LATE REQUEST FOR A EMI R&D PROJECT 2026–2028

Country/Organisation: Belgium

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Project Title: Causes and consequences of extreme Arctic sea ice reduction investigated with rare event sampling in EC-Earth3

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP**	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2026	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for project year:		**2026**	**2027**	**2028**
High Performance Computing Facility	[SBU]	45,000,000		
Graphics Processing Unit Cluster-A	[GBU]			
Graphics Processing Unit Cluster-B	[GBU]			
Accumulated data storage (total archive volume)[2]	[GB]	110,000		

EWC resources required for project year:		**2026**	**2027**	**2028**
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

Continue overleaf.

[1] The Principal Investigator will act as contact person for this EMI R&D Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.

[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.

[3] The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

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Extended abstract

1 Introduction

1.1 Scientific background and motivation

The late summer Arctic sea ice cover dropped by about 40% compared to the beginning of the satellite-based observations in the late 1970s [Fetterer et al. 2017; Notz and SIMIP Community 2020). This downward trend occurred in the context of steadily increasing greenhouse gas conditions and associated anthropogenically-induced global warming [Notz and Stroeve 2016; Meinshausen et al. 2017; Ding et al. 2017]. However, the decline of Arctic sea ice cover is non-linear, and internal climate variability both can substantially modulate the downward trend of sea ice area and can cause **extreme fluctuations of the annual sea ice minimum** [Ding et al. 2017; Baxter et al. 2019; Francis and Wu 2020].

Extremes of Arctic sea ice reduction, such as observed in the summers of 2007 and 2012, have implications for marine accessibility [Eicken 2013; Smith and Stephenson 2013; Melia et al. 2017], can influence mid to high latitude weather and climate [e.g. Balmaseda et al. 2010; Koenigk et al. 2016; Screen 2018] and potentially have repercussions on ocean stratification and circulation [Häkkingen 1993; Guémas and Salas-Mélia 2008; Sévellec et al. 2017, Wu et al. 2021]**.** A precise understanding of the **drivers, predictability** and **impacts** of **extremes of Arctic sea ice reduction** remains however challenging**.**

A key obstacle in studying climate extremes is the **lack of robust statistics** in observations and in numerical simulations with computationally expensive climate models**.** A possible solution to this problem is given by rare event algorithms, i.e., computational techniques developed in statistical physics to increase the sampling efficiency of rare events in numerical simulations [e.g. Kahn and Harris 1951; Del Moral 2004; Giardina et al. 2011; Ragone et al. 2018; Grafke and Vanden-Eijnden 2019]. While preserving the dynamical consistency of a climate model, these techniques allow to drastically increase the number of simulated extremes compared to direct sampling for the same computational cost, and to sample ultra-rare events that are hardly possible to study otherwise.

Recently, these techniques have been applied to climate science and fluid dynamics to study heatwaves [Ragone et al. 2018; Ragone and Bouchet 2020; Ragone and Bouchet 2021], large-scale precipitation [Wouters et al. 2023], tropical storms [Plotkin et al. 2019; Webber et al. 2019], turbulent flows [Lestang et al. 2018; Bouchet et al. 2019], and extremes of Arctic sea ice reduction in the intermediate complexity climate model Planet Simulator (PlaSim) [Sauer et al. 2024; 2025]. **As described in section 1.2, we recently applied a rare event algorithm to improve the sampling efficiency of extremes of Arctic sea ice reduction in the comprehensive Coupled Model Intercomparison Project Phase 6 (CMIP6)-generation European community Earth-System-Model version 3 (EC-Earth3) [Döscher et al. 2022].**

1.2 Specific goals of the project and scientific questions

This Special Project will build on existing simulations from the Special Project SPBERAGO (2024-2026; https://www.ecmwf.int/sites/default/files/special_projects/2024/spberago-2024-report3.pdf; section 1.3 contains a list of publications originating from SPBERAGO). In SPBERAGO, we applied the statistical-physics-based Giardina-Kurchan-Lecomte-Tailleur (GKTL) rare event algorithm to ensemble simulations with the EC-Earth3 climate model to improve the sampling of trajectories leading to extremes of pan-Arctic sea ice area reduction within one single melting season (Figures 1-2). Thanks to the algorithm, we have access to a much more robust sea ice low statistics than available from observations and conventional numerical simulations. We also dispose over trajectories characterized by negative sea ice area anomalies that are substantially larger in magnitude compared to the deviation of the observed 2012 late summer sea ice area from the trend line. During the SPBERAGO project phase, we exploited the improved statistics of low sea ice states to perform a quantitative statistical analysis of their precursors on sub-seasonal time scales.

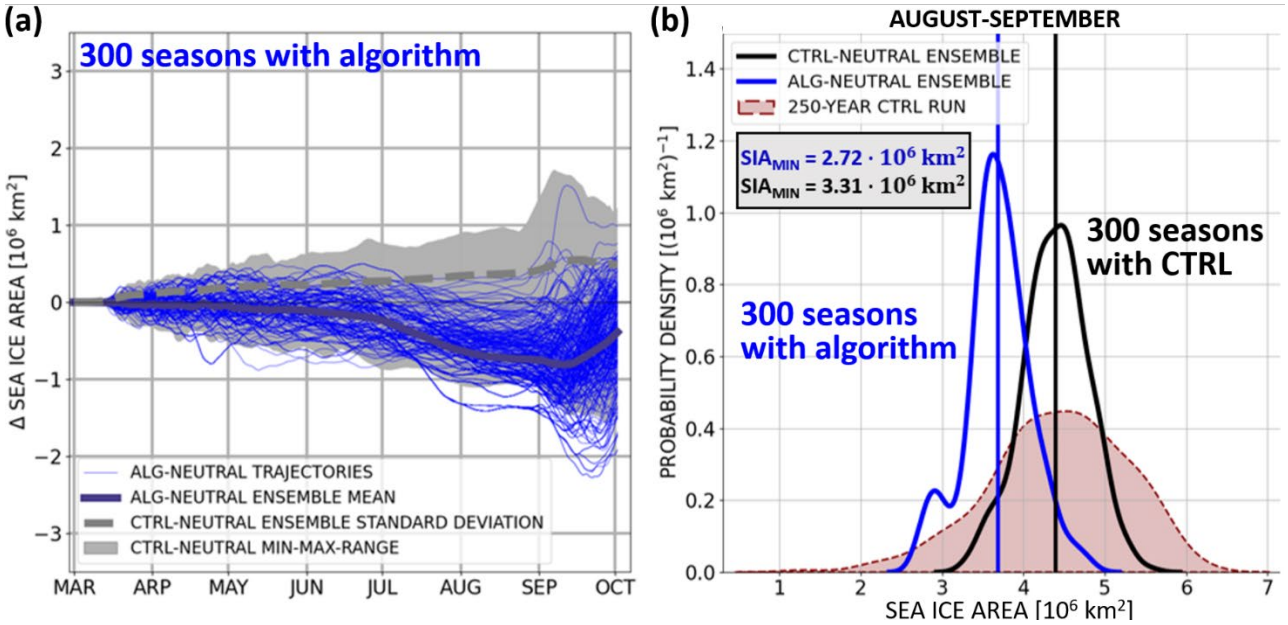

Figure 1: EC-Earth3: Pair of N=300 control and rare event algorithm ensemble simulation running from 01 March to 01 October: (a) Daily sea ice area anomalies (blue) obtained with the algorithm and computed relative to the control ensemble mean. The thick blue line is the algorithm ensemble mean. The dashed gray line shows the control ensemble standard deviation and the gray shading the control minimum-maximum range. (b) Probability density functions for August-September sea ice area for (black) the control ensemble, (blue) the algorithm and (red) a 250-year N=1 trajectory control run.

Here we design new experiments with EC-Earth3, selectively activating or deactivating the rare event algorithm, to better understand **1) the impacts** of extreme sea ice lows on the atmosphere-sea ice-ocean system within lead times of a few months to a few years and **2) the importance of different precursors in acting as direct drivers** of extreme annual sea ice minima on sub-seasonal time scales. Regarding the latter, we will address precursors of extreme annual sea ice minima that we identified in the experiments of the Special Project SPBERAGO. We will exploit the new experiments to address the following scientific questions:

- What are the **consequences of extreme Arctic sea ice lows** for the atmospheric and oceanic circulations, in particular for the North Atlantic Subpolar Gyre, on lead times of a few months to a few years?

- How extreme can a sea ice low become under the very unlikely, but physically plausible situation of a **strong internally-generated two-year forcing**, and what is the **recovery time** of extremely negative pan-Arctic sea ice area anomalies?
- How likely is the occurrence of an extreme annual sea ice minimum after **anomalous states of the atmosphere-sea ice-ocean system** during spring-summer?

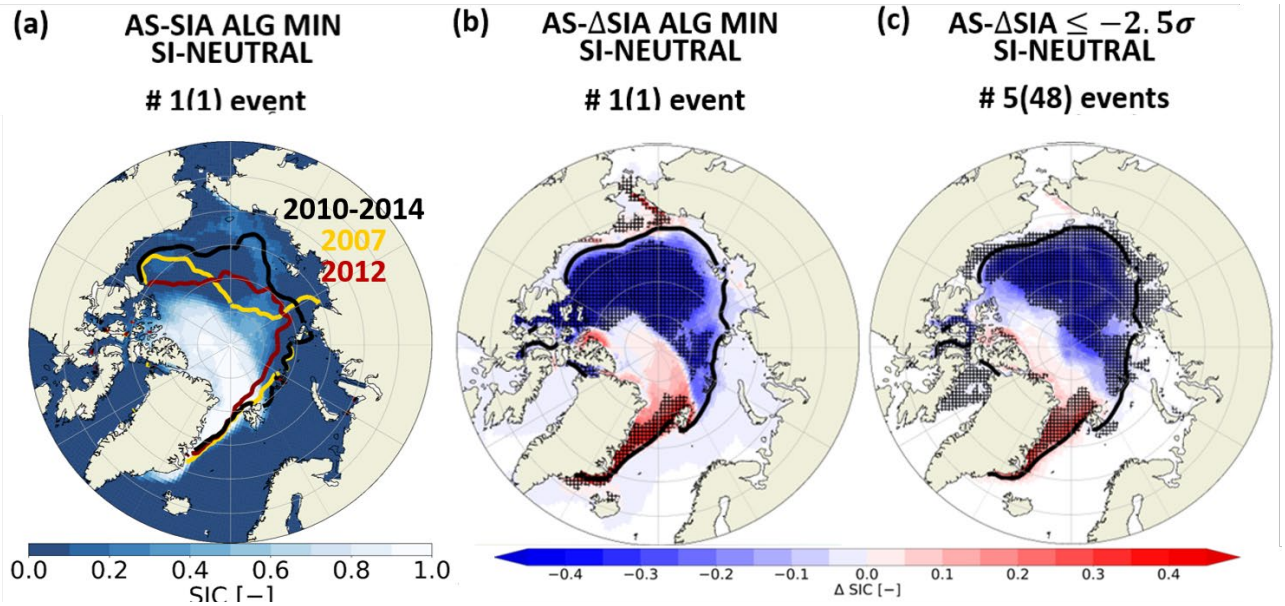

Figure 2:EC-Earth3: August-September (AS) sea ice concentration (SIC) obtained with the rare event algorithm for (a) absolute values and (b-c) anomalies relative to the control ensemble mean. (a-b) Trajectory with the most extreme sea ice reduction available from the ensemble. (c) Composite mean anomalies conditional on the occurrence of trajectories with an AS sea ice area at least 2.5 control ensemble standard deviations below the control ensemble mean. Hatching marks SIC anomalies that are (b) larger in magnitude than the control ensemble standard deviation and (c) statistically significant at a 5% level. The red, yellow and black lines in (a) show the observed 2012, 2007 an 2010-2014 mean AS 15%SIC lines [EUMETSAT Ocean and Sea Ice Satellite Application Facility, 2017] and the black lines in (b-c) are the AS 15%SIC lines in the control ensemble.

1.3 List of publications originating from the Special Project SPBERAGO

During the SPBERAGO project phase, we published a rare event algorithm study with the intermediate complexity coupled climate model "PlaSim-Large Scale Geostrophic (LSG) ocean". This study provided us with the necessary expertise to reasonably apply the algorithm to the comprehensive climate model EC-Earth3 and was thus relevant for SPBERAGO. As described in section 1.2, we successfully applied the algorithm to EC-Earth3, and we will submit a resulting new paper to the Journal of Climate in November 2026:

Sauer, J., F. Massonnet, G. Zappa, 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.

Sauer, J., F. Ragone, F. Massonnet, 2026: Disentangling the thermodynamic *vs.* dynamic drivers of extreme Arctic sea ice reduction using rare event sampling in EC-Earth3, *in preparation for submission to Journal of Climate*.

2 State of the art

While Arctic sea ice decline is an indicator of global climate change, the presence of sea ice *vs.* open water conditions, in turn, impacts the surface energy [e.g. Serreze and Barry, 2024], momentum [Martin et al., 2016] and water budget [e.g. Wu et al. 2021] and therefore influences the climate system. Different and partly competing impacts of Arctic sea ice variability on the oceanic circulation are suggested in the literature. On the one hand, the studies of Guémas and Salas-Mélia [2008], Wu et al. [2021] and Våge et al. [2018] argue that **enhanced winter sea ice retreat in the Nordic Seas potentially favours deep water formation** due to increased heat release from the ocean to the atmosphere and due to enhanced wind-induced mechanical mixing. On the other hand, **increased freshwater and heat input due to large-scale sea ice loss increases ocean buoyancy** and is expected to reduce the strength of the Atlantic Meridional Overturning Circulation (AMOC) on sub-decadal and longer time scales [Sévellec et al. 2017; Liu and Fedorov 2022; Lohmann et al. 2026]. Apart from large-scale sea ice loss, **strong interannual pulses of fresh water and sea ice export from the Arctic Ocean to the North Atlantic,** such as observed during episodes of great salinity anomalies in the late 20th century, can substantially alter the ocean stratification and circulation in the North Atlantic [Belkin 1998; Häkkingen 1993; Haak et al. 2003; Zhang and Vallis 2005].

Although debated, **sea ice retreat and variability potentially affect the atmospheric circulation in the mid latitudes** [Honda et al. 2009; Balmaseda et al. 2010; Petrie et al. 2015, Koenigk et al. 2016; Blackport et al. 2019; Blackport and Screen 2020]. Changes in sea ice can affect the strength and position of the jet stream through the thermal wind balance [Petrie et al. 2015; Screen 2018] and by modulating Rossby waves through the impact of anomalous surface heat fluxes on vertical motions in the atmosphere [Honda et al. 2009]. Sea ice has a much larger memory than the atmosphere, typically a few months for pan-Arctic sea ice area and up to a few years for sea ice volume [Blanchard-Wrigglesworth et al. 2011 and Massonnet et al. 2026]. The accurate representation and prediction of the state of Arctic sea ice within climate models is therefore relevant for seasonal climate forecast systems [Koenigk et al. 2016; Bunzel et al. 2016; Balmaseda et al. 2010].

A **quantitative statistical analysis** of the **impacts** of **drastic Arctic sea ice loss events** on the atmospheric and oceanic circulations is hard to obtain, in large part due to the lack of robust statistics of sea ice reduction extremes in observations and simulations with complex numerical models. Common approaches to investigate the consequences of low Arctic sea ice states consist in artificially prescribing low sea ice conditions in climate model ensemble simulations [Tietsche et al. 2011; Screen 2018; England et al. 2022]. In this context, the studies of Screen [2018] and England et al. [2022] argue that common techniques used to impose sea ice loss, such as e.g. ghost flux, nudging and albedo modification, partly include unphysical assumptions and can lead to an artificial warming on top of the warming induced by the sea ice loss itself. **In this Special Project, instead, the rare event algorithm provides a possibility to study the responses of different climate variables to extremely low sea ice states that emerge as a natural consequence of the dynamics of the system.**

3 Proposed activities

3.1 Rare event algorithm

The GKLT rare event algorithm is applied on top of an ensemble simulation and is designed to improve the sampling efficiency of trajectories characterized by extreme anomalies of a target observable on time-average over the full length of simulation. We refer to Ragone et al. [2018], Ragone and Bouchet [2020, 2021] and Sauer et al. [2024, 2025] for details regarding this algorithm and provide here a short qualitative description of the method.

We consider an ensemble of $\boldsymbol{N}$ trajectories running for a total simulation time $\boldsymbol{T_a}$, e.g. from 01 March to 01 October. Instead of letting evolve the ensemble independently, we resample the trajectories at regular intervals of a fixed resampling time $\boldsymbol{\tau_r}$. This resampling is performed in such a way that trajectories tending to lead to a desired extreme state of the target observable produce replicates of themselves, while other trajectories are likely to be killed. The number of replicates produced by a trajectory is given by exponential functions of the time-average of the target observable during a past resampling interval (e.g. five days). After each resampling event, the ensemble size is kept constant, and the replicates of each trajectory are slightly perturbed by adding a small random noise to be able to evolve differently during the next interval of the simulation. When the final time $\boldsymbol{T_a}$ is reached, we reconstruct an effective ensemble by attaching at each resampling event from the end to the beginning of the simulation the ancestors to the pieces of surviving trajectories. Trajectories that did not survive until the end of the simulation are discarded from the ensemble.

Finally, the math of the method allows to compute the ratio between the probability of observing a trajectory in a normal ensemble simulation to that of observing the same trajectory in a simulation with the algorithm. This allows to compute statistical quantities (return times, composite maps, etc.) related to the original statistics of the model, using data generated with the algorithm. However, since the algorithm increases the sampling efficiency of the extremes, the accuracy of the estimation of statistical quantities conditional on the occurrence of the extremes is improved compared to a standard simulation, and ultra-rare events appear that are hardly possible to be studied otherwise.

3.2 Plan of the experiments

We perform simulations with the Coupled Model Intercomparison Project Phase 6 (CMIP6)-generation European community Earth-System-Model version 3 (EC-Earth3) [Döscher et al., 2022] (respository tag 3.3.1 in the EC-Earth development portal for members of the consortium: http://www.ec-earth.org). We will run EC-Earth3 in TL255L91-ORCA1L75 configuration, including the atmospheric model Integrated Forecast System (IFS) cycle r34, the H-TESSEL land-surface scheme, the Nucleus for European Modelling of the ocean (NEMO) version 3.6, the Louvain-la-Neuve sea ice model version 3 (LIM3), and the OASIS-MCT coupler version 3.0.

Consistent with the simulations produced in the Special Project SPBERAGO, we will run EC-Earth3 under constant year-2000 greenhouse gas conditions and an annually repeating seasonal cycle in the solar radiation (representative of the year 2000). Starting from the experiments produced in SPBERGAO, we will construct two new groups of experiments. **The**

first group of ensembles will be designed to study the consequences of extreme annual sea ice minima on lead times of a few months to a few years. These ensembles will be initialized using the 01 October state of the rare event simulation denoted as "SI-NEUTRAL" in the SPBERAGO progress report 2026 (see Figure 1 above). **The second group of ensembles will be designed to study the importance of different precursors in anticipating low sea ice states on sub-seasonal time scales.** For this purpose, we will run ensembles from 01 March to 01 October as in SPBERAGO. This time, however, we will use the rare event algorithm to better sample trajectories characterized by anomalous spring-summer states of variables that we identified as precursors of extreme sea ice lows in the previous experiments.

Group 1: Consequences of extreme annual sea ice minima

(a) We continue the "SI-NEUTRAL" rare event simulation for another 12 months, but switching off the algorithm. This allows us to investigate the atmospheric and oceanic responses to low sea ice states within lead times of up to one year, exploiting a relatively large ensemble of N=300 trajectories.

In the "SI-NEUTRAL" experiment, extremely low sea ice conditions are associated with substantially enhanced sea ice export out of the Arctic Ocean towards the North Atlantic (Figure 2). These trajectories therefore provide appropriate initial conditions to investigate a potential impact of freshwater export from the Arctic Ocean on the ocean stratification and circulation in the subpolar North Atlantic.

(b) We reactivate the rare event algorithm on 01 March of the simulation of (a) and run that new rare event simulation until 01 October. The purpose of this experiment is to determine how extreme a sea ice low can become after an unlikely, but physically plausible situation of a strong forcing acting over two consecutive melting seasons. Based on this experiment, we will discuss the possibility of a total disappearance of sea ice for one year in current climate conditions.

(c) In order to address a possible oceanic response on longer lead times than one year, we will further continue a subset of 30 trajectories for additional four years (i.e. a total length of five years). These 30 trajectories are run without the rare event algorithm and represent either a continuation of the ensemble from (a) or of the ensemble from (b). In this context, the advantage of the ensemble from (b) compared to the one from (a) is that the system is pushed towards low sea ice states over two consecutive melting seasons, potentially leading to a larger impact on the oceanic circulation compared to single-year sea ice lows.

Group 2: Targeted physical drivers of extremes of sea ice reduction

Here we will perform three ensemble experiments with the rare event algorithm running for one single melting season between 01 March and 01 October. In contrast to SBPERAGO, the algorithm observable will not be the pan-Arctic sea ice area or sea ice volume, but quantities that we identified as precursors of extreme annual sea ice minima in previous experiments. Reasonable choices for the rare event algorithm observables will be given by the Arctic Dipole index [Wang et al. 2009], vertically integrated moisture flux convergence as a proxy for cyclonic mean sea level pressure conditions over the Arctic Ocean [Kapsch et al. 2018] and the cumulative area with sea ice thickness larger than a given threshold (e.g. $\geq$ 2.0

metres). Our previous experiments strongly suggested that anomalous weather patterns favouring extreme annual sea ice minima do not necessarily have to occur during the entire melting season, but are particularly important during the May-July spring-summer transition, temporarily coinciding with the predictability barrier of late summer sea ice area [cf. Bushuk et al. 2020]. Consequently, we will activate the rare event algorithm exclusively from mid-April to the end of July, while switching off the algorithm both from 01 March to the mid-April and during August-September.

3.3 Technical aspects and justification of computational resources

As in the Special Project SPBERAGO, we will use the TL255L91-ORCA1 configuration of EC-Earth3 on Atos. According to existing reports from other researchers, the optimal EC-Earth3 setup on Atos is obtained with five nodes (IFS: 490 cores, NEMO: 148 cores, runoff mapper: 1 core, XIOS: 1 core). In our application, however, we conducted and will conduct ensemble simulations with N=300 trajectories, and we run a subset of four model trajectories simultaneously in order to accelerate these simulations compared to running the trajectories one after the other. The above-mentioned five-node configuration thereby appeared to be less efficient than using a three-node configuration (IFS: 240 cores, NEMO: 118 cores, runoff mapper: 1 core, XIOS: 1 core) and reserving 12 nodes for the sake of trajectory parallelization. This setup requires 2,000 SBUs to run one model month per trajectory when the algorithm is switched off and about 5,000 SBUs when the algorithm is switched on. Simulations with the algorithm require more computational resources than standard simulations due to the regular resampling of model trajectories with a frequency of five model days.

The conduction of the new experiments will be straightforward as we already performed successful simulations with the rare event algorithm and EC-Earth3 on Atos during 2024-2026. We summarize the required computational resources in Table 1. The sum of the indicated resources is 48,500,000 SBUs and thus slightly exceeds the maximum of 45,000,000 SBUs that are allowed in the ECMWF Late Request. We will use additional resources owing to the regular account from the Royal Meteorological Institute of Belgium to account for the excess of 3,500,000 SBUs.

Table 1: Ensemble experiments planned within the Special Project. "DIRECT" refers to ensemble simulations without the rare event algorithm, i.e., standard ensemble simulations, while "ALG" refers to ensemble simulations with the rare event algorithm. The ensemble simulations in the second group "Targeted physical drivers of extremes of sea ice reduction" run over one single melting season from 01 March to 01 October, but the algorithm is exclusively switched on from mid-April to the end of July. The second group contains three ensemble experiments as three different algorithm observables will be used.

Experiment group	Characteristics	# of trajectories	# SBUs
1) Consequences of extreme annual sea ice minima	12 months DIRECT	N=300	8,000,000
	48 months DIRECT	N=30	3,000,000
	7 months ALG	N=300	12,000,000
2) Targeted physical drivers of extremes of sea ice reduction	3 X [1.5 months DIRECT + 3.5 months ALG + 2.0 months DRECT]	3 X [N=300]	3 X 8,500,000 = 25,500,000
			TOTAL: 48,500,000 SBUs

We will save the output of IFS on a 6-hourly basis and the NEMO output will be saved on a five model days basis. This amounts to about 3.0 GB of data per model month and per trajectory, yielding a total of about 40 TB. Additional data volume will emerge from the restart files that need to be saved every five model days when the algorithm is applied. An effective restart file data volume of 12 GB per model month and per trajectory yields an additional data volume of 65 TB on top of the 40 TB. Consequently, the total expected data volume is 105 TB.

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