SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2026 (3rd year of the project)
Project Title:	Simulation of extremes of Arctic sea ice reduction with a rare event algorithm in EC-Earth3
Computer Project Account:	…………………spberago…………………………
Principal Investigator(s):	Francesco Ragone
Affiliation:	School of Computing and Mathematical Sciences, University of Leicester, Leicester, UK
Name of ECMWF scientist(s) collaborating to the project (if applicable)	……………………………………………………… ……
Start date of the project:	01 January 2024
Expected end date:	31 December 2026

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	14,000,000	13,999,999	14,000,000	669,360
Data storage capacity	(Gbytes)	125,000	- *	160,000	- *

*As discussed with the IT-team from the ECMWF, we do not have access to the amount of data volume located on the ECFS storage system that is specifically attributed to this Special Project. Part of our data volume located on the ECFS storage system can be attributed to the regular account through the Royal Meteorological Institute of Belgium.

Summary of project objectives (10 lines max)

In this project, we apply the Giardina-Kurchan-Lecomte-Tailleur (GKLT) rare event algorithm [1-7] to ensemble simulations with EC-Earth3 [8] to increase the sampling efficiency of extreme Arctic sea ice lows. Taking advantage of the improved statistics provided by the algorithm, we estimate the probabilities of extreme sea ice lows and we investigate their physical drivers. The aim is to better understand the relative importance of winter-spring sea ice-ocean preconditioning vs. spring-summer thermodynamic and dynamic processes in favouring extremely low sea ice conditions. Finally, we are interested in the probability of ultra-rare but high impact events, including sea ice area anomalies larger in magnitude than observed in 2012 and events with a total disappearance of Arctic sea ice for one year under current climate conditions.………………………………………………………………………………………
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Summary of problems encountered (10 lines max)

No specific problem occurred in the period July 2025 – June 2026.
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Summary of plans for the continuation of the project (10 lines max)

During the period 07/2026 – 12/2026, we will perform the third group of experiments. This will consist in a 12 months continuation of the SI-NEUTRAL experiment of the first group. While the model months October to February will be run without the algorithm, the period between the subsequent March to September will be run without and with the algorithm respectively. This third group of experiments serves 1) to estimate the recovery time until the sea ice returns to a neutral state after an extreme annual sea ice minimum, 2) to investigate how extreme a sea ice low can become under a strong two-year long forcing and 3) to study the response of the autumn-winter atmospheric circulation to extreme annual sea ice minima. Finally, we will submit a paper about our results of the first two groups of experiments before the end of September 2026.
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List of publications/reports from the project with complete references

We published a rare event algorithm study with the intermediate complexity coupled climate model PlaSim-LSG. This study provided us with the necessary expertise to reasonably apply the algorithm to the comprehensive climate model EC-Earth3 and is thus relevant for this special project:

Sauer J., F. Massonnet, G. Zappa, and F. Ragone, 2025: Ensemble design for seasonal climate predictions: studying extreme Arctic sea ice lows with a rare event algorithm. Earth System Dynamics, **16(3)**, 683-702, https://doi.org/10.5194/esd-16-683-2025.

We are currently preparing a paper about the rare event simulations with EC-Earth3. This will be submitted before the end of September 2026.

Summary of results

1. Experiments with EC-Earth3 and importance sampling of extreme annual sea ice minima

In section 2 of the report 2025, we explained that we perform three groups of control and rare event algorithm ensemble simulations with $N = 300$ trajectories running from 01 March to 01 October. In year 2025, the first group of experiments was finalized. For this first group, we initialized ensembles from a neutral winter sea ice-ocean state (referred to as "SI-NEUTRAL" hereafter). **During the period 07/2025 – 06/2026, we finalized the second group of experiments.** For this second group of experiments, we used "anomaly initialization" [9] to add to the initial condition of the first group on a grid point level the sea ice thickness and sea ice concentration difference between 2012 and the 1995-2005 climatology. From the methodological point of view, the second group of experiments confirmed the result from the first group: **the rare event algorithm successfully performs importance sampling of trajectories leading to extremely low late summer sea ice area values** (Figure 1**;** note that the black curves in Figure 1 correspond to the orange ones in Figure 4 of the report 2025)**.** In both groups of experiments, simulations with the rare event algorithm provide sea ice area anomalies larger in magnitude than the observed deviation of the 2012 sea ice area from the 1979-2025 linear trend line. **In this context, our experiments suggest that – for present-day climate conditions – the probability of a fluctuation with larger amplitudes than the deviation of the 2012 sea ice area from the 1979-2025 linear trend is in the order of $10^{-2} - 10^{-3}$ (Figure 1)**.

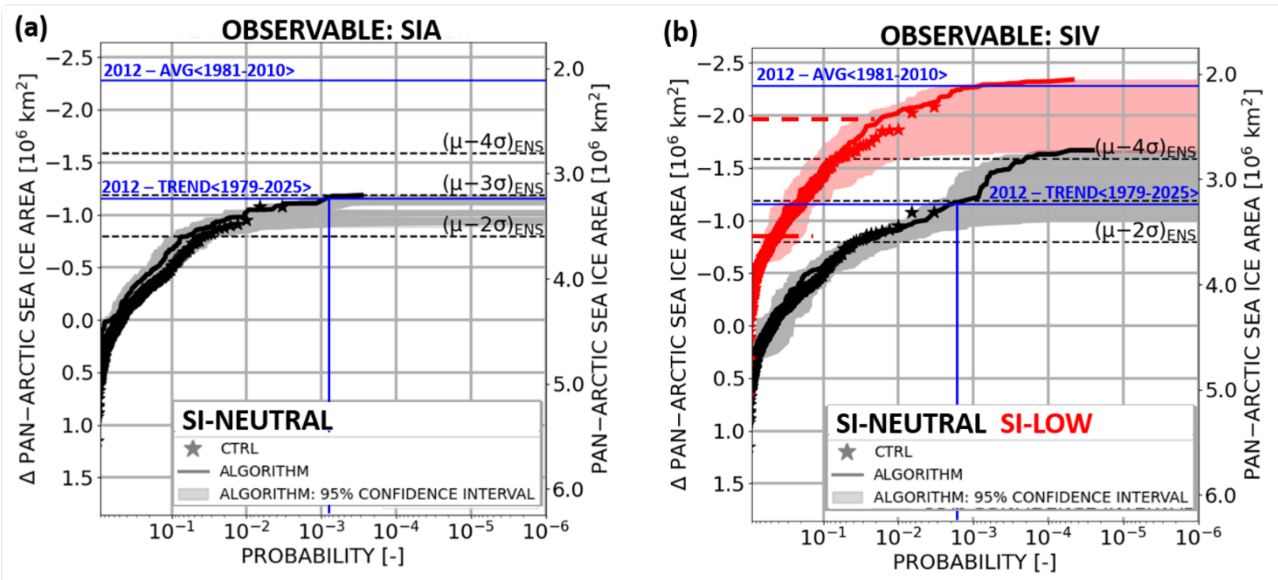

Figure 1: Probabilities (x-axes) of August-September mean sea ice area equal or smaller than a given threshold (y-axes) as a function of two different sea ice-ocean initial conditions for the N = 300 trajectory (stars) control and (solid lines) rare event algorithm ensembles. The observable used for the simulations with the algorithm is the pan-Arctic (a) sea ice area and (b) sea ice volume. Note that black stars in (a) and (b) show the same curve and are displayed twice for the purpose of visualization. While the right y-axes shows absolute sea ice area values, the left y-axes expresses these as anomalies relative to the SI-NEUTRAL control ensemble mean. Both are displayed in reverse order. The shading in direction of the x-axes shows ± 2σ intervals around the probability estimates. The gray dashed lines indicate how many standard deviations a sea ice area value is below the mean of the SI-NEUTRAL control ensemble. The blue lines indicate the 2012 observed August-September mean sea ice area anomaly relative to the 1979-2025 linear trend line and 1981-2010 average. The horizontal dashed red lines in (b) indicate the mean of the SI-LOW control ensemble and the location of the blue "2012 – TREND<1979-2025>" line with respect to the SI-LOW control ensemble mean.

2. **Statistical link between extreme sea ice reduction and the atmospheric circulation**

Thanks to the rare event algorithm, we are able to perform a quantitative statistical analysis of the physical processes and conditions leading to extreme reductions of the pan-Arctic sea ice area within one single melting season (Figures 2-4). We find that extreme annual sea ice minima are systematically preceded by enhanced sea ice volume loss from May-July, suggesting an increase in the predictability of extreme annual sea ice minima during that period (Figure 2). Moreover, by means of composite analyses, we demonstrate that enhanced May-July sea ice volume loss is systematically triggered by cyclonic mean sea level pressure anomalies over the central to eastern Arctic Ocean (Figure 3(a-d)). Anomalously cyclonic flow over the Arctic Ocean substantially modulates the thermodynamic state of the near-surface atmosphere (Figure 3(e-h)). Thus, significantly positive two metre temperature anomalies prevail during May-July downstream of the cyclonic anomalies (Figure 3(e-h)). Apart from the thermodynamic impact, cyclonic circulation anomalies are associated with Ekman drift of sea ice out of the central Arctic Ocean towards the marginal seas of the Arctic Ocean (Figure 3(i-l)).

Finally, we quantitatively explore the impact of anomalous atmospheric circulation on the sea ice by means of a sea ice volume and sea ice area budget analyses according to Holland and Kwok [2011] [10]. On statistical average (i.e. composite) and integrated over the entire melting season, extremes of sea ice reduction are characterized by strongly enhanced loss of sea ice volume on the Pacific and Eurasian side of the Arctic and slightly reduced sea ice loss eastern of Greenland (Figure 4). Spatially, the contribution of thermodynamic *vs.* dynamic forcing shows a dipole-like structure: statistically significant enhanced thermodynamic sea ice melting occurs from the Canadian Archipelago over the Pacific side of the Arctic to Siberia. Enhanced thermodynamic melting therefore spatially coincides with positive two metre temperature anomalies during spring (cf. Figures 2 and 4). Dynamics-related sea ice anomalies are smaller in magnitude than the thermodynamic ones, but statistically significant enhanced sea ice loss is noticeable on the Eurasian side of the Arctic and thus spatially coincides with the centre of anomalously low spring-summer mean sea level pressure (cf. Figures 2 and 4).

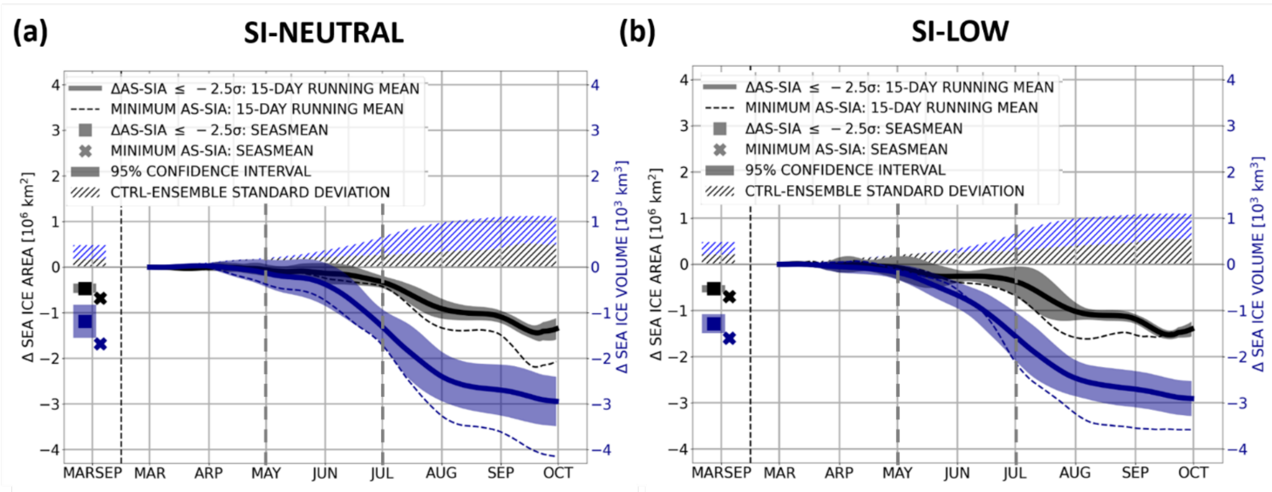

Figure 2: March-September (MARSEP) and 15-day running mean (blue) sea ice volume and (black) sea ice area anomalies relative to the control ensemble means for (a) the "SI-NEUTRAL: ALG(SIV)" and (b) the "SI-LOW: ALG(SIV)" experiments. Thick lines and square markers are composite mean anomalies conditional on the occurrence of an August-September sea ice area of at least 2.5 control ensemble standard deviations below the control ensemble means. The shading shows 95% confidence intervals around the composite estimates and the hatching shows the control ensemble standard deviations. The thin lines are the trajectories with the most extreme sea ice reduction available from the two experiments respectively.

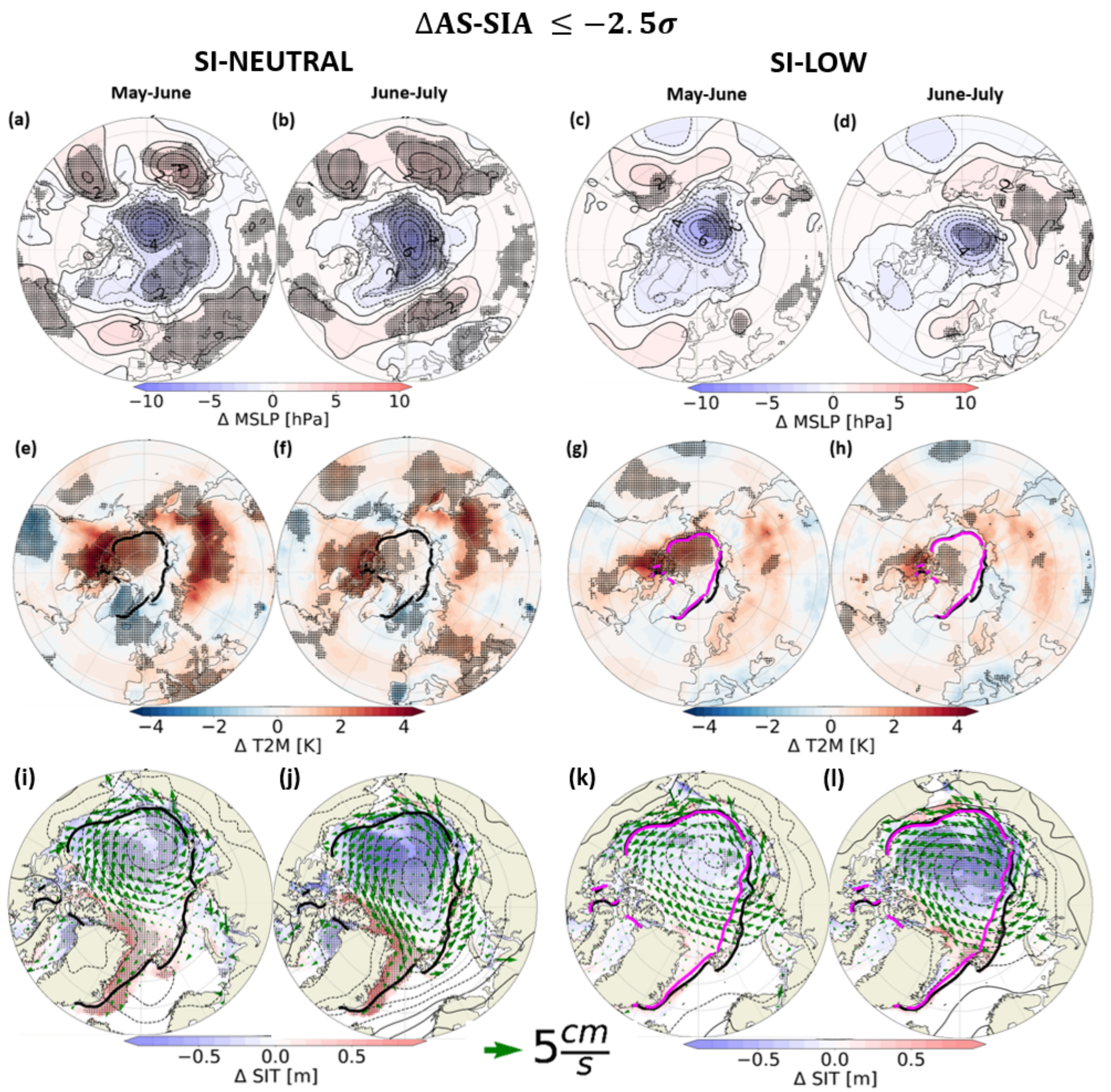

Figure 3: May-June and June-July composite mean (a-d) mean sea level pressure [hPa], (e-h) two metre temperature [K] and (i-l) horizontal sea ice motion vector [cm s^{-1}] and sea ice thickness [m] anomalies conditional on the occurrence of an August-September sea ice area of at least 2.5 control ensemble standard deviations below the control ensemble means. The hatching indicates statistical significance at the 5% level. The results are based on (a,b,e,f,i,j) the "SI-NEUTRAL: ALG(SIV)" and (c,d,g,h,k,l) the "SI-LOW: ALG(SIV)" experiments. The black and magenta contour lines indicate the August-September mean 15% sea ice concentration line in the SI-NEUTRAL and SI-LOW control ensembles respectively

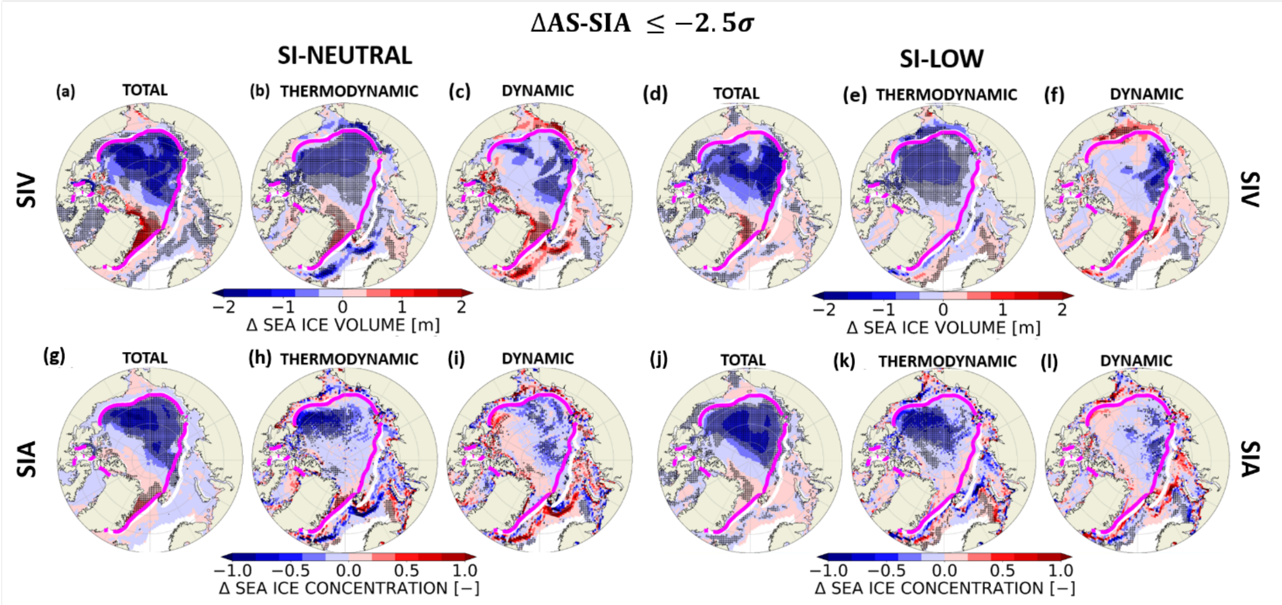

Figure 4: Composite mean anomalies of the seasonally-integrated (AVG<01 March-01 August, 01 March-02 August,..., 01 March-30 September>) terms of (a-f) the sea ice volume [m] and (g-l) the sea ice area [-] budget analysis conditional on trajectories with an AUGSEP sea ice area of at least 2.5 control ensemble standard deviations below the control ensemble means. The results are based on (a-c,g-i) the "SI-NEUTRAL: ALG(SIV)" and (d-f,j-l) the "SI-LOW: ALG(SIV) experiments". The white and magenta lines indicate the AUGSEP mean 15% SIC line in the SI-NEUTRAL and SI-LOW control ensembles respectively. Hatching indicates statistical significance at the 5% level. The term "DYNAMIC" is the sea ice transport.

References

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