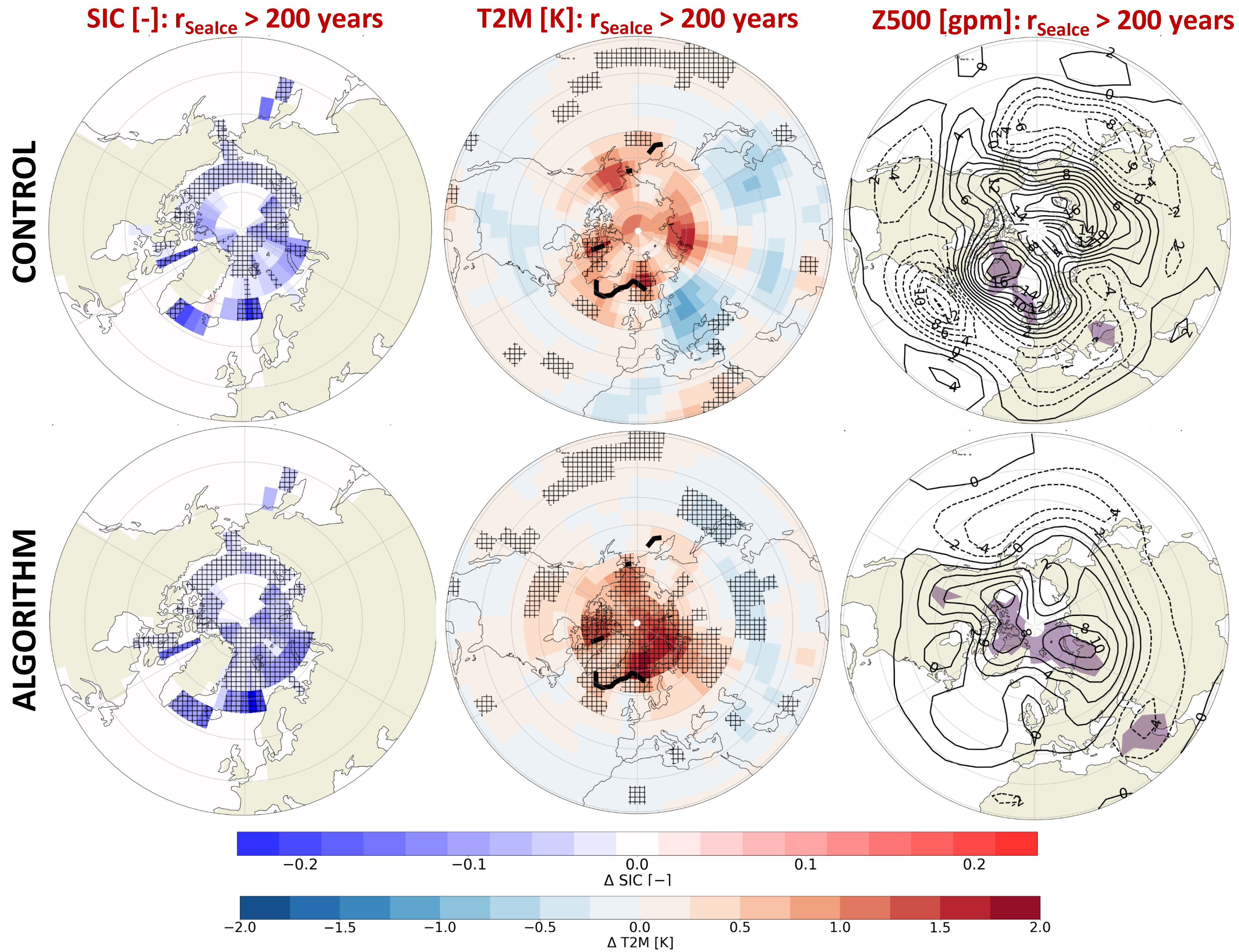
Results: Application of the rare event algorithm to PlaSim-T21-LSG

February-September mean sea ice area anomalies



- Independent initial conditions sampled from long control run (stationary pre-industrial climate)
- 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 order 10^3 years

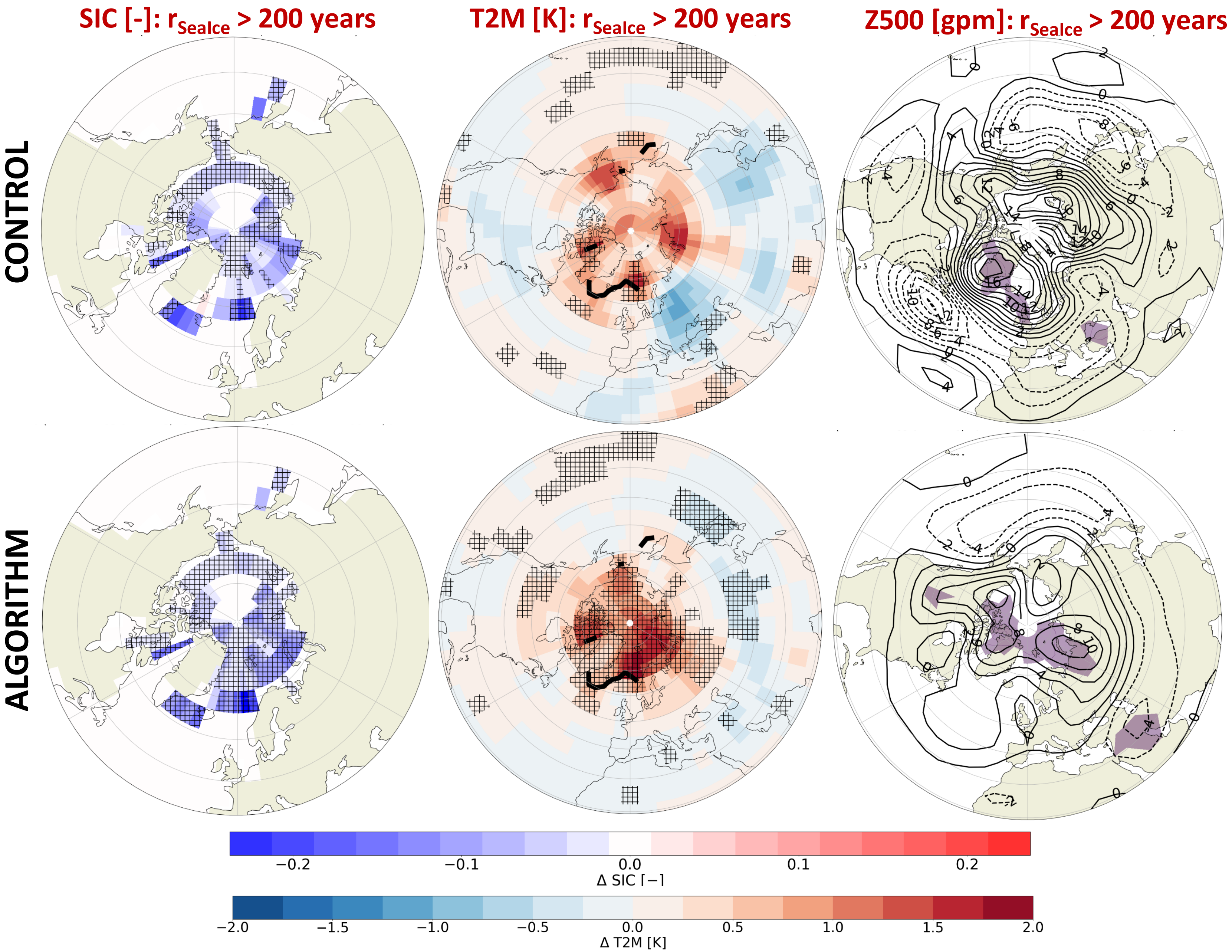
Results: Application of the rare event algorithm to PlaSim-T21-LSG



Hatching and shading: Significance at the 5% level

- Improved composite statistics with the algorithm compared to control run

Results: Application of the rare event algorithm to PlaSim-T21-LSG



Hatching and shading: Significance at the 5% level

- Improved composite statistics with the algorithm compared to control run

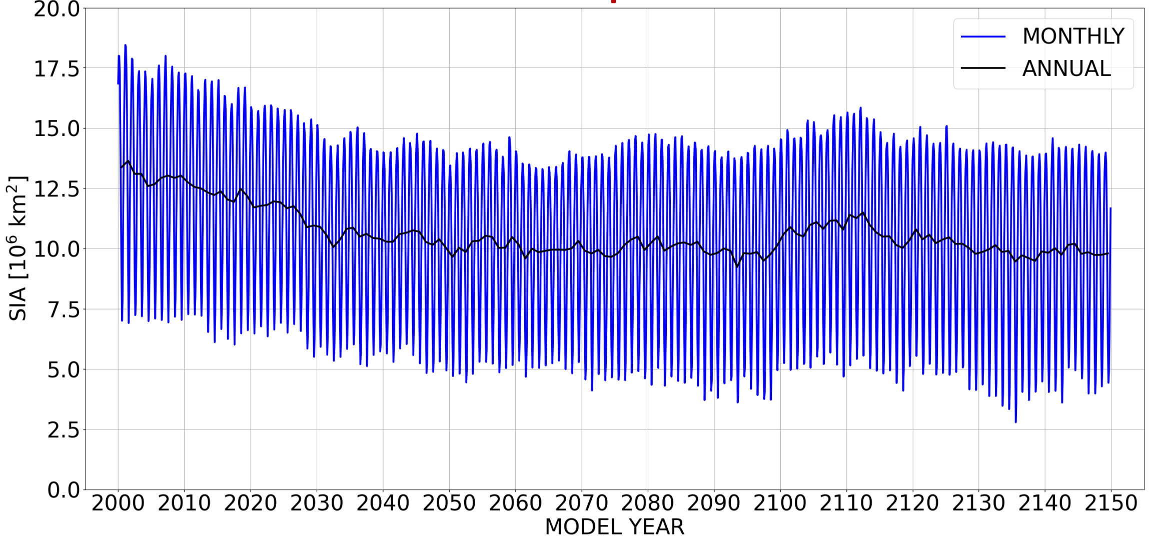
- Drivers of warm Arctic and low sea ice in PlaSim-T21-LSG:
  - winter preconditioning
  - warm and moist/cloudy spring atmosphere
  - sea ice-albedo feedback

  (see Sauer et al. 2024)

Work in progress: Application of the rare event algorithm to EC-Earth3.3.1

- EC-Earth3.3.1 under stationary present day climate (IFS-36r4-T255L91, NEMO-3.6-ORCA1L75, LIM3.6)

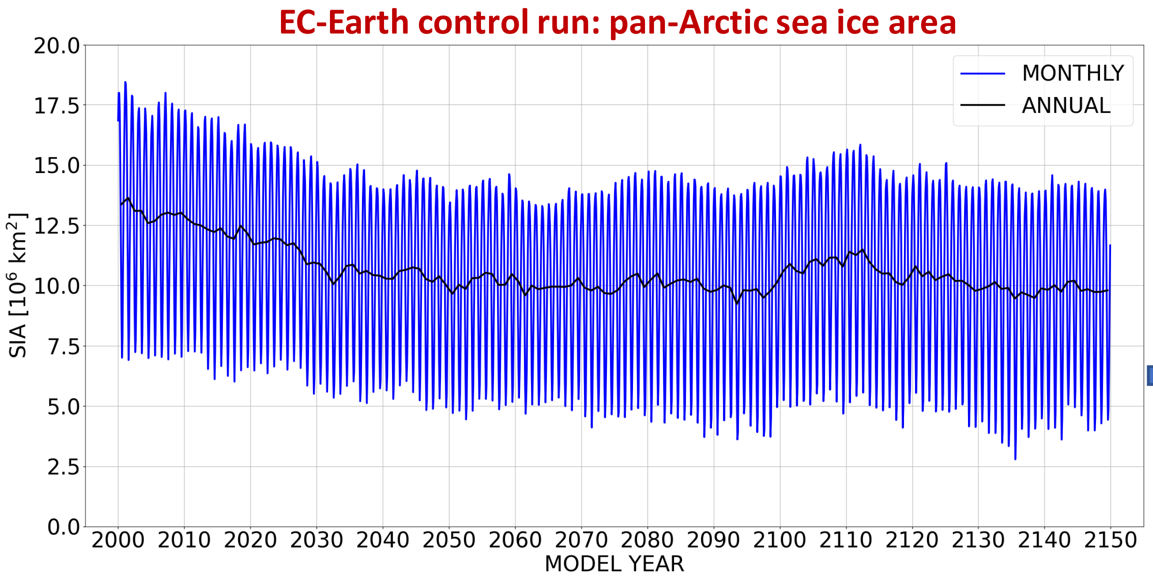
EC-Earth control run: pan-Arctic sea ice area



Work in progress: Application of the rare event algorithm to EC-Earth3.3.1

- EC-Earth3.3.1 under stationary present day climate (IFS-36r4-T255L91, NEMO-3.6-ORCA1L75, LIM3.6)

- Start ensemble from specific initial condition: e.g. winter prior to extreme sea ice low
  -> What was the probability of the extreme as a function of that initial state?
  -> How extreme could the sea ice low have become?
  -> What are the typical drivers of extreme sea ice lows considering the large amount of available events?



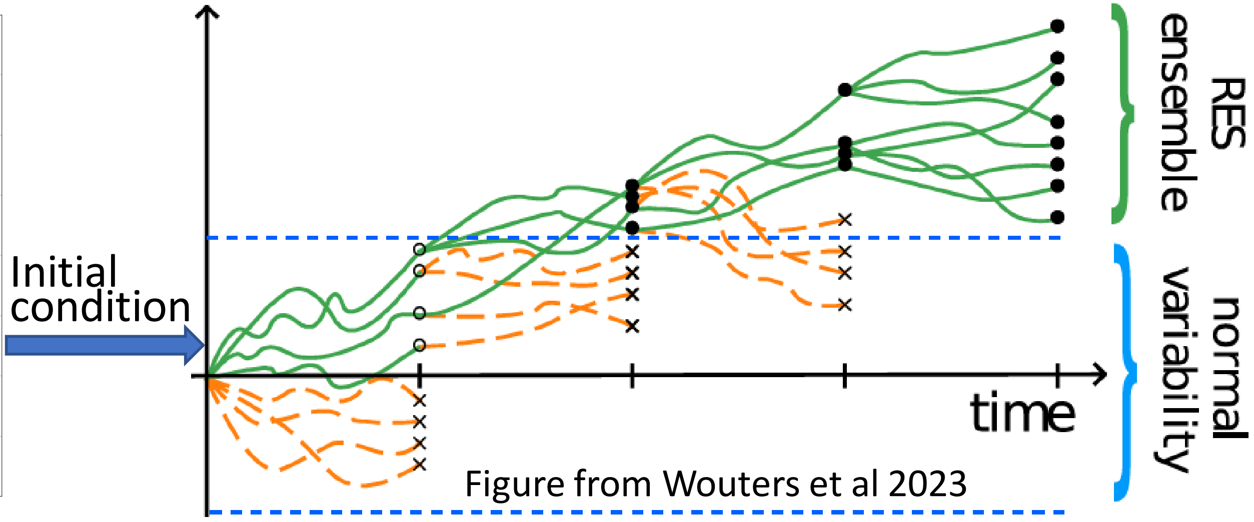


Figure from Wouters et al 2023

Appendix

Methodology: Rare event algorithm

1) Consider N **trajectories** $\{X_n(t)\}$ $(n = 1, 2, \dots, N)$, an **observable** $A(\{X_n(t)\})$, a **total simulation time** T_a and a **resampling time** τ_r

2) At regular times $t_i = i\tau_r$ $\left(i = 1, \dots, \frac{T_a}{\tau_r}\right)$, trajectories are **killed or generate a number of replicates** depending on 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 **biasing parameter**

3) After the simulation: **reconstruction of effective ensemble** based on surviving trajectories

4) **Importance sampling formula**: relates probabilities of trajectories between control simulation and simulation with the rare event algorithm

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

P_k, P_0: prob. dens. in biased and unbiased statistics
k, R: biasing parameter and normalization term
t, T_a: time and simulation length
$A, \{X_n(t)\}$: observable and model trajectories

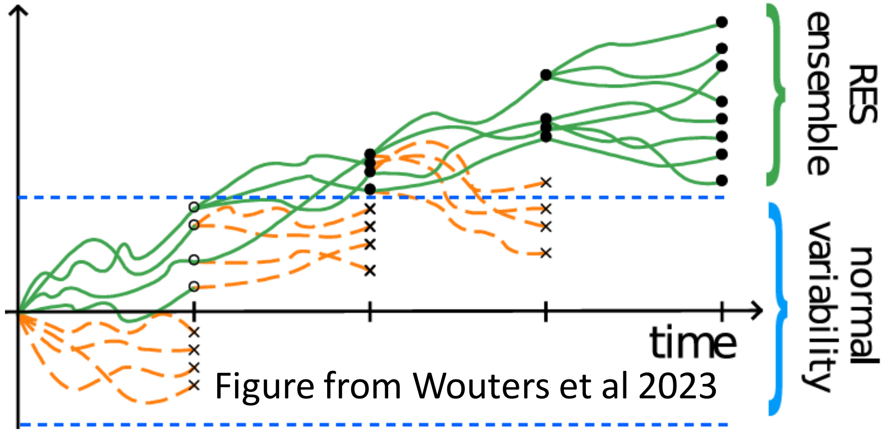
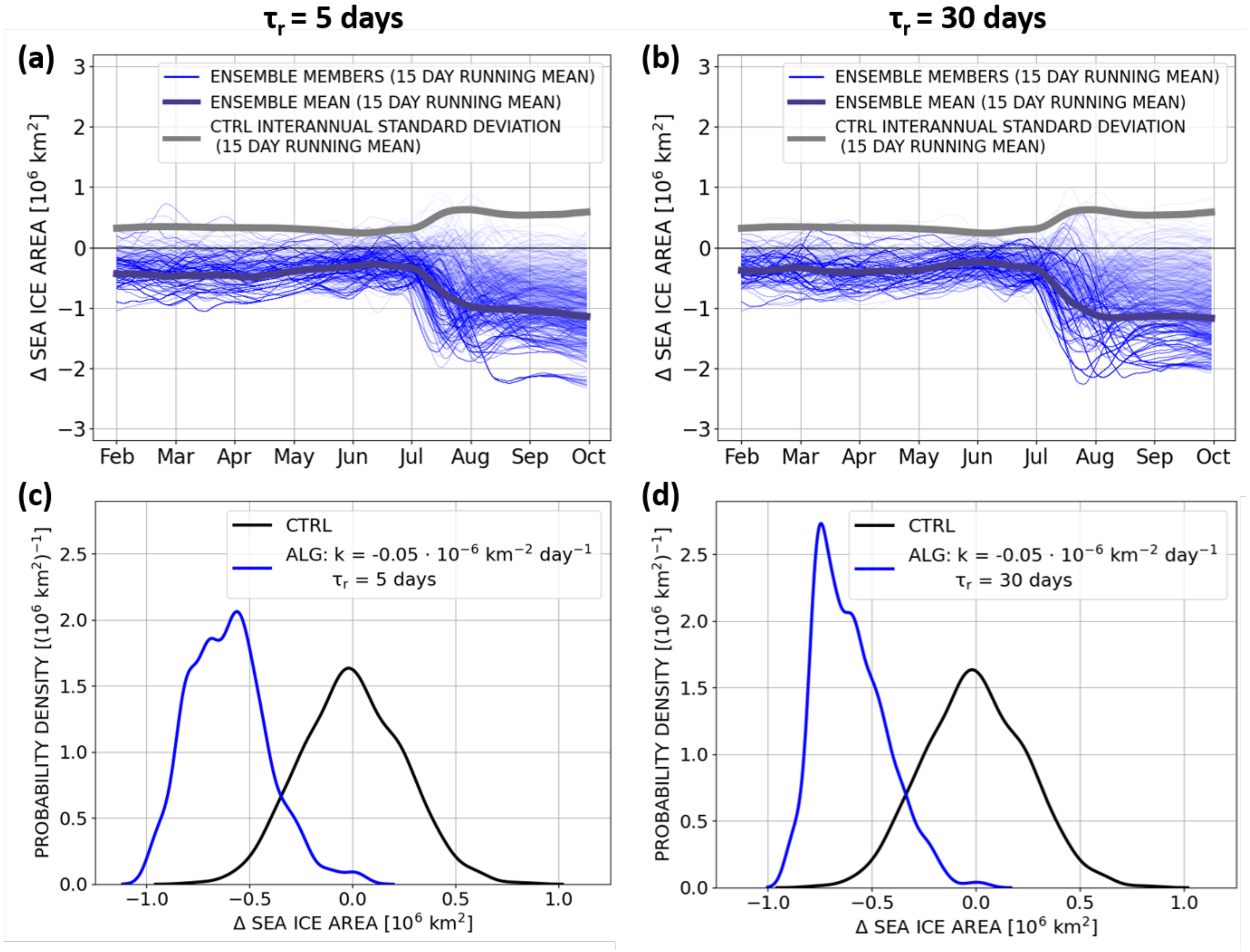


Figure from Wouters et al 2023

Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I

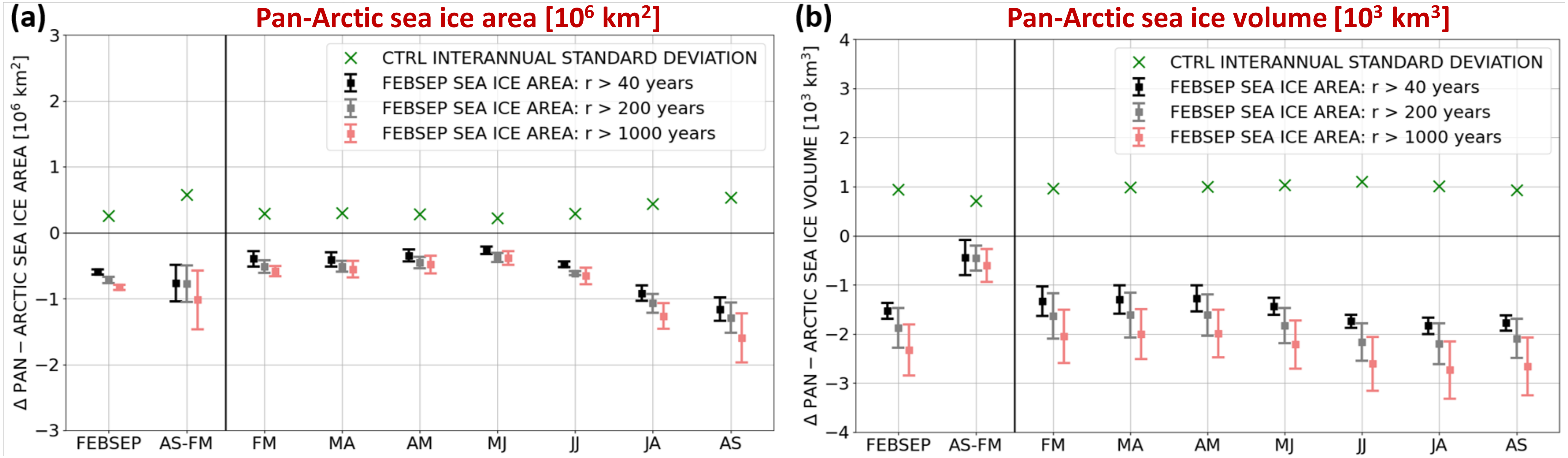


Pan-Arctic sea ice area [10^6 km^2]

Daily mean

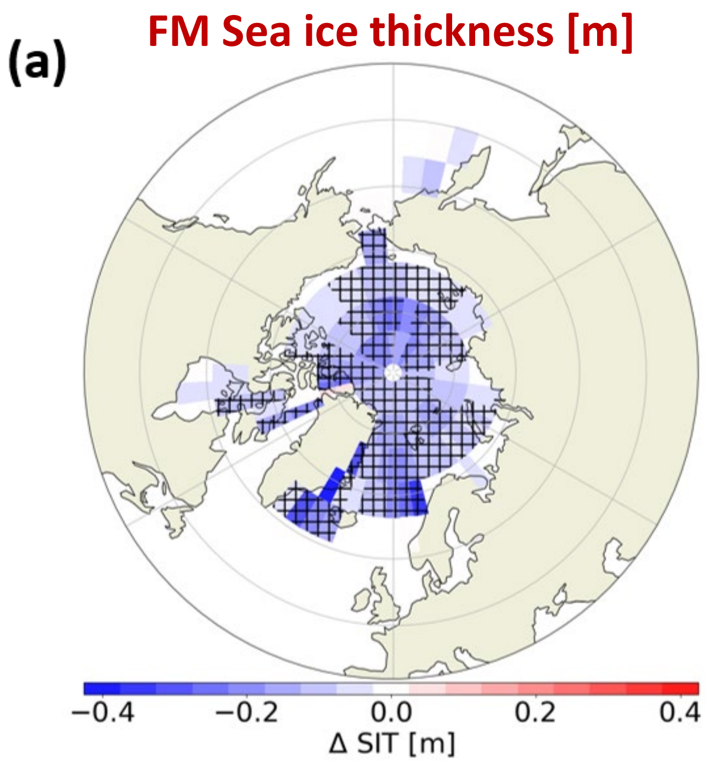
February-September mean

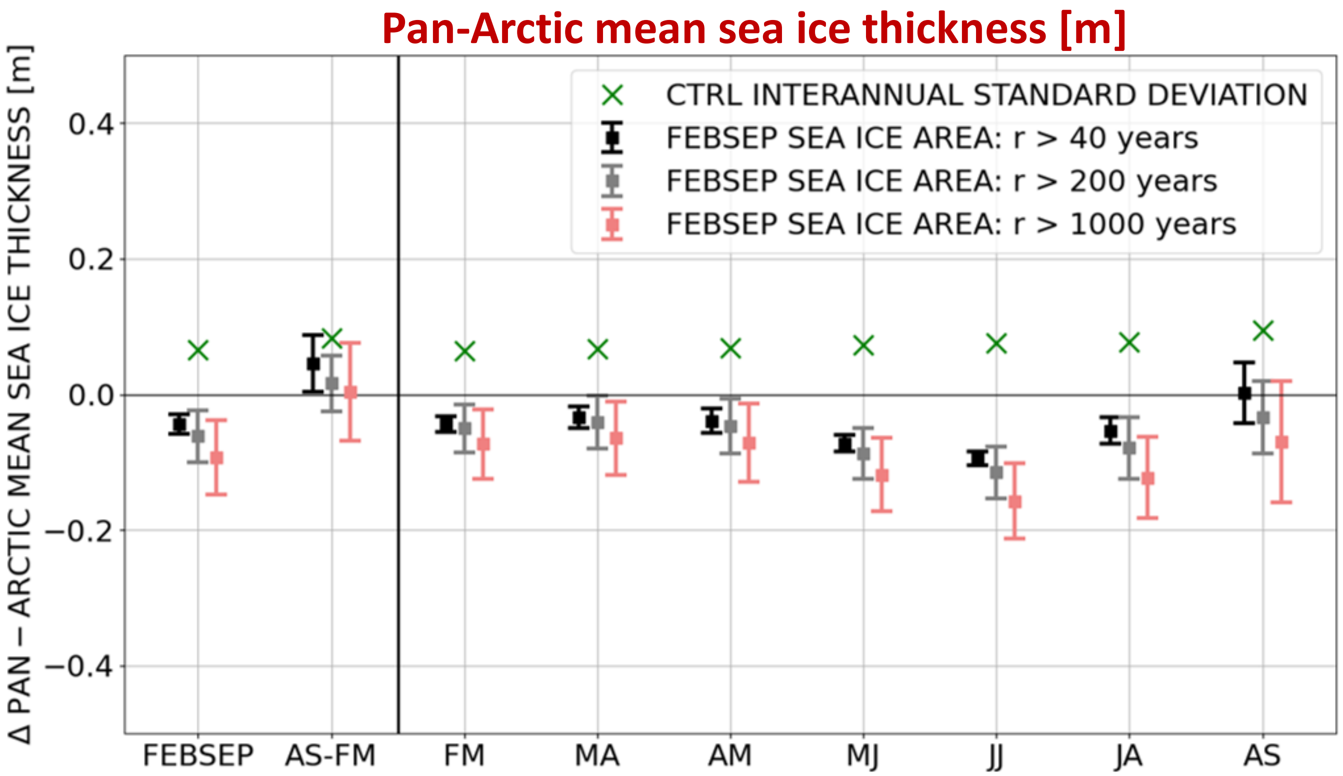
Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I



Error bars: 95 % confidence interval

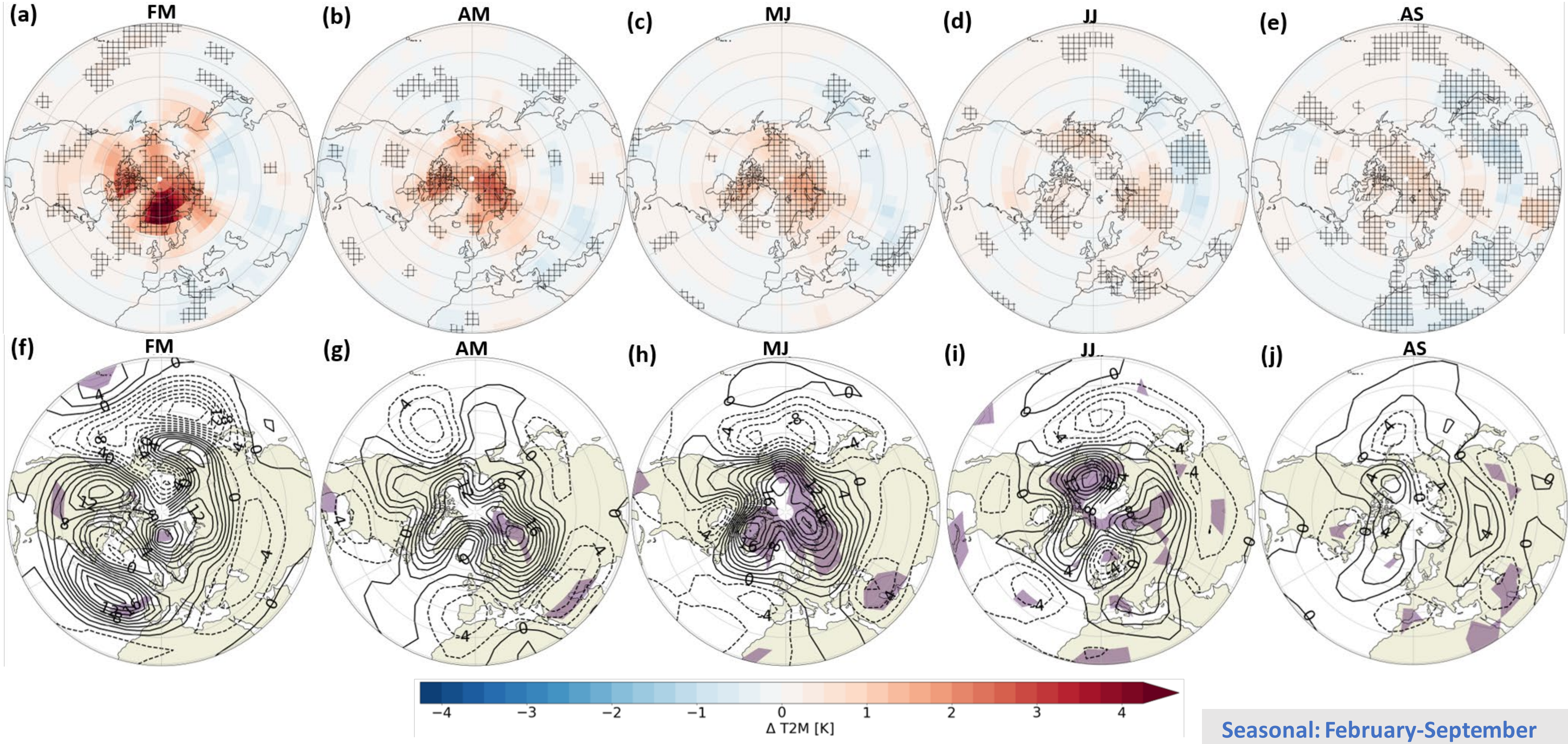
Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I





Hatching and error bars:
Signif. at 5% level and 95 % confidence interval

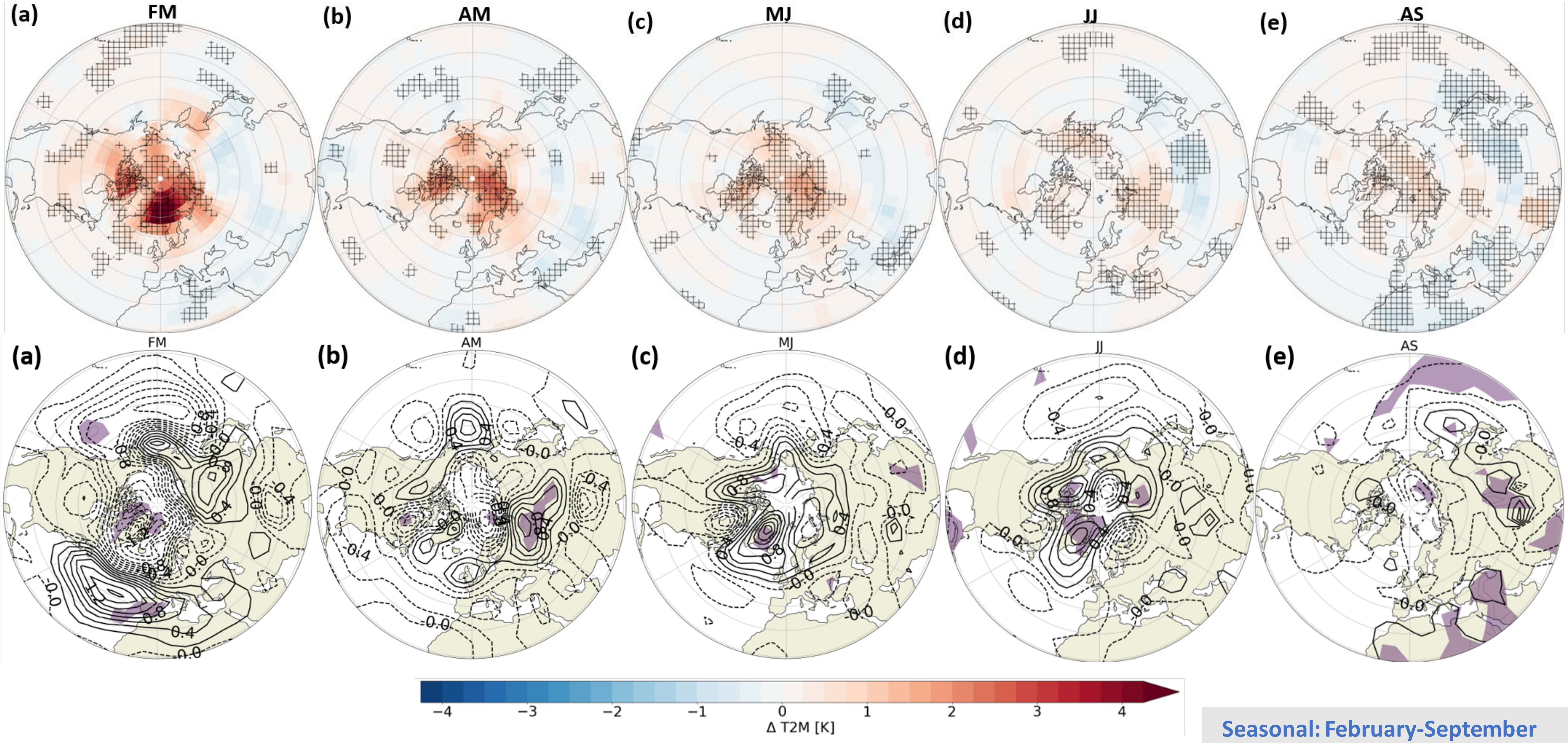
Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I



Seasonal: February-September

Hatching and shading: Significance at the 5% level

Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I

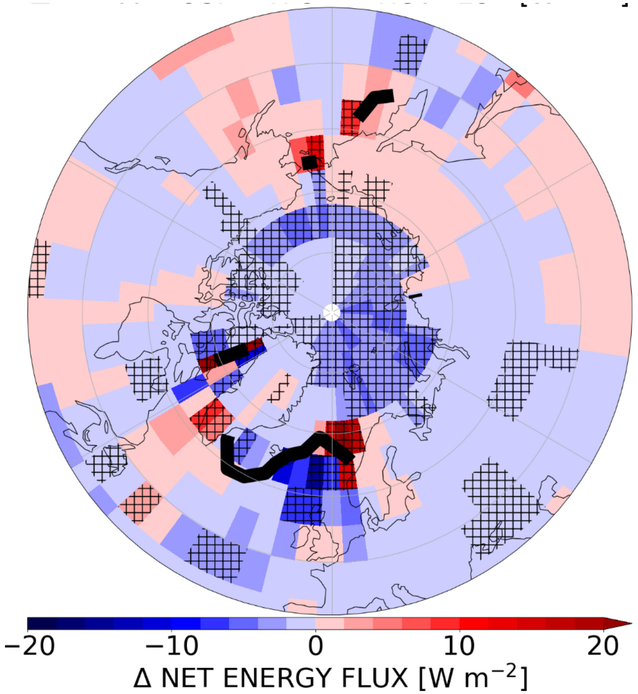


Seasonal: February-September

Hatching and shading: Significance at the 5% level

Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I

February-September mean net energy fluxes



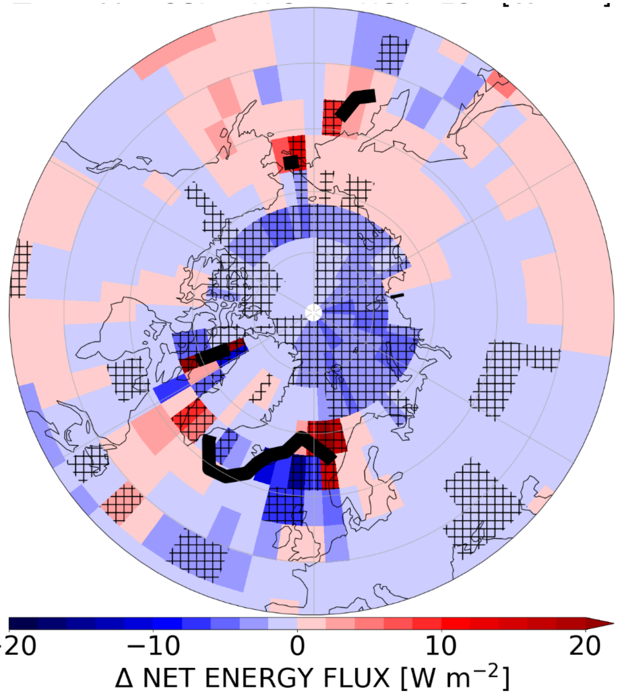
- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean

Seasonal: February-September

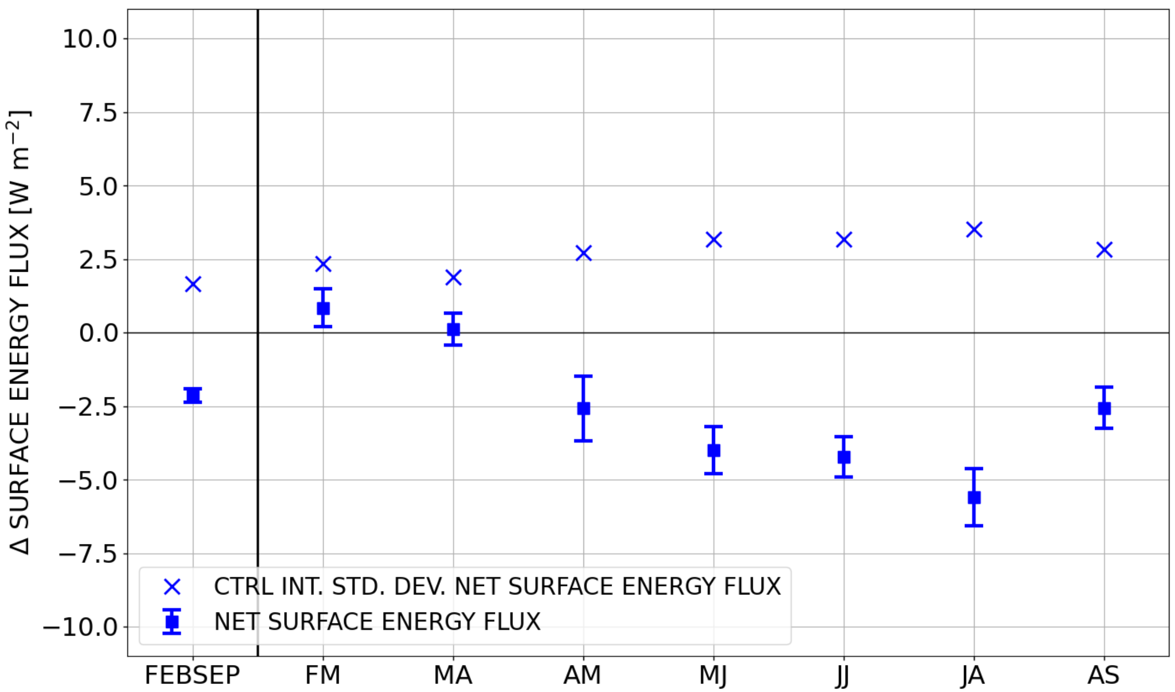
Hatching/Error bars: Significance at the 5% level/95% confidence interval

Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I

February-September mean net energy fluxes



Seasonal evolution of net energy fluxes



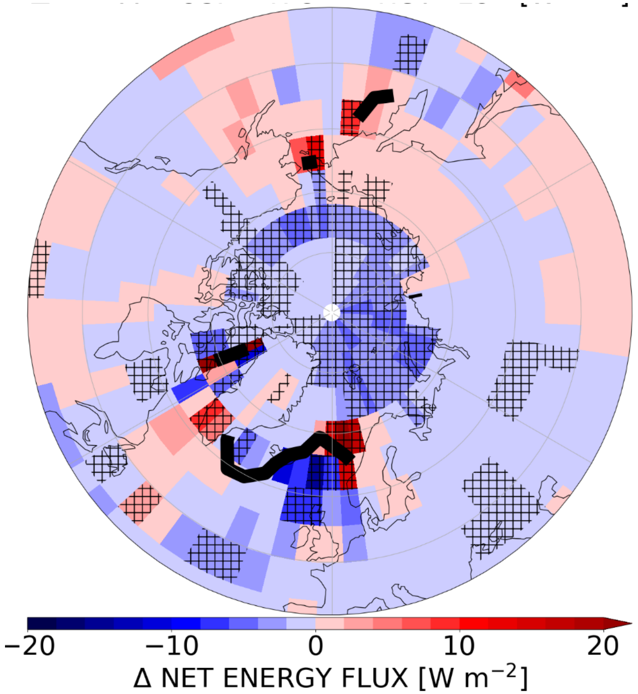
- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean
- Enhanced upward heat fluxes in winter and strongly enhanced downward fluxes from spring onwards

Seasonal: February-September

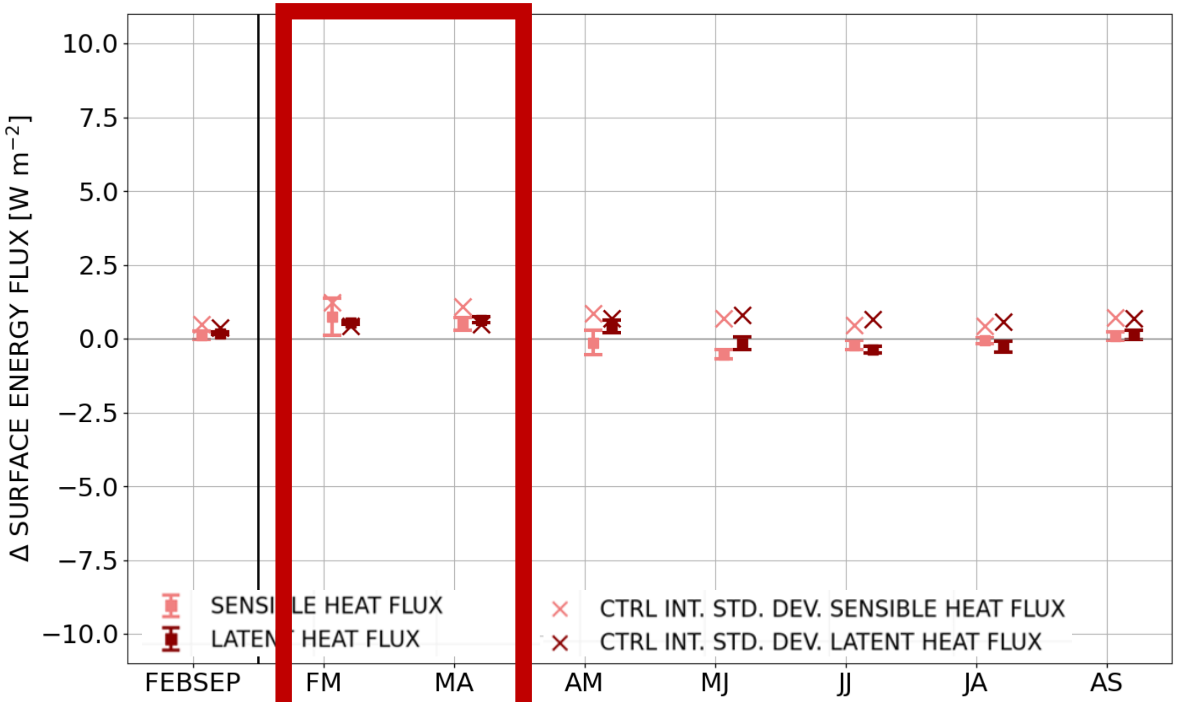
Hatching/Error bars: Significance at the 5% level/95% confidence interval

Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I

February-September mean net energy fluxes



Seasonal evolution of sensible and latent heat fluxes



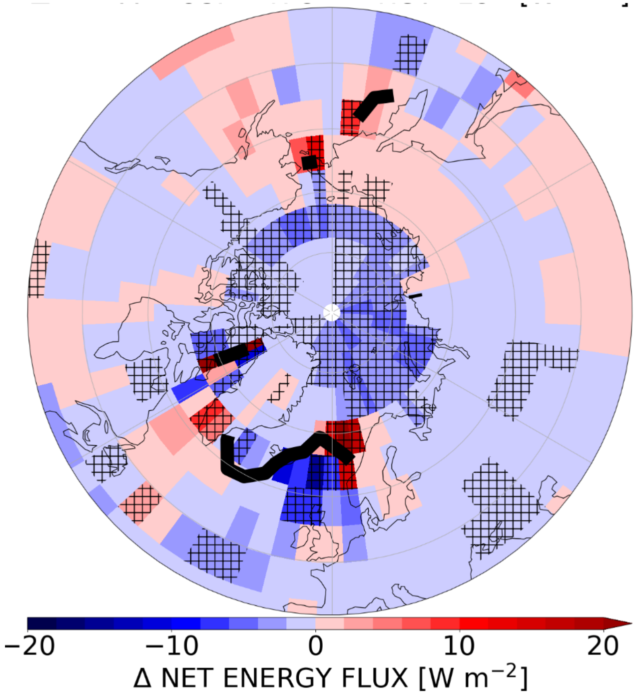
- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean
- **Enhanced upward sensible and latent heat flux in late winter**

Seasonal: February-September

Hatching/Error bars: Significance at the 5% level/95% confidence interval

Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I

February-September mean net energy fluxes



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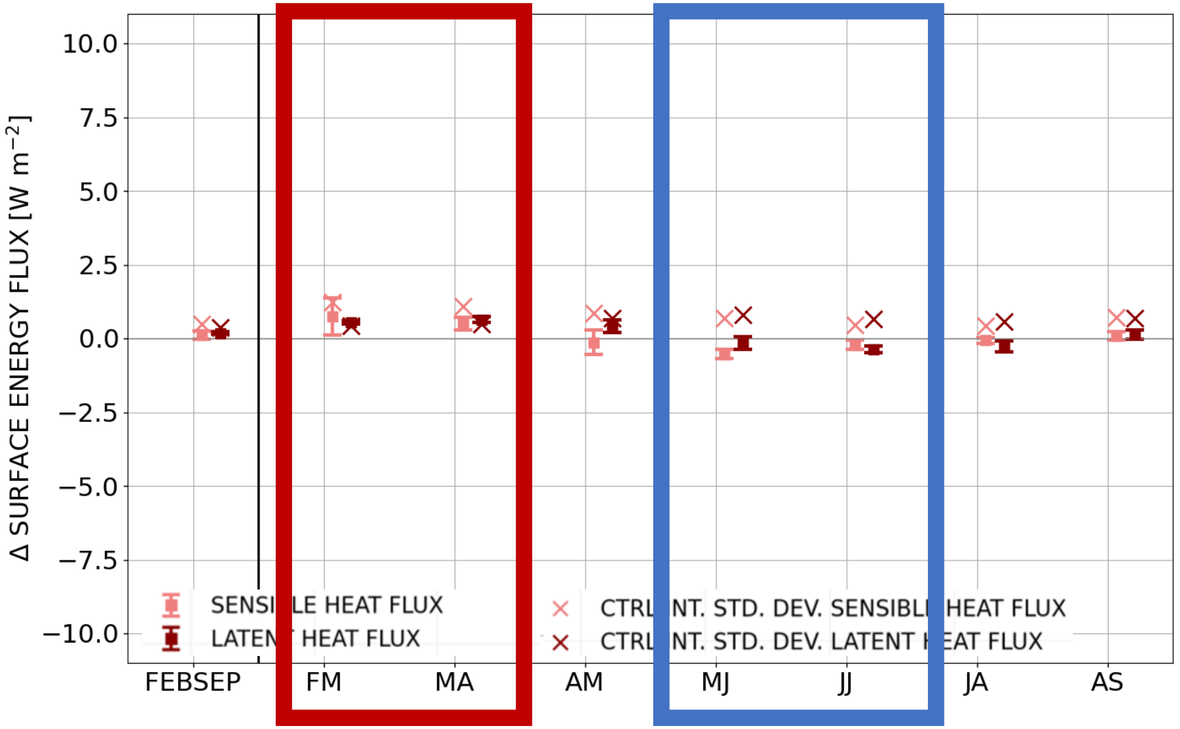


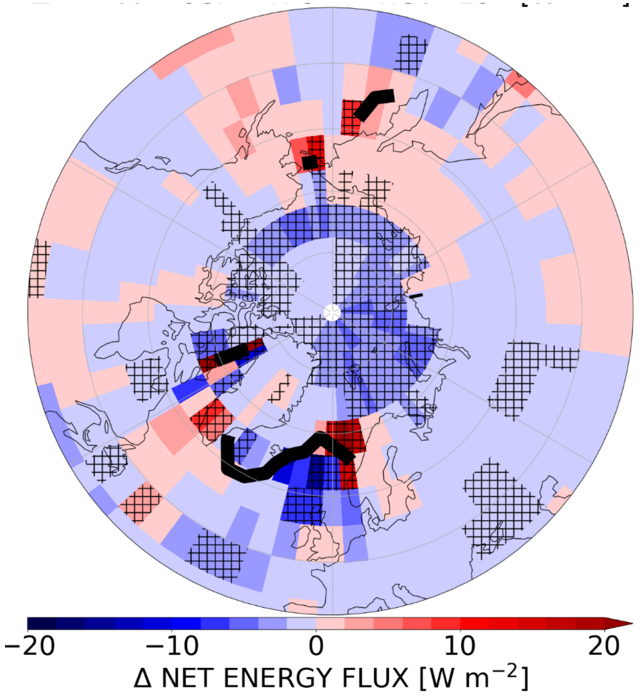
- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean
- **Enhanced upward sensible and latent heat flux in late winter**
- **Enhanced downward sensible heat fluxes** in May-June consistent with heat wave-like Z500 pattern

Seasonal: February-September

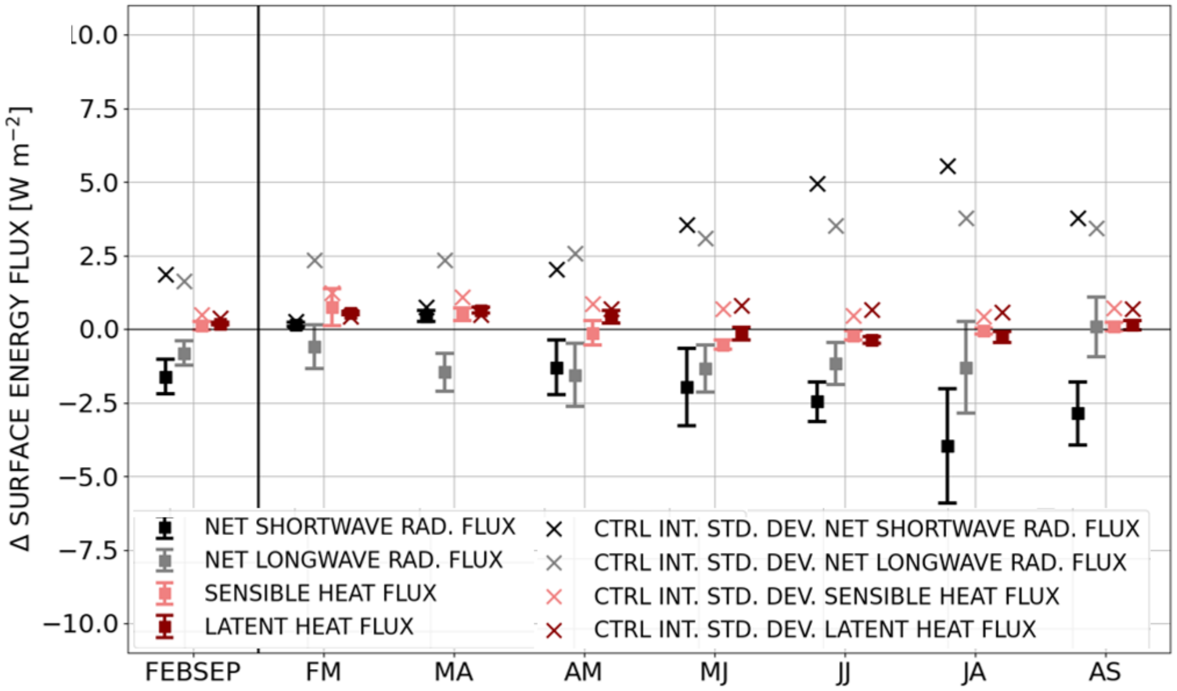
Hatching/Error bars: Significance at the 5% level/95% confidence interval

Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I

February-September mean net energy fluxes



Seasonal evolution of all flux components

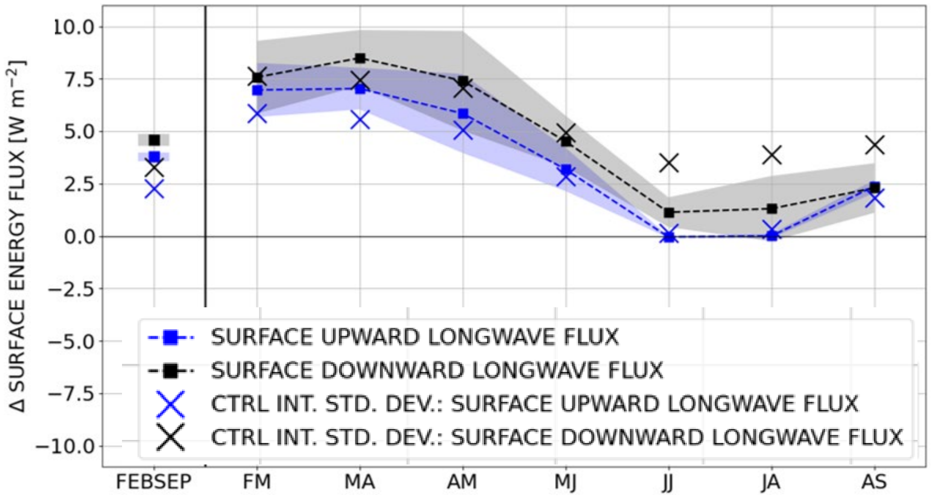


- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean
- **Enhanced upward sensible and latent heat flux in late winter**
- **Enhanced downward sensible heat fluxes** in May-June consistent with heat wave-like Z500 pattern
- **Radiative fluxes** dominate net surface flux anomalies
  -> **Longwave dominant in spring** – **shortwave dominant in summer**

Seasonal: February-September

Hatching/Error bars: Significance at the 5% level/95% confidence interval

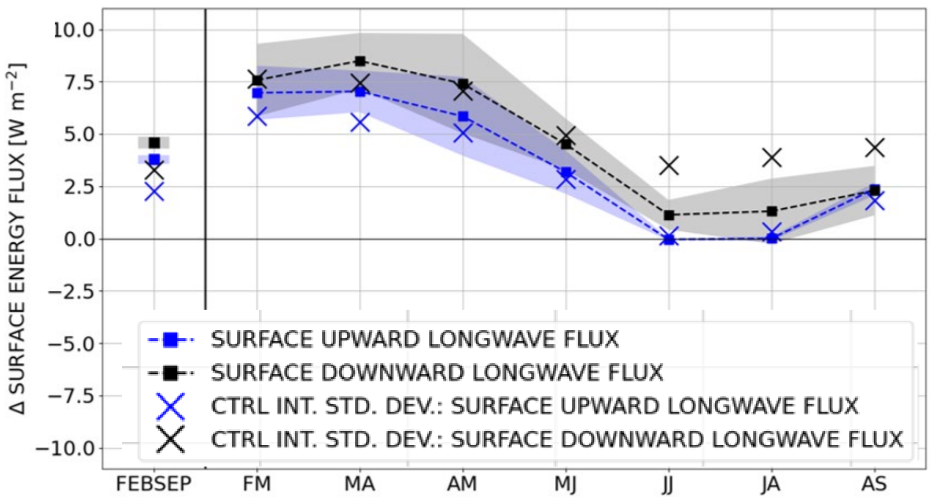
Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I

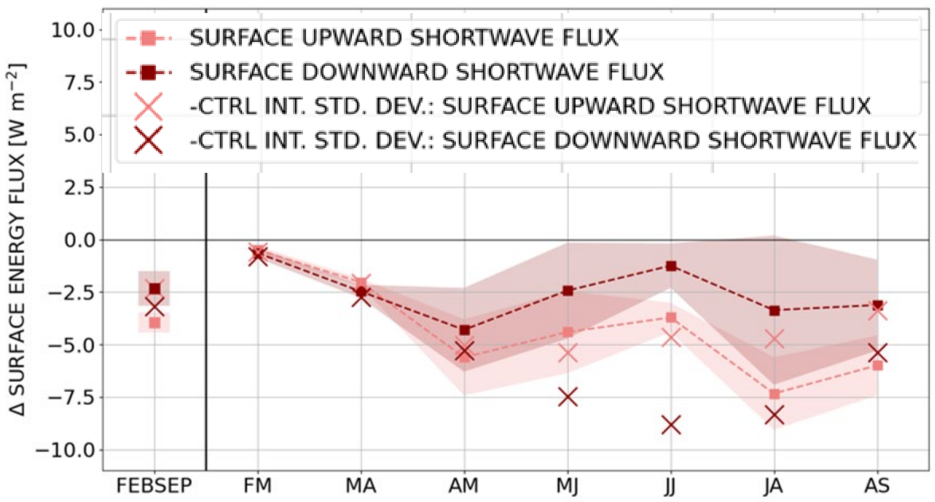


Seasonal: February-September

Shading: 95% confidence interval

Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I

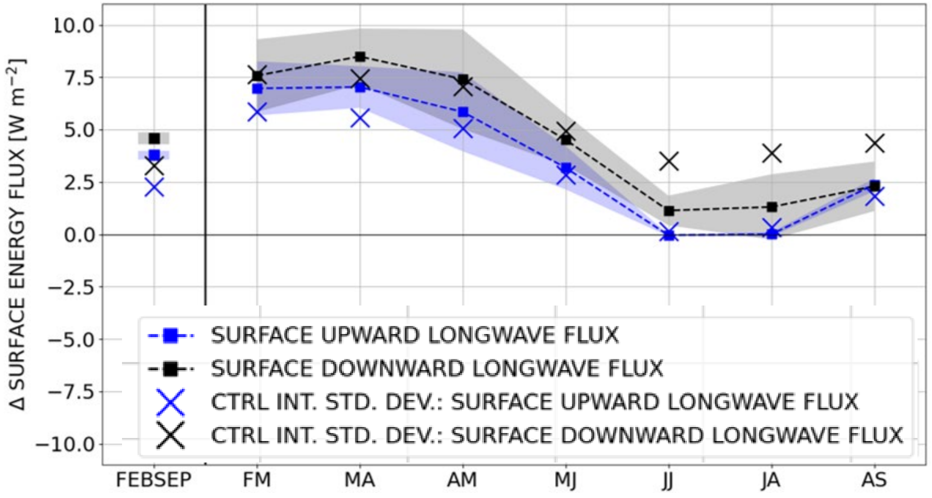


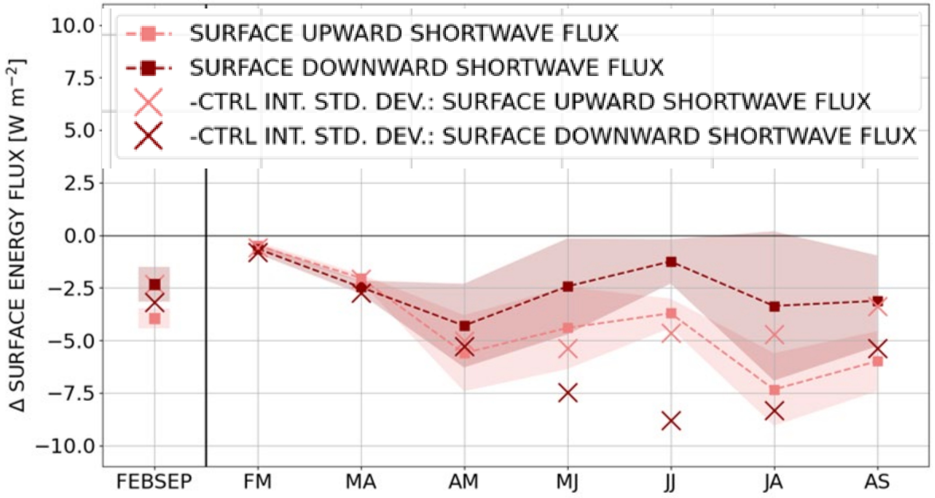


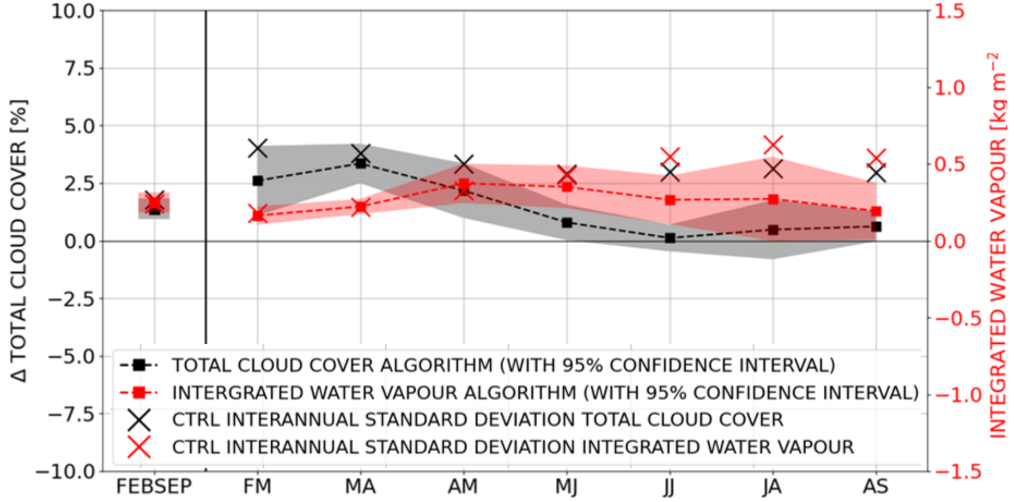
Seasonal: February-September

Shading: 95% confidence interval

Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I



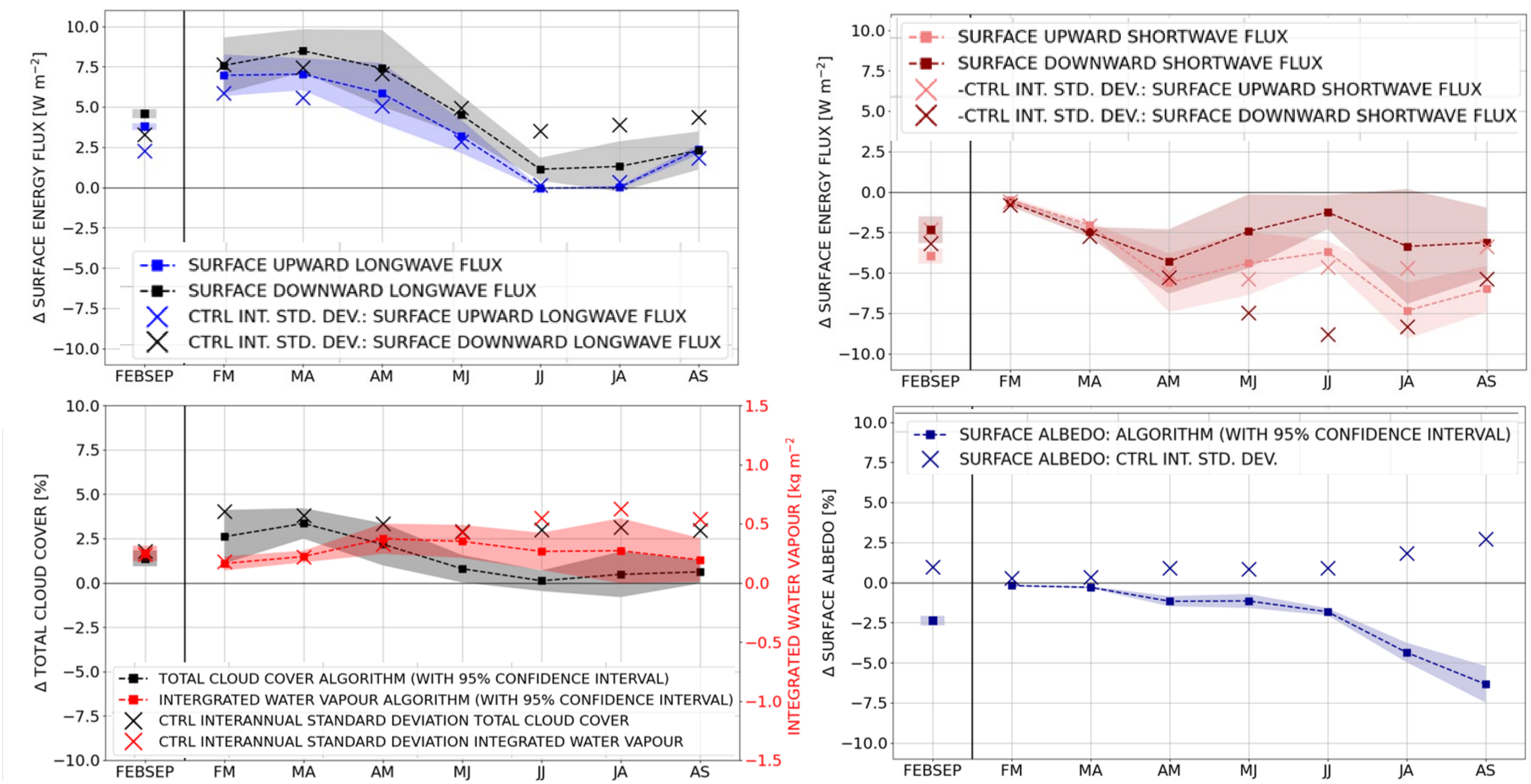




Seasonal: February-September

Shading: 95% confidence interval

Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I

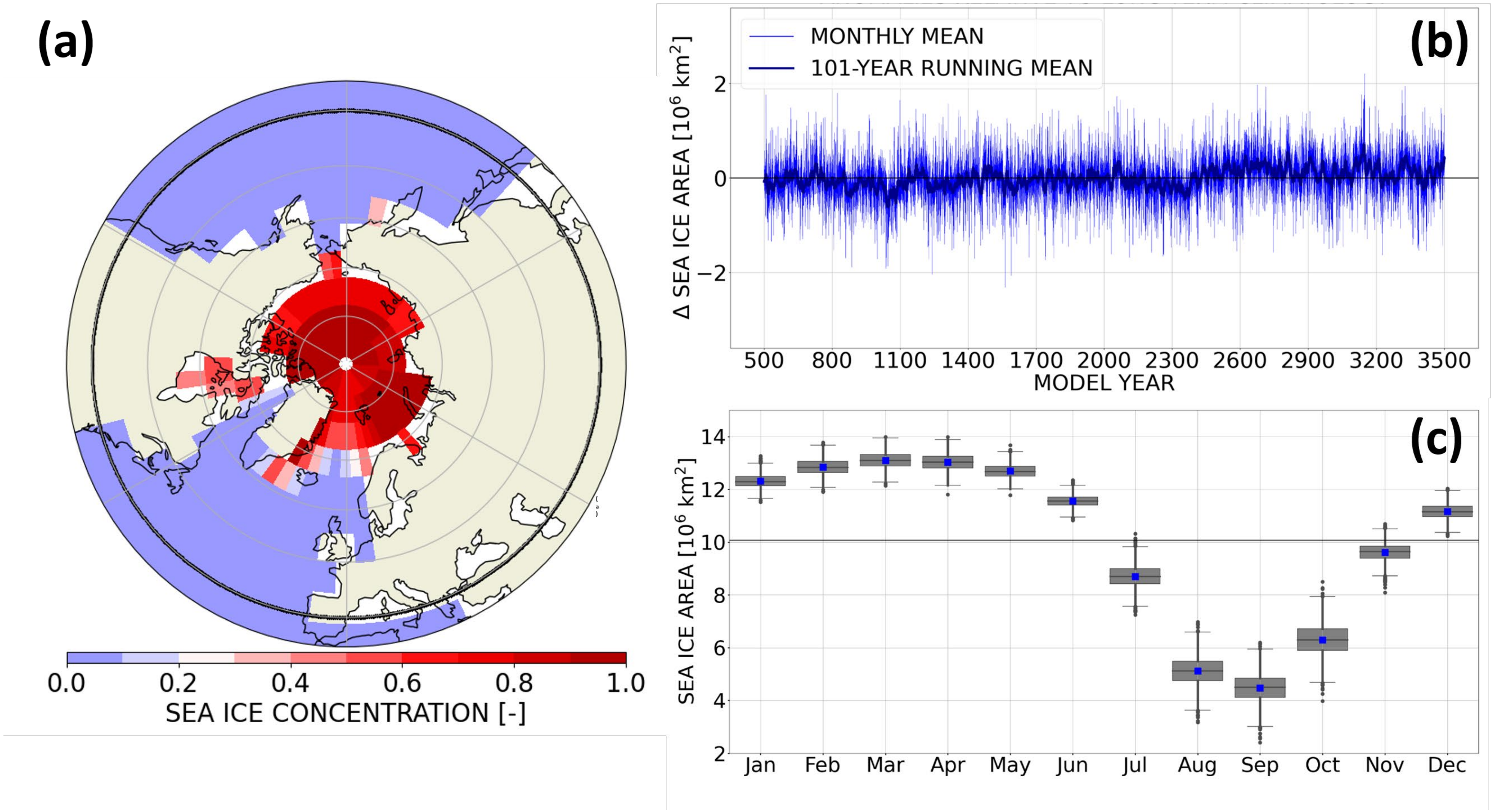


- Intra-seasonal sea ice reduction: enhanced by an anomalously moist, cloudy and warm spring atmosphere + sea ice-albedo feedback

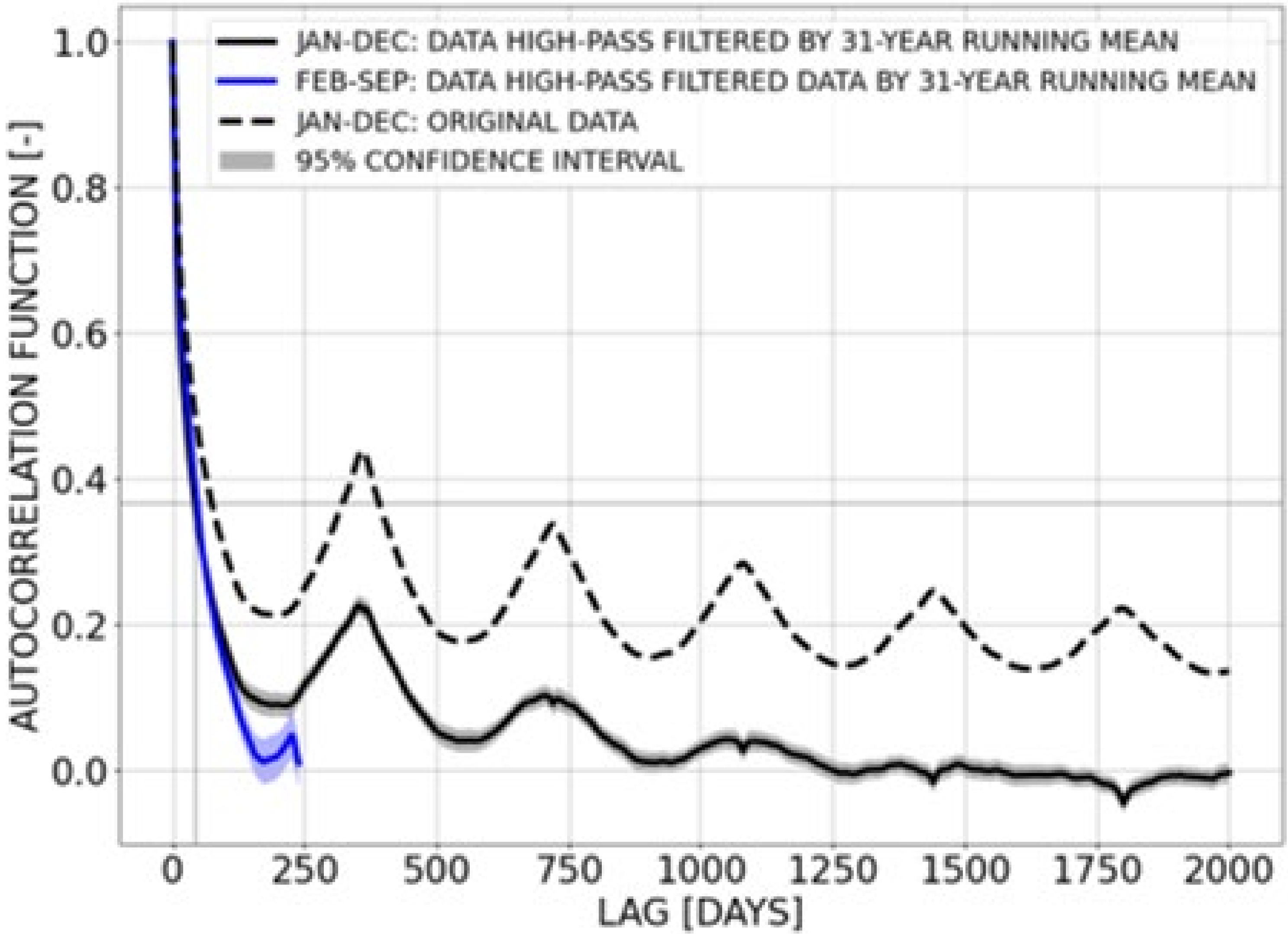
Seasonal: February-September

Shading: 95% confidence interval

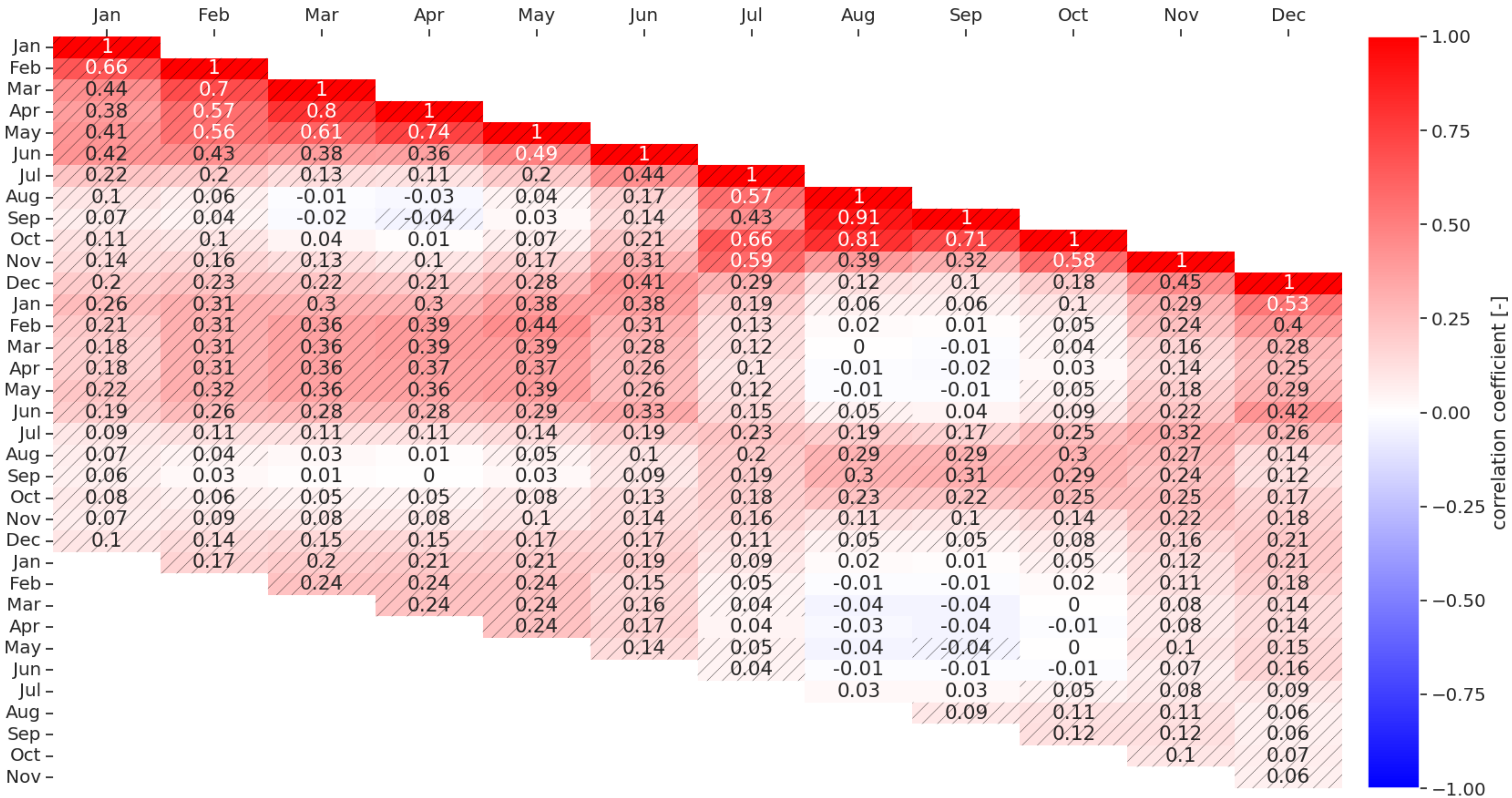
Results: Sea ice climatology in PlaSim-T21-LSG



Results: Sea ice persistence in PlaSim-T21-LSG

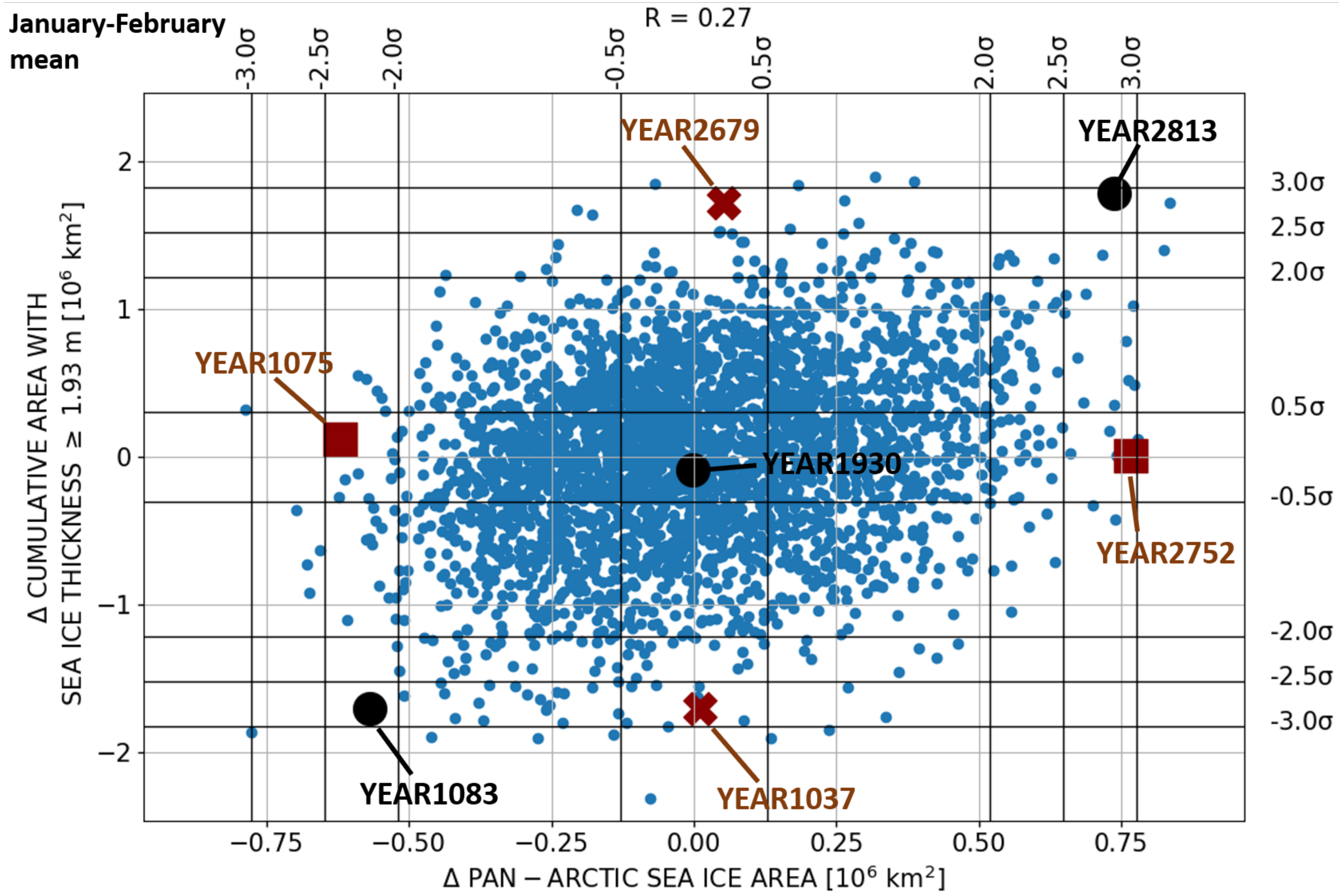


Results: Sea ice persistence in PlaSim-T21-LSG



Hatching: statistical significance at 5% level

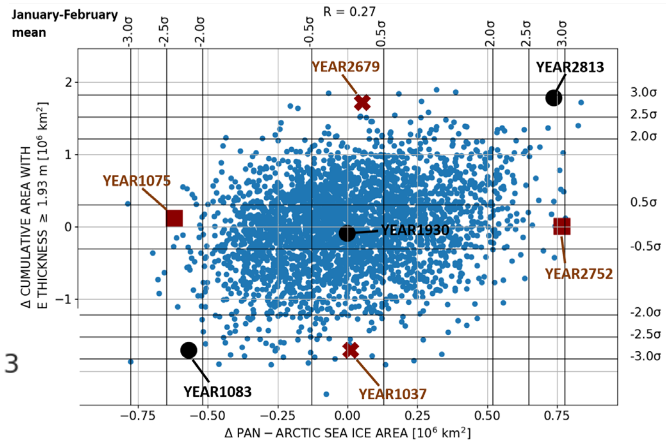
Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II



Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II

- Choice of **initial conditions** according to **different sea ice properties in January-February**:

  - sea ice area *vs.* area with sea ice thickness larger than 1.93 m
  - cf. Chevallier and Salas y Melia, 2012; Lindsay et al. 2008

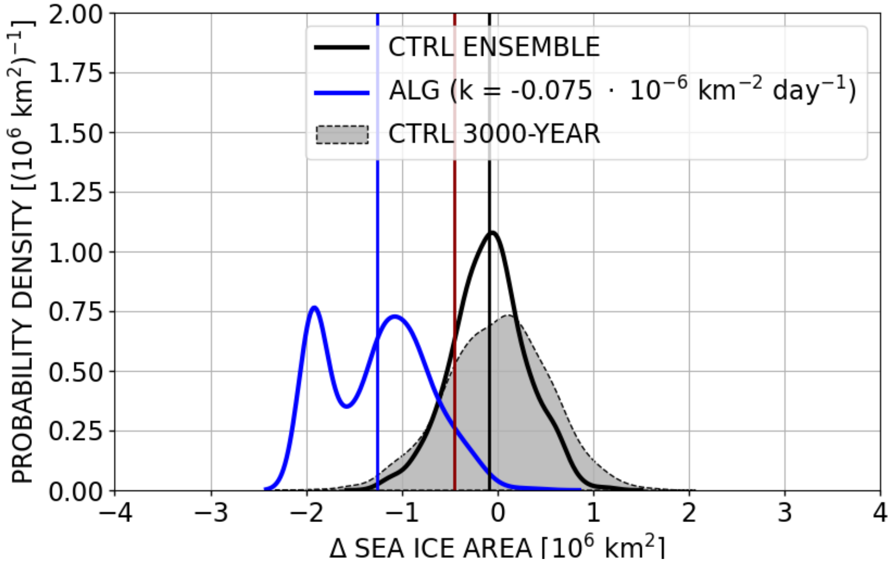


	JF	FM	MA	AM	MJ	JJ	JA	AS
STRD	0.59	0.56	0.73	0.89	0.76	-0.08	0.03	0.49
HFSS	0.24	0.14	0.24	-0.21	-0.78	-0.49	-0.35	0.14
ALB	-0.6	-0.56	-0.59	-0.88	-0.86	-1.5	-2.6	-2.8
SIT	-1.9	-1.9	-1.8	-1.9	-2.2	-2.3	-0.99	0.48
SIV	-1.8	-1.8	-1.8	-1.9	-2	-2.1	-2.4	-2.4
SIA	-0.47	-0.28	-0.27	-0.32	-0.46	-1.3	-2.5	-2.9
SIT ≥ 0.10m	-0.47	-0.28	-0.27	-0.32	-0.46	-1.3	-2.5	-3
≥ 0.20m	-0.47	-0.28	-0.27	-0.32	-0.46	-1.3	-2.5	-3
≥ 0.50m	-0.65	-0.37	-0.27	-0.36	-0.51	-1.4	-2.6	-3
≥ 0.66m	-0.58	-0.51	-0.5	-0.44	-0.55	-1.6	-2.7	-2.9
≥ 0.90m	-0.85	-0.46	-0.35	-0.25	-0.64	-2.1	-2.7	-2.5
≥ 1.30m	-1.5	-1.1	-0.86	-0.82	-1.5	-2.6	-2.4	-1.5
≥ 1.40m	-1.7	-1.4	-0.95	-0.91	-1.7	-2.5	-2.2	-1.3
≥ 1.50m	-1.8	-1.6	-1.1	-0.93	-1.8	-2.5	-2.1	-1.2
≥ 1.60m	-1.9	-1.6	-1.4	-0.99	-1.9	-2.5	-2	-1.2
≥ 1.70m	-2	-1.6	-1.5	-1.3	-2.2	-2.4	-1.9	-1.1
≥ 1.80m	-2.1	-1.6	-1.6	-1.6	-2.4	-2.3	-1.7	-1
≥ 1.90m	-2.1	-1.8	-1.5	-1.7	-2.5	-2.2	-1.5	-0.96
≥ 1.93m	-2.1	-1.9	-1.5	-1.6	-2.5	-2.2	-1.5	-0.93
≥ 2.00m	-2.1	-2.1	-1.5	-1.4	-2.3	-2.2	-1.4	-0.87
≥ 2.10m	-2.1	-2.2	-1.7	-1.5	-2.2	-2.2	-1.2	-0.81
≥ 2.20m	-1.9	-2.2	-2	-1.7	-2.2	-2.1	-1.1	-0.8
≥ 2.30m	-1.7	-2.1	-2.1	-1.8	-2.3	-2.1	-1.1	-0.8
≥ 2.40m	-1.6	-2	-2.1	-1.8	-2.2	-2	-0.95	-0.7
≥ 2.50m	-1.4	-1.9	-2.2	-2.1	-2.2	-1.9	-0.95	-0.84
≥ 4.00m	-0.44	-0.6	-0.72	-0.72	-0.62	-0.37	-0.14	-0.22
≥ 4.20m	-0.39	-0.49	-0.59	-0.65	-0.59	-0.42	-0.26	-0.2
≥ 6.00m	-0.15	-0.16	-0.17	-0.18	-0.18	-0.18	-0.16	-0.13

NORMALIZED COMPOSITE [-] (colour scale from −3 to 3)

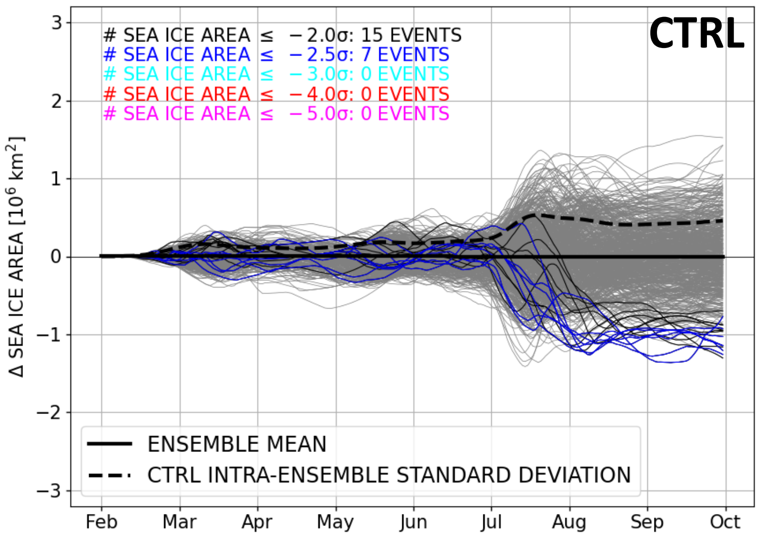
Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II

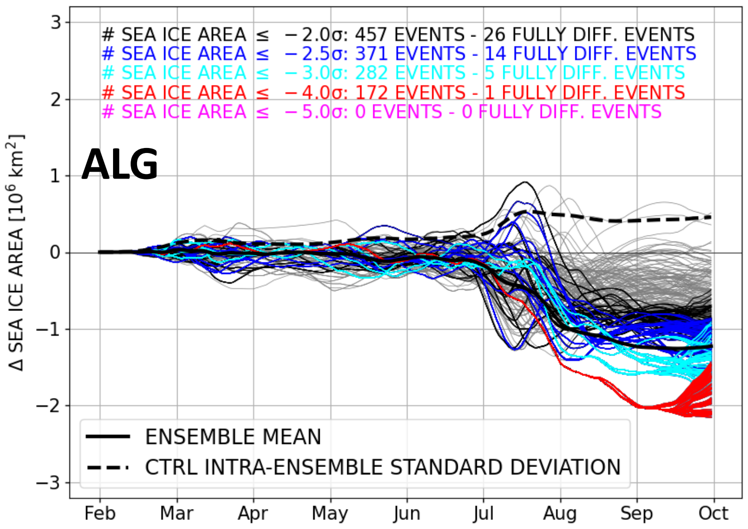
YEAR1930
Neutral sea ice

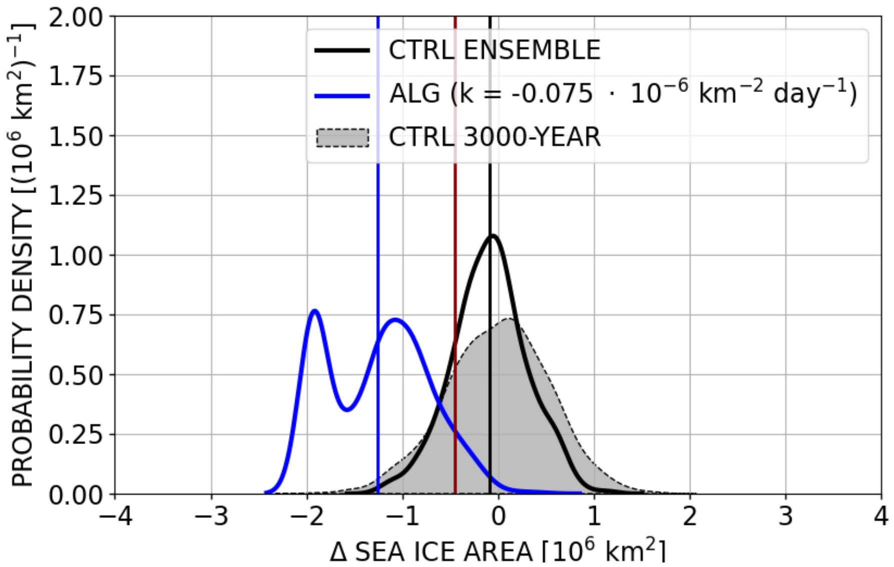


Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II

YEAR1930
Neutral sea ice

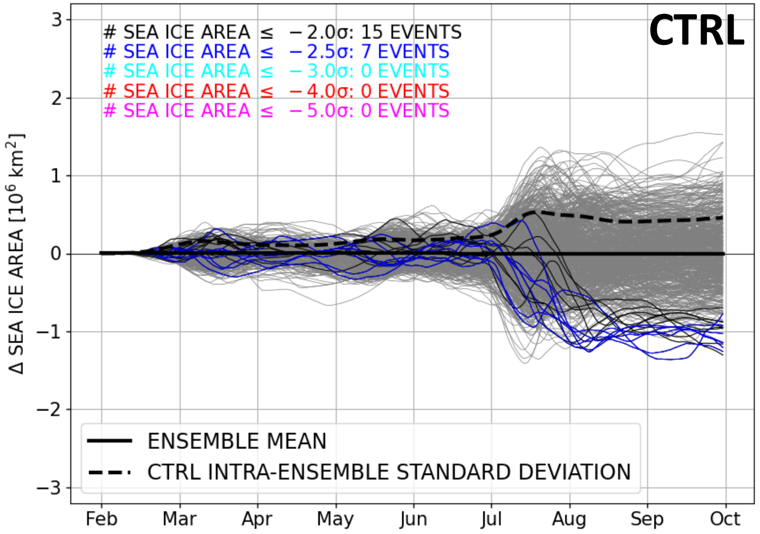


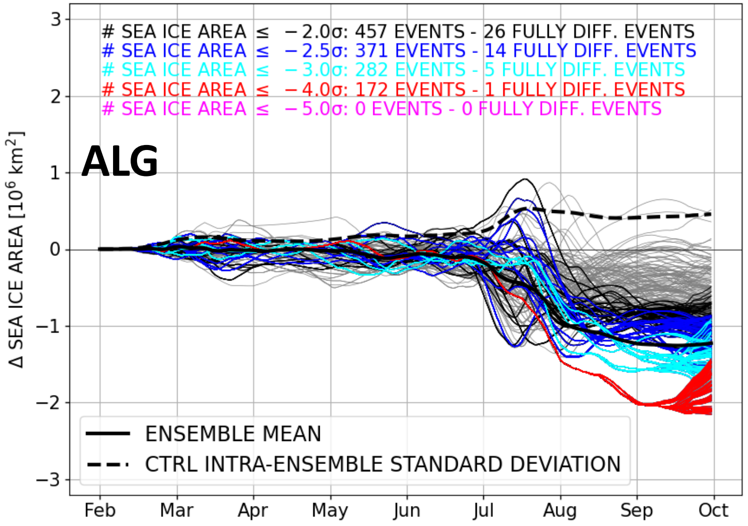


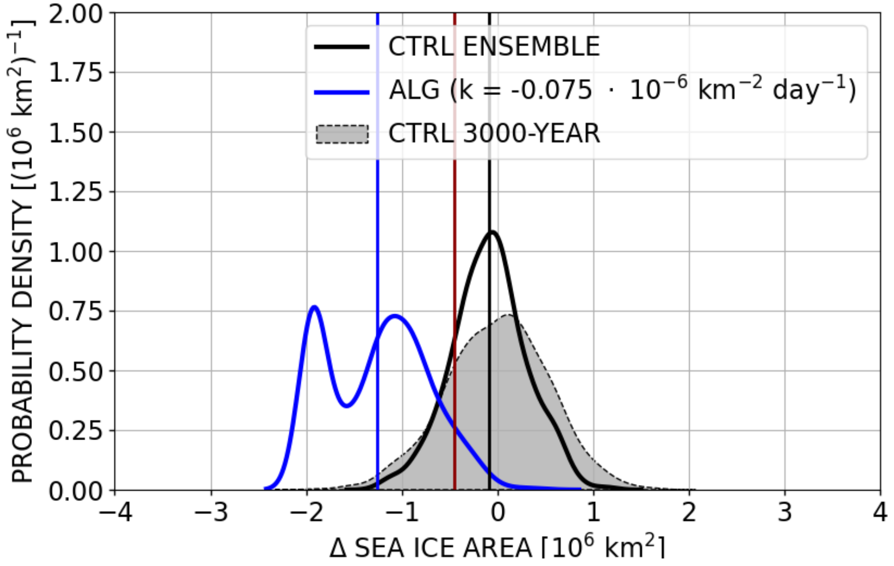


Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II

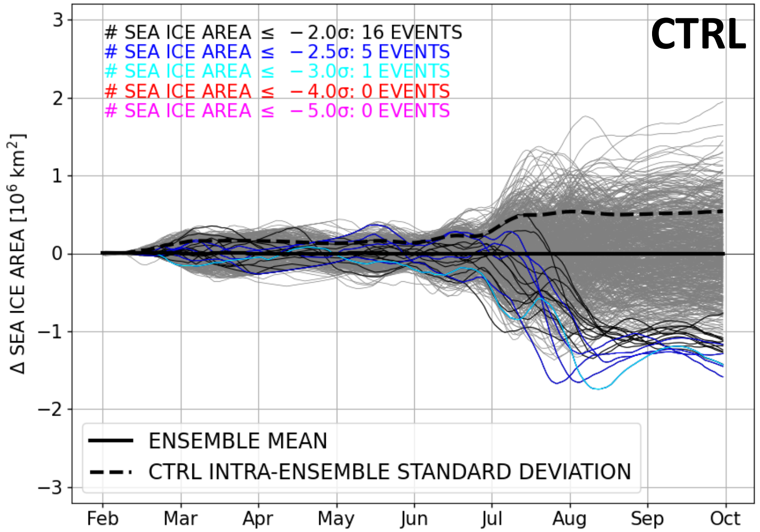
YEAR1930
Neutral sea ice

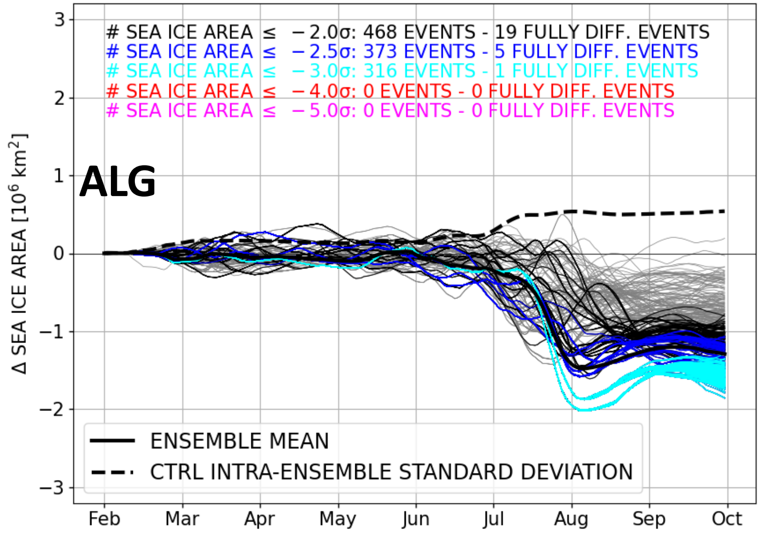


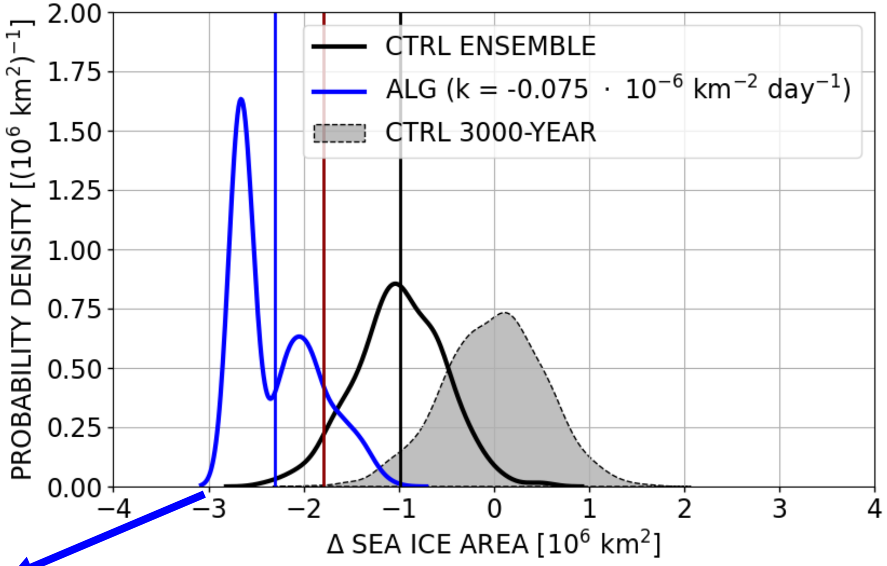




YEAR1037
Low sea ice thickness

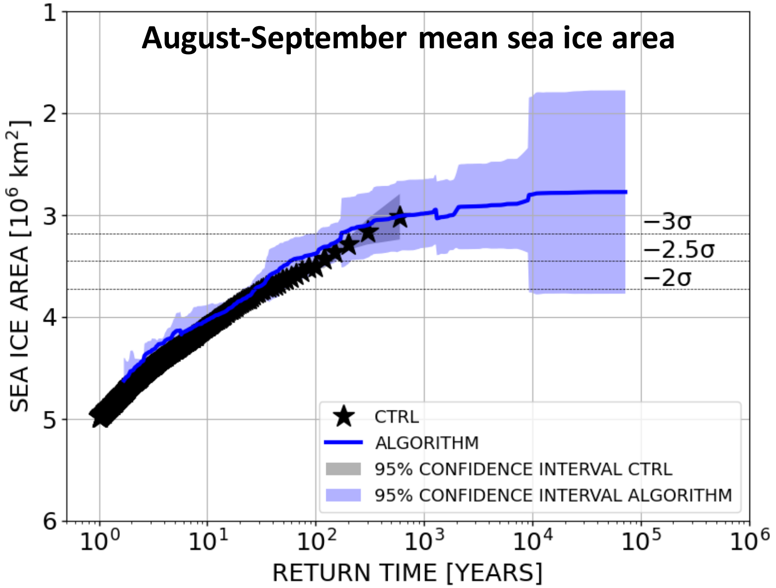






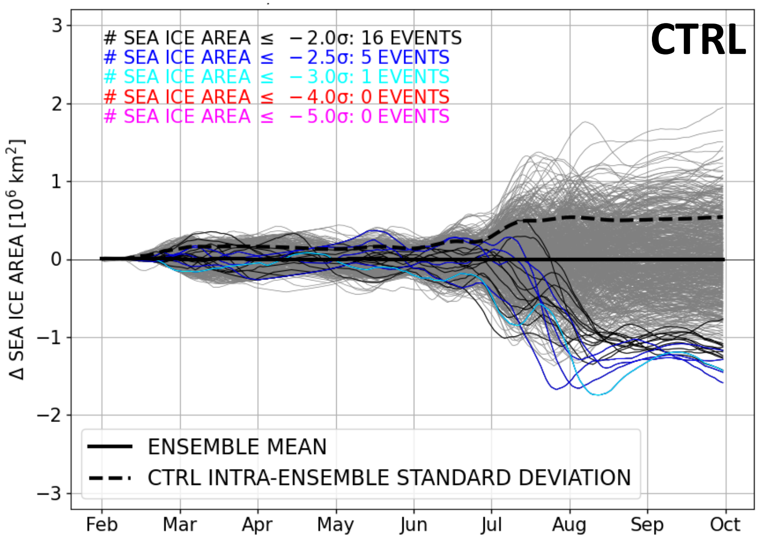
August-September sea ice area = 2.07 · 10^6 km^2

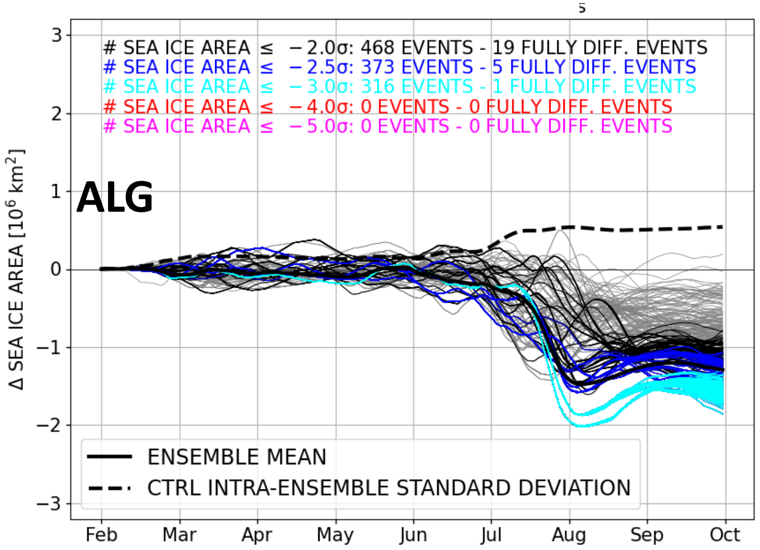
Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II

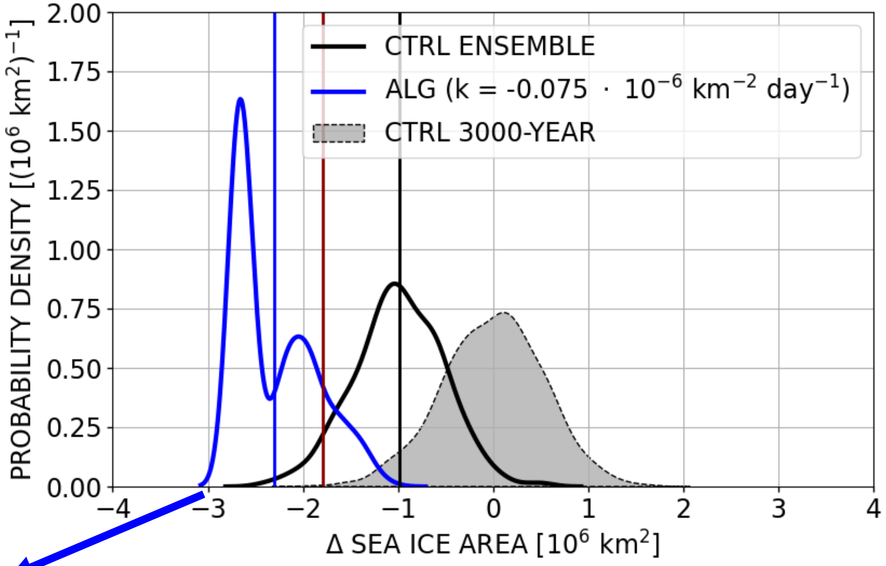


- Simulation of extreme August-September sea ice low with r ≥ 10^4 years with computational cost of 10^2 – 10^3 years

YEAR1037
Low sea ice thickness





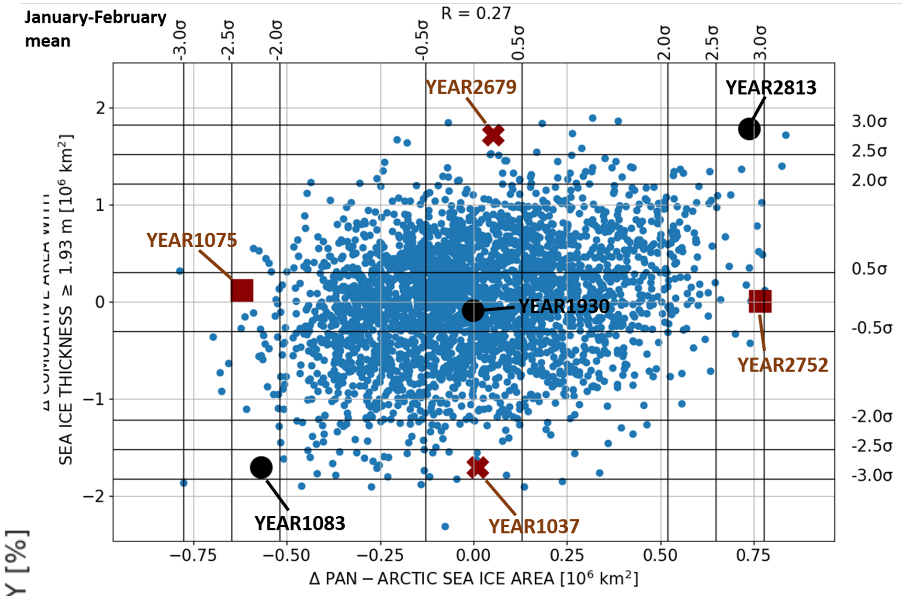


August-September sea ice area = 2.07 · 10^6 km^2

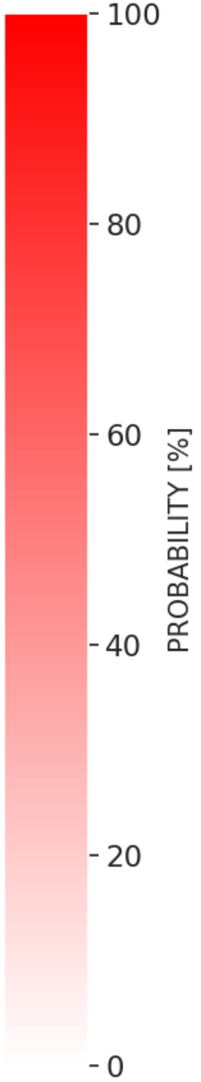
Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II

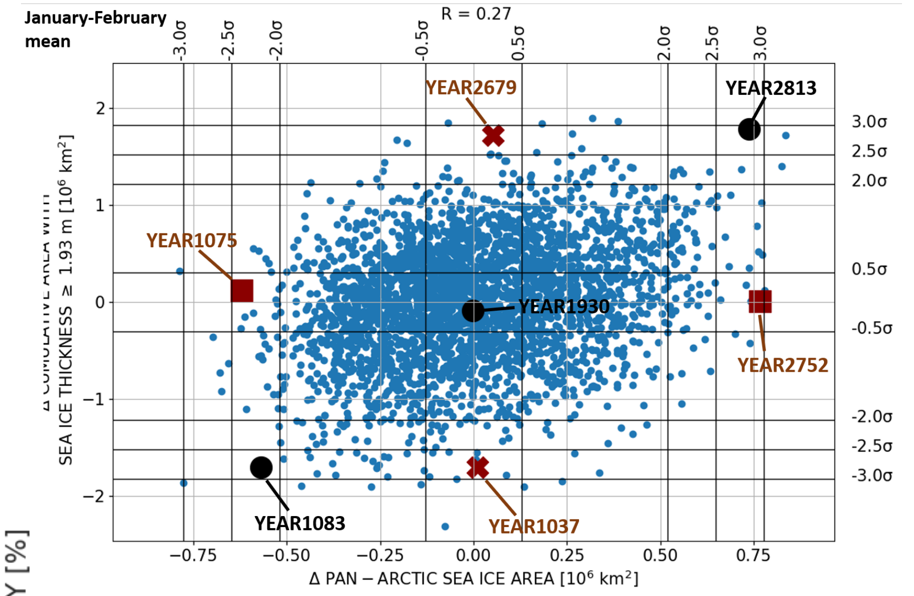
January-February	AUGSEP SIA ≤ −2.0σ	AUGSEP SIA ≤ −2.5σ	AUGSEP SIA ≤ −3.0σ
SIA-LOW SIT1.93-LOW	24.17 +/- 3.43	7.83 +/- 2.15	3.0 +/- 1.36
SIA-NEUTRAL SIT1.93-LOW	41.83 +/- 3.95	21.33 +/- 3.28	9.83 +/- 2.38
SIA-LOW SIT1.93-NEUTRAL	1.0 +/- 0.8	0.17 +/- 0.33	0.0 +/- 0.0
SIA-NEUTRAL SIT1.93-NEUTRAL	1.17 +/- 0.86	0.0 +/- 0.0	0.0 +/- 0.0
SIA-LARGE SIT1.93-NEUTRAL	3.5 +/- 1.47	0.5 +/- 0.56	0.0 +/- 0.0
SIA-NEUTRAL SIT1.93-LARGE	0.0 +/- 0.0	0.0 +/- 0.0	0.0 +/- 0.0
SIA-LARGE SIT1.93-LARGE	0.0 +/- 0.0	0.0 +/- 0.0	0.0 +/- 0.0

PROBABILITY [%]: 0 – 20 – 40 – 60 – 80 – 100



January-February	AUGSEP SIA $\leq -2.0\sigma$	AUGSEP SIA $\leq -2.5\sigma$	AUGSEP SIA $\leq -3.0\sigma$
SIA-LOW SIT1.93-LOW	24.17 +/- 3.43	7.83 +/- 2.15	3.0 +/- 1.36
SIA-NEUTRAL SIT1.93-LOW	41.83 +/- 3.95	21.33 +/- 3.28	9.83 +/- 2.38
SIA-LOW SIT1.93-NEUTRAL	1.0 +/- 0.8	0.17 +/- 0.33	0.0 +/- 0.0
SIA-NEUTRAL SIT1.93-NEUTRAL	1.17 +/- 0.86	0.0 +/- 0.0	0.0 +/- 0.0
SIA-LARGE SIT1.93-NEUTRAL	3.5 +/- 1.47	0.5 +/- 0.56	0.0 +/- 0.0
SIA-NEUTRAL SIT1.93-LARGE	0.0 +/- 0.0	0.0 +/- 0.0	0.0 +/- 0.0
SIA-LARGE SIT1.93-LARGE	0.0 +/- 0.0	0.0 +/- 0.0	0.0 +/- 0.0



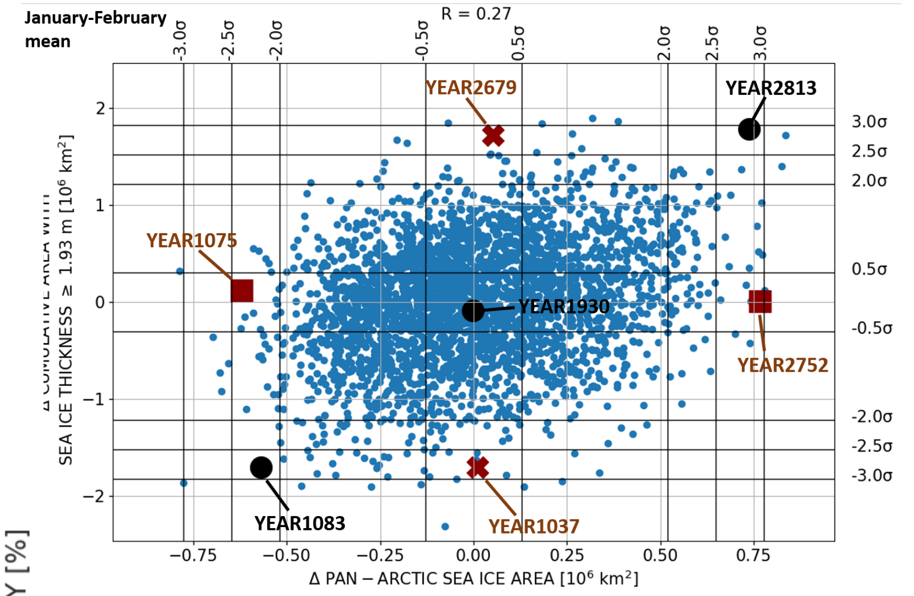


- Probability of extreme August-September sea ice low strongly dependent on the previous **winter sea ice thickness** state
- No impact of the winter sea ice area on the probability of extreme August-September sea ice low detectable

Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II

January-February	AUGSEP SIA ≤ −2.0σ	AUGSEP SIA ≤ −2.5σ	AUGSEP SIA ≤ −3.0σ
SIA-LOW SIT1.93-LOW	2.83 +/- 1.33	0.67 +/- 0.65	0.0 +/- 0.0
SIA-NEUTRAL SIT1.93-LOW	2.67 +/- 1.29	0.83 +/- 0.73	0.17 +/- 0.33
SIA-LOW SIT1.93-NEUTRAL	2.33 +/- 1.21	0.67 +/- 0.65	0.17 +/- 0.33
SIA-NEUTRAL SIT1.93-NEUTRAL	2.5 +/- 1.25	1.17 +/- 0.86	0.0 +/- 0.0
SIA-LARGE SIT1.93-NEUTRAL	1.17 +/- 0.86	0.0 +/- 0.0	0.0 +/- 0.0
SIA-NEUTRAL SIT1.93-LARGE	1.5 +/- 0.97	0.17 +/- 0.33	0.0 +/- 0.0
SIA-LARGE SIT1.93-LARGE	1.33 +/- 0.92	0.17 +/- 0.33	0.0 +/- 0.0
SIA-LOW SIT1.93-LOW	24.17 +/- 3.43	7.83 +/- 2.15	3.0 +/- 1.36
SIA-NEUTRAL SIT1.93-LOW	41.83 +/- 3.95	21.33 +/- 3.28	9.83 +/- 2.38
SIA-LOW SIT1.93-NEUTRAL	1.0 +/- 0.8	0.17 +/- 0.33	0.0 +/- 0.0
SIA-NEUTRAL SIT1.93-NEUTRAL	1.17 +/- 0.86	0.0 +/- 0.0	0.0 +/- 0.0
SIA-LARGE SIT1.93-NEUTRAL	3.5 +/- 1.47	0.5 +/- 0.56	0.0 +/- 0.0
SIA-NEUTRAL SIT1.93-LARGE	0.0 +/- 0.0	0.0 +/- 0.0	0.0 +/- 0.0
SIA-LARGE SIT1.93-LARGE	0.0 +/- 0.0	0.0 +/- 0.0	0.0 +/- 0.0

PROBABILITY [%]: 0, 20, 40, 60, 80, 100

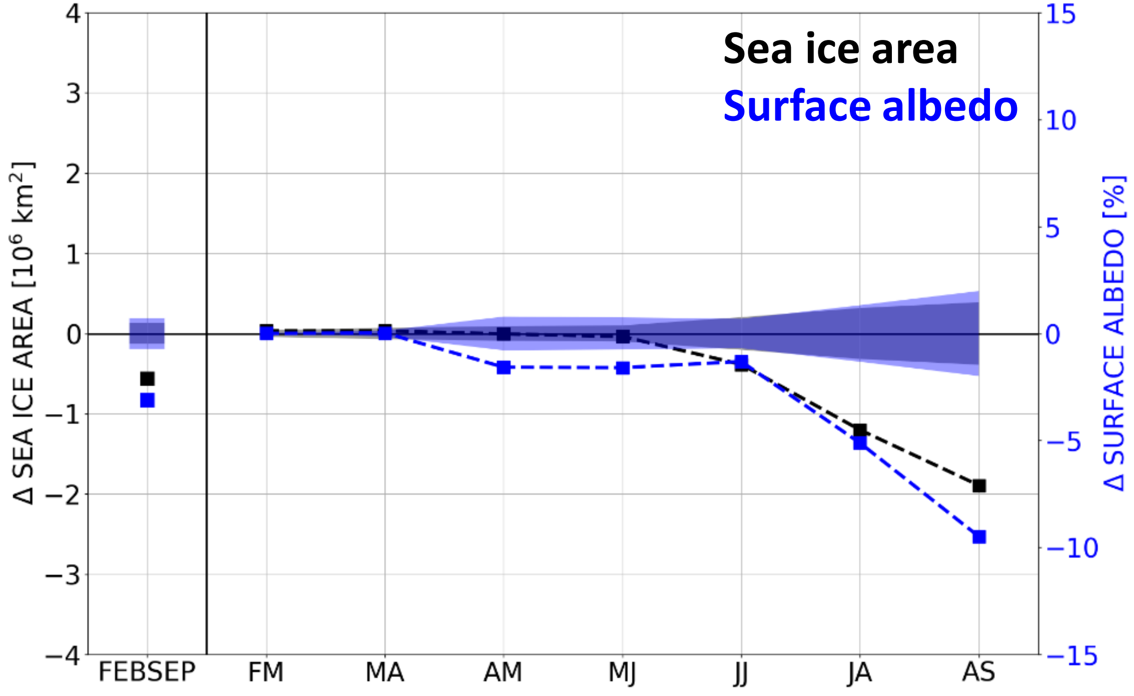


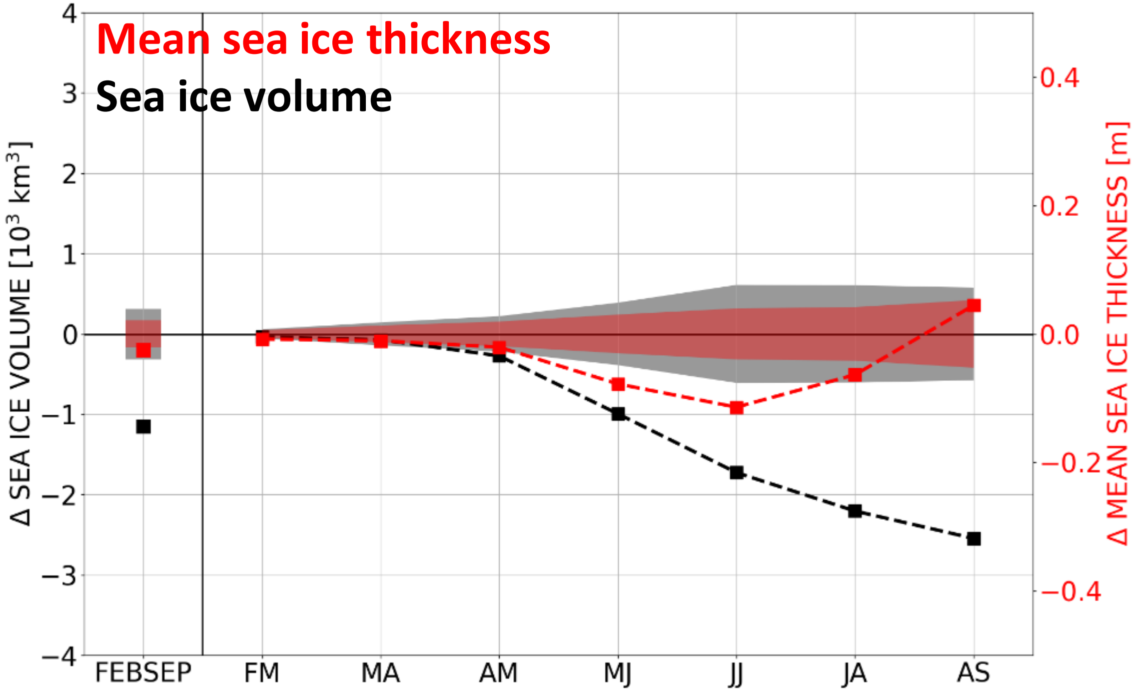
- Probability of extreme August-September sea ice low strongly dependent on the previous **winter sea ice thickness** state
- No impact of the winter sea ice area on the probability of extreme August-September sea ice low detectable

Results: Application of the rare event algorithm to PlaSim-T21-L

Shading: +/- intra-ensemble standard deviation

Trajectory with lowest August-September mean pan-Arctic sea ice area





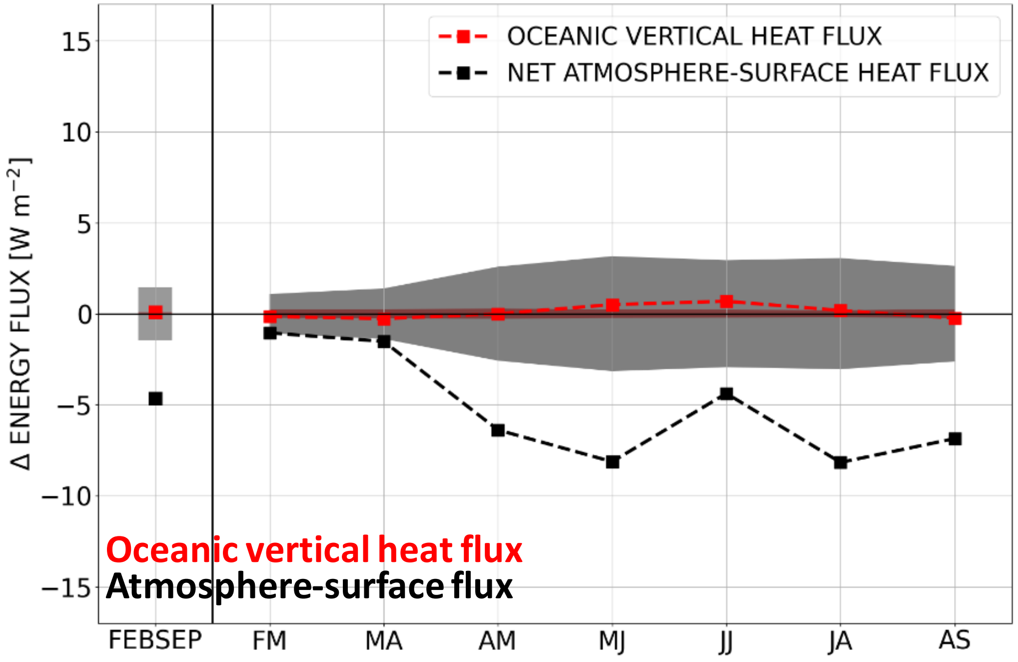
- Negative sea ice area anomalies develop in June-July
- Negative spring sea ice thickness/sea ice volume anomalies “anticipate” the negative summer sea ice area anomalies

Results: Application of the rare event algorithm to PlaSim-T21-L

Shading: +/- intra-ensemble standard deviation

Domain-average over the Arctic Ocean northern of 70°N

Trajectory with lowest August-September mean pan-Arctic sea ice area



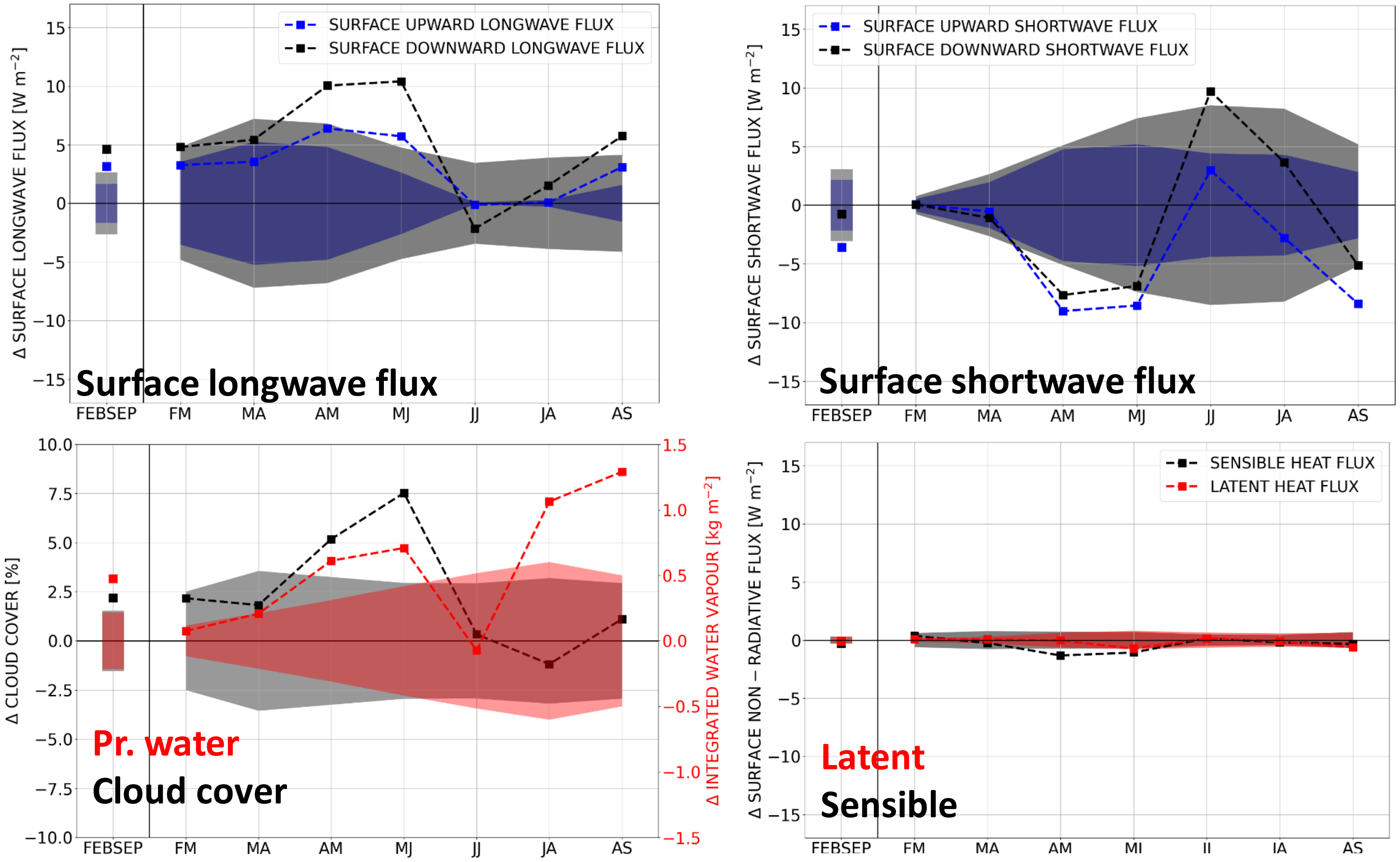
- Strongly enhanced downward atmosphere-surface energy fluxes accompanied by weak oceanic forcing in summer

Results: Application of the rare event algorithm to PlaSim-T21-L

Shading: +/- intra-ensemble standard deviation

Domain-average over the Arctic Ocean northern of 70°N

Trajectory with lowest August-September mean pan-Arctic sea ice area

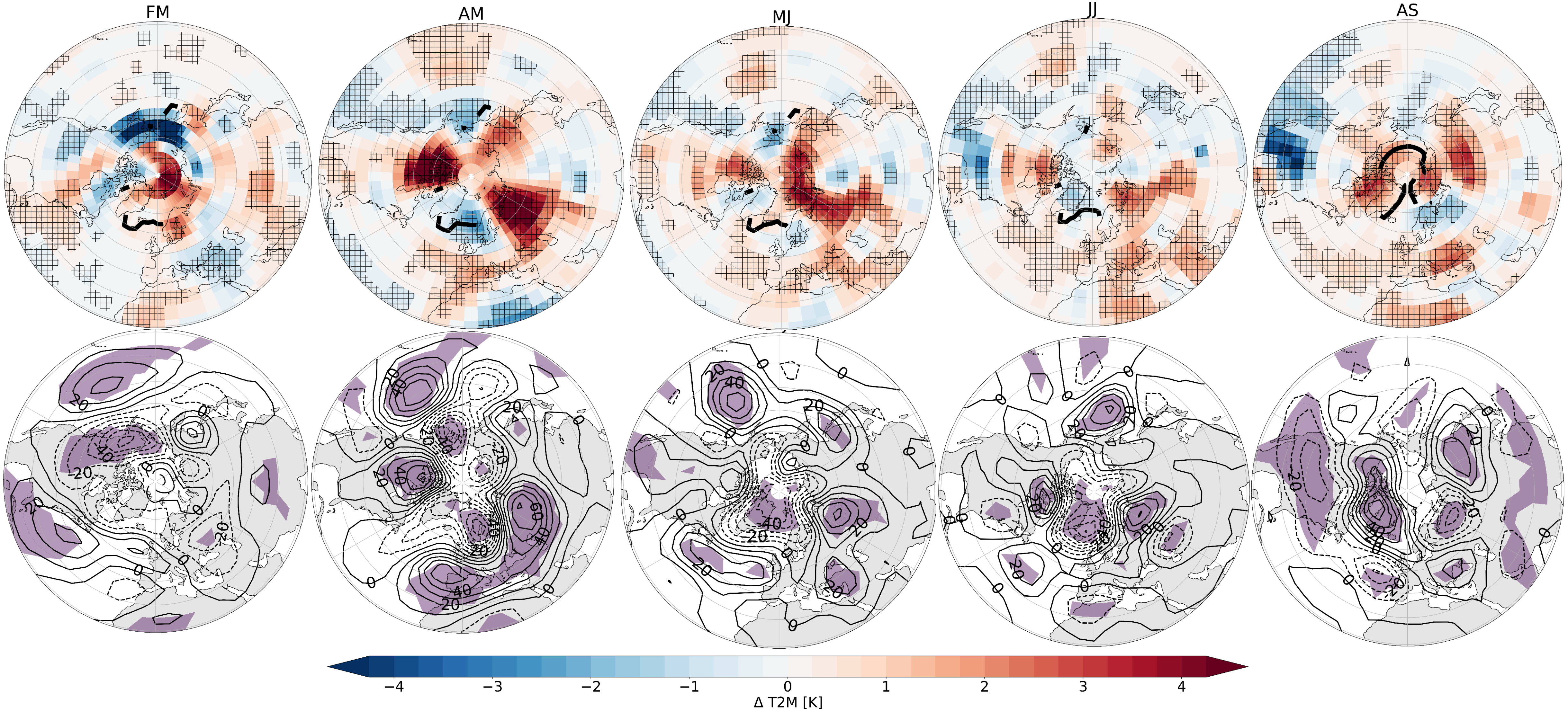


- 1. Phase in spring: enhanced longwave radiative and downward sensible heat fluxes due to moist/warm atmosphere
- 2. Phase in summer: reduction of clouds and dominant shortwave forcing

Results: Application of the rare event algorithm to PlaSim-T2

Shading/Hatching: anomalies larger in magnitude than intra-ensemble standard deviation

Trajectory with lowest August-September mean pan-Arctic sea ice area

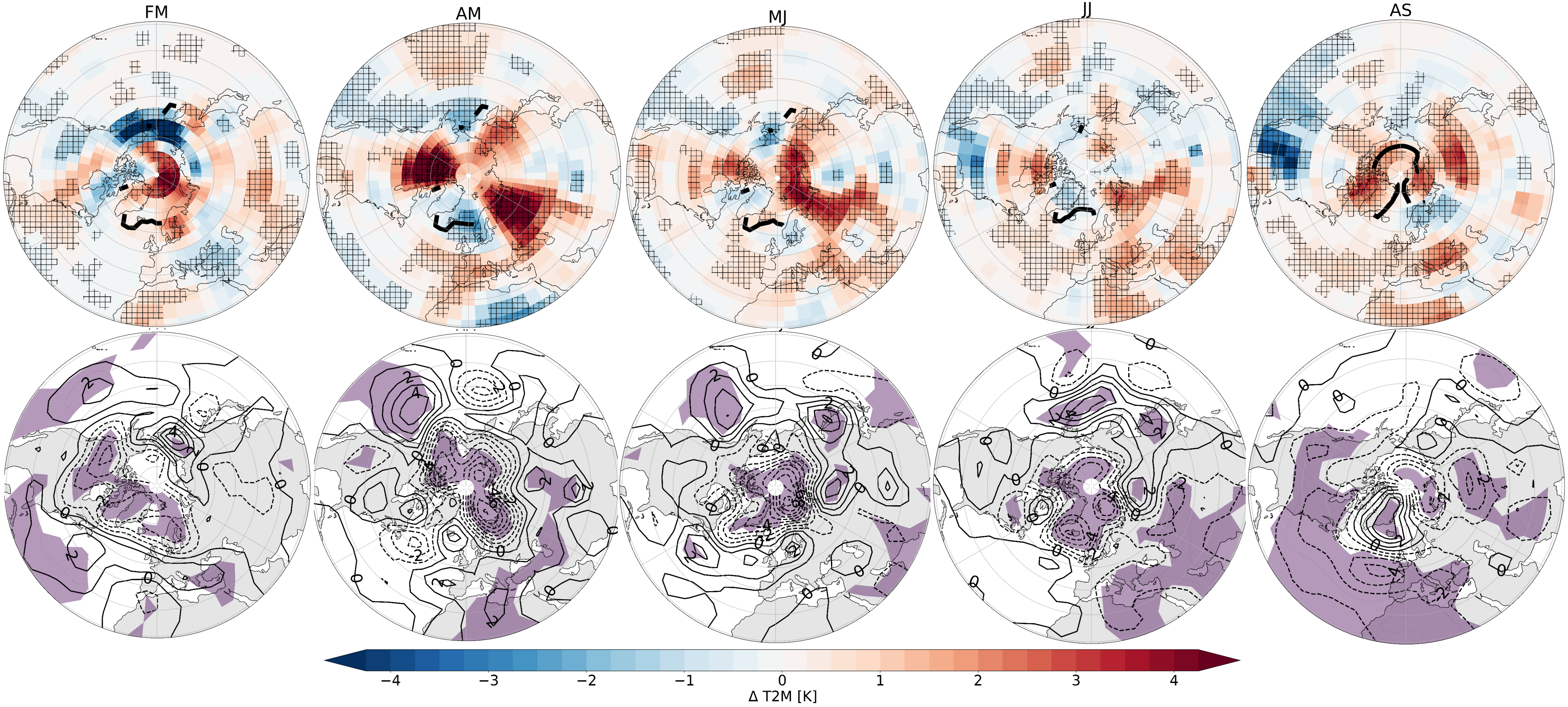


- Wavenumber 3-like positive T2M anomaly pattern in spring + baroclinic Z500 signal over the Arctic Ocean

Results: Application of the rare event algorithm to PlaSim-T2

Shading/Hatching: anomalies larger in magnitude than intra-ensemble standard deviation

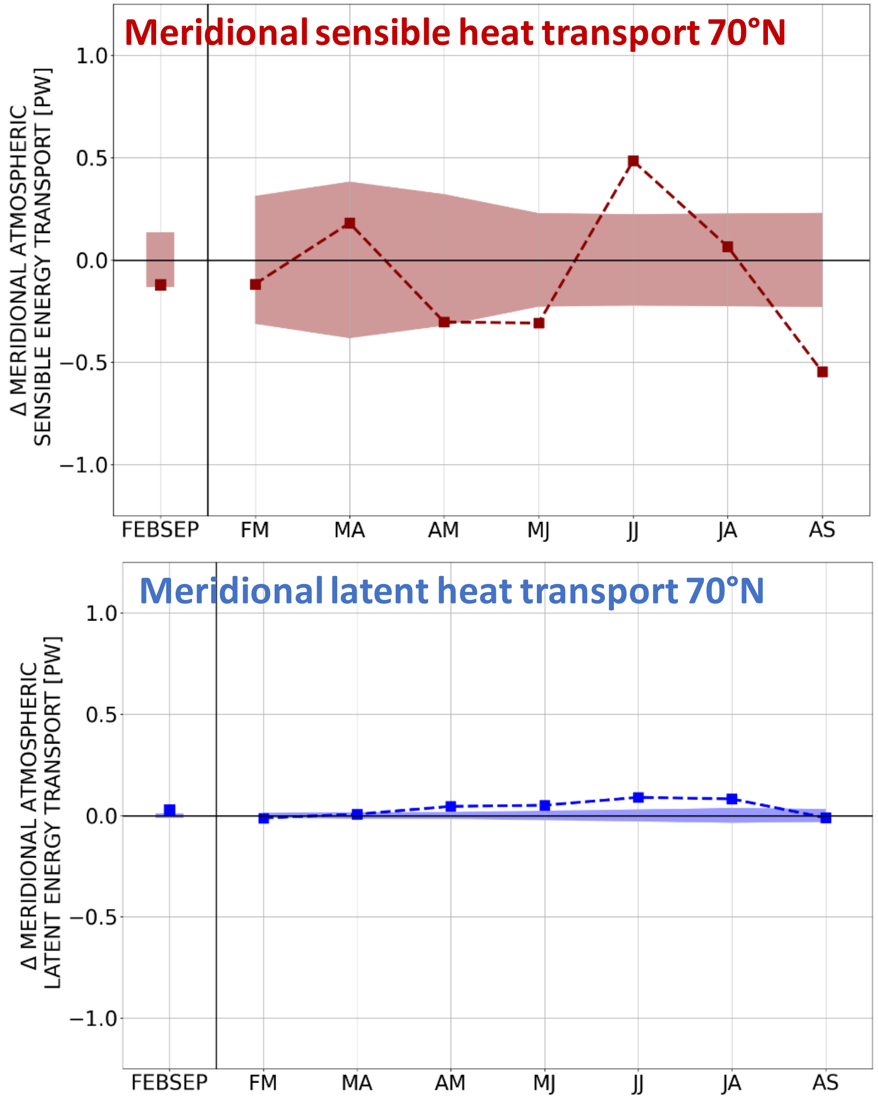
Trajectory with lowest August-September mean pan-Arctic sea ice area



- Wavenumber 3-like positive T2M anomaly pattern in spring + cyclonic MSLP conditions over the Arctic Ocean
- Warm Arctic due to (regional) transport processes + due to enhanced moisture/cloudiness in a cyclonic environment

YEAR1930 neutral sea ice initial condition experiment

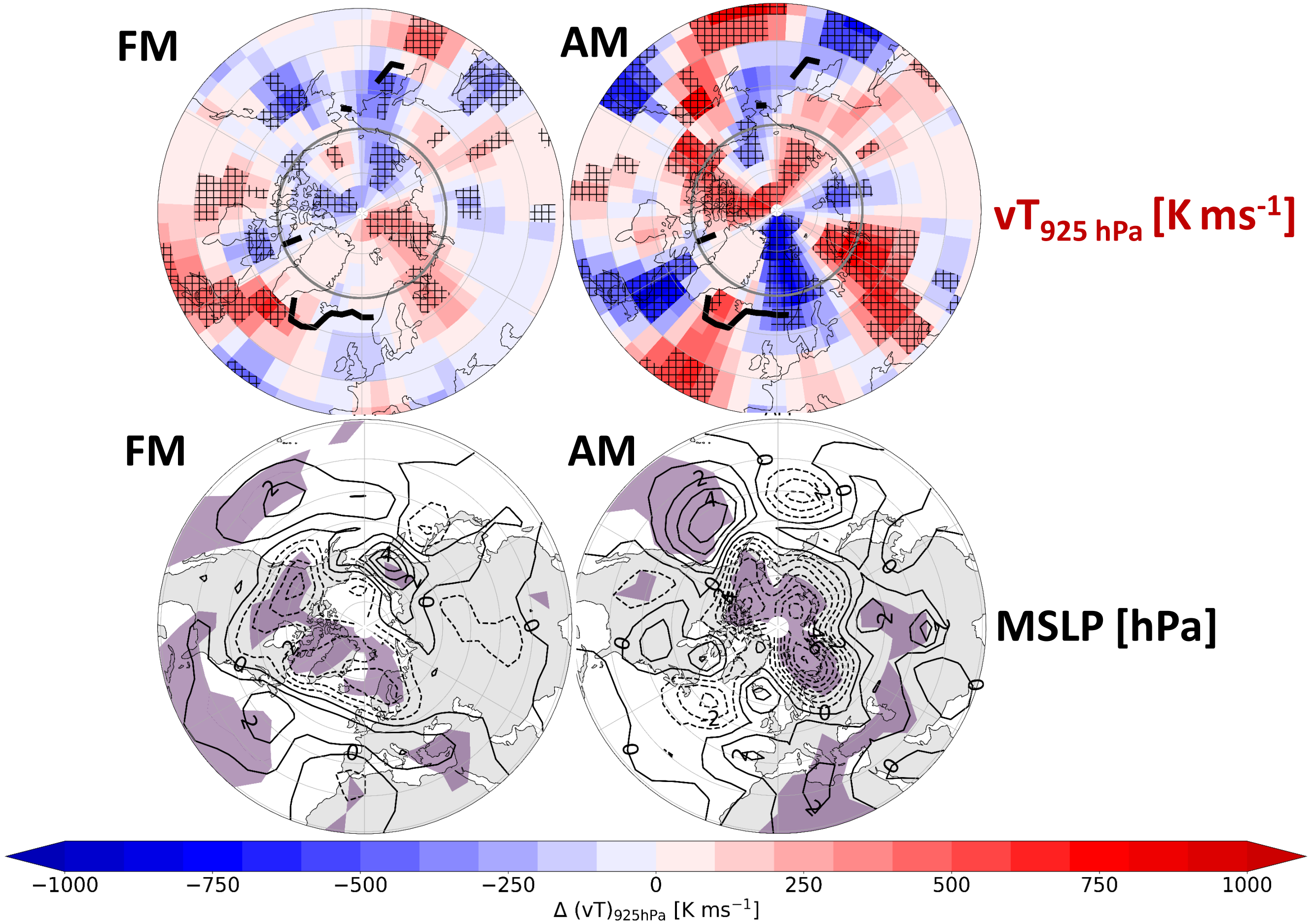
Trajectory with lowest August-September mean pan-Arctic sea ice area

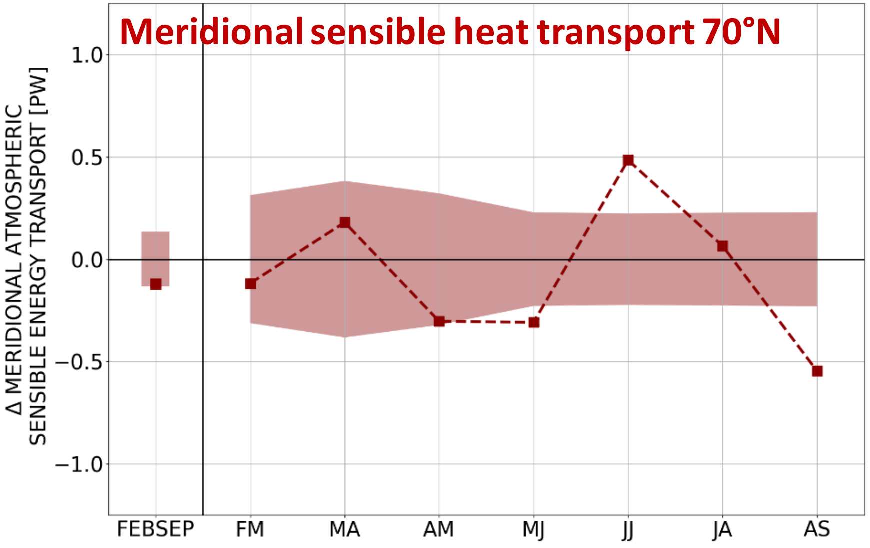


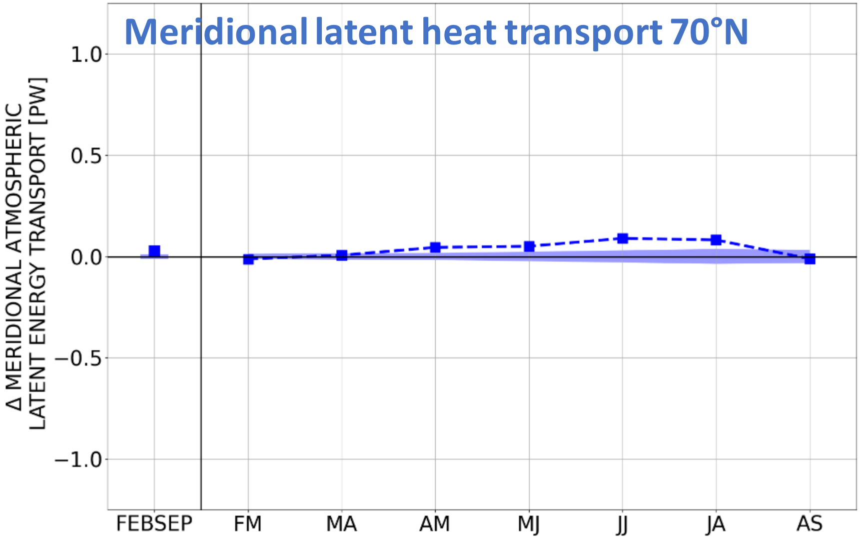
- No systematic signal in the zonally and vertically integrated meridional sensible heat transport at 70°N
- “Significant” zonally and vertically integrated meridional latent heat transport at 70°N in spring and summer

Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II

Trajectory with lowest August-September mean pan-Arctic sea ice area







- No systematic signal in the zonally and vertically integrated meridional sensible heat transport at 70°N
- “Significant” zonally and vertically integrated meridional latent heat transport at 70°N in spring and summer
- Regional transport of sensible heat and moisture into the Arctic on the eastern flank of cyclones

Methodology: Rare event algorithm

- 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

- Importance sampling of trajectories in ensemble simulation with numerical model

- Resampling at constant time intervals: trajectories are killed or cloned depending on weights measuring their likelihood to lead to an extreme

- Importance sampling formula: 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

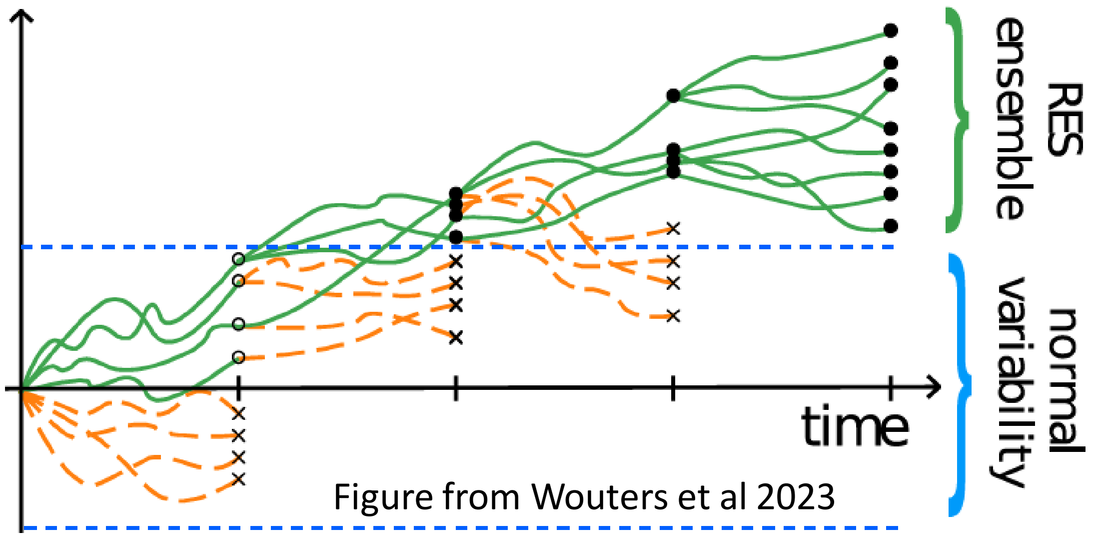


Figure from Wouters et al 2023