

# Extreme Arctic sea ice lows investigated with a rare event algorithm

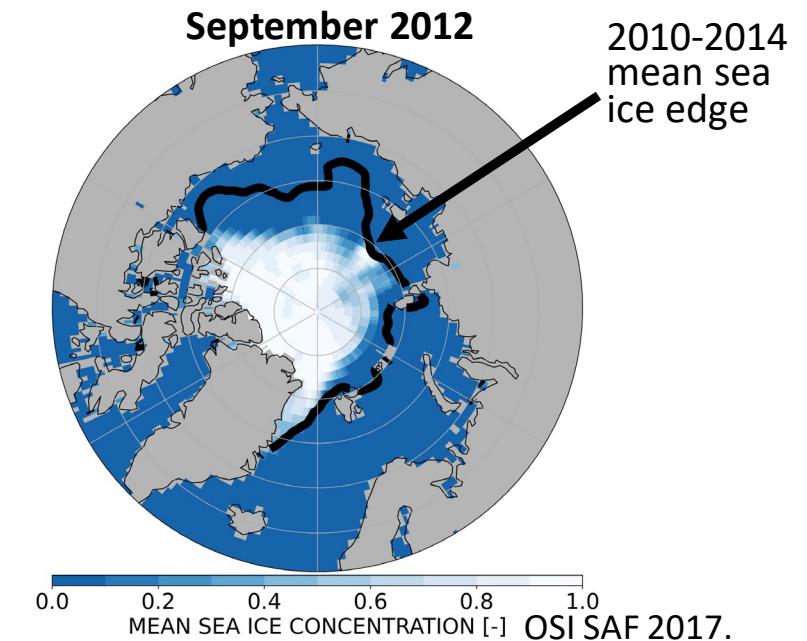
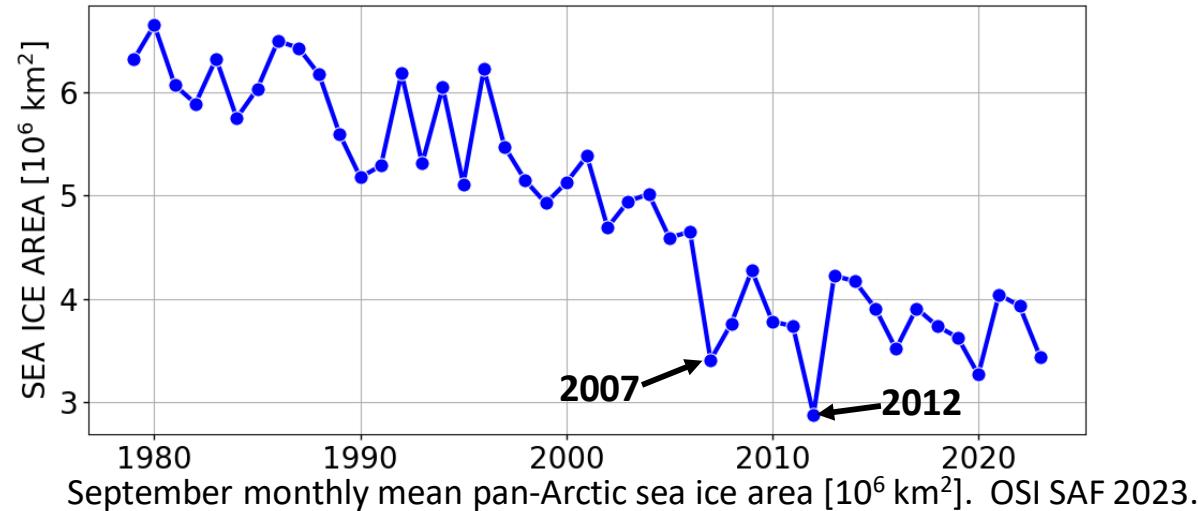
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with Francesco Ragone, François Massonnet, Giuseppe Zappa, Jonathan Demaeyer

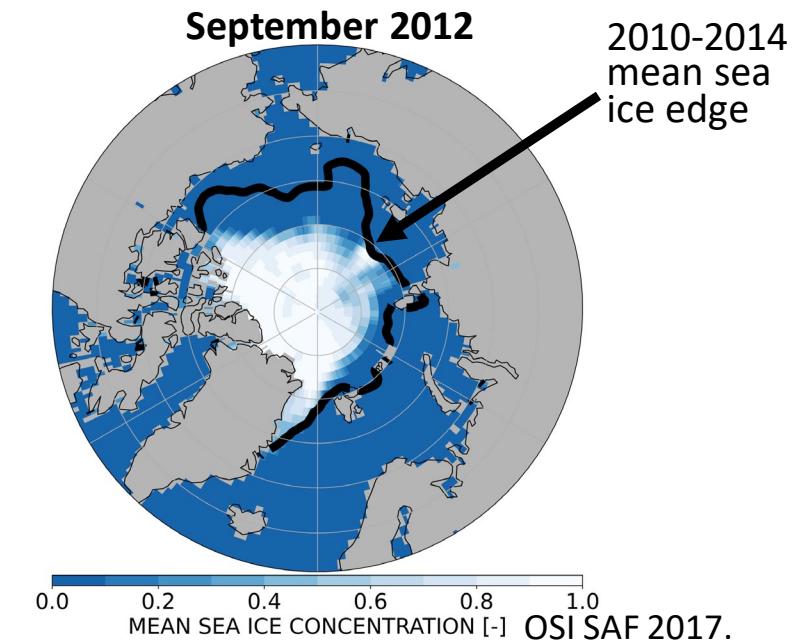
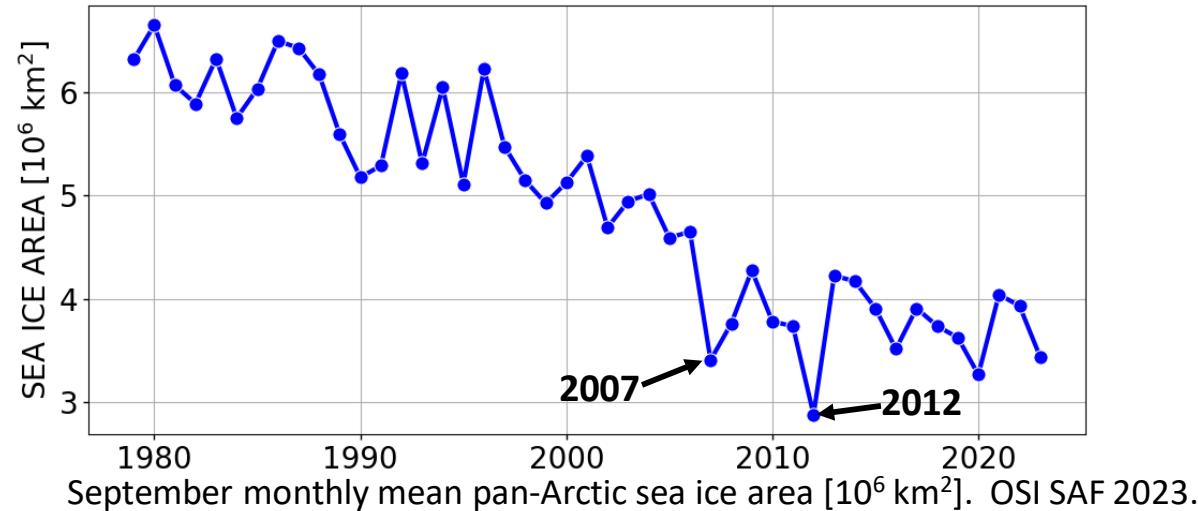


# Extreme reductions in the summer pan-Arctic sea ice area



- 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

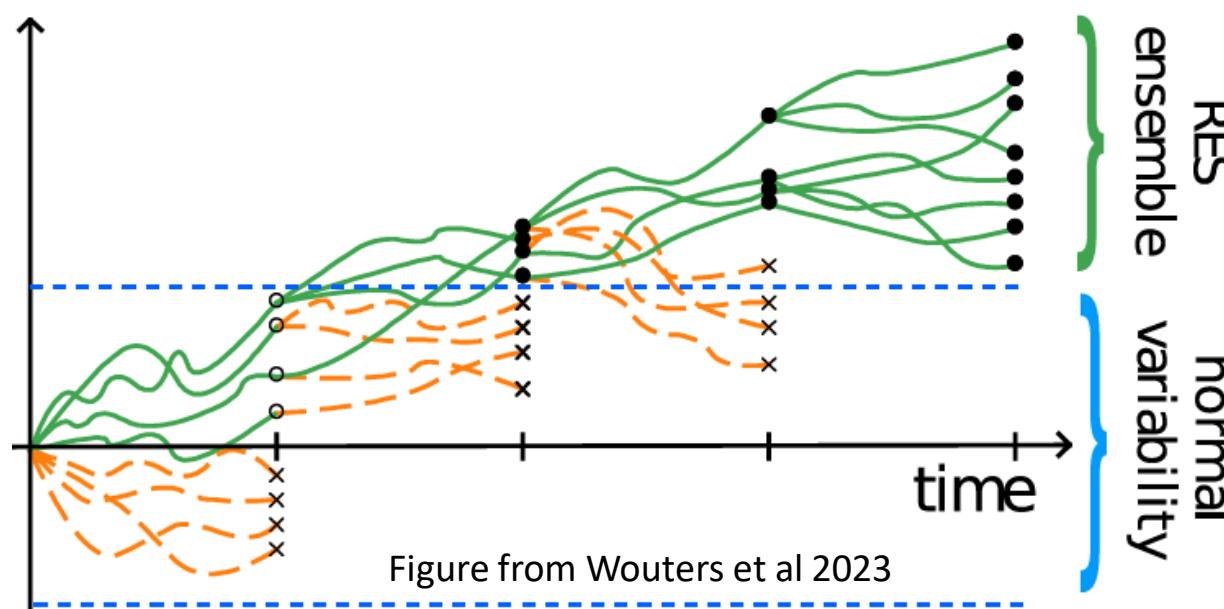
# Extreme reductions in the summer pan-Arctic sea ice area



- 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

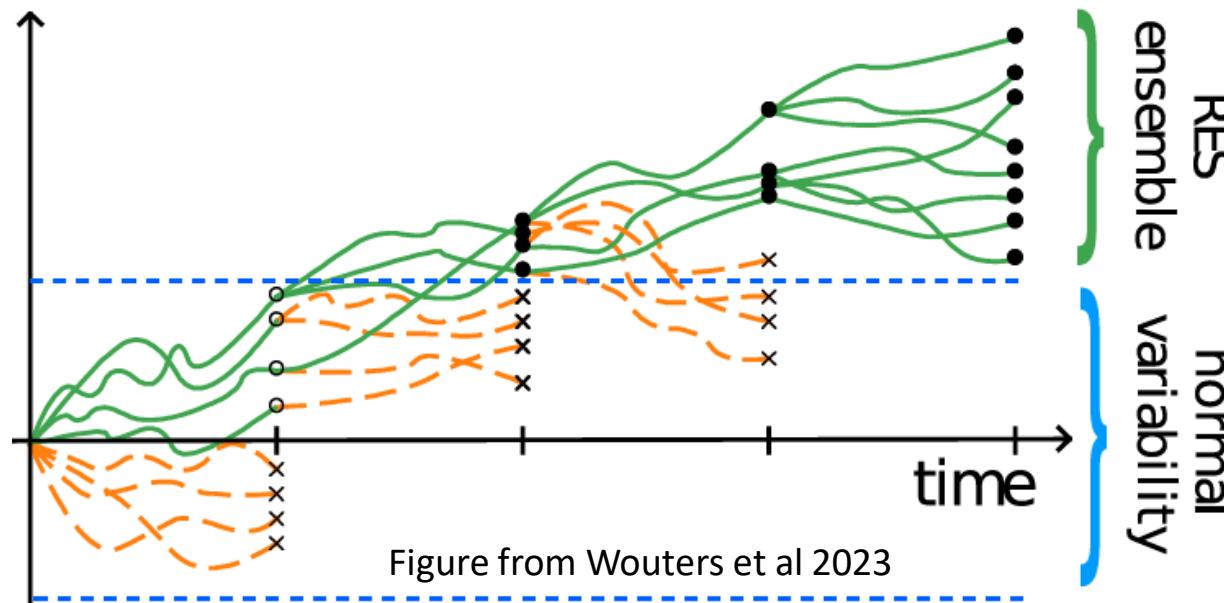
# Methodology: Rare event algorithm

- 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



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

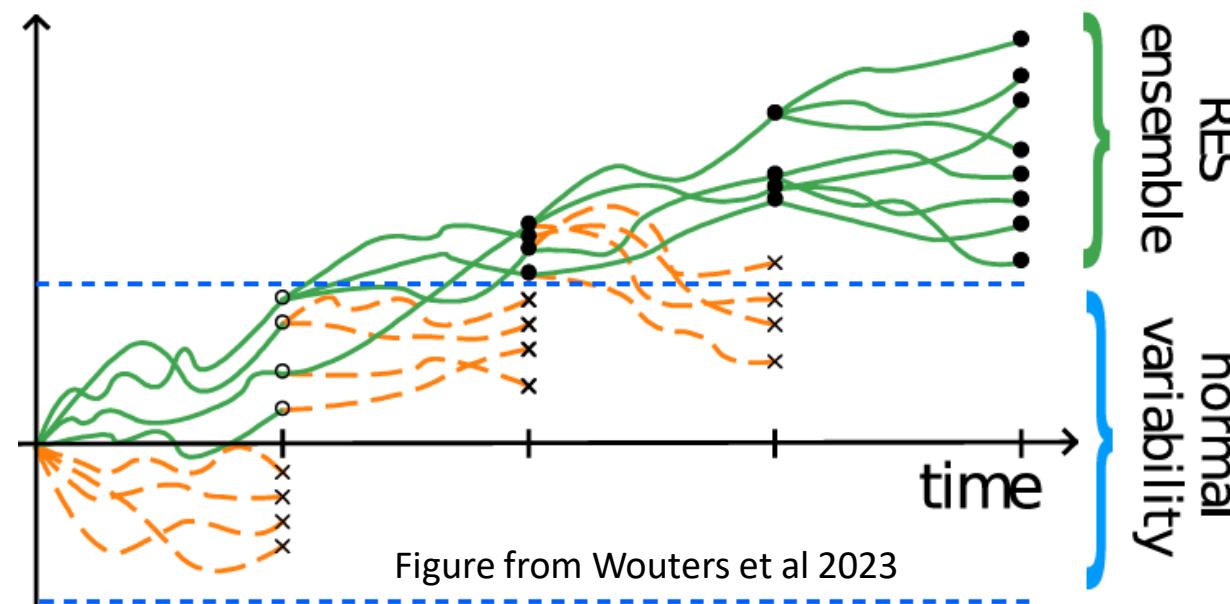


# Methodology: Rare event algorithm

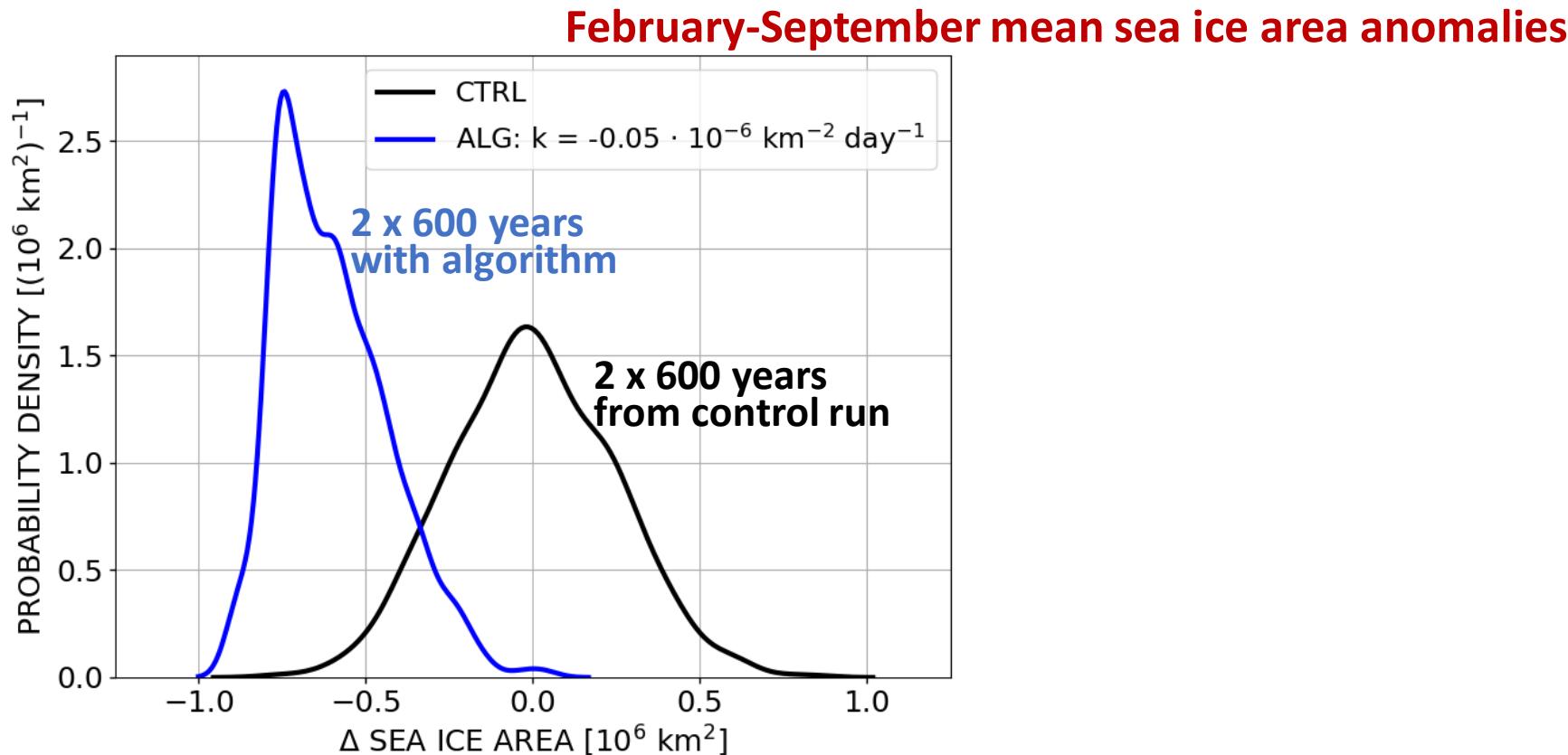
- Importance sampling of dynamical trajectories in ensemble simulation with numerical model  
-> make trajectories leading to large anomalies of a time-averaged observable (e.g. sea ice area) common
- Resampling at constant time intervals: trajectories are killed or cloned depending on weights measuring the likelihood to lead to an extreme event
- 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

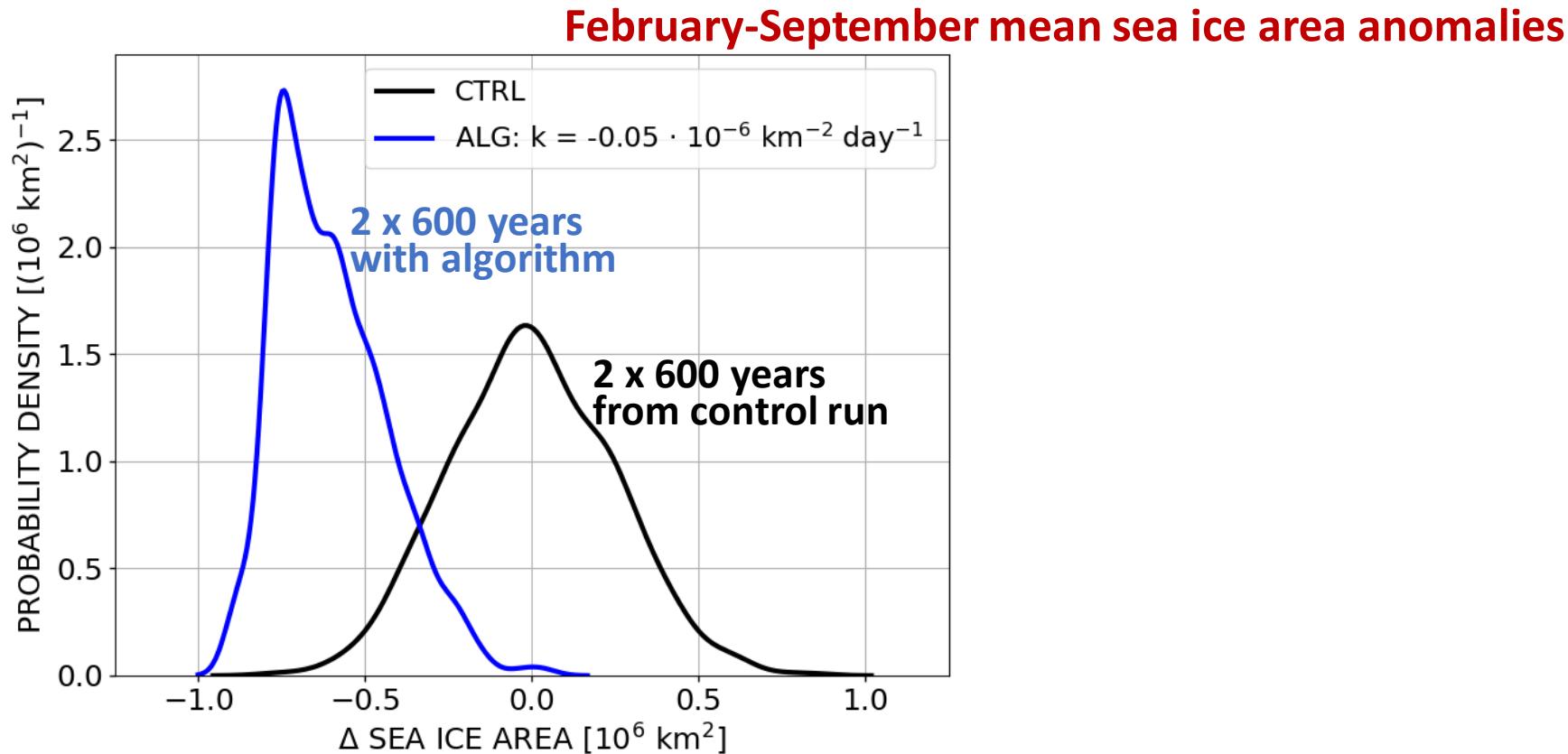


# Results: Application of the rare event algorithm to PlaSim-T21-LSG



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

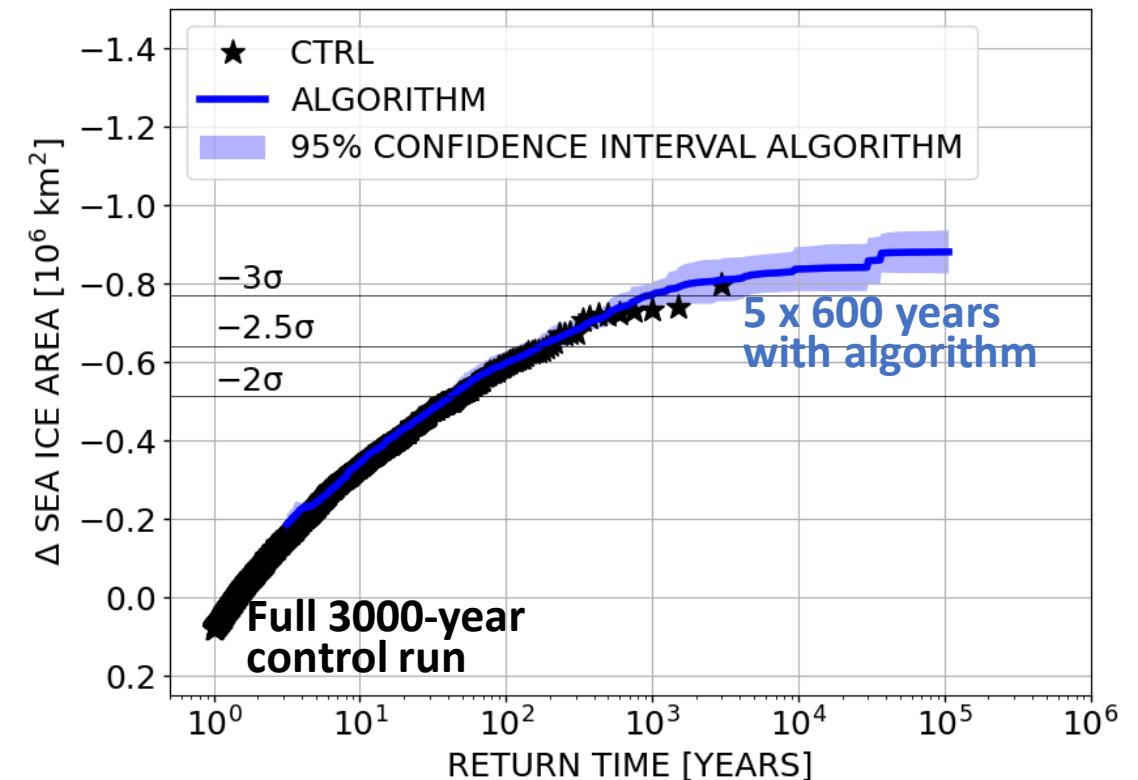
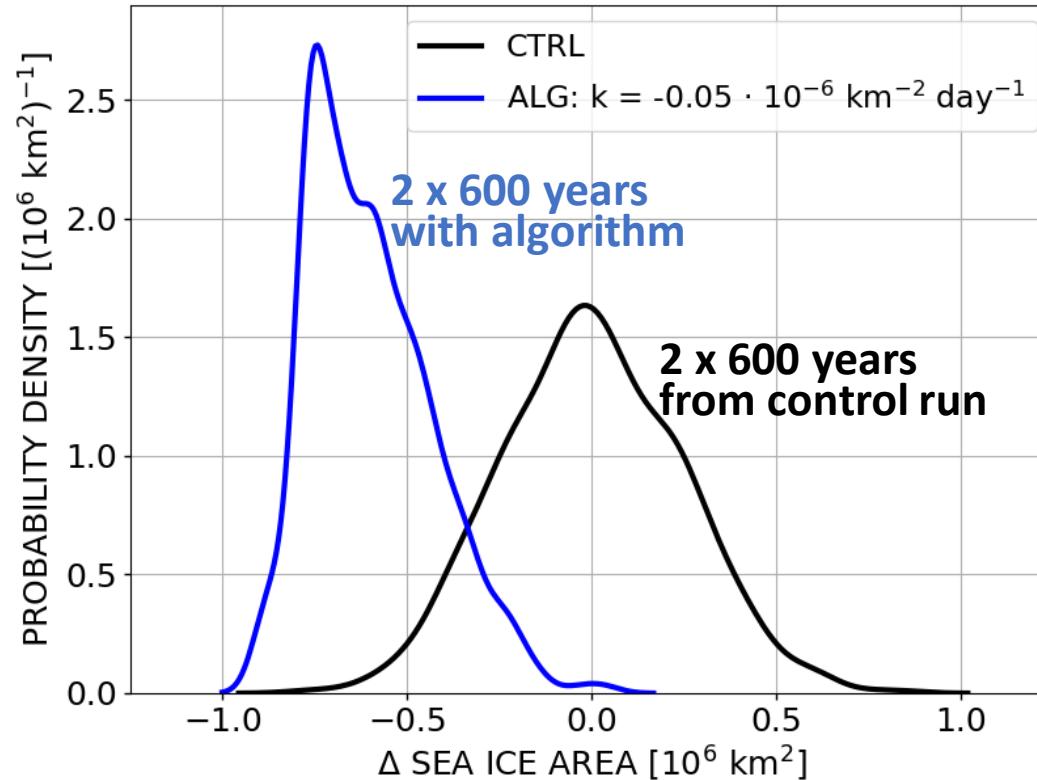
# Results: Application of the rare event algorithm to PlaSim-T21-LSG



- 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

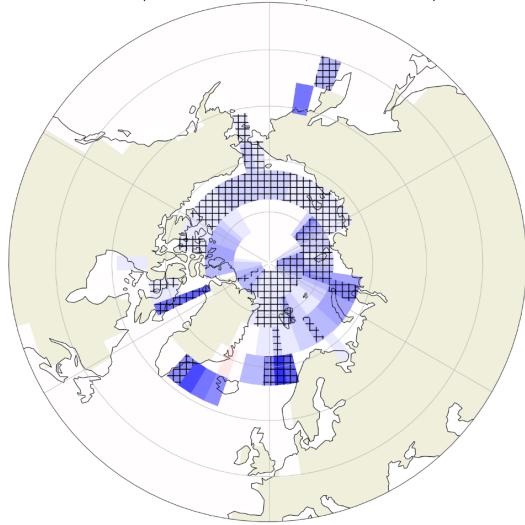


- Independent initial conditions sampled from long control run (stationary pre-industrial climate)
- Importance sampling of extreme negative February-September mean pan-Arctic sea ice area anomalies
- The algorithm allows to compute return times up to  $10^5$  years with computational cost of order  $10^3$  years

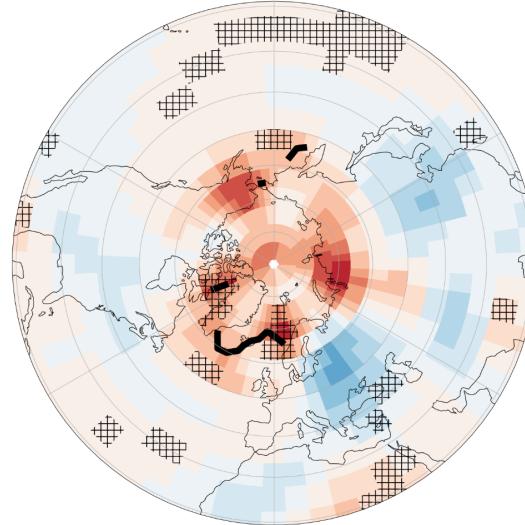
# Results: Application of the rare event algorithm to PlaSim-T21-LSG

CONTROL

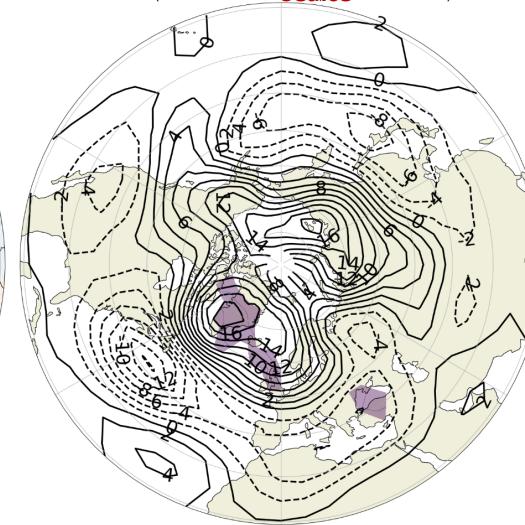
SIC [-]:  $r_{\text{Sealce}} > 200 \text{ years}$



T2M [K]:  $r_{\text{Sealce}} > 200 \text{ years}$



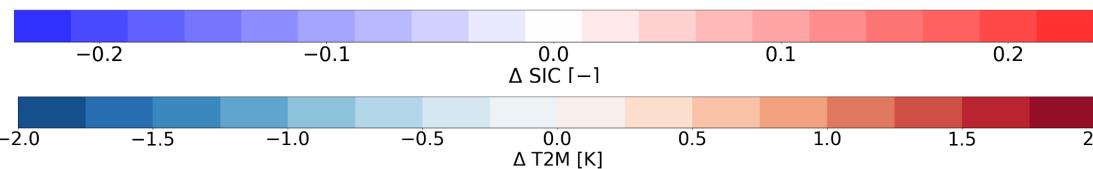
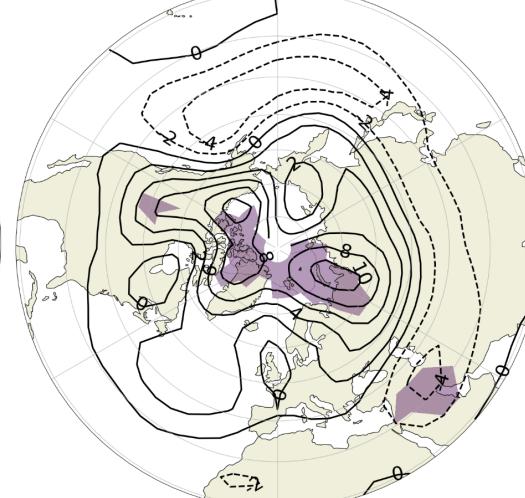
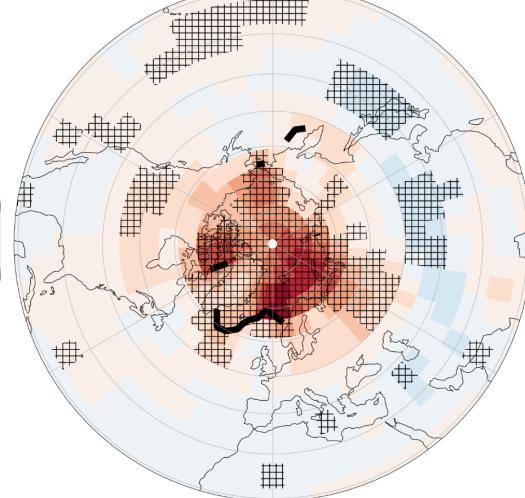
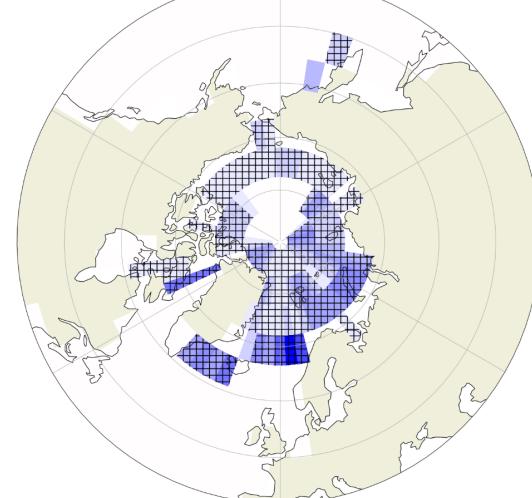
Z500 [gpm]:  $r_{\text{Sealce}} > 200 \text{ years}$



Hatching and shading:  
Significance at the 5% level

- Improved composite statistics with the algorithm compared to control run

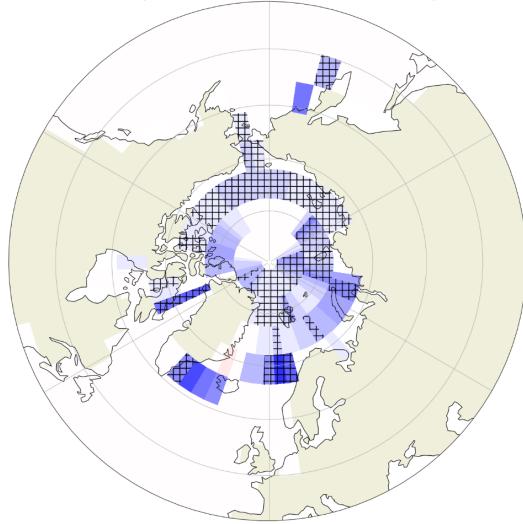
ALGORITHM



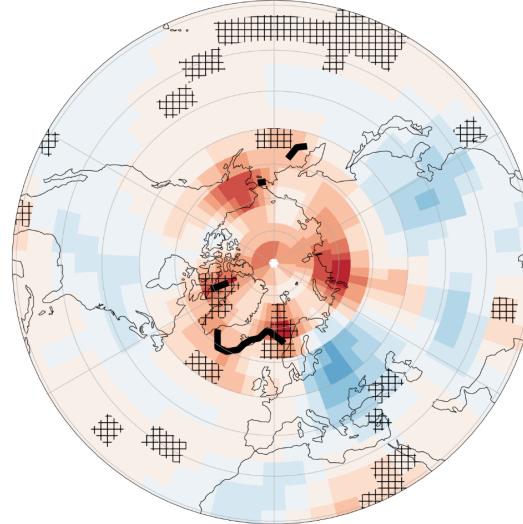
# Results: Application of the rare event algorithm to PlaSim-T21-LSG

CONTROL

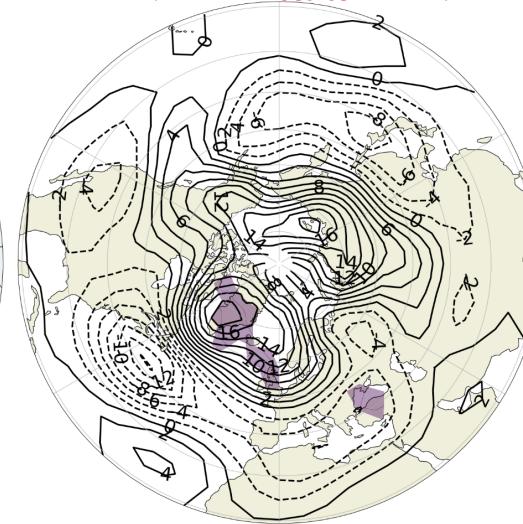
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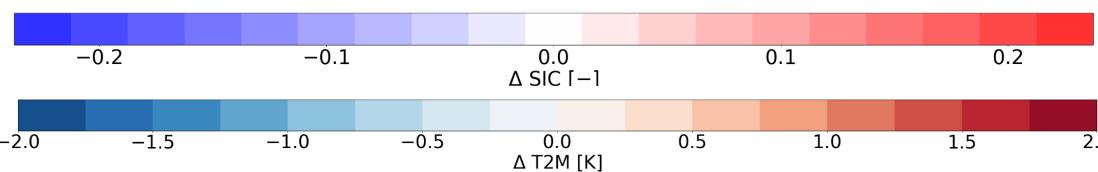
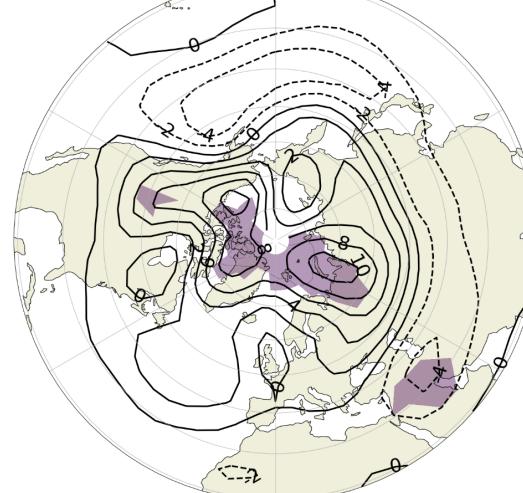
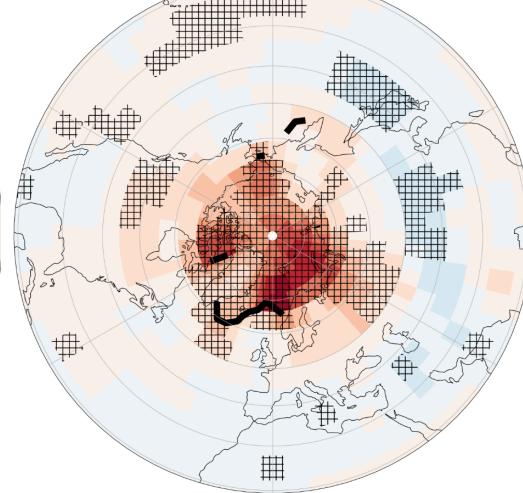
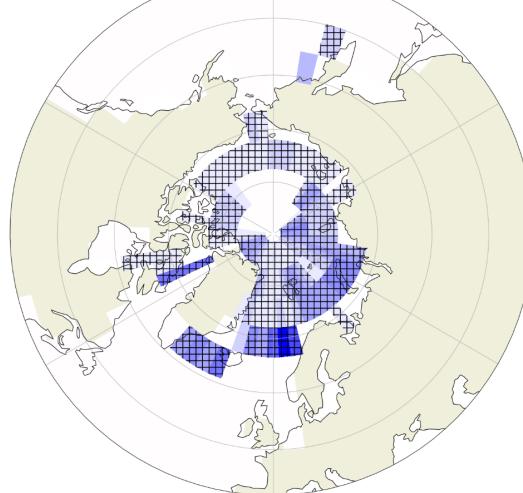


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Hatching and shading:  
Significance at the 5% level

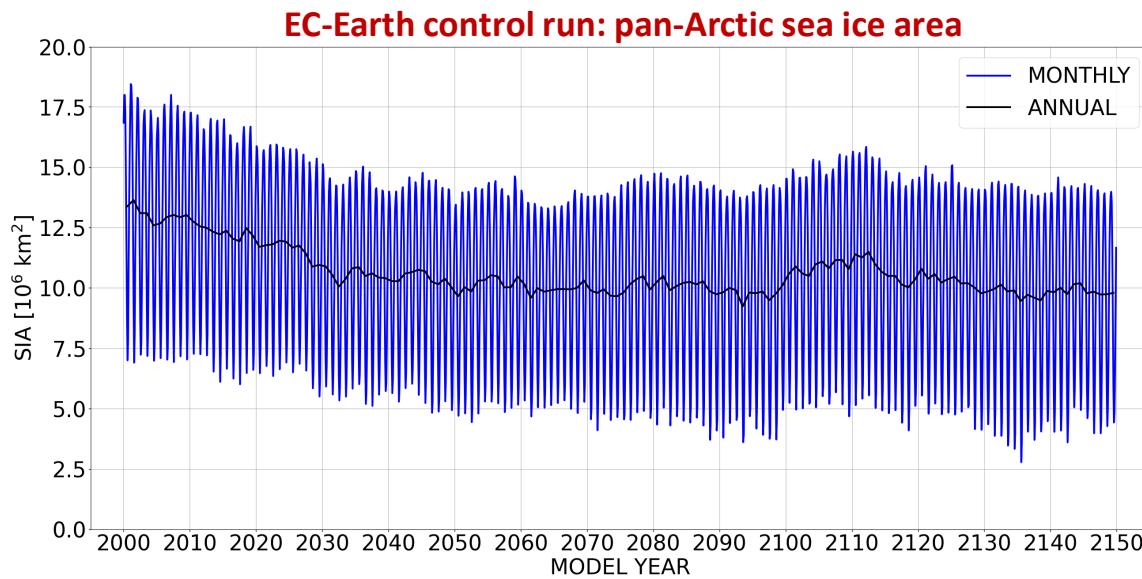
ALGORITHM



- 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)

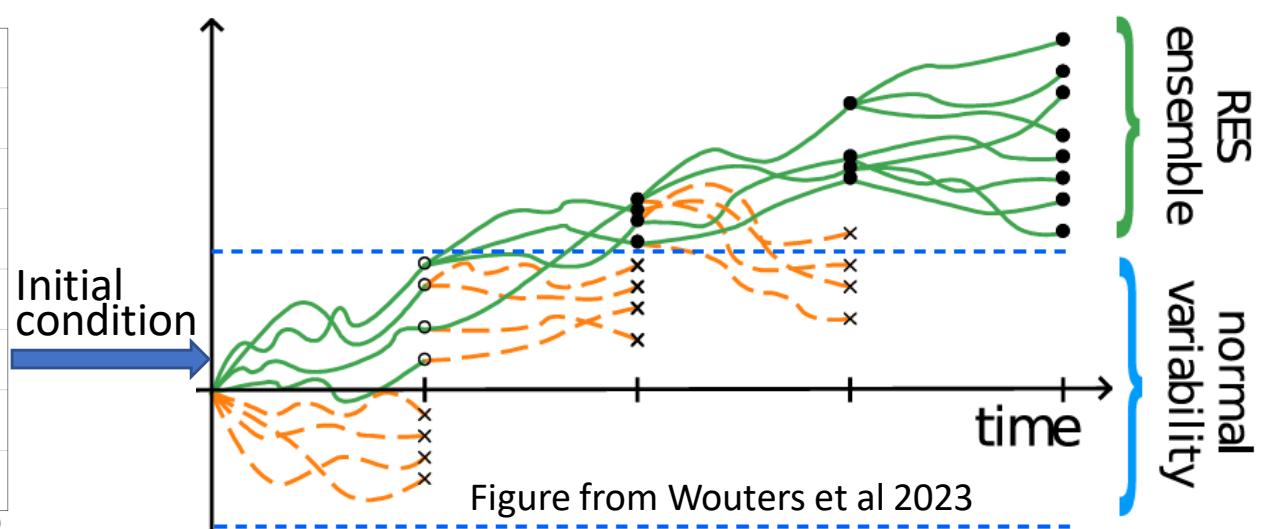
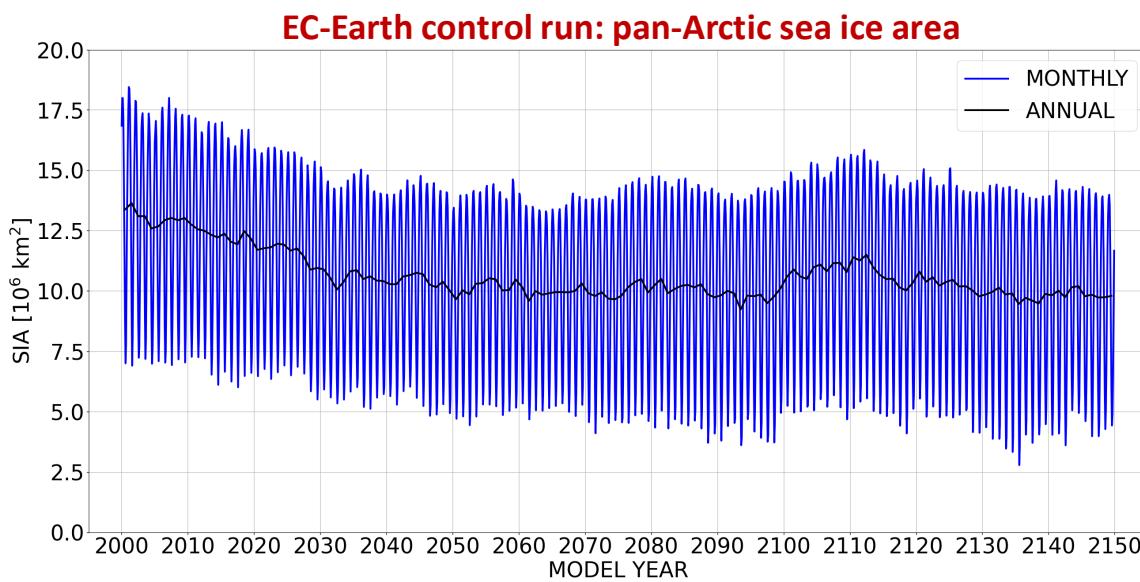
# Work in progress: Application of the rare event algorithm to EC-Earth3.3.1

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



# 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?



# 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  $\tau_r$
- 2) At regular times  $t_i = i\tau_r$  ( $i = 1, \dots, \frac{T_a}{\tau_r}$ ), trajectories are killed or generate a number of replicates depending on the weights

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

- 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

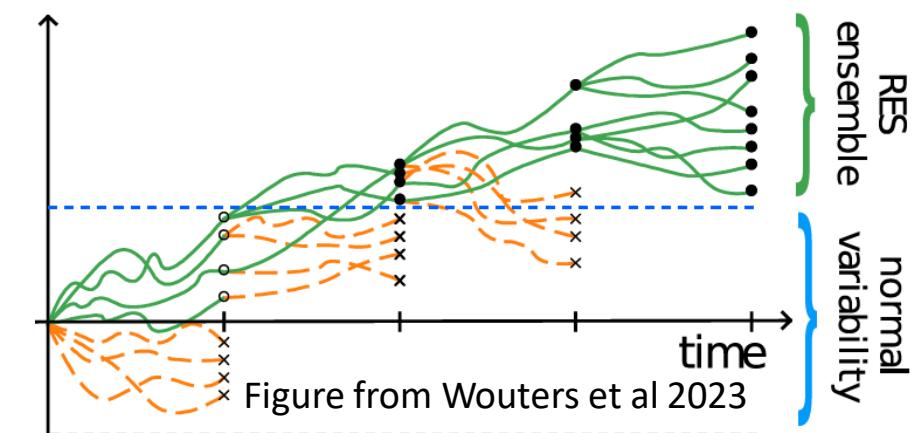
$$P_k (\{X(t)\}_{0 \leq t \leq T_a}) = \frac{e^{k \int_0^{T_a} A(\{X(t)\}) dt}}{R} P_0 (\{X(t)\}_{0 \leq t \leq T_a})$$

$P_k, P_0$ : prob. dens. in biased and unbiased statistics

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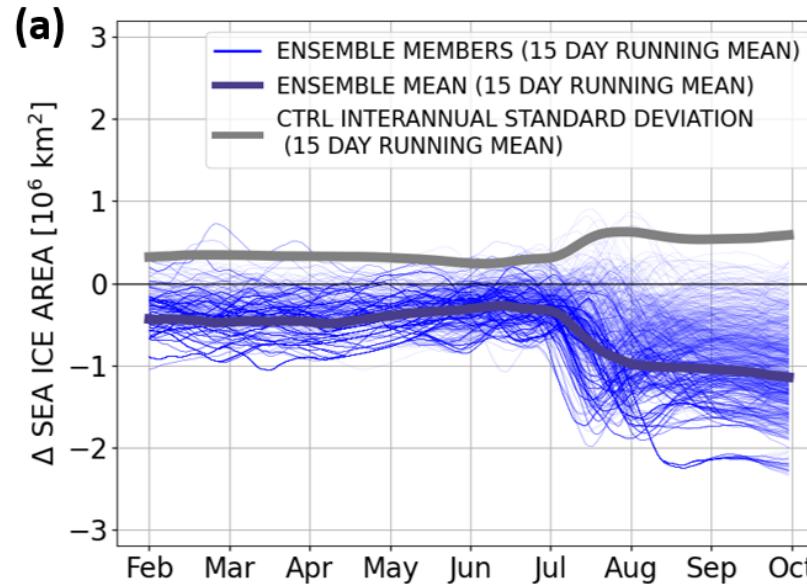
$t, T_a$ : time and simulation length

$A, \{X_n(t)\}$ : observable and model trajectories

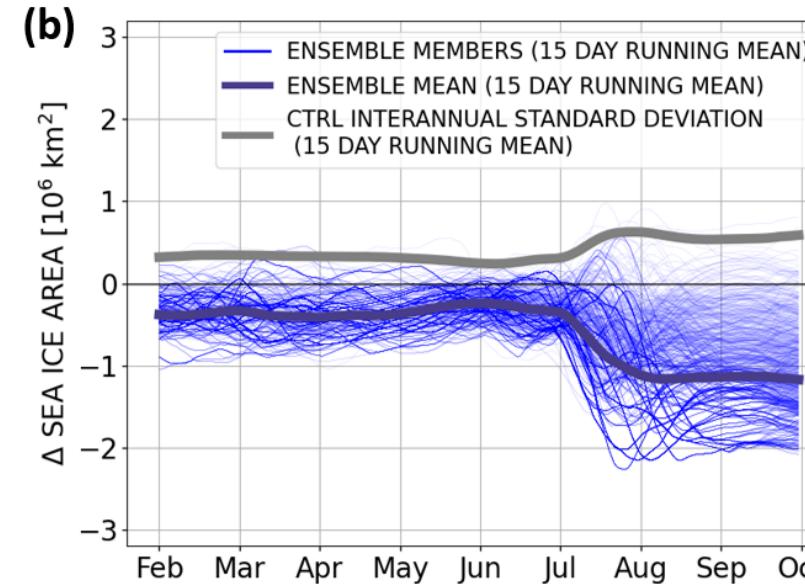


# Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I

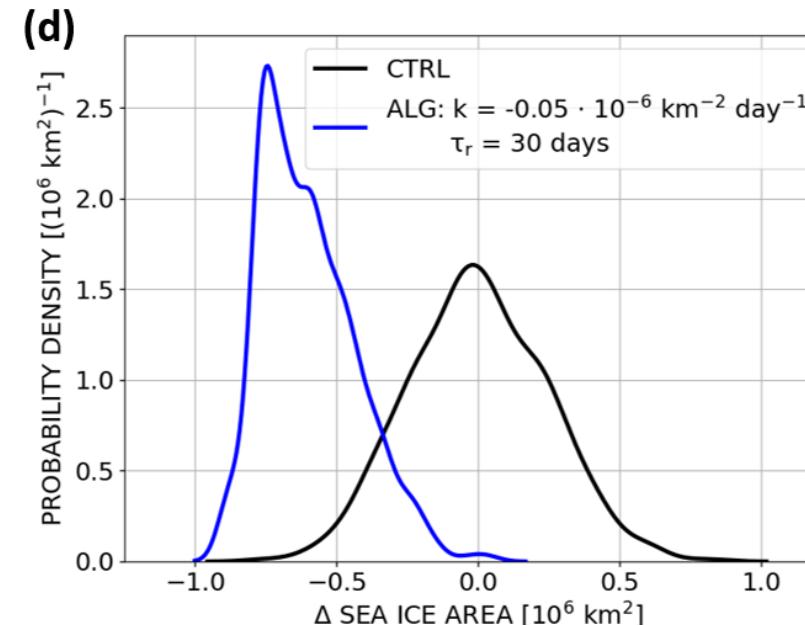
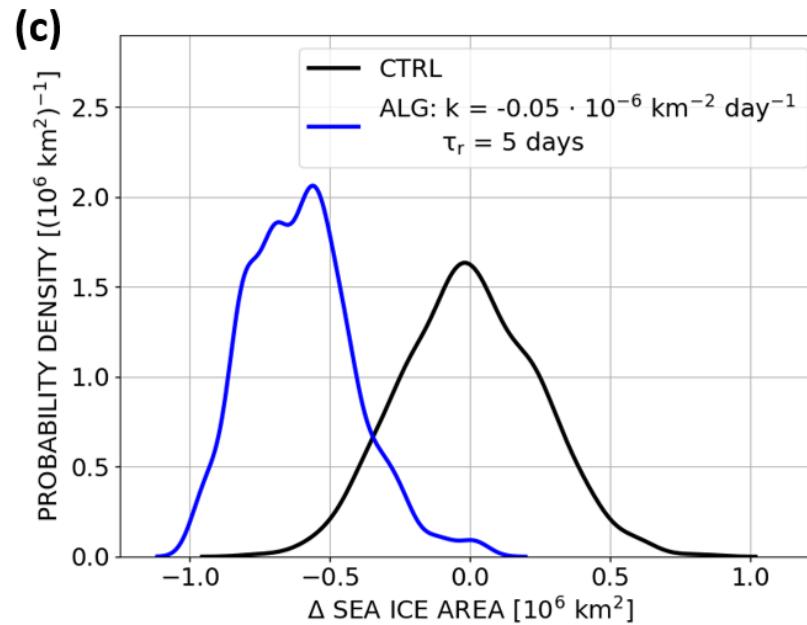
$\tau_r = 5$  days



$\tau_r = 30$  days



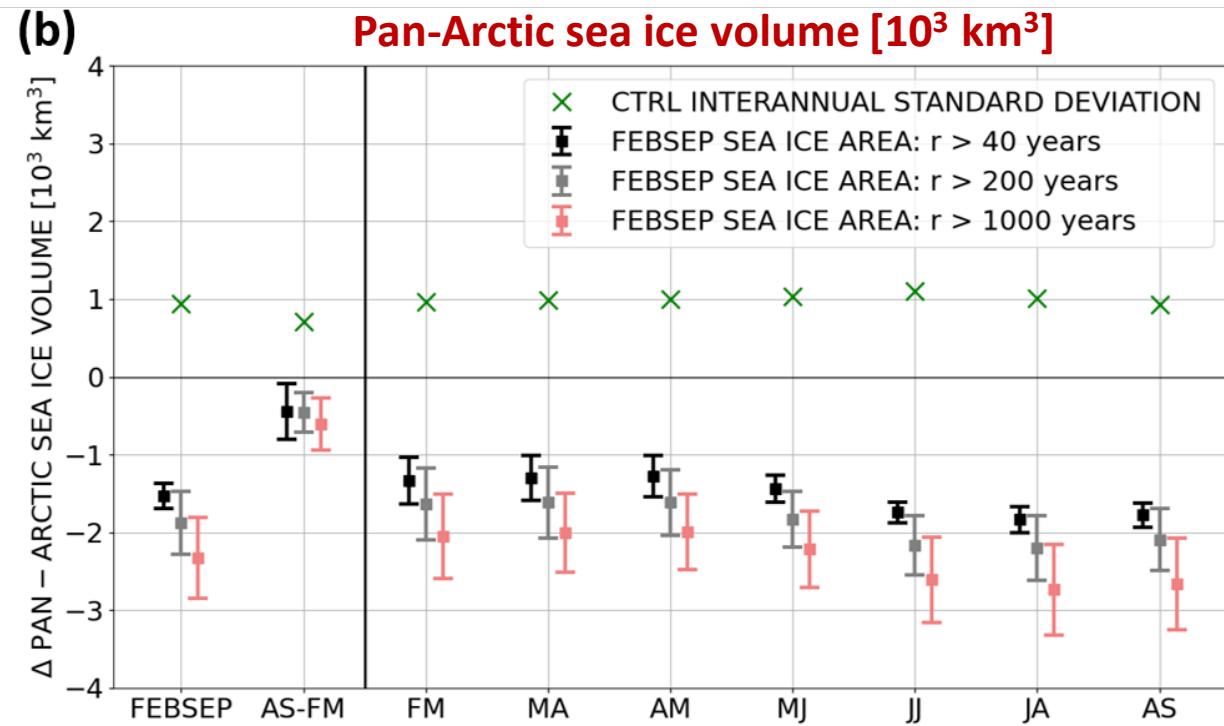
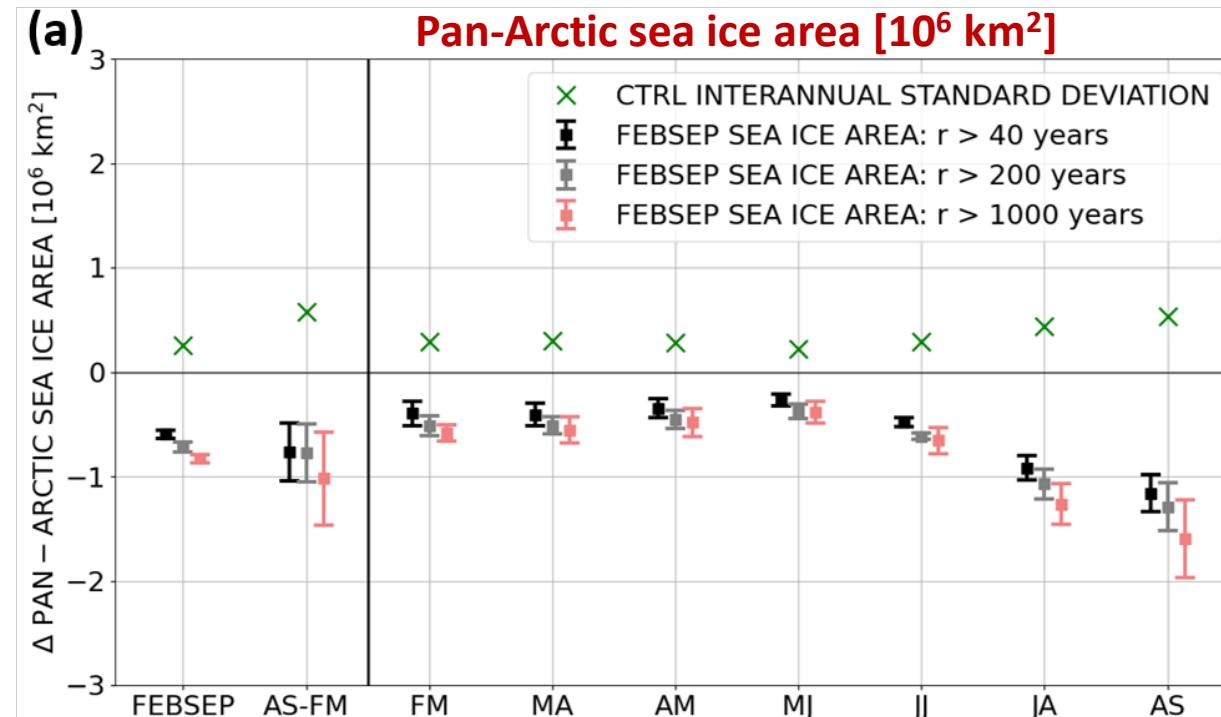
Pan-Arctic sea ice area [ $10^6 \text{ km}^2$ ]



Daily mean

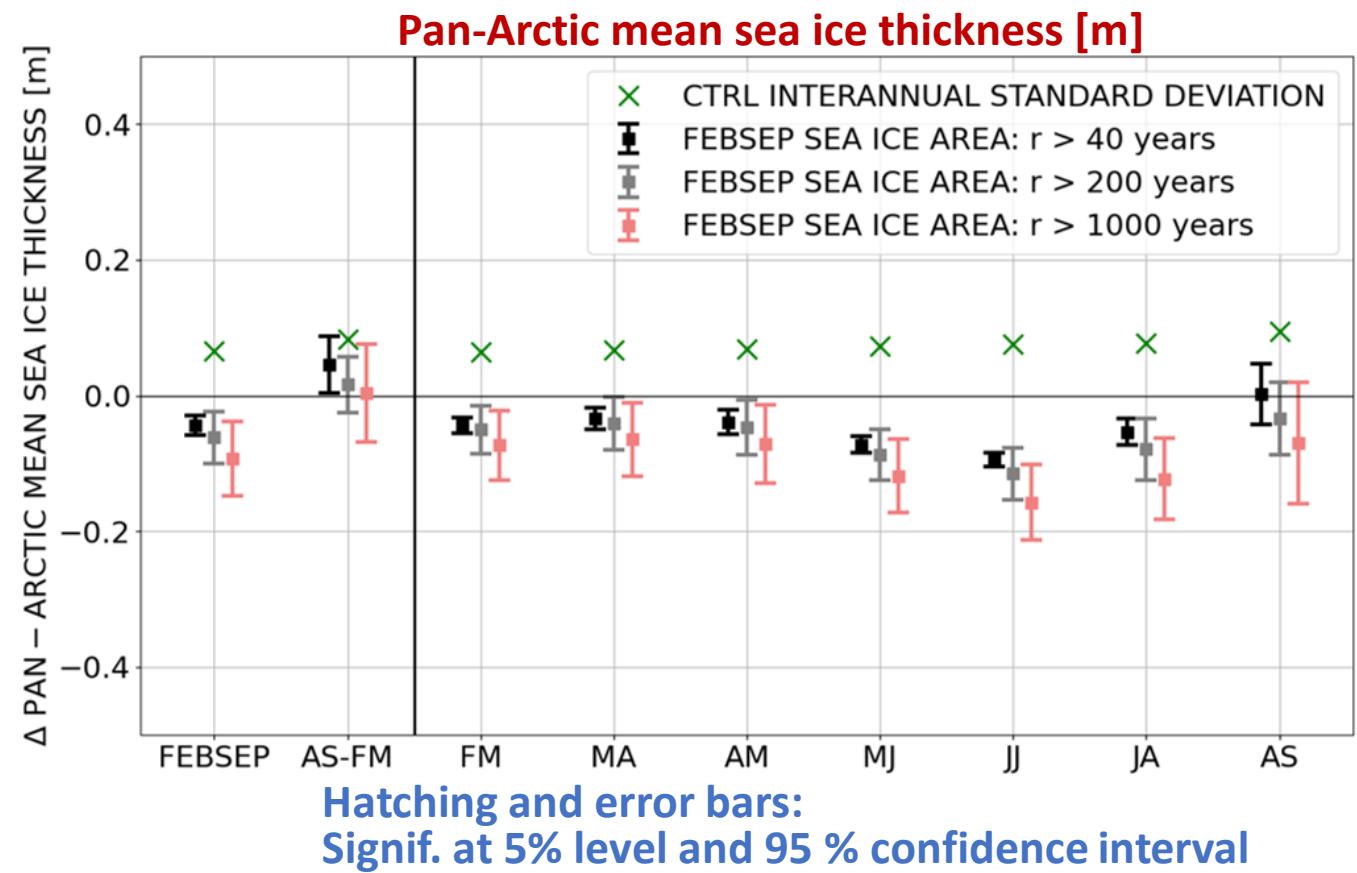
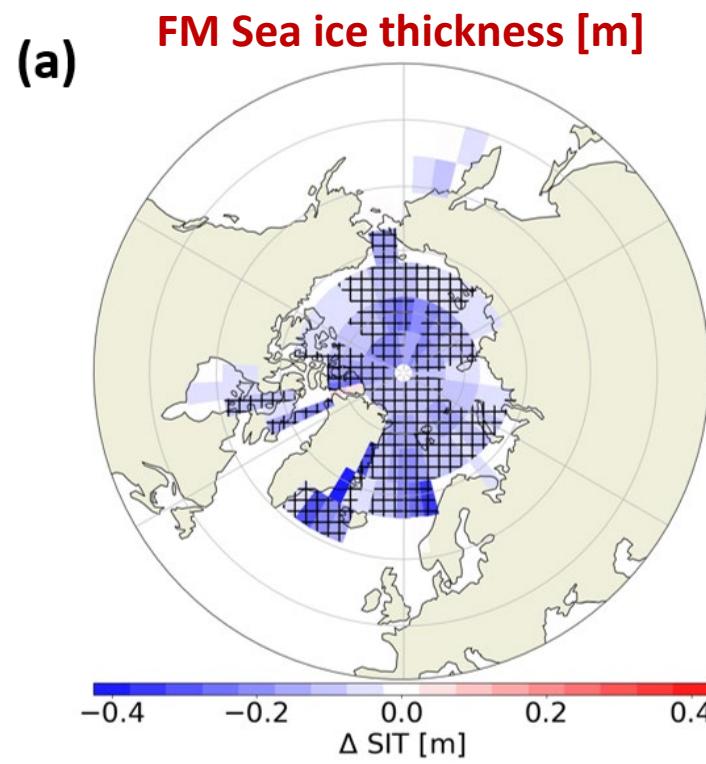
February-September mean

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

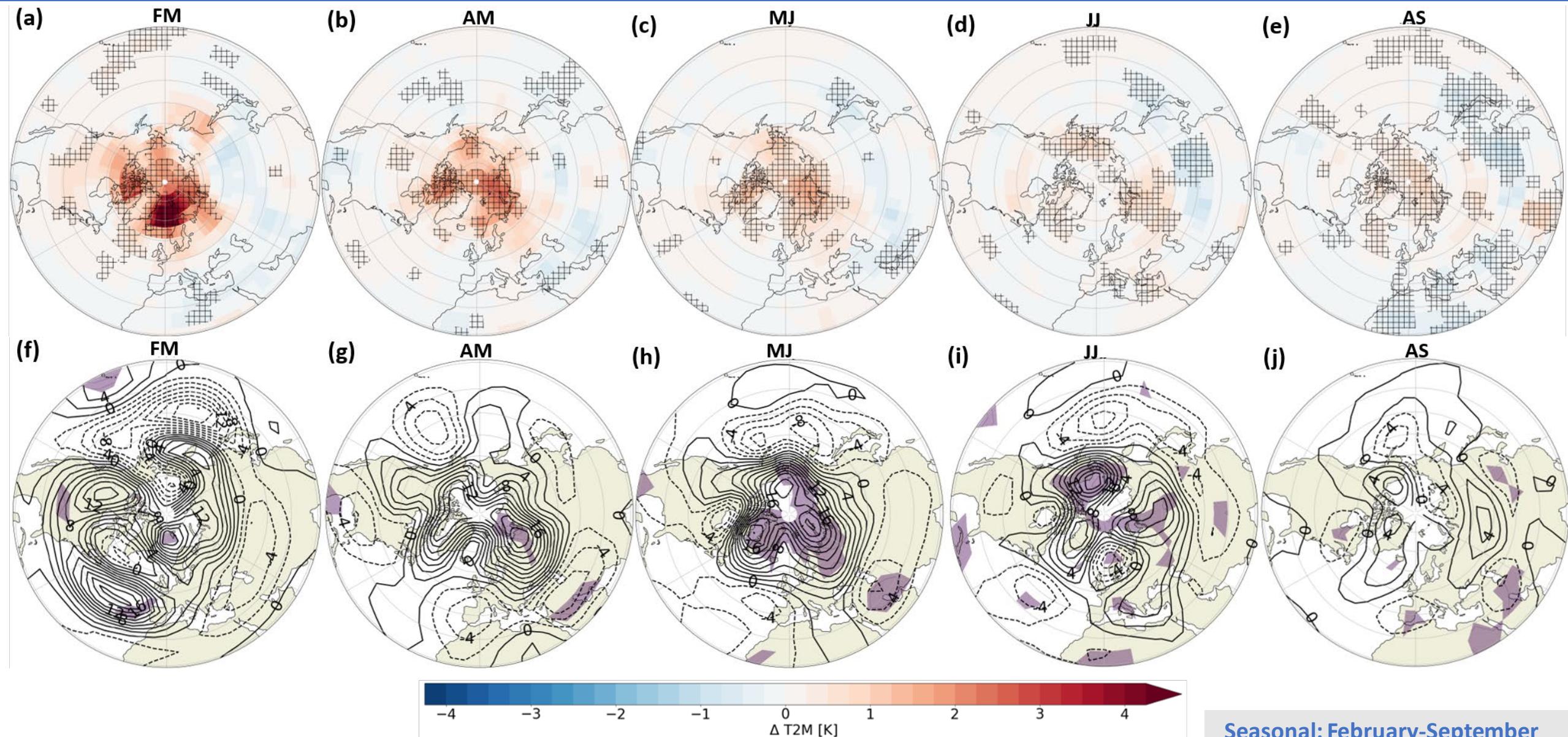


Error bars: 95 % confidence interval

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



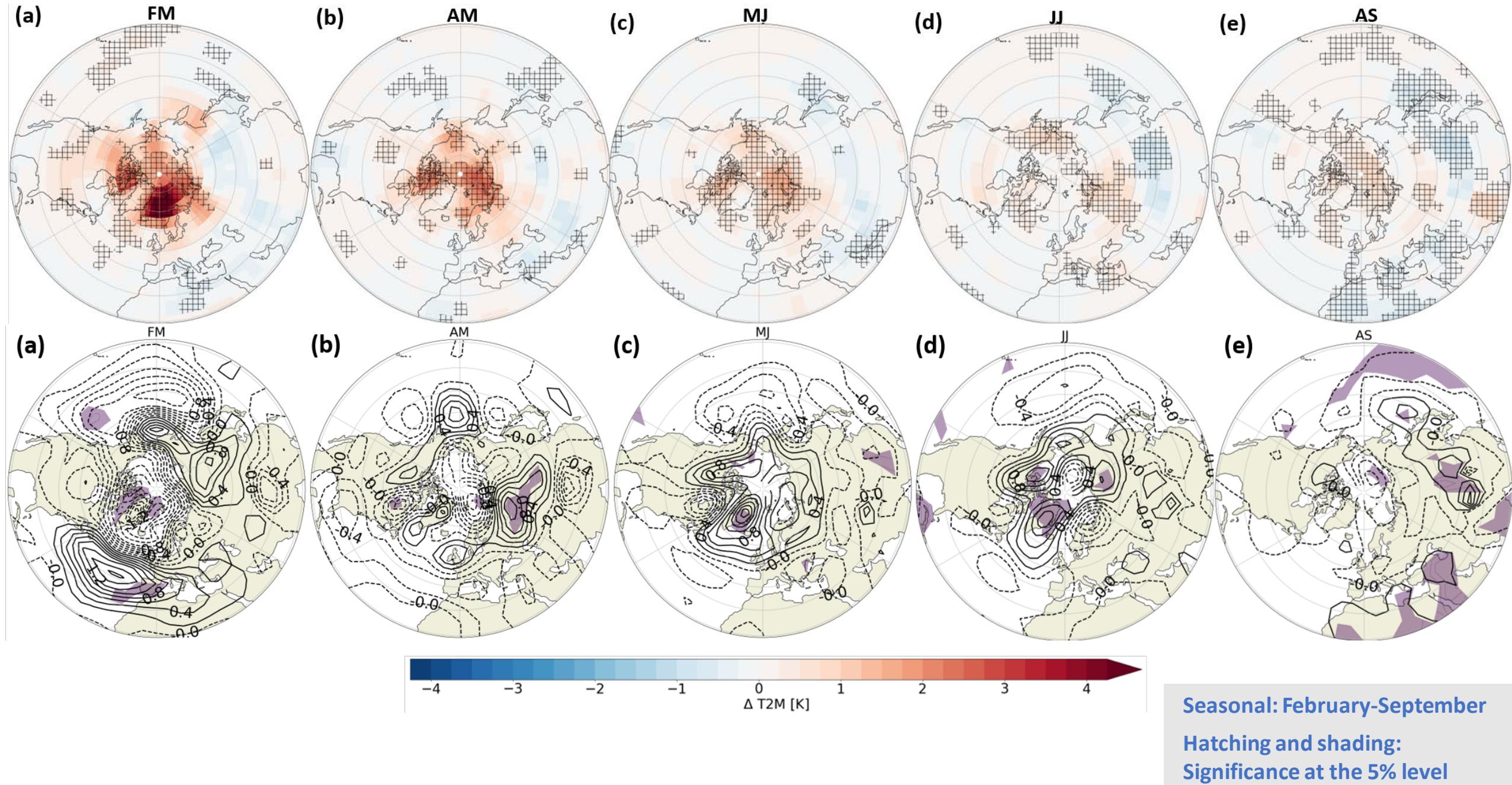
# Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I



Seasonal: February-September

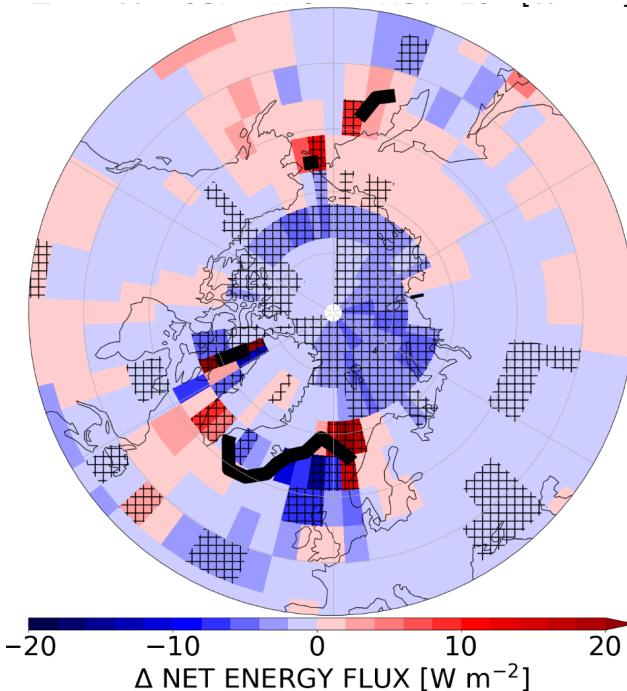
Hatching and shading:  
Significance at the 5% level

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



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

February-September mean  
net energy fluxes



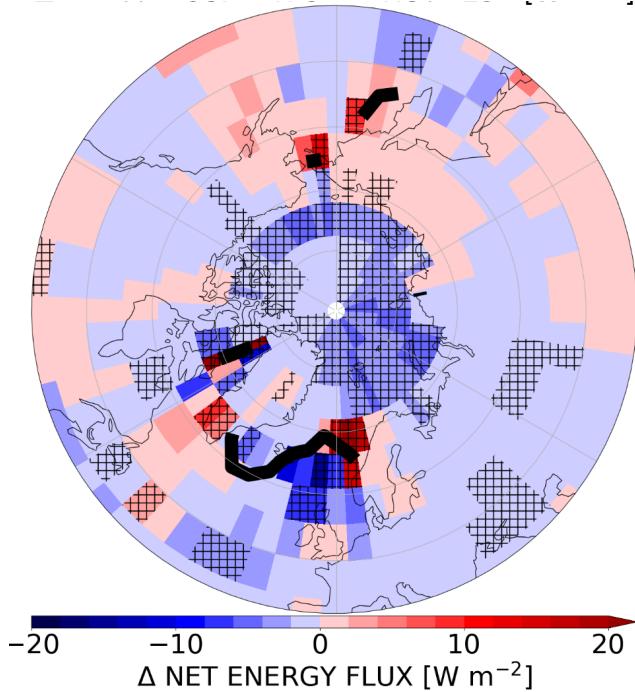
- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean

Seasonal: February-September

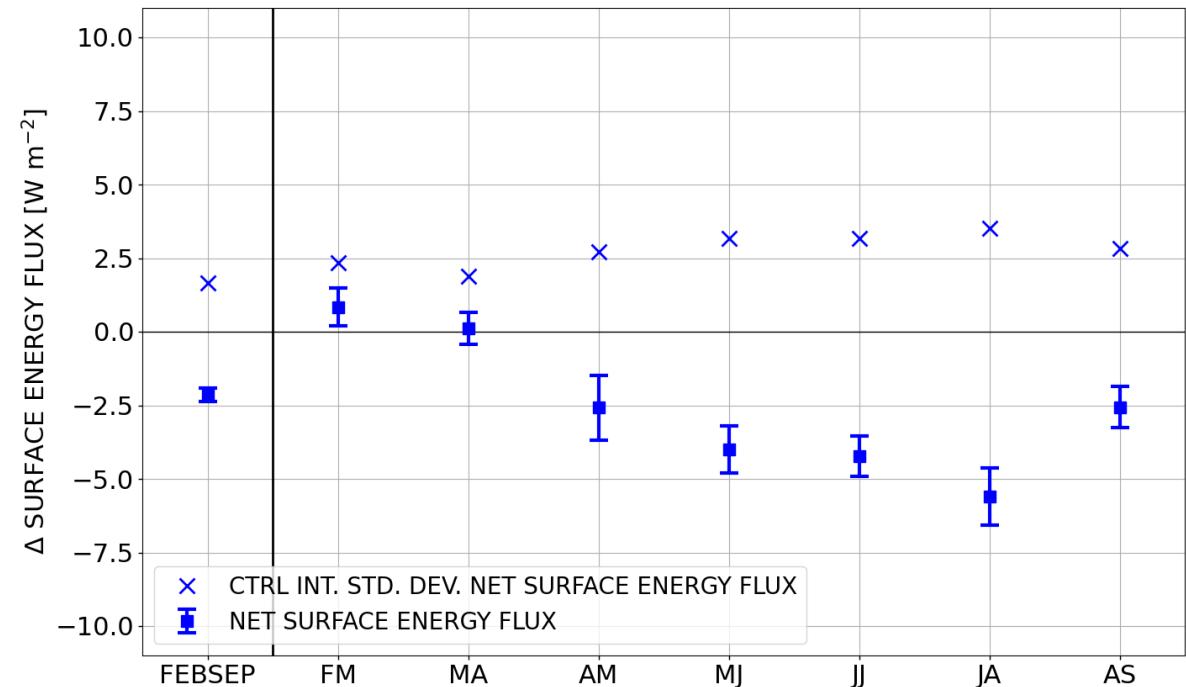
Hatching/Error bars: Significance at the  
5% level/95% confidence interval

# 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



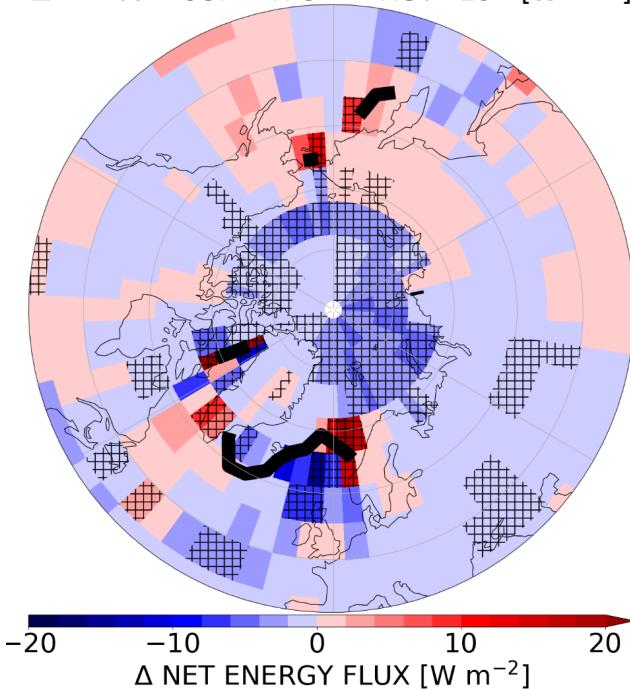
- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean
- Enhanced upward heat fluxes in winter and strongly enhanced downward fluxes from spring onwards

Seasonal: February-September

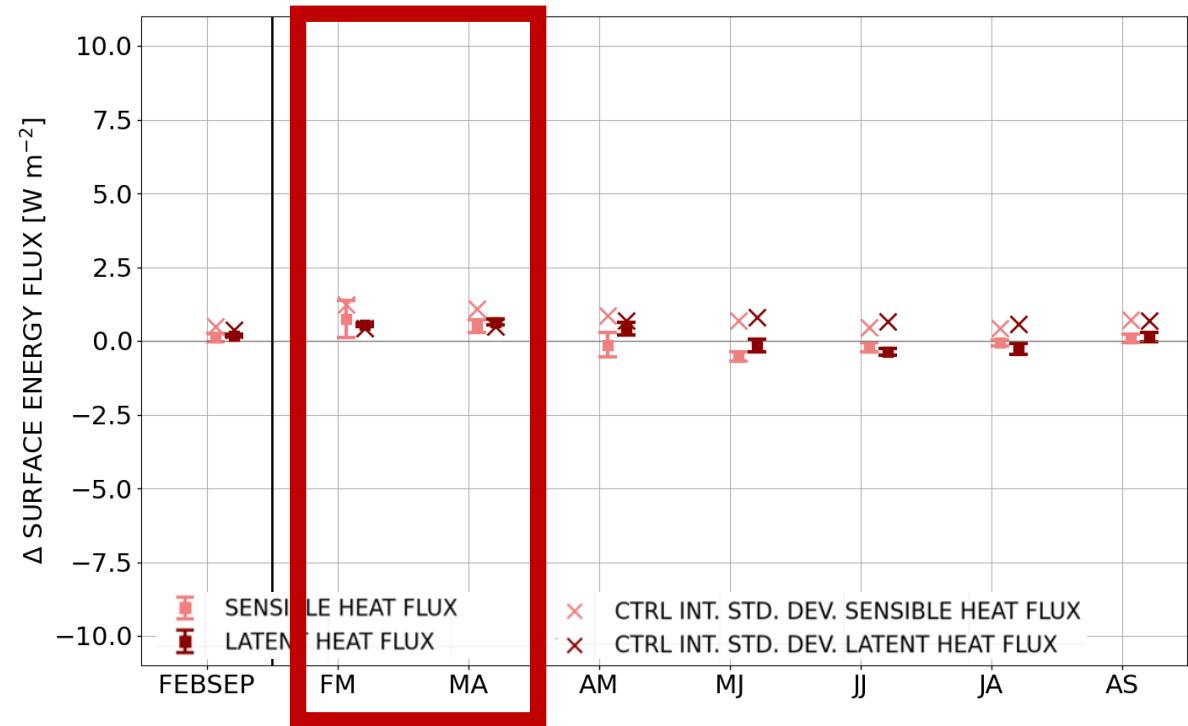
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# Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase I

February-September mean net energy fluxes



Seasonal evolution of sensible and latent heat fluxes



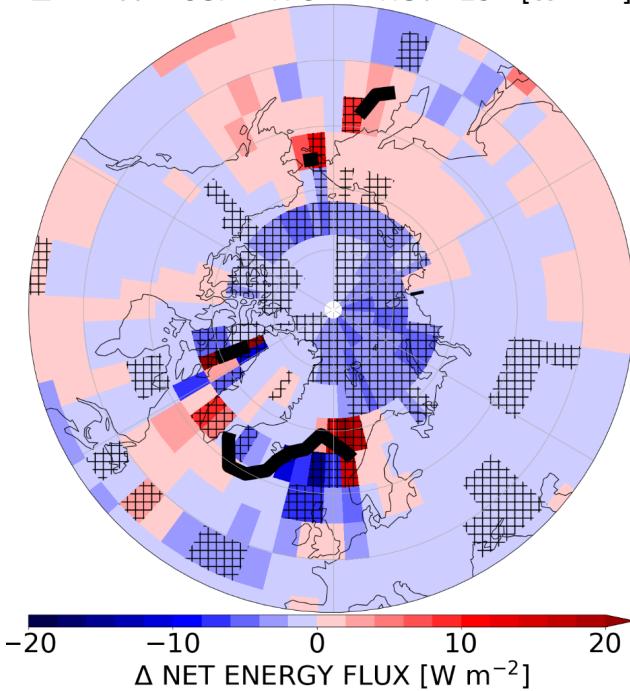
- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean
- Enhanced upward sensible and latent heat flux in late winter**

Seasonal: February-September

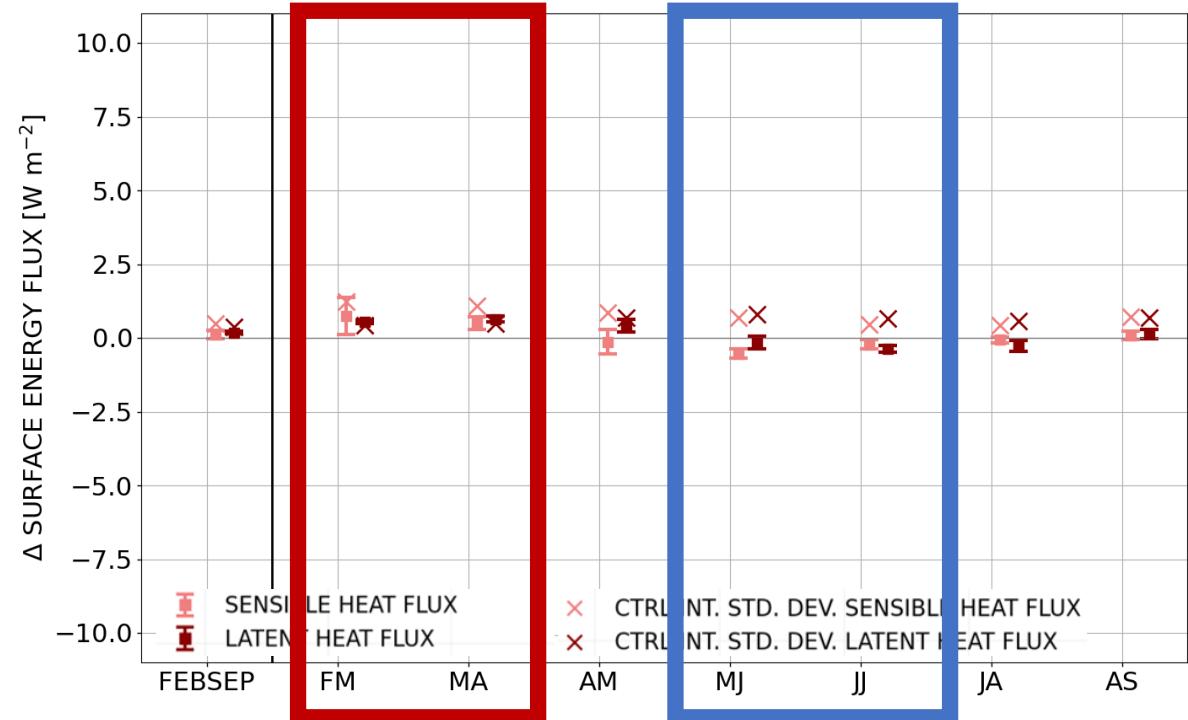
Hatching/Error bars: Significance at the 5% level/95% confidence interval

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

February-September mean net energy fluxes



Seasonal evolution of sensible and latent heat fluxes



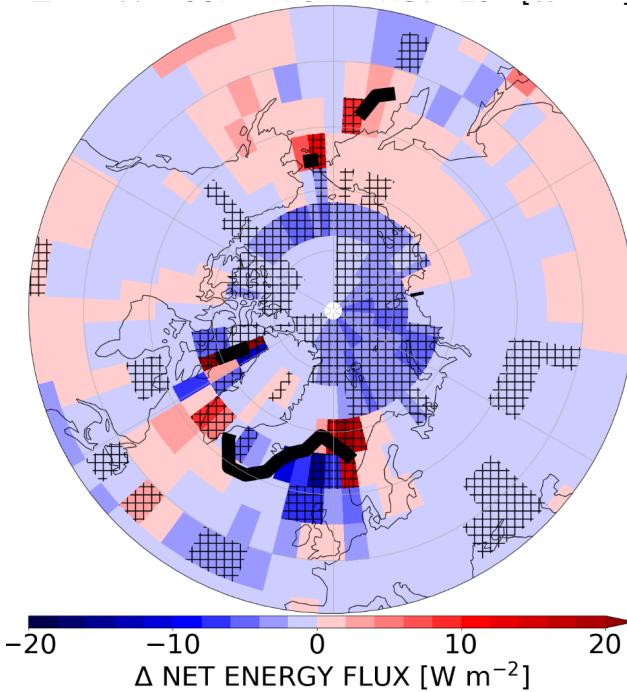
- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean
- Enhanced upward sensible and latent heat flux in late winter**
- Enhanced downward sensible heat fluxes** in May-June consistent with heat wave-like Z500 pattern

Seasonal: February-September

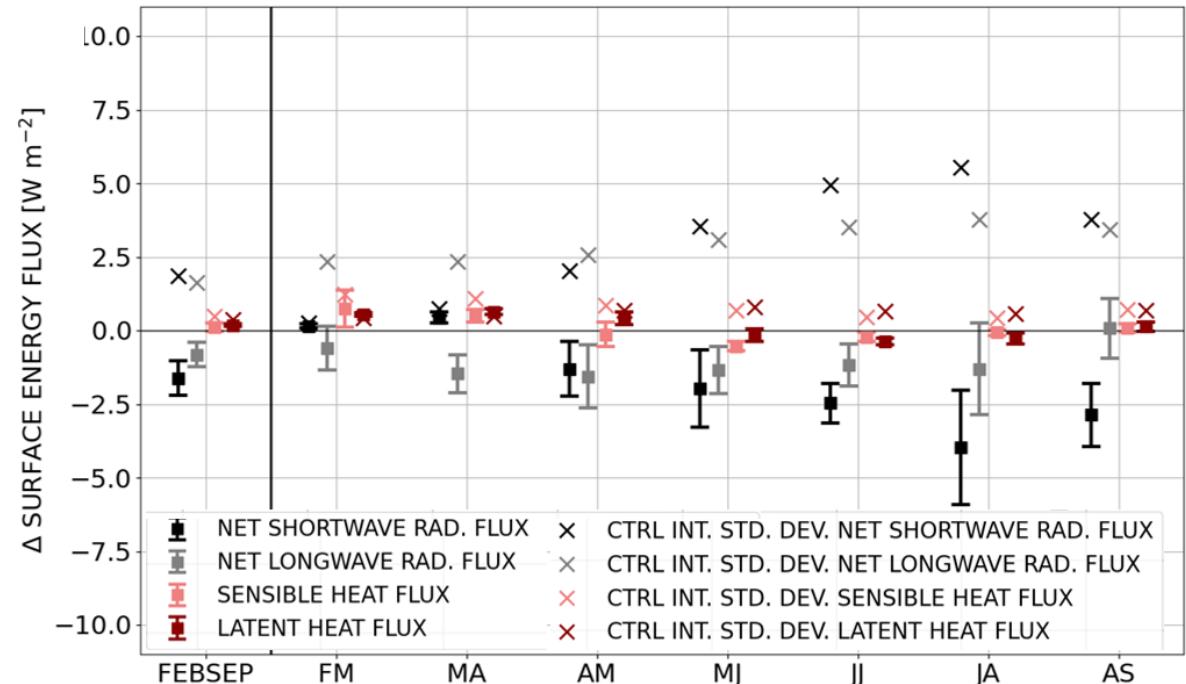
Hatching/Error bars: Significance at the 5% level/95% confidence interval

# 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

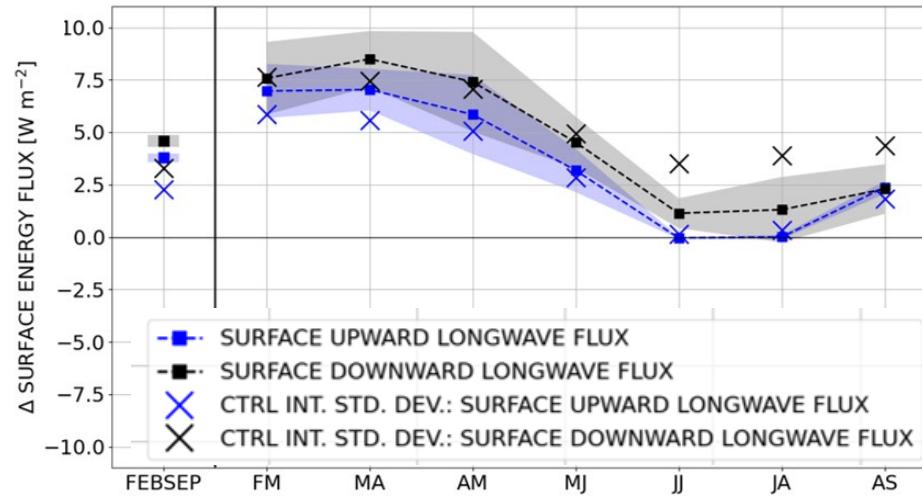


- Enhanced seasonal mean **net surface energy flux** from the atmosphere to sea ice-ocean
- Enhanced upward sensible and latent heat flux in late winter**
- Enhanced downward sensible heat fluxes** in May-June consistent with heat wave-like Z500 pattern
- Radiative fluxes** dominate net surface flux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

Seasonal: February-September

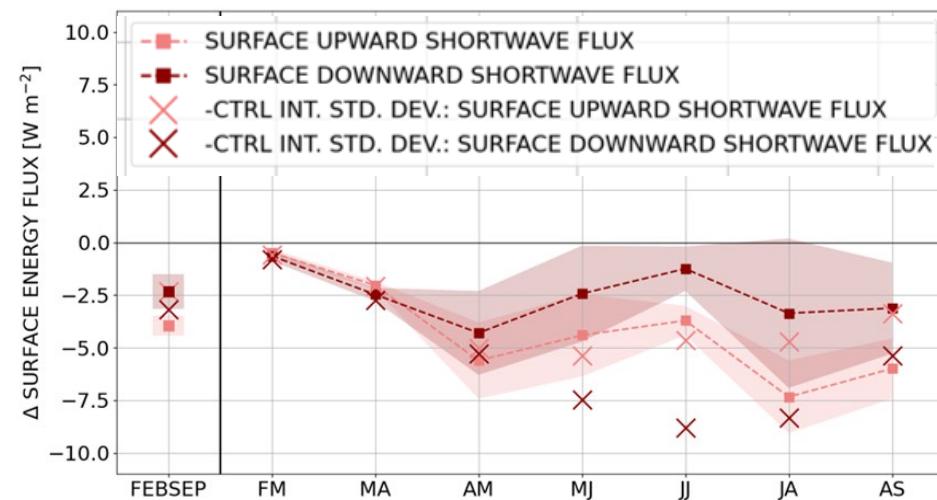
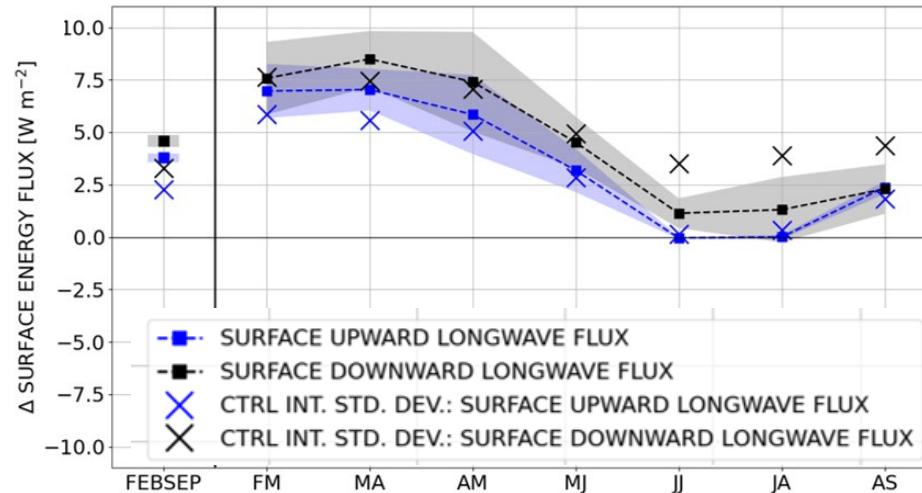
Hatching/Error bars: Significance at the 5% level/95% confidence interval

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



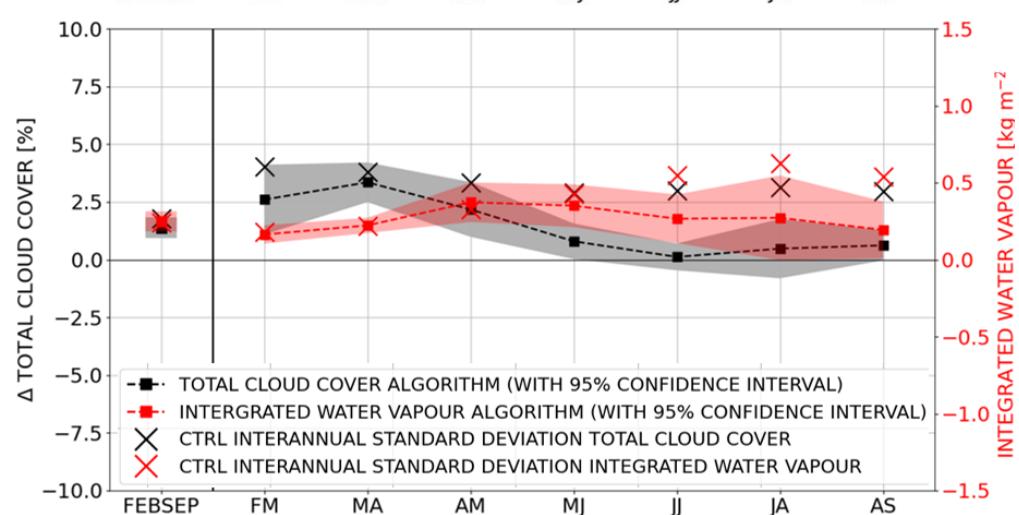
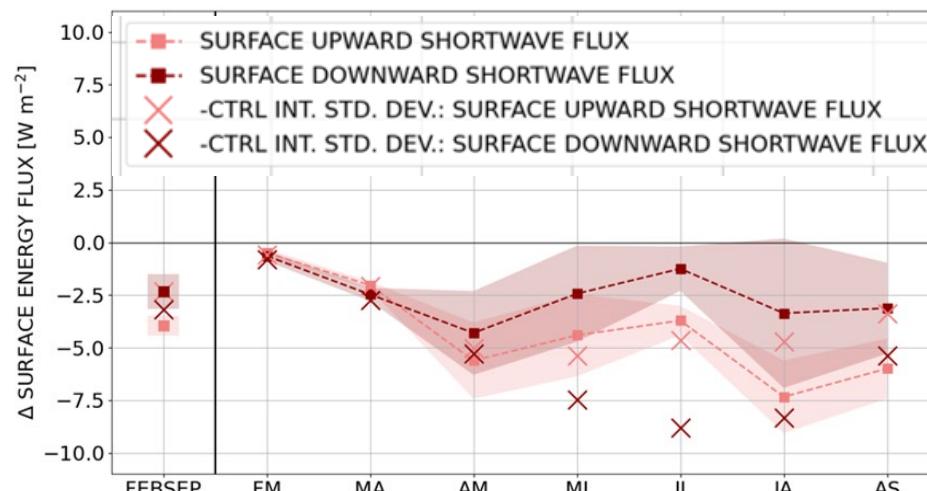
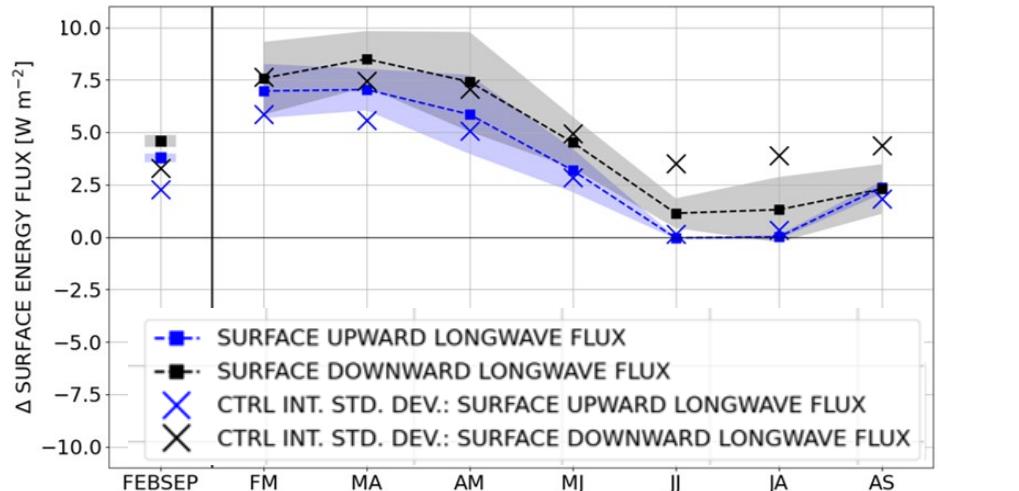
Seasonal: February-September  
Shading: 95% confidence interval

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



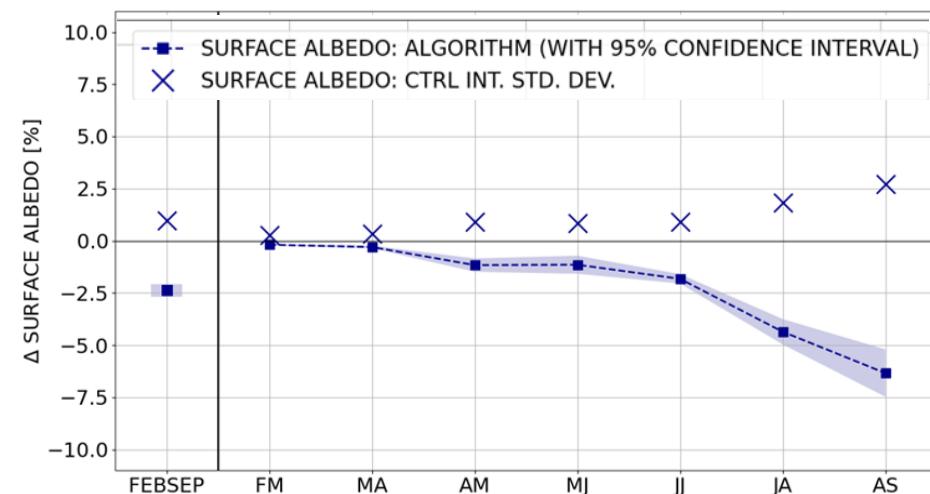
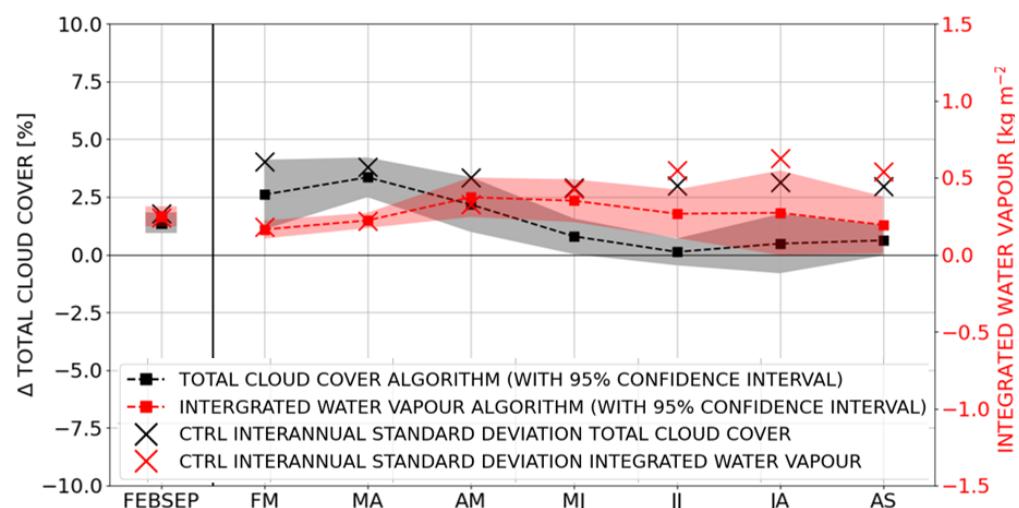
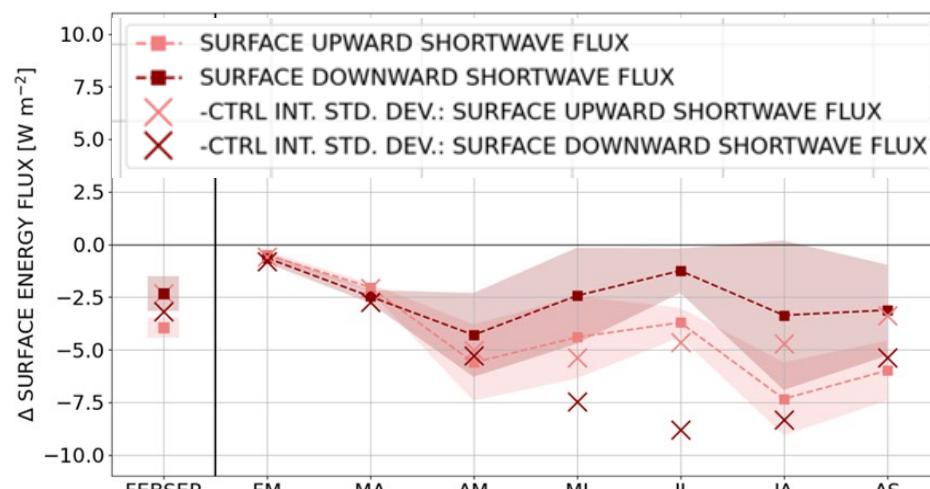
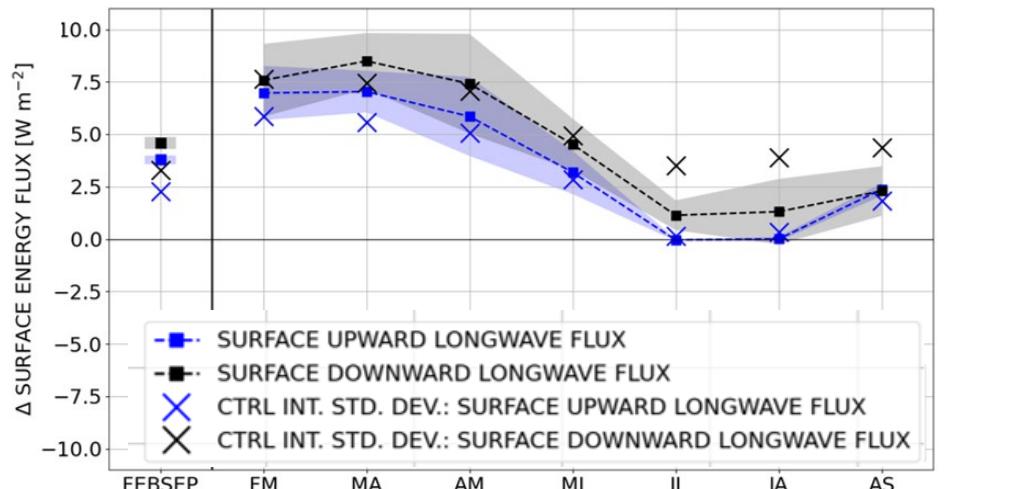
Seasonal: February-September  
Shading: 95% confidence interval

# 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



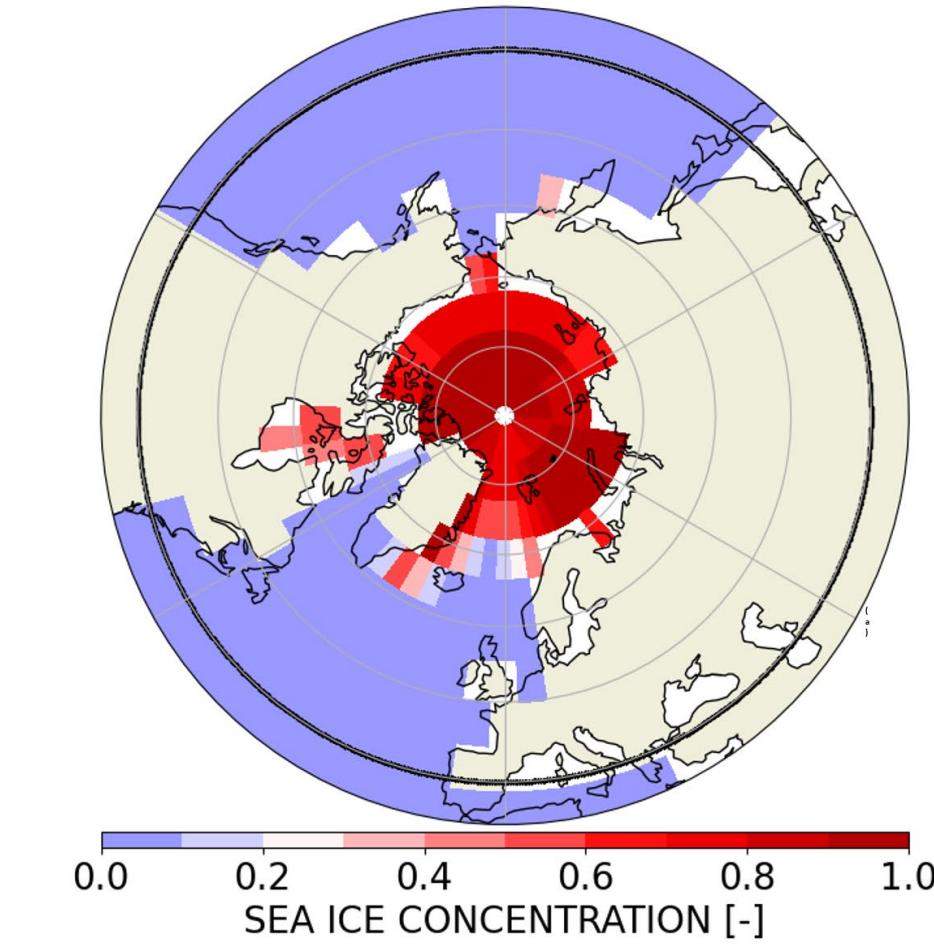
- Intra-seasonal sea ice reduction: enhanced by an anomalously moist, cloudy and warm spring atmosphere + sea ice-albedo feedback

Seasonal: February-September

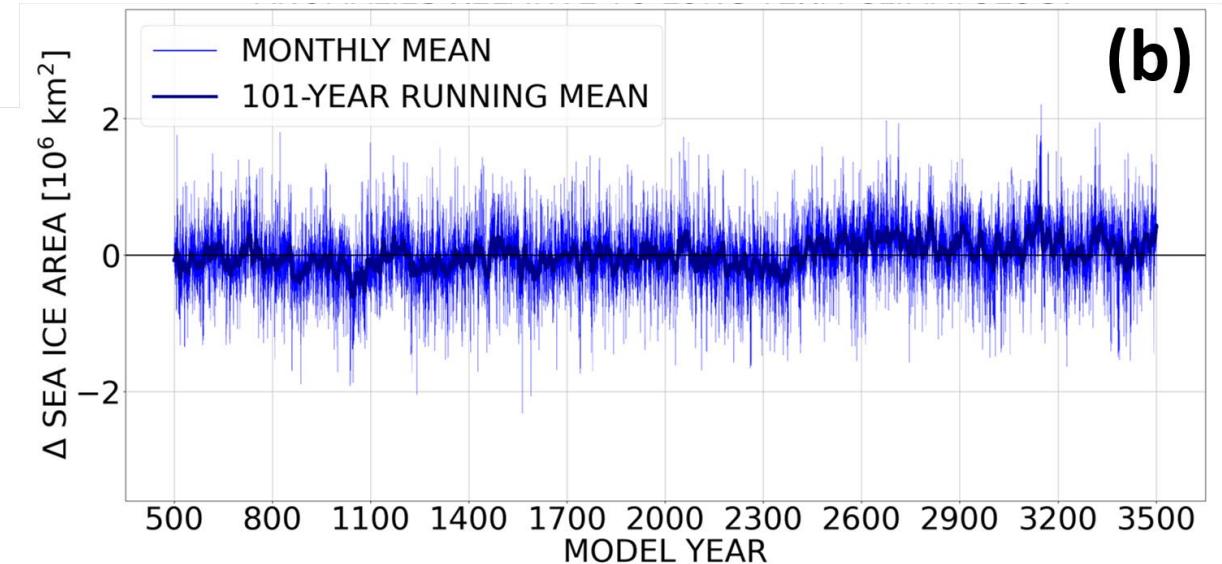
Shading: 95% confidence interval

# Results: Sea ice climatology in PlaSim-T21-LSG

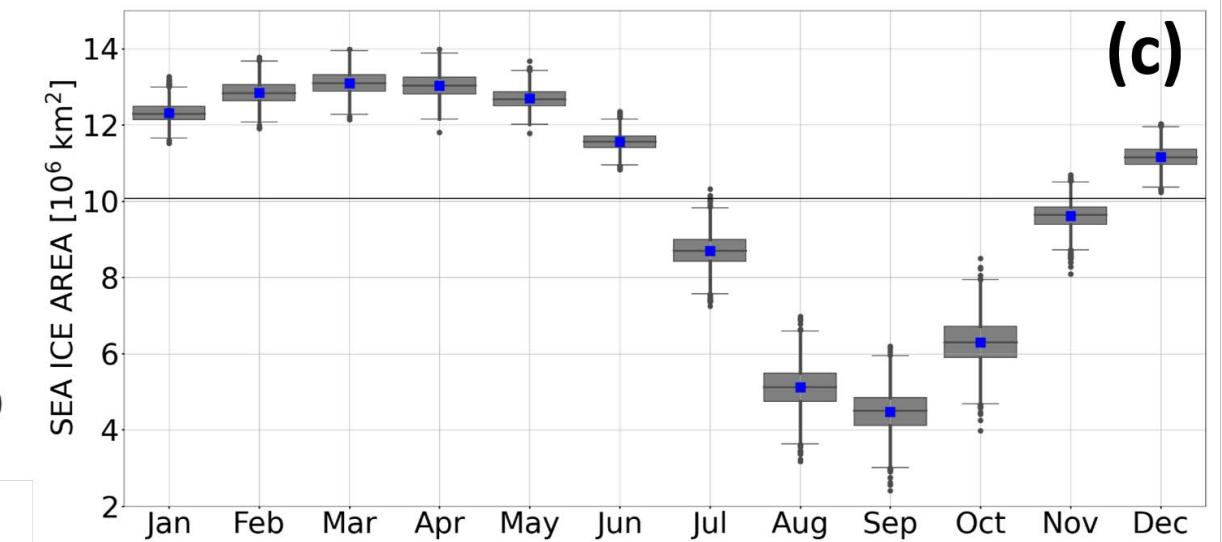
(a)



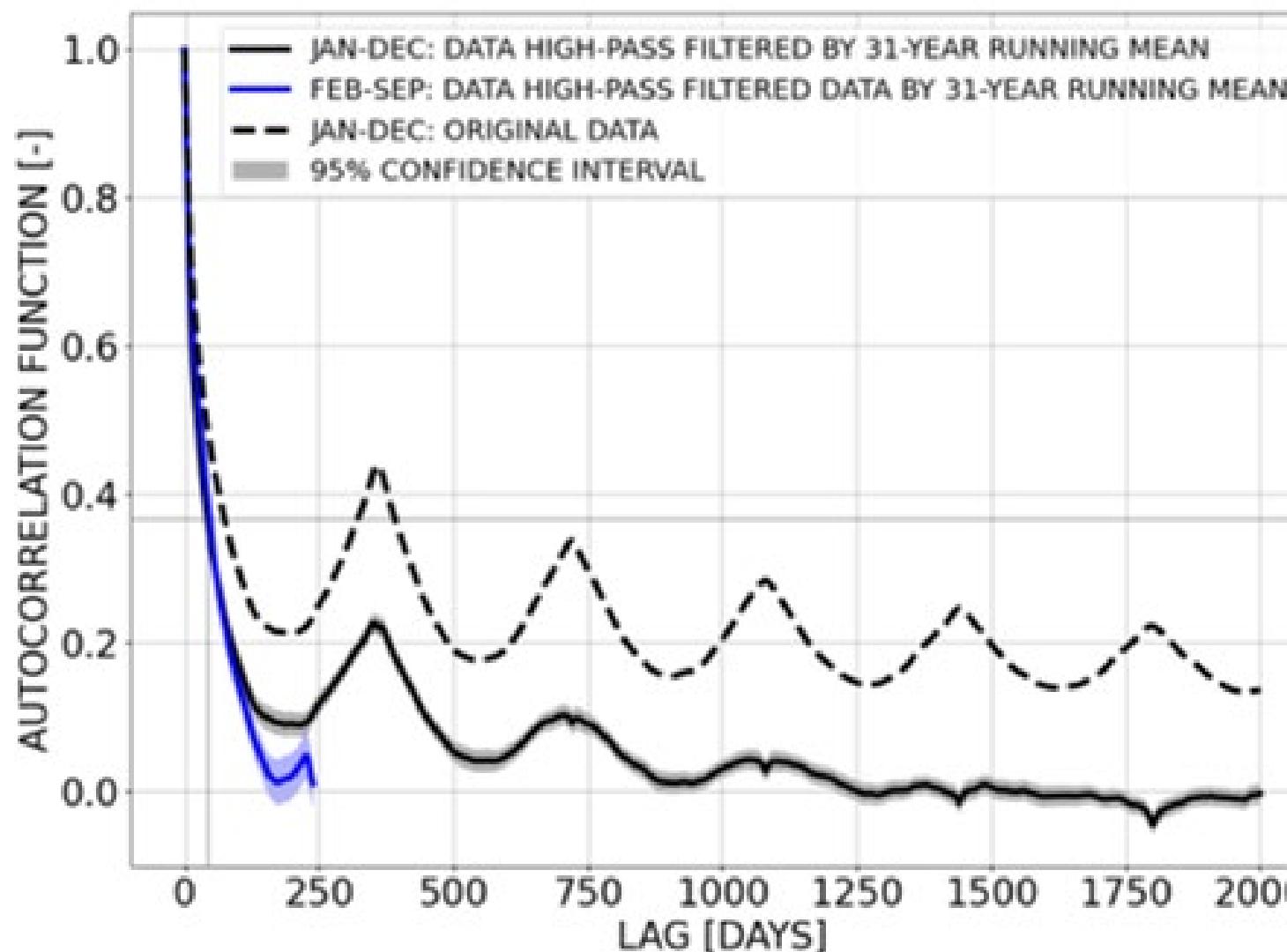
(b)



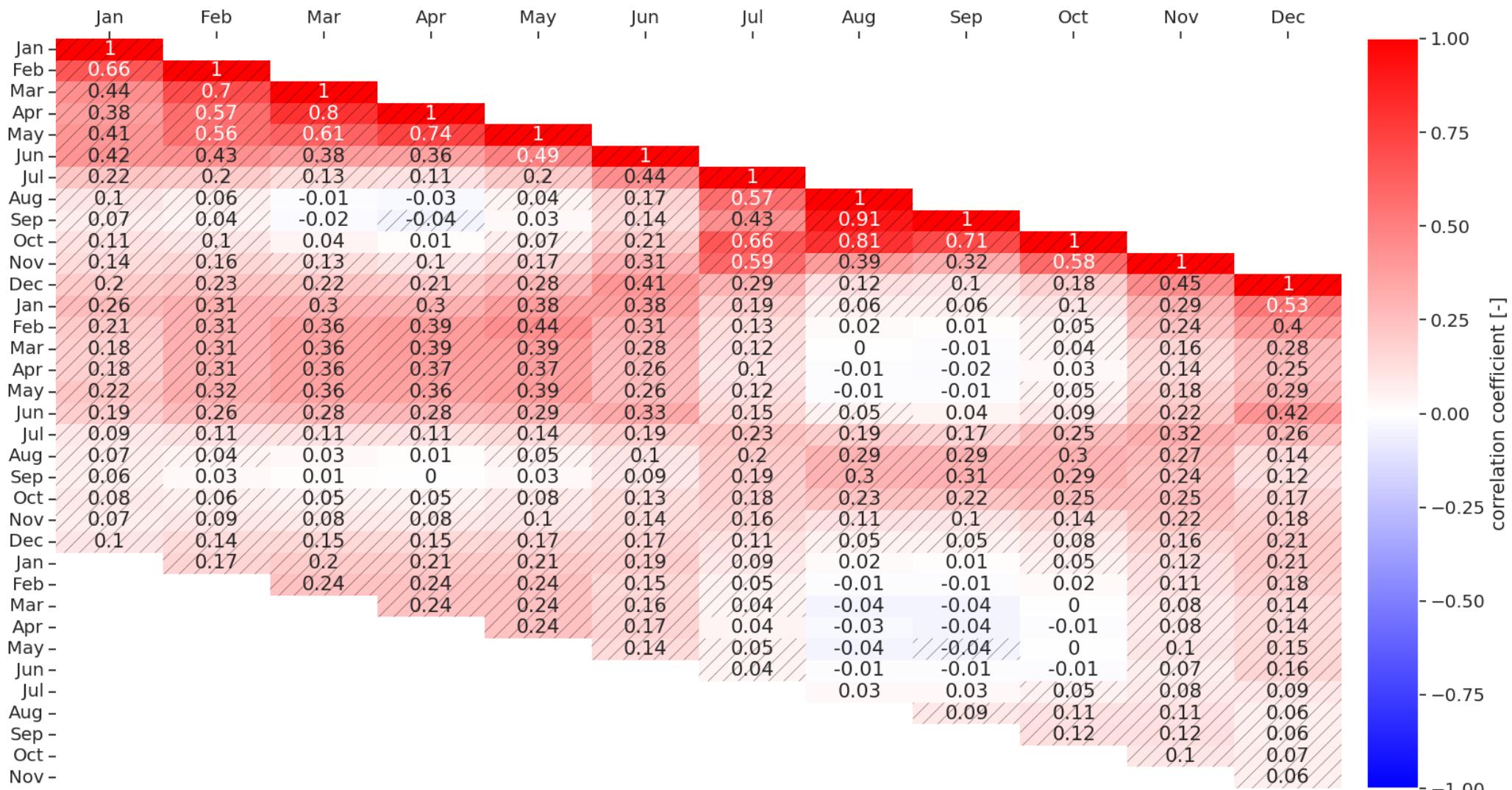
(c)



# Results: Sea ice persistence in PlaSim-T21-LSG

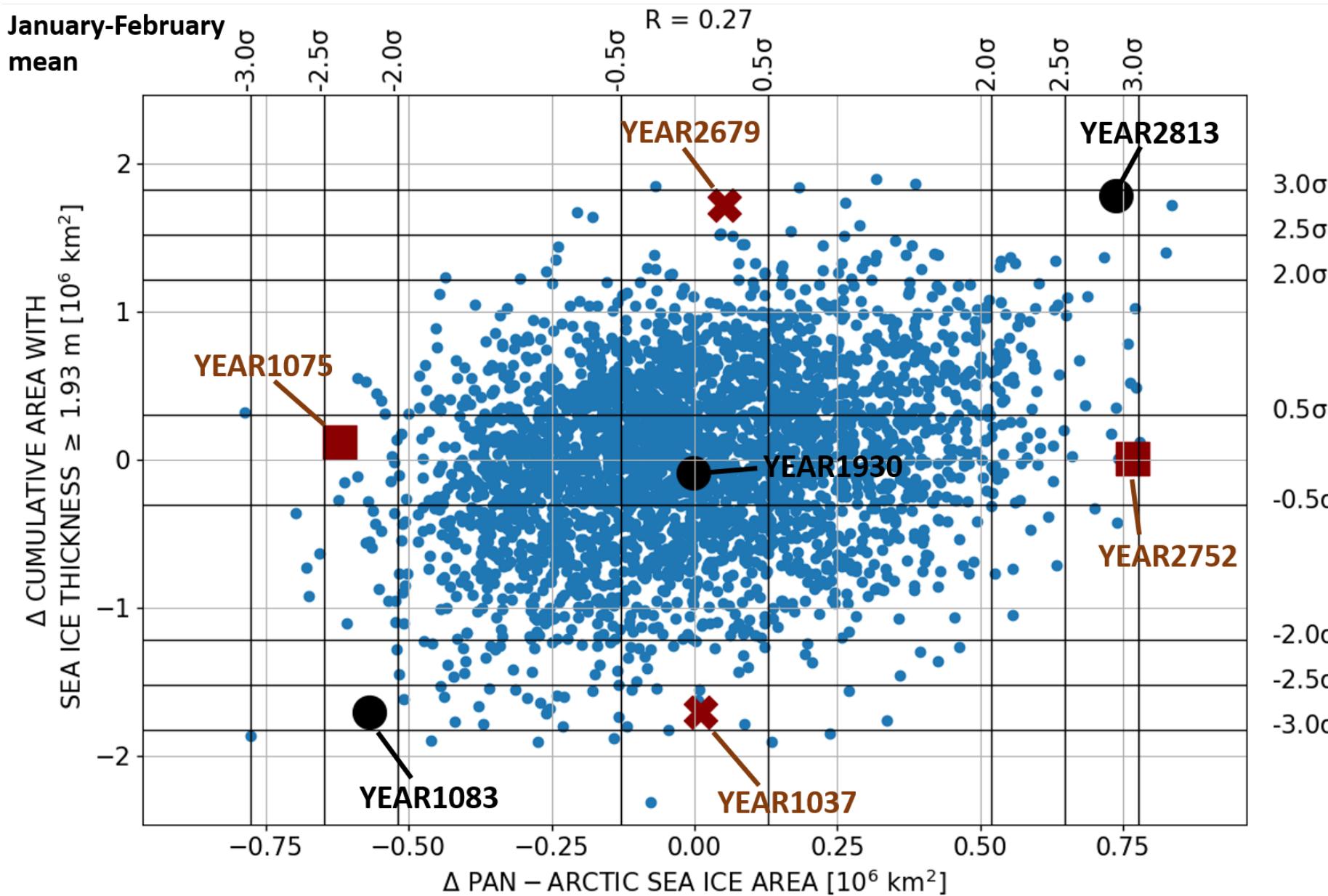


# Results: Sea ice persistence in PlaSim-T21-LSG



Hatching: statistical significance at 5% level

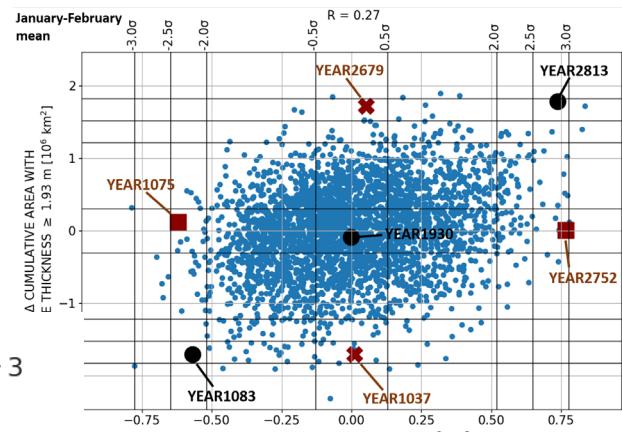
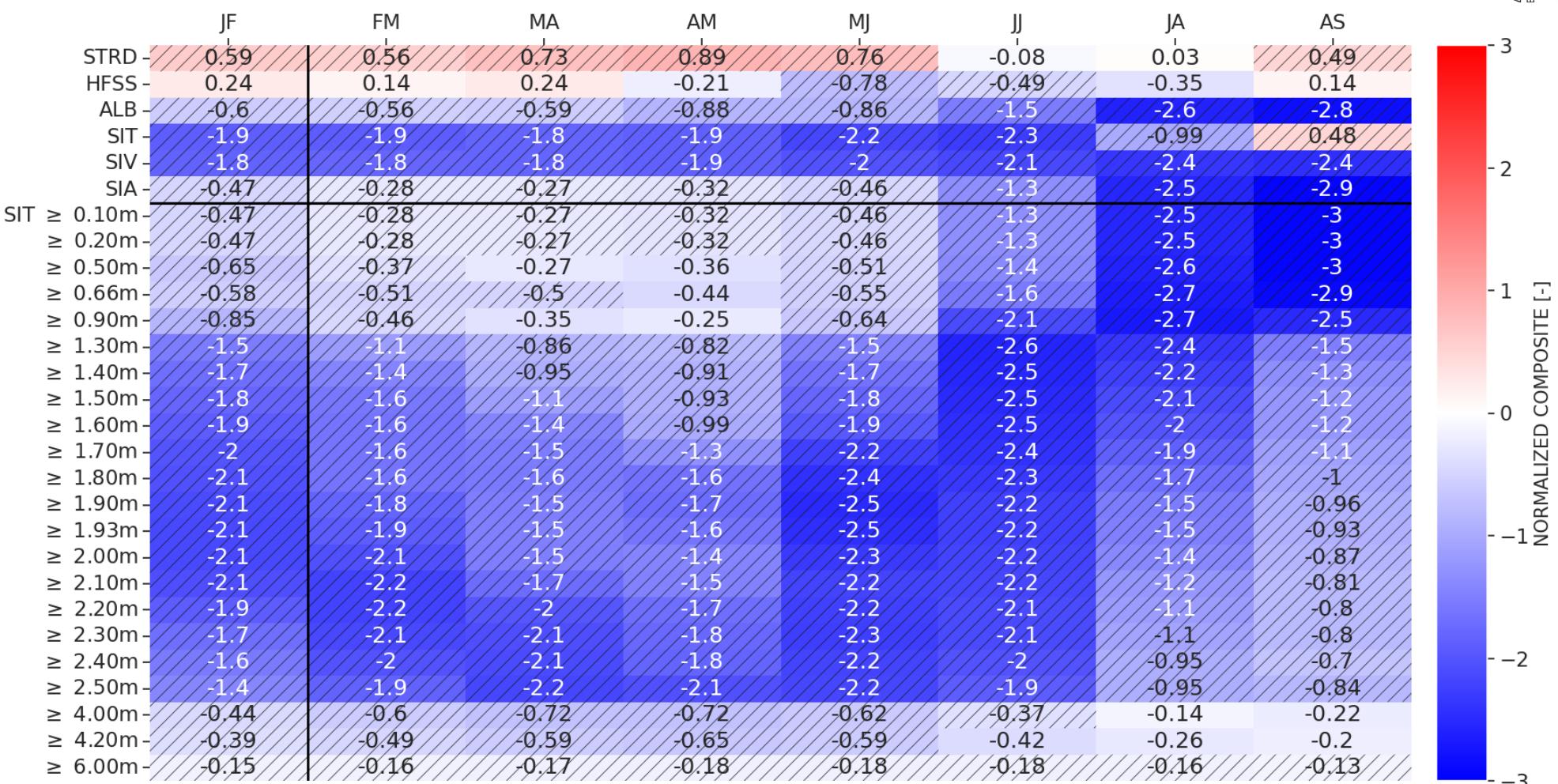
# Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II



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

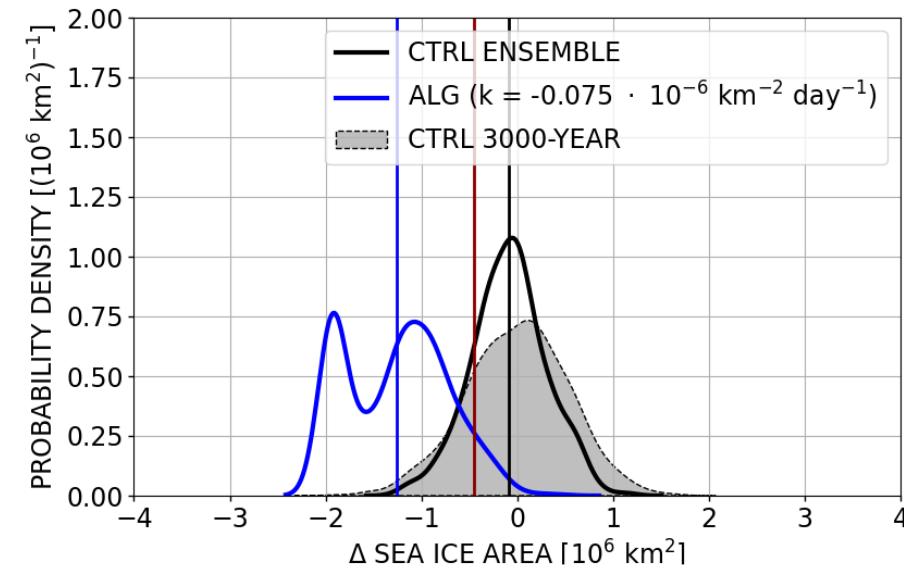
- Choice of **initial conditions** according to **different sea ice properties in January–February:**

- 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

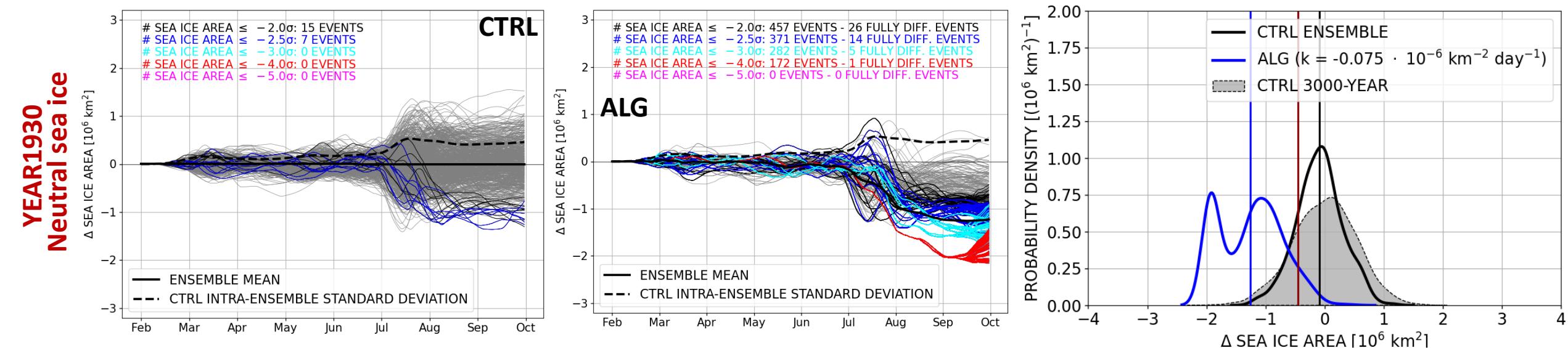


# Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II

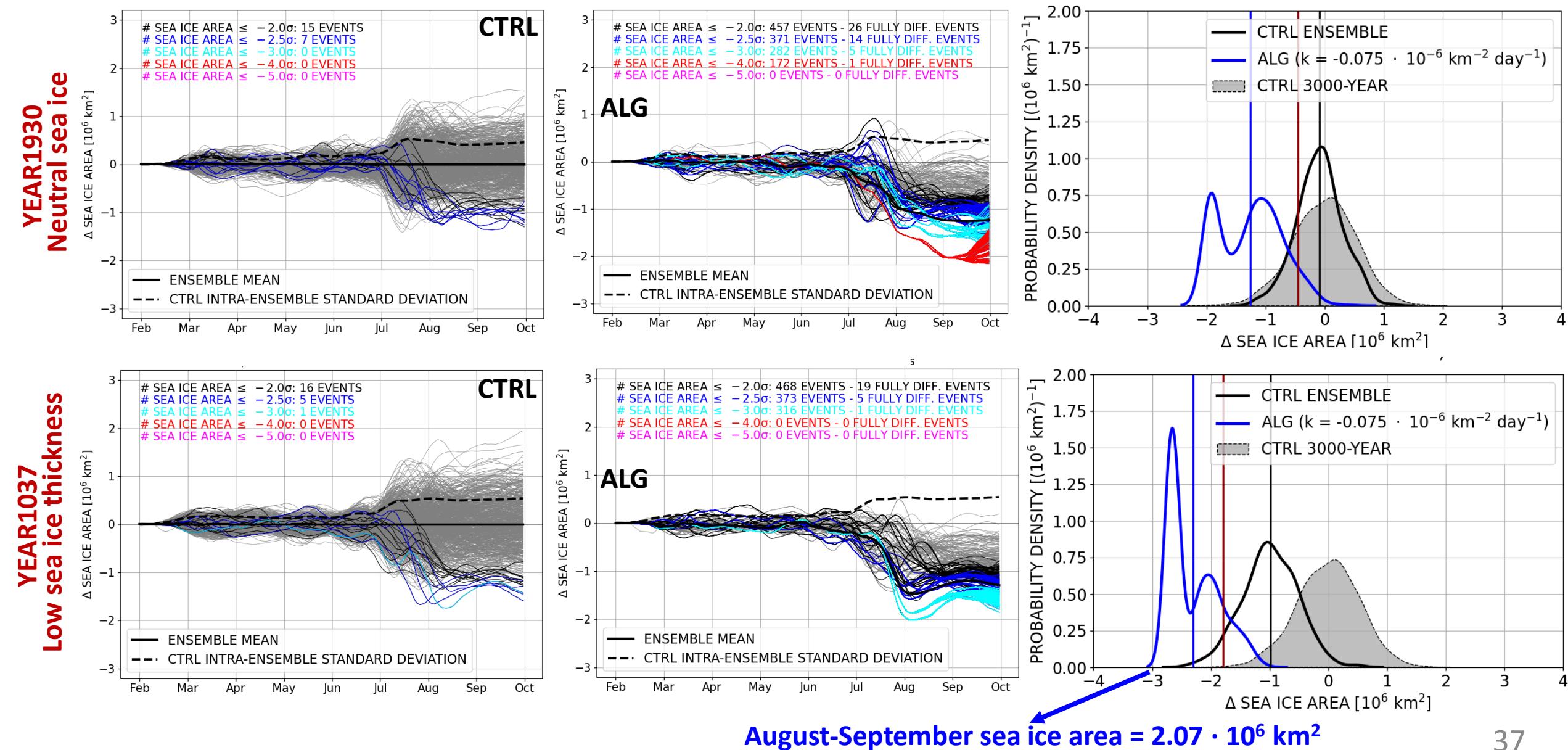
YEAR1930  
Neutral sea ice



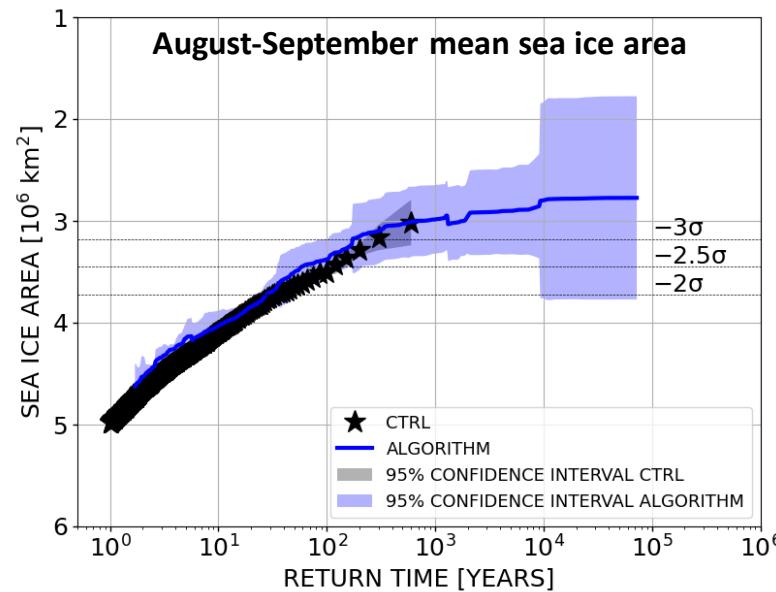
# Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II



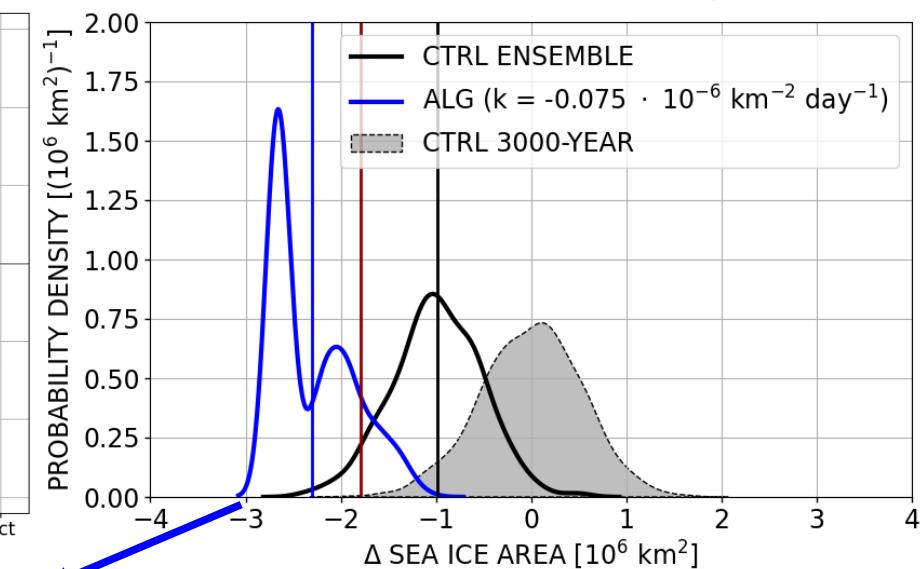
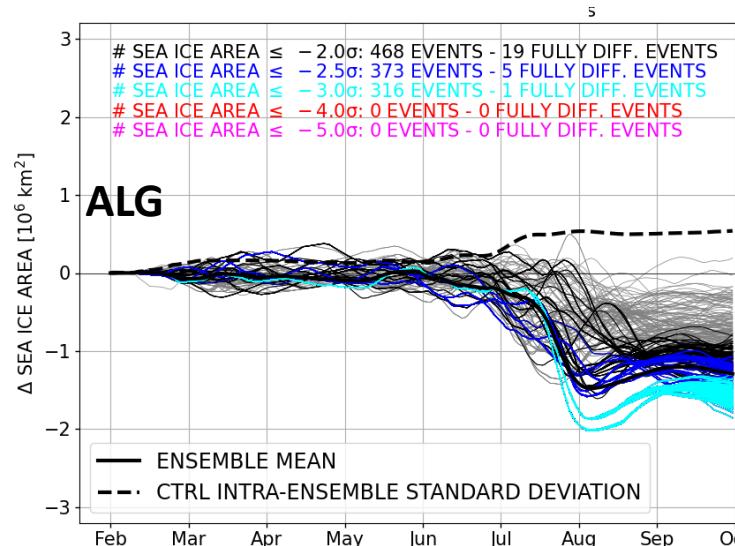
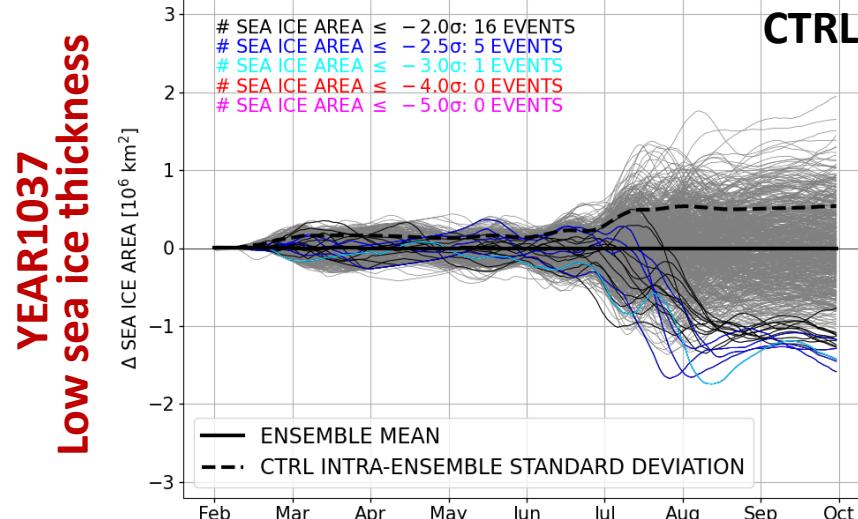
# Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II



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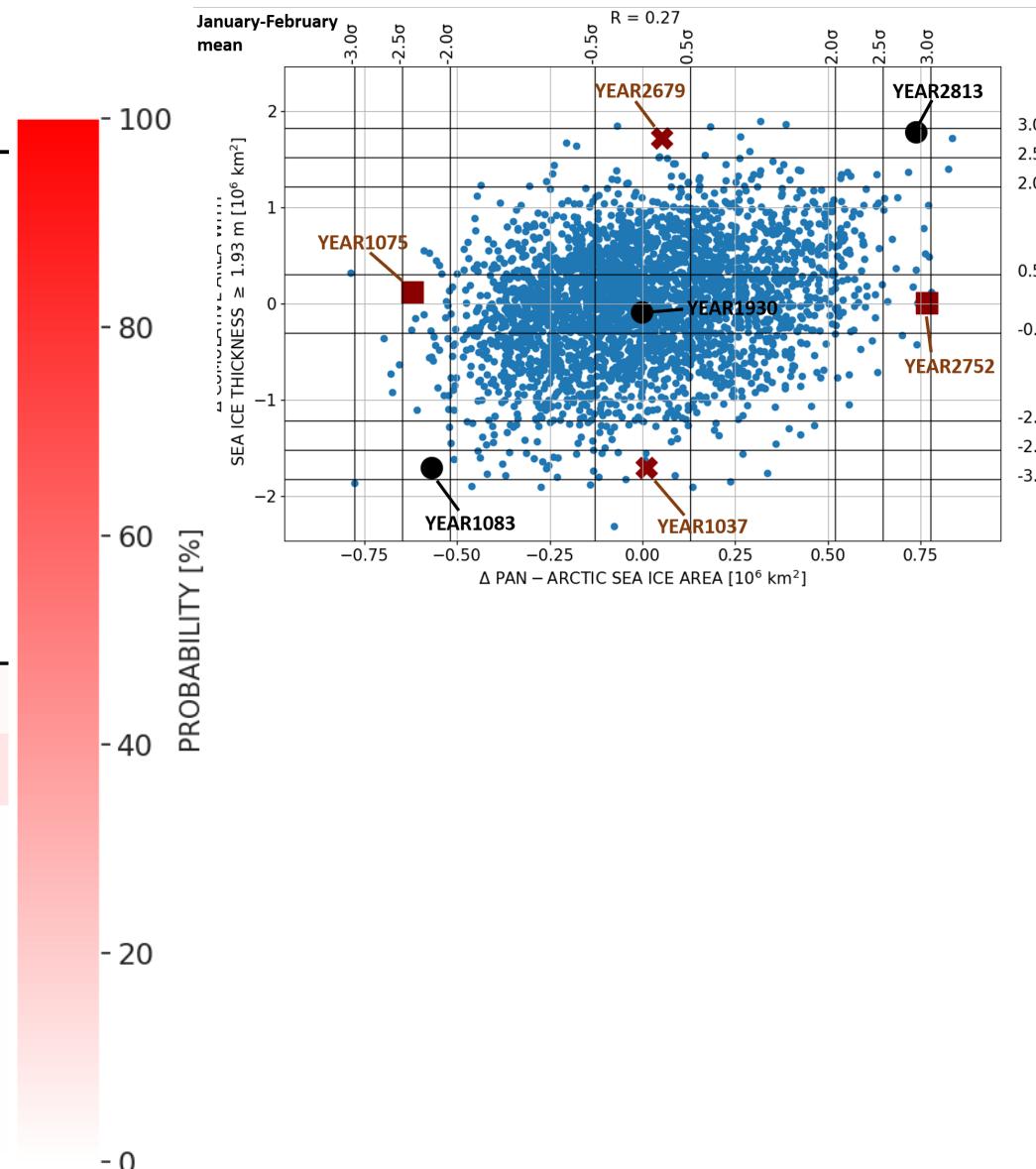
- Simulation of extreme August-September sea ice low with  $r \geq 10^4$  years with computational cost of  $10^2 - 10^3$  years



August-September sea ice area =  $2.07 \cdot 10^6 \text{ km}^2$

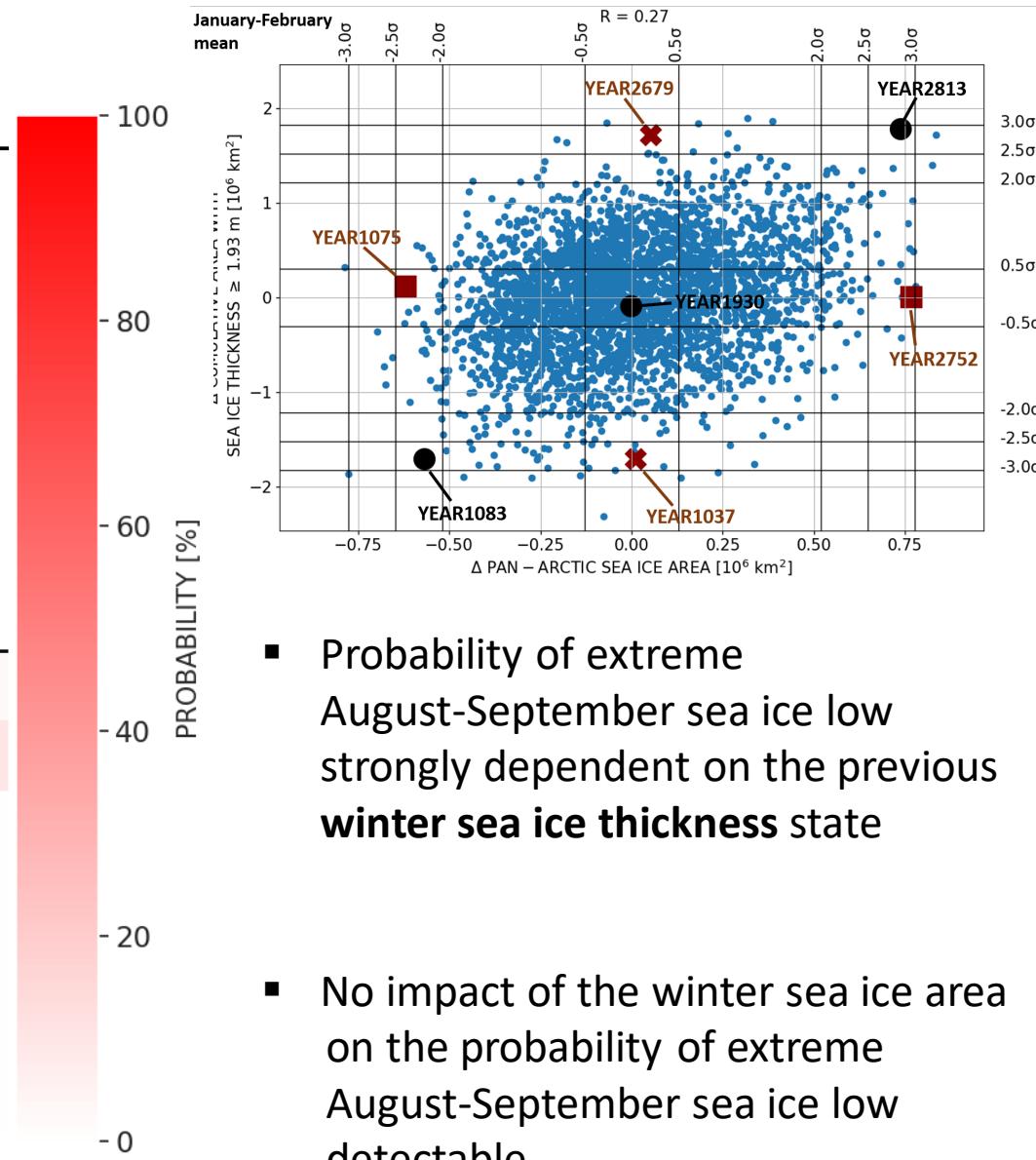
# Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II

January-February	$\leq -2.0\sigma$	AUGSEP SIA $\leq -2.5\sigma$	$\leq -3.0\sigma$
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



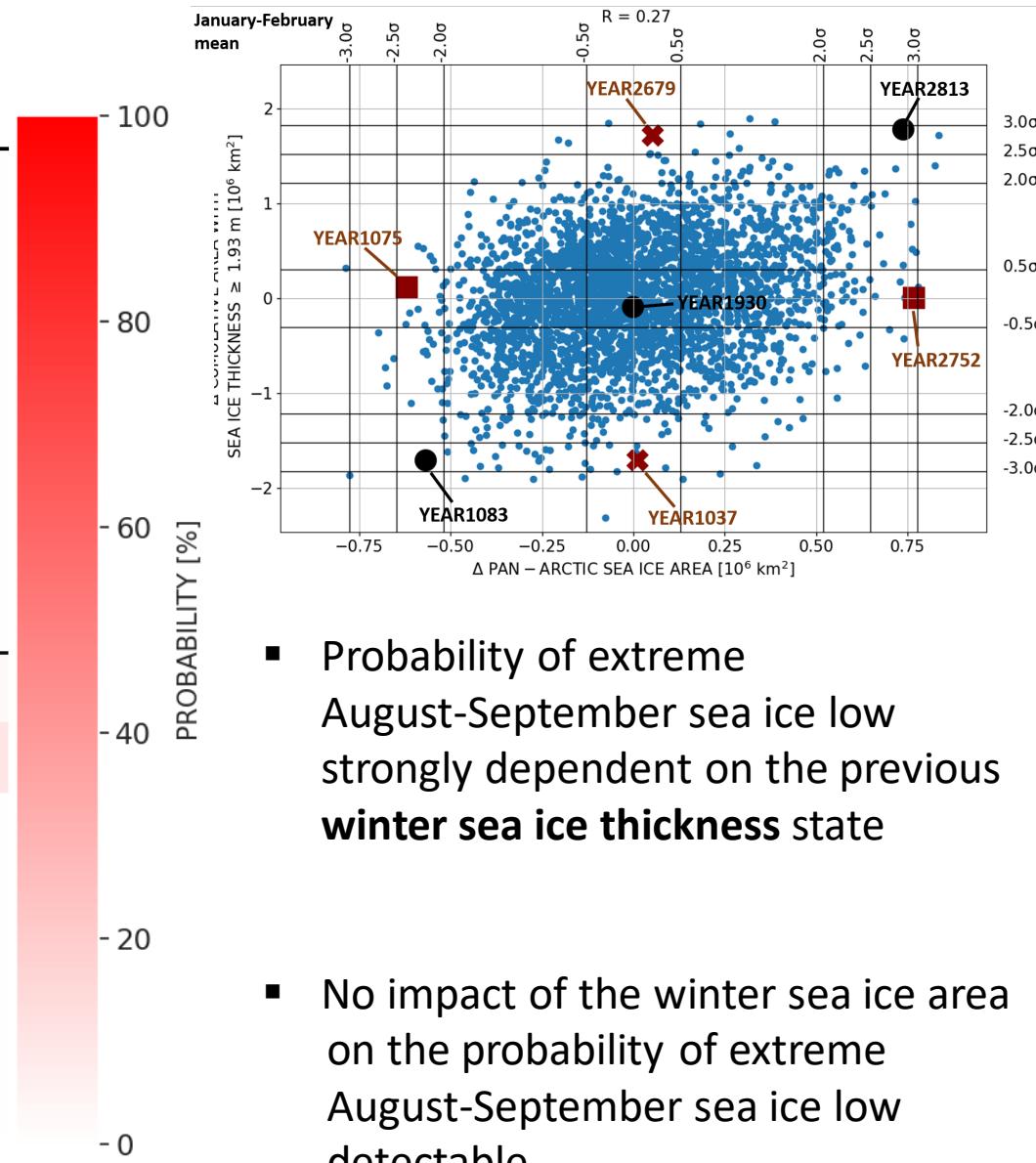
# Results: Application of the rare event algorithm to PlaSim-T21-LSG – Phase II

January-February	$\leq -2.0\sigma$	AUGSEP SIA $\leq -2.5\sigma$	$\leq -3.0\sigma$
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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



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

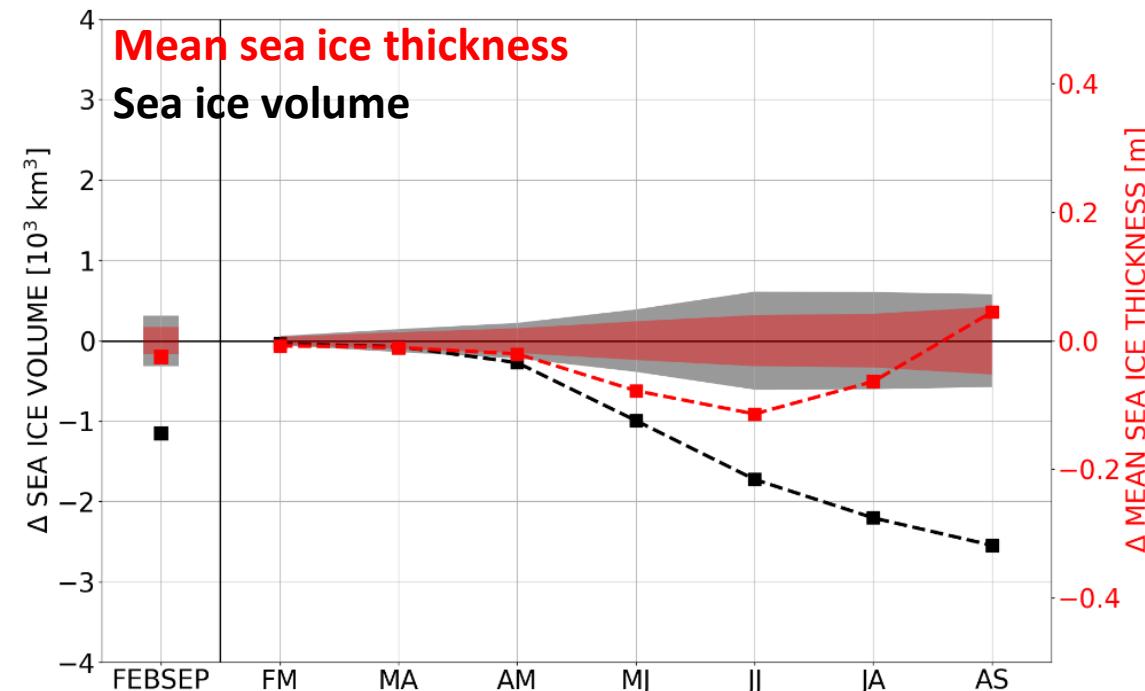
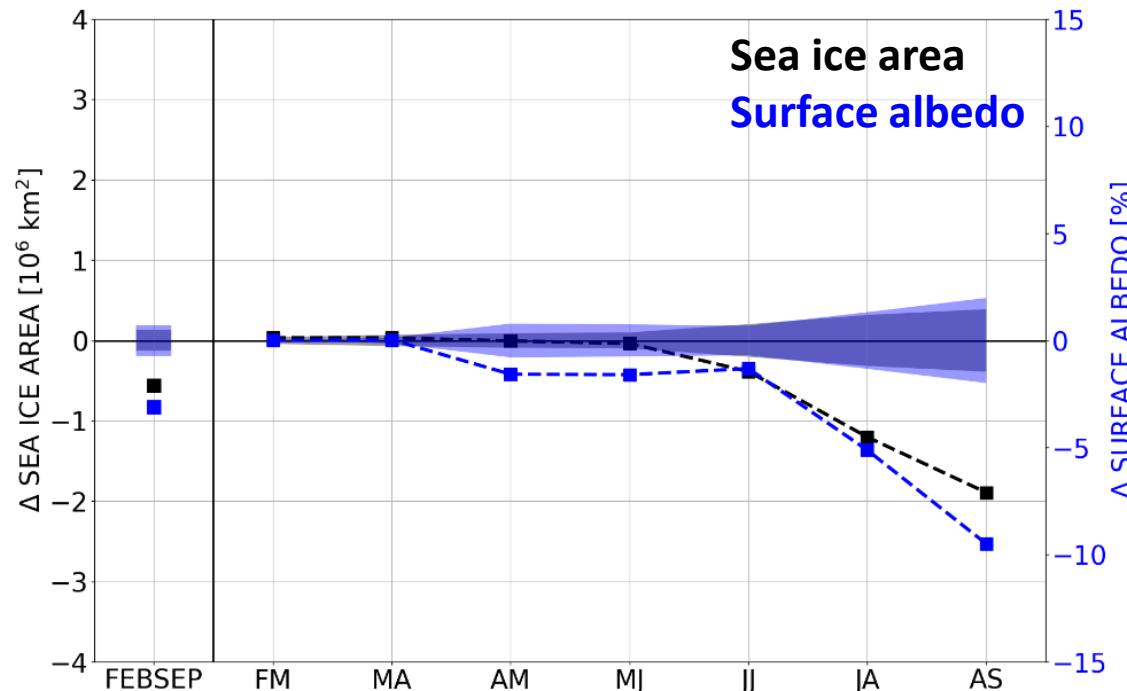
January-February	$\leq -2.0\sigma$	AUGSEP SIA $\leq -2.5\sigma$	$\leq -3.0\sigma$
	SIA-LOW SIT1.93-LOW	2.83 +/- 1.33	0.67 +/- 0.65
SIA-NEUTRAL SIT1.93-LOW	2.67 +/- 1.29	0.83 +/- 0.73	0.17 +/- 0.33
SIA-LOW SIT1.93-NEUTRAL	2.33 +/- 1.21	0.67 +/- 0.65	0.17 +/- 0.33
SIA-NEUTRAL SIT1.93-NEUTRAL	2.5 +/- 1.25	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



# 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



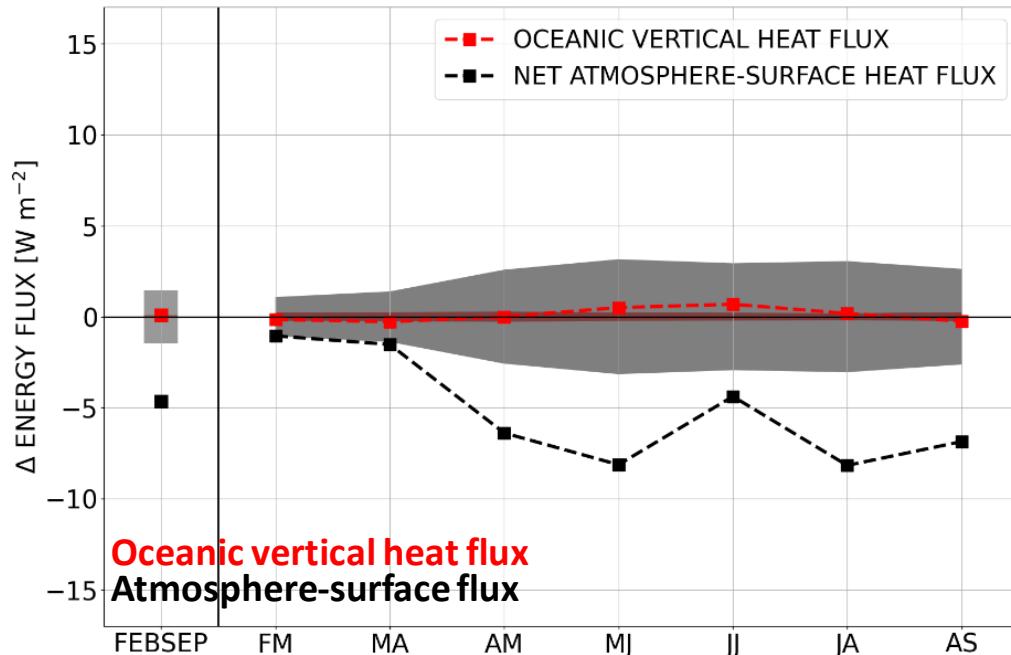
- Negative sea ice area anomalies develop in June-July
- Negative spring sea ice thickness/sea ice volume anomalies “anticipate” the negative summer sea ice area anomalies

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

Shading: +/- intra-ensemble standard deviation

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

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

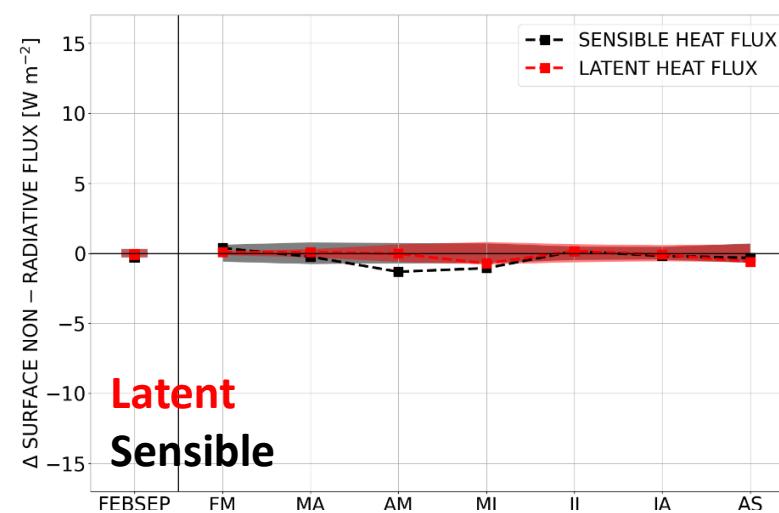
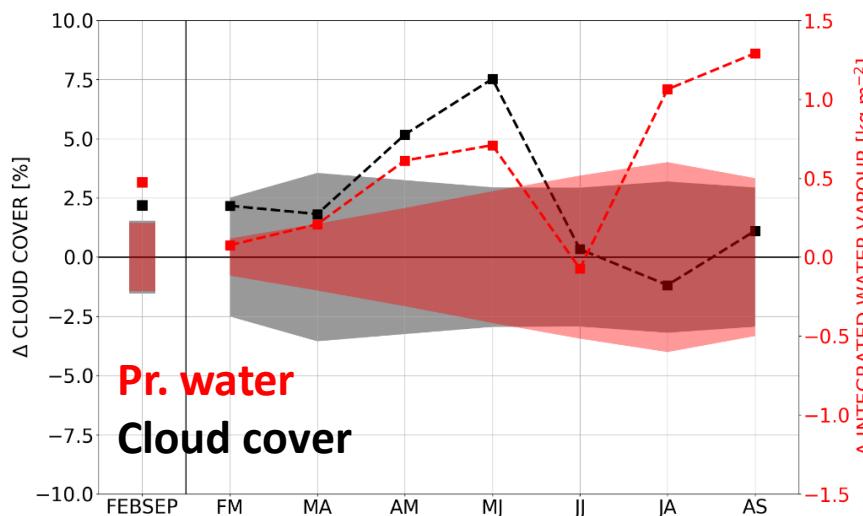
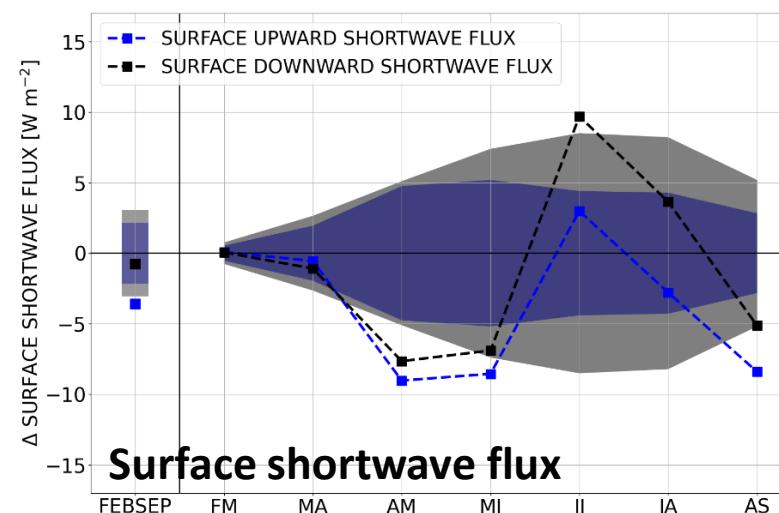
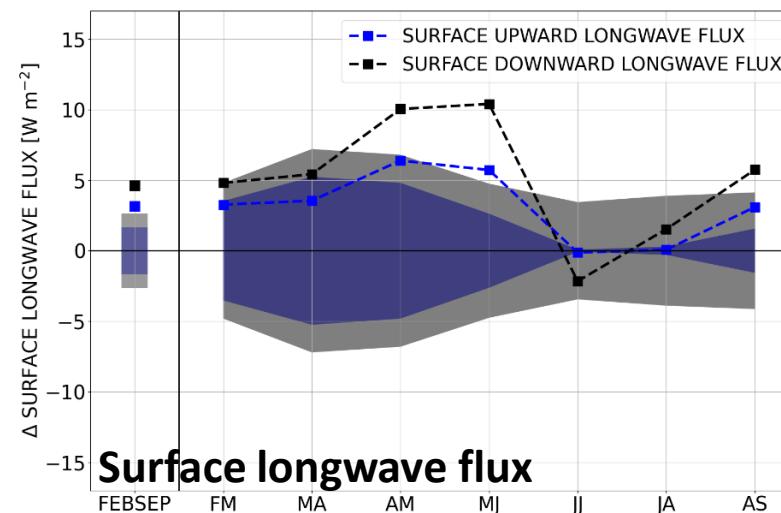


- Strongly enhanced downward atmosphere-surface energy fluxes accompanied by weak oceanic forcing in summer

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

Shading: +/- intra-ensemble standard deviation

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



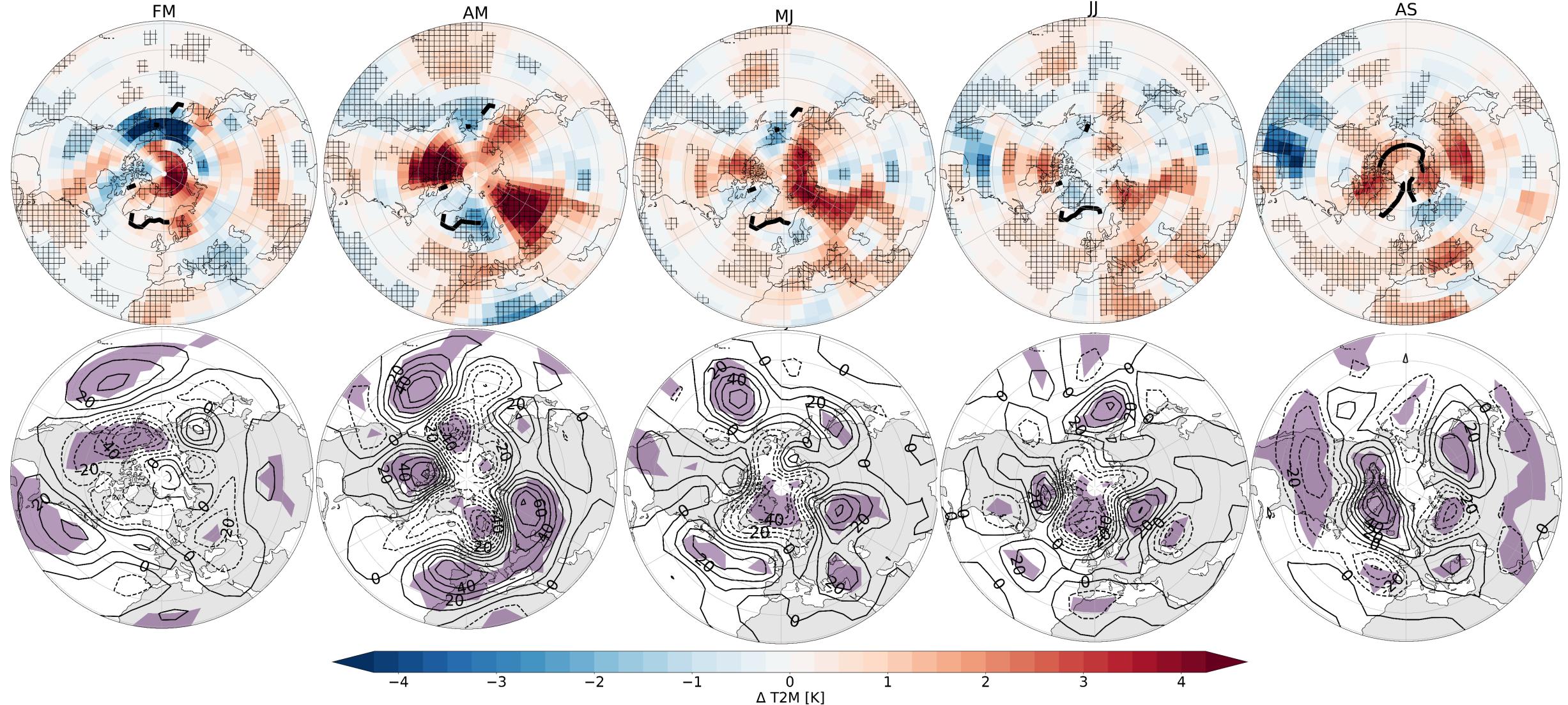
Domain-average over the Arctic  
Ocean northern of 70°N

- 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

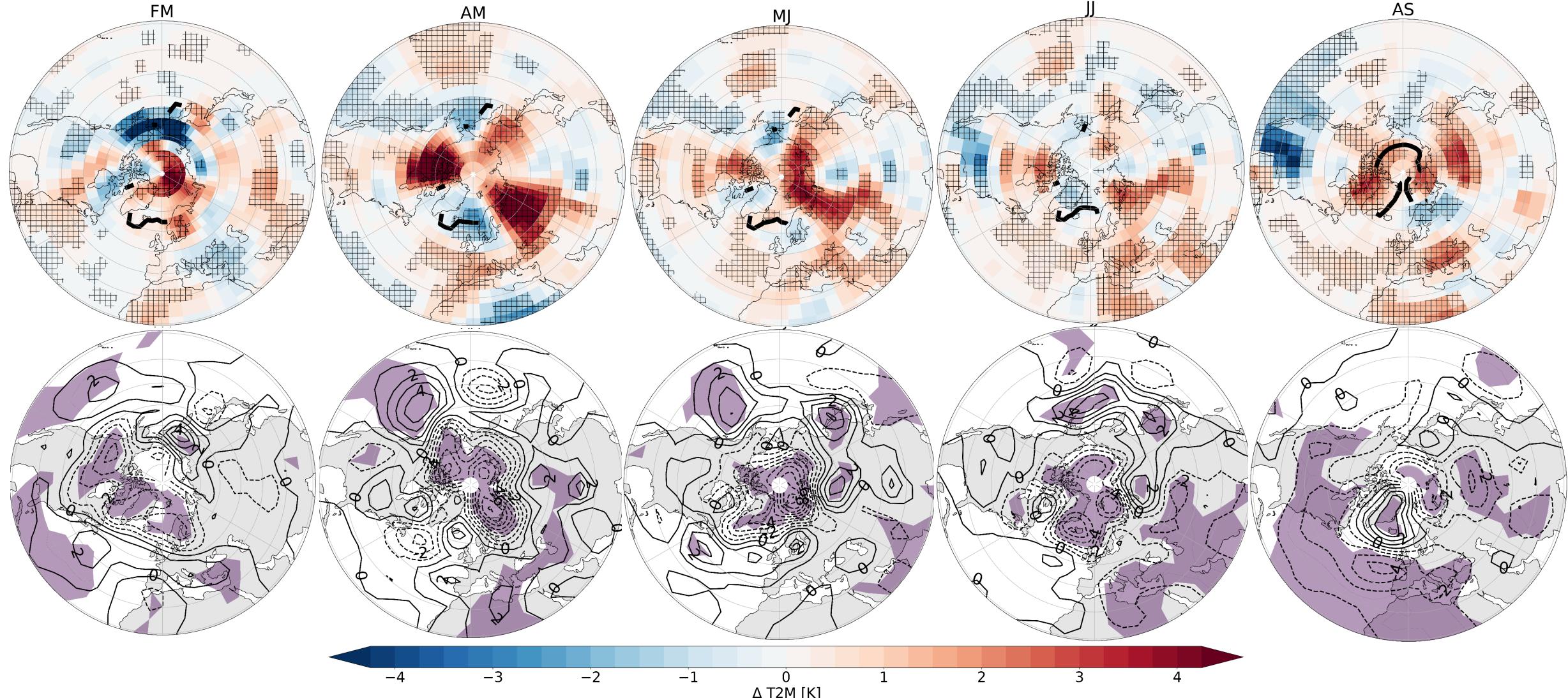


- Wavenumber 3-like positive T2M anomaly pattern in spring + baroclinic Z500 signal over the Arctic Ocean

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

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

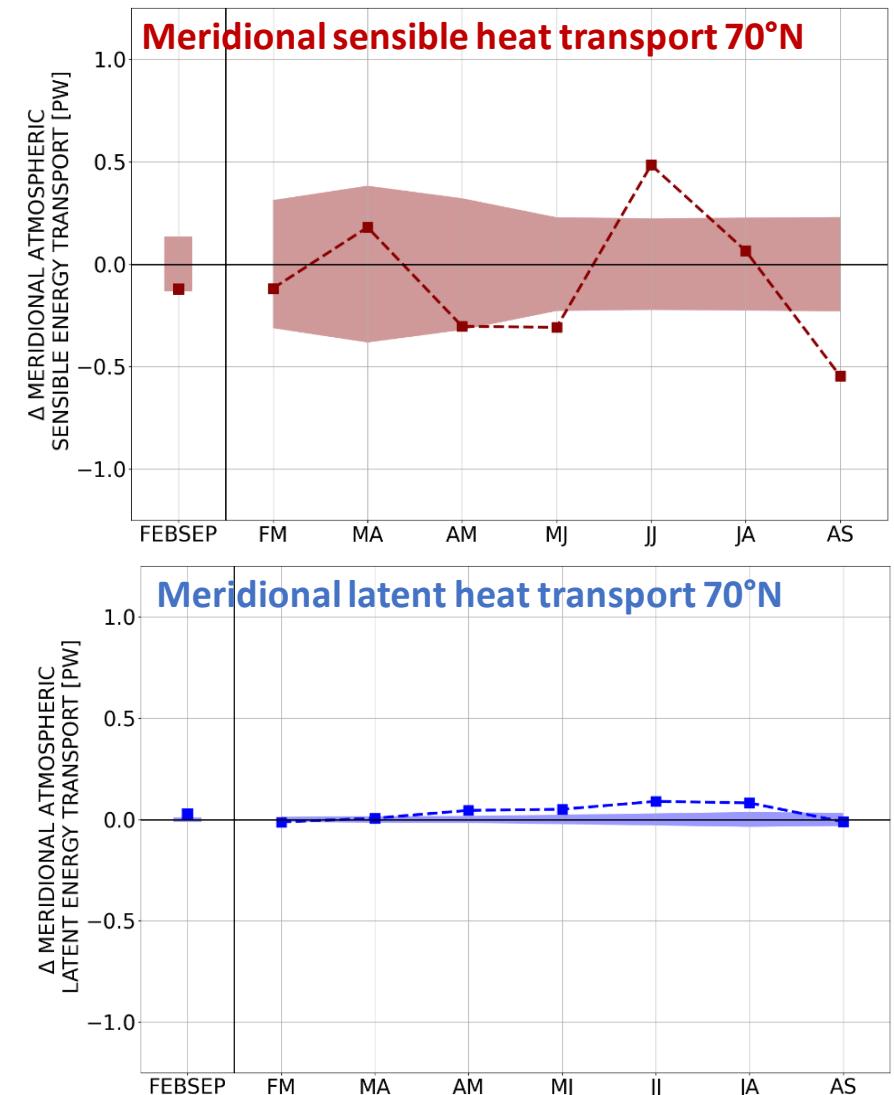
## Trajectory with lowest August-September mean pan-Arctic sea ice area



- 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

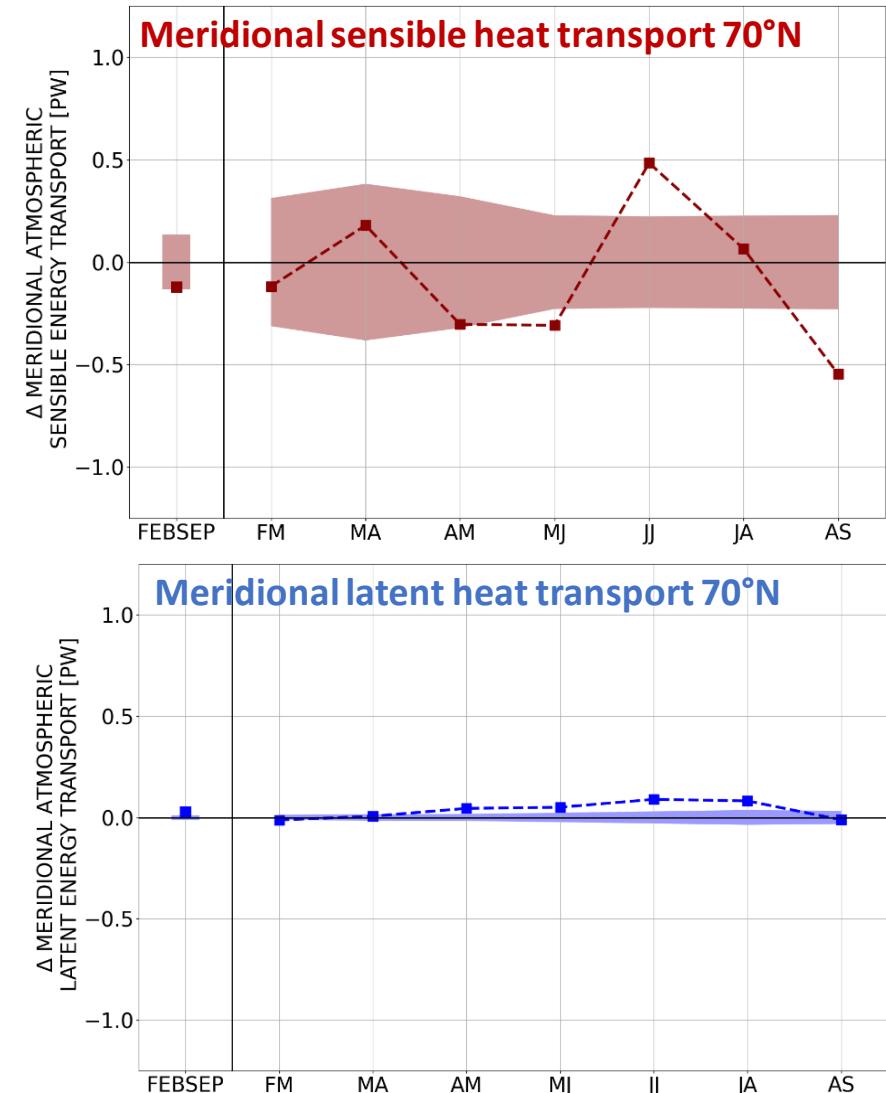
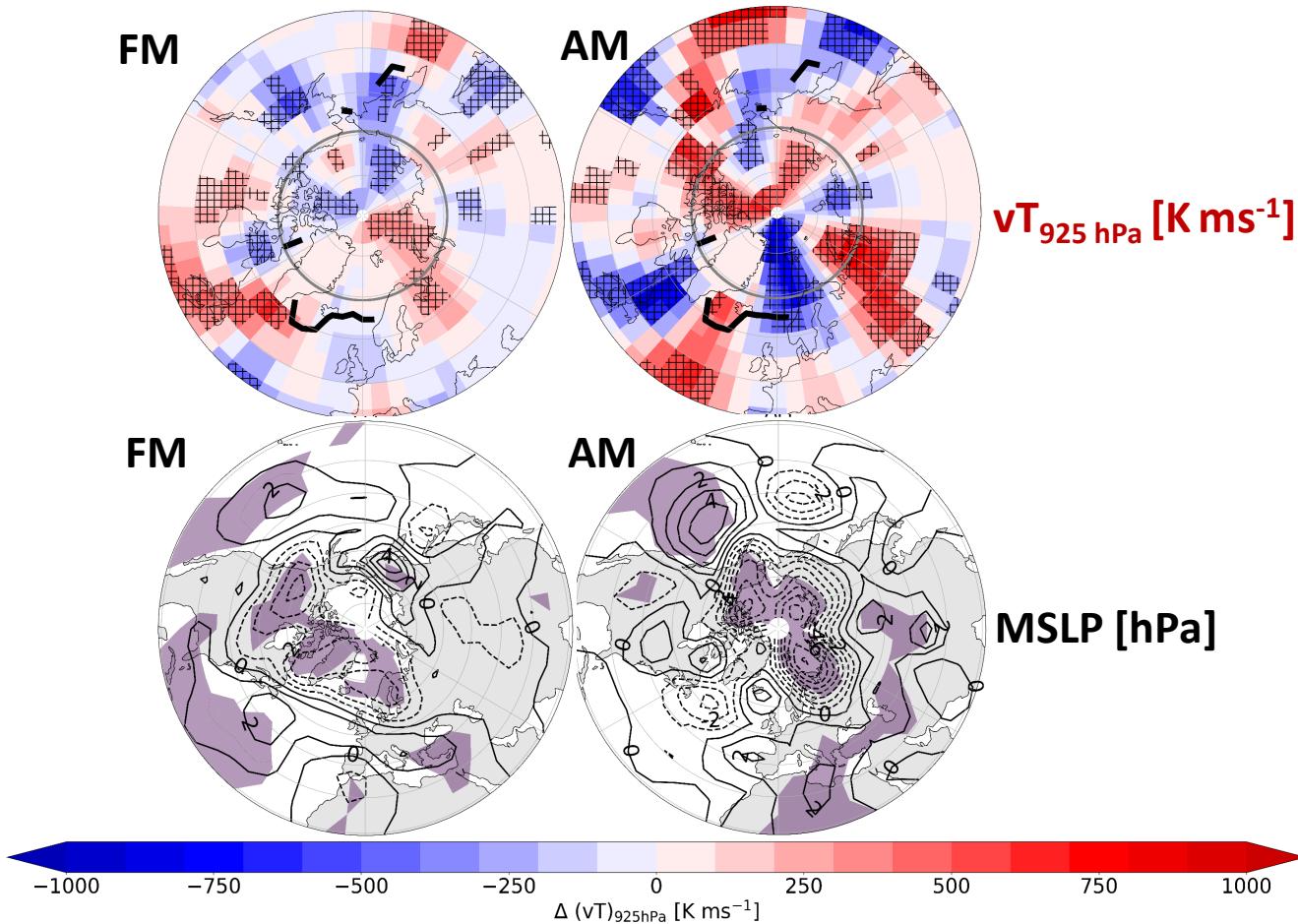
Trajectory with lowest August-September mean pan-Arctic sea ice area



- 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

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

$P_k, P_0$ : 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

