

LATE REQUEST FOR A SPECIAL PROJECT 2026–2028

MEMBER STATE: Switzerland

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Project Title: Quantifying Cloud Process Uncertainties using Perturbed Parameter Ensembles in OpenIFS cycle 48r1 portable global aerosol-climate and weather prediction model

To make changes to an existing project please submit an amended version of the original form.)

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 <input type="checkbox"/> X	NO <input type="checkbox"/>

Computer resources required for project year:	2026	2027	2028
High Performance Computing Facility [SBU]	25 000 000		
Accumulated data storage (total archive volume) ² [GB]	100000		

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 Special 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

Cloud processes are central to the Earth's energy balance, yet they remain one of the largest sources of uncertainty in climate projections. Within the framework of the **Horizon Europe CleanCloud project** (Grant Agreement 101137639), which aims to improve understanding of aerosol–cloud–precipitation interactions in a changing atmosphere, this Project application focuses on quantifying uncertainties in cloud process representation using a **Perturbed Parameter Ensemble (PPE)** approach with the OpenIFS CY48R1 model.

Despite decades of model development, large uncertainties persist in the simulation of both **microphysical** (droplet activation, phase transitions, ice processes) and **macrophysical** (entrainment, detrainment, convective organisation) cloud properties (Collins et al., 2011; Regayre et al., 2014). These processes are parameterized in all global climate models through empirical relationships and tunable coefficients whose values are only loosely constrained by observations. Errors in their specification contribute directly to the spread in **cloud feedbacks**, **precipitation formation**, and **effective radiative forcing (ERF)** across models (Korolev and Jason., 2022).

Traditional model tuning strategies often compensate one parameterization error with another, achieving acceptable climatologies but masking the true physical uncertainty. To overcome these limitations, the **Perturbed Parameter Ensemble (PPE)** methodology has become an essential tool for systematic uncertainty quantification. In a PPE, uncertain model parameters are perturbed within plausible ranges to generate an ensemble of model variants that span the multidimensional parameter space while keeping the model structure fixed (Collins et al., 2011; Yoshioka et al., 2019). Ensemble output is then evaluated against observations using statistical emulators and Bayesian inference to identify the most consistent regions of parameter space (Partridge et al., 2012; Johnson et al., 2018).

Because the parameter space is high-dimensional and strongly nonlinear, the present project will employ Latin Hypercube Sampling (LHS) to generate an optimally stratified ensemble design. LHS provides an efficient and statistically uniform coverage of the multi-dimensional parameter space, ensuring that every parameter range is well sampled while minimizing the number of required ensemble members. This approach allows us to achieve near-optimal sampling efficiency for a given computational budget, which is a crucial aspect when each simulation is computationally expensive.

The PPE framework has been successfully applied to aerosol processes (Regayre et al., 2014; Bhatti et al., 2025), revealing that a relatively small number of uncertain parameters can dominate the spread in aerosol–cloud radiative forcing. However, comparable studies targeting **cloud parameters** remain rare, even though cloud processes contribute equally or more to the total forcing uncertainty. Key parameters governing autoconversion, accretion, mixed-phase transitions, and convective cloud fraction are particularly poorly constrained, and their interactions with aerosol parameters are complex and nonlinear (Michibata et al., 2025).

The proposed CleanCloud–Cloud PPE addresses this gap by extending the PPE framework to cloud-specific parameters within OpenIFS/AC CY48R1, the atmospheric component of the EC-Earth4 Earth System Model (ESM). The ensemble will perturb both microphysical and macrophysical parameters,

including droplet activation, ice fall speed, entrainment/detrainment rates, and convective cloud-fraction coefficients.

By performing approximately 150–200 one-year simulations, the project will enable a statistically robust exploration of the cloud parameter space and its impact on simulated radiative feedbacks and precipitation. The resulting ensemble will provide an observation-constrained posterior distribution of cloud parameters, reduce parametric uncertainty in EC-Earth’s cloud schemes, and deliver improved physical realism for future climate simulations.

Through this effort, the CleanCloud–Cloud PPE will contribute directly to CleanCloud’s overarching goal of improving the representation of aerosol–cloud–precipitation interactions in Earth System Models and reducing one of the dominant uncertainties in climate projections, primarily utilizing ECMWF’s high-performance computing to enable a scale of experimentation otherwise unachievable.

Objectives and Methodology

1. Quantify parametric uncertainty in cloud feedbacks and radiative forcing within OpenIFS/AC CY48R1.
2. Identify key microphysical and macrophysical parameters controlling the spread in cloud radiative and precipitation properties.
3. Use satellite observations (EarthCARE, PACE) to constrain parameter ranges via Bayesian inference.
4. Deliver an observation-constrained cloud parameter ensemble for next-generation EC-Earth configurations.

This project applies the Perturbed Parameter Ensemble (PPE) methodology (Collins et al., 2011; Yoshioka et al., 2019), extended using Maximin Latin Hypercube Sampling (LHS) to design an optimal ensemble that efficiently explores the multidimensional parameter space. LHS divides each parameter’s range into equal-probability intervals and samples one value from each interval in a stratified way, ensuring even coverage of all parameters and minimizing redundant combinations. An example Latin hypercube sampling with three normalized perturbed parameters are shown in Fig. 1. A sample set of cloud parameters for the PPE are listed in Table 1.

Parameter ranges will be guided by:

- Prior PPE and inverse-modelling studies (Partridge et al., 2012; Regayre et al., 2014; Bhatti et al., 2025).
- Recent satellite-derived constraints on cloud phase, droplet number, and vertical structure.
- CleanCloud’s aerosol PPE experiments to ensure physical consistency across aerosol–cloud coupling.

Each simulation will cover one model year using AMIP configuration (prescribed SST and sea-ice), with ERA5-nudged dynamics for realism. Two simulation years will be targeted:

- **2010**, for comparability with previous PPEs (e.g., AEROCOM).
- **2025**, corresponding to the first full year of EarthCARE observations.

Post-processing will use Gaussian-process emulators to quantify sensitivities and constrain posterior parameter distributions. Emulator training will use the LHS ensemble to ensure statistically balanced

sampling and smooth surrogate performance. Fig. 2 Illustrates the workflow of the PPE–emulator approach used to quantify and constrain uncertainty in ERF.

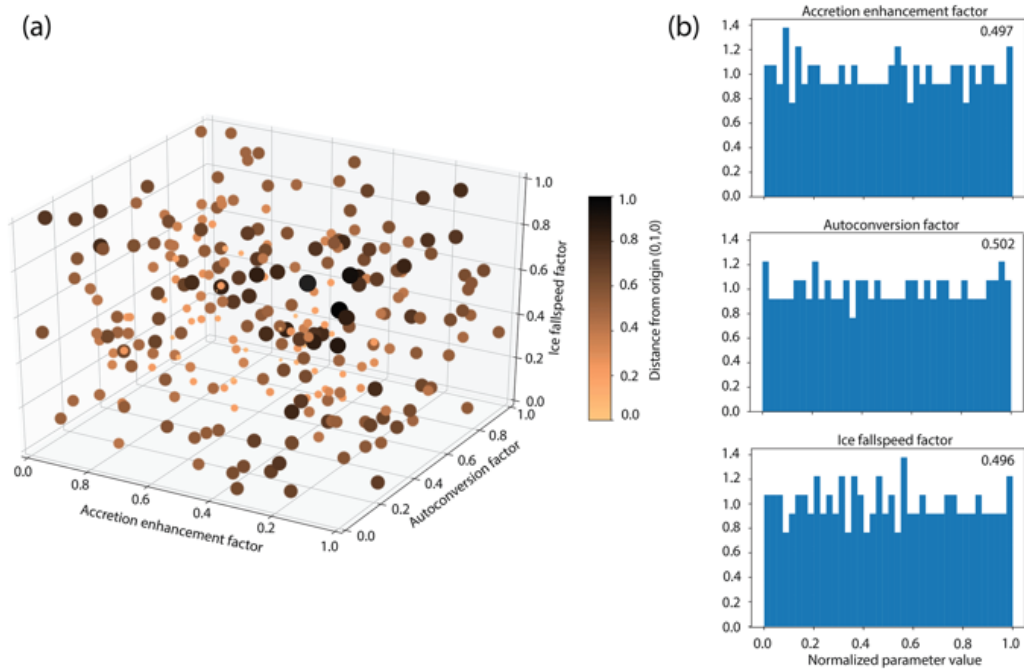


Figure 1: Illustration of the Latin Hypercube Sampling (LHS) design used to construct the perturbed parameter ensemble (adapted from Trude Eidhammer et al., 2025). Panel (a) shows an example of the normalized three-dimensional parameter space, including the accretion enhancement factor, autoconversion factor, and ice fall-speed factor for 263 ensemble members. The color and size of the symbols indicate the Euclidean distance from the origin (0, 1, 0), with darker and larger symbols appearing closer to the viewer. Panel (b) presents normalized histograms of the one-dimensional parameter marginals, with mean values reported in the upper-right corner of each plot, demonstrating the stratified and uniformly distributed nature of the LHS design.

Table 1: An example of the cloud parameters for the PPE in OpenIFS

Parameter name	Variable	Default Value	Process
Autoconversion threshold	RCLCRIT	4.00E-04	Microphysics
Aggregation threshold	RSNOWLIN1	1.00E-03	Microphysics
Fall speed of ice particles	RVICE	0.13	Microphysics
critical relative humidity at surface	ZRH2	0.5	Cloud Cover
critical relative humidity aloft	ZRH3	0.9	Cloud Cover
Entrainment rate for deep convection	ENTRORG	1.75E-03	Convection
Entrainment rate for mid/shallow convection	ENTSHALP	3.50E-03	Convection
Cloud heterogeneity	FSD	1	Cloud Optics
conversion rate from cloud water to rain in convective clouds	RPRCON	1.00E-04	Convection
Convective mass flux	PMFU	1	Convection
neutral Prandtl number	--	1	Turbulence

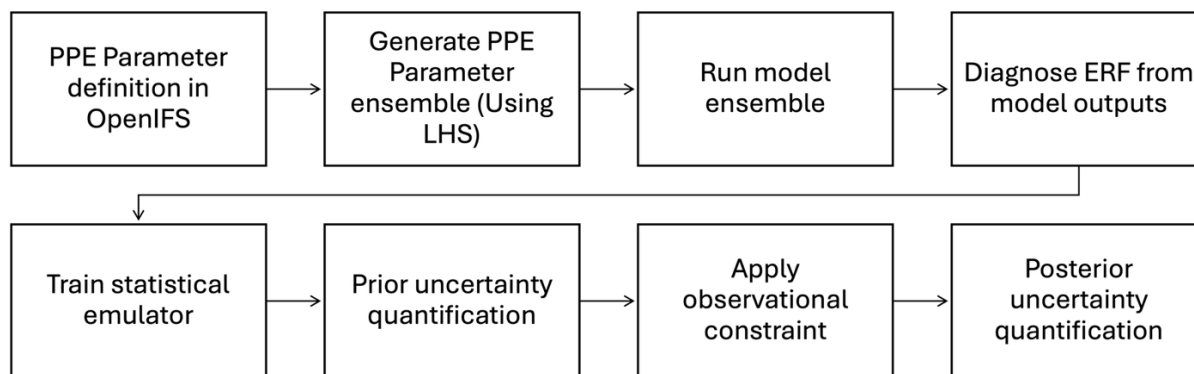


Figure 2: Schematic of the parameter perturbation ensemble (PPE) framework. A Latin hypercube-sampled ensemble of model simulations is used to diagnose ERF and train a statistical emulator. The emulator is then employed to quantify prior uncertainty and to apply observational constraints, yielding posterior uncertainty estimates.

Justification of Computer Resources

Resource	Estimate	Description
Simulations	150–200	1 model year each, AMIP mode
Runtime per simulation	2 days per node	Based on CleanCloud aerosol PPE benchmarks
Total compute	~25 million SBUs	Includes reruns and calibration
Data storage	~100 TB	3-hourly model output, diagnostics, emulator training

The use of **LHS** allows efficient ensemble design but still requires a sufficiently large number of simulations (≥ 150) to capture nonlinearities and parameter interactions over a high dimensional space. Smaller ensembles would under-sample the multidimensional parameter space, reducing the statistical robustness of inferred sensitivities. OpenIFS/AC CY48R1 runs efficiently on ECMWF’s HPC system. The CleanCloud aerosol PPE project provides validated runtime and I/O estimates, ensuring realistic resource planning.

Technical Implementation

- **Model configuration:** OpenIFS/AC CY48R1 (Huijnen et al., 2022), coupled with IFS cloud microphysics and aerosol activation parameterisations (Betancourt & Nenes, 2014).
- **Experimental setup:** AMIP SST/sea-ice forcing; ERA5-nudging; simulation years 2010 and 2025.
- **Parameter control:** Python-based perturbation manager generating LHS-designed parameter sets interfaced with EC-Earth namelists.
- **Analysis:** Gaussian Process (GP) emulator from Earth System Emulator package (ESEm; Watson-Parris et al., 2021).

All outputs will be archived on EC-Earth data nodes and analysed within the CleanCloud data management framework, ensuring reproducibility and integration with the aerosol PPE datasets.

Expected Outcomes and Impact

- Quantitative constraints on key cloud-process parameters in OpenIFS/AC.
- Improved representation of phase partitioning, autoconversion, and precipitation initiation.
- Reduced parametric uncertainty in cloud feedbacks and ERF.
- A harmonised aerosol–cloud PPE dataset supporting EC-Earth4 and CleanCloud synthesis.
- Enhanced predictive capability for future climate scenarios under reduced anthropogenic aerosol forcing.
- Provide input into the CMIP7 and the AR7 of the IPCC.
- Help develop the next generation of OpenIFS/AC planned for upcoming funded projects by the Horizon Europe Program (e.g., project realESM).

The project will deliver a robust, observation-constrained ensemble of cloud parameters that strengthens EC-Earth's cloud physics and advances the Horizon Europe CleanCloud programme's objective of reducing fundamental uncertainties in Earth system projections.

References

Betancourt, R.M. and Nenes, A. (2014). Droplet activation parameterization: the population-splitting concept revisited. *Geoscientific Model Development*, 7(5), 2345–2357. <https://doi.org/10.5194/gmd-7-2345-2014>

Bhatti, Y., Watson-Parris, D., Regayre, L., Jia, H., Neubauer, D., Im, U., Svenhag, C., Schutgens, N., Tsikerdekis, A., Nenes, A., Muhammed, I. et al. (2025). Uncertainty in aerosol effective radiative forcing from anthropogenic and natural aerosol parameters in ECHAM6. 3-HAM2. 3. *EGU sphere*, 2025, pp.1-35.

Collins, M., Booth, B.B.B., Bhaskaran, B. et al. (2011). Climate model errors, feedbacks and forcings: a comparison of perturbed physics and multi-model ensembles. *Climate Dynamics*, 36, 1737–1766. <https://doi.org/10.1007/s00382-010-0808-0>

Huijnen, V., Sager, P.L., Köhler, M.O., Carver, G., Rémy, S., Flemming, J., Chabrilat, S., Errera, Q., & Van Noije, T. (2022). OpenIFS/AC: atmospheric chemistry and aerosol in OpenIFS 43r3. *Geoscientific Model Development*, 15, 6221–6241. <https://doi.org/10.5194/gmd-15-6221-2022>

Korolev, A., and Jason, M. (2022). "How are mixed-phase clouds mixed?." *Geophysical Research Letters* 49.18.e2022GL099578.

Michibata, T., Wall, C. J., Hirota, N., Duran, B. M., & Nozawa, T. (2025). Recent Advances in the Observation and Modeling of Aerosol-Cloud Interactions, Cloud Feedbacks, and Earth's Energy Imbalance: A Review. *Current Pollution Reports*, 11(1), 50.

Partridge, D.G., Vrugt, J.A., Tunved, P., Ekman, A.M.L., Struthers, H., & Sorooshian, A. (2012). Inverse modelling of cloud–aerosol interactions – Part 2: Sensitivity tests on liquid phase clouds using a Markov chain Monte Carlo approach. *Atmospheric Chemistry and Physics*, 12, 2823–2847. <https://doi.org/10.5194/acp-12-2823-2012>

Regayre, L.A., Pringle, K.J., Booth, B.B.B., Lee, L.A., Mann, G.W., Browse, J., Woodhouse, M.T., Rap, A., Reddington, C.L., & Carslaw, K.S. (2014). Uncertainty in the magnitude of aerosol–cloud radiative forcing over recent decades. *Geophysical Research Letters*, 41, 9040–9049. <https://doi.org/10.1002/2014GL062029>

Yoshioka, M., Regayre, L.A., Pringle, K.J., Johnson, J.S., Mann, G.W., Partridge, D.G., et al. (2019). Ensembles of global climate model variants designed for the quantification and constraint of

uncertainty in aerosols and their radiative forcing. *Journal of Advances in Modeling Earth Systems*, 11, 3728–3754. <https://doi.org/10.1029/2019MS001628>

Watson-Parris, D., Williams, A., Deaconu, L., and Stier, P. (2021). Model calibration using ESEm v1.1.0 – an open, scalable Earth system emulator, *Geoscientific Model Development*, 14, 7659–7672, <https://doi.org/10.5194/gmd-14-7659-2021>, publisher: Copernicus GmbH, 2021.