

LATE REQUEST FOR A SPECIAL PROJECT 2026–2028

MEMBER STATE: Switzerland

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Project Title: Multi-Model Perturbed Parameter Ensemble (MMPPE) Simulations of
Aerosol–Cloud Interactions using EC-Earth for Observation-
Constrained Radiative Forcing Assessment

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

Aerosol-cloud interactions remain one of the largest sources of uncertainty in estimates of anthropogenic climate forcing and future climate projections (Collins et al., 2011; Regayre et al., 2014). Although substantial progress has been made in constraining structural uncertainty across climate models, parametric uncertainty associated with aerosol emissions, cloud microphysics, aerosol activation, convection, deposition, and optical processes remains poorly quantified. These uncertainties directly influence estimates of aerosol effective radiative forcing (ERF), cloud feedbacks, precipitation responses, and climate sensitivity.

To address this challenge, we propose a large Perturbed Parameter Ensemble (PPE) experiment using the EC-Earth Earth System Model within the framework of the international Multi-Model Perturbed Parameter Ensemble (MMPPE) initiative for aerosol-cloud interactions. The project contributes directly to ongoing AeroCom and CMIP7-era activities focused on reducing uncertainty in aerosol radiative forcing using coordinated multi-model ensembles constrained by observations from EarthCARE and PACE.

The proposed simulations will use the EC-Earth atmospheric configuration with nudged meteorology and prescribed sea-surface temperatures to systematically perturb aerosol- and cloud-related parameters controlling emissions, aerosol optical properties, hygroscopicity, wet and dry deposition, nucleation, aerosol activation, cloud microphysics, convection, turbulence, and cloud optical properties.

The MMPPE protocol is designed to jointly quantify two dominant uncertainty sources in climate simulations: structural uncertainty across Earth System Models and parametric uncertainty within individual models. Previous PPE studies have largely focused on aerosol-only processes (Yoshioka et al., 2019; Bhatti et al., 2025), while the present project extends the framework to fully coupled aerosol-cloud interactions within EC-Earth.

The simulations will target Present-Day (PD) year 2025 and Pre-Industrial (PI) year 1850 conditions. The year 2025 is selected to enable direct comparison with next-generation satellite observations from EarthCARE and PACE, while the 1850 baseline provides a CMIP7-compatible estimate of anthropogenic aerosol forcing.

The experimental setup follows the coordinated MMPPE protocol:

- Nudged atmospheric simulations using ERA5 reanalysis.
- Winds-only nudging with approximately 6-hour relaxation timescale.
- Prescribed SST and sea-ice conditions.
- One-year control spin-up followed by PPE integrations.
- Approximately 100 perturbed parameter members for each PI and PD configuration.
- Total ensemble size of approximately 200 simulations.

The PPE will perturb key aerosol and cloud parameters including anthropogenic and biomass-burning aerosol emissions, DMS and sea-salt emissions, aerosol optical properties, wet and dry deposition,

aerosol activation, cloud autoconversion and aggregation rates, convective entrainment parameters, and cloud optical inhomogeneity factors.

The ensemble design will employ Latin Hypercube Sampling (LHS) to efficiently explore the multidimensional parameter space while minimizing the number of simulations required for robust uncertainty quantification (Partridge et al., 2012). Statistical emulators and Bayesian inference techniques will subsequently be used to identify observationally constrained parameter combinations and quantify the contribution of individual processes to total ERF uncertainty.

The proposed work directly supports CleanCloud objectives on aerosol-cloud interactions, AeroCom aerosol forcing assessments, CMIP7 forcing protocol development, and next-generation EC-Earth model development. The scale of experimentation required for this PPE is only feasible using ECMWF's HPC infrastructure.

2. Objectives and Methodology

Objectives

The project has five primary scientific objectives:

1. Quantify parametric uncertainty in aerosol effective radiative forcing (ERF) within EC-Earth.
2. Identify the dominant aerosol and cloud parameters controlling uncertainty in aerosol-cloud interactions.
3. Evaluate EC-Earth aerosol and cloud responses against EarthCARE and PACE observations.
4. Constrain aerosol and cloud parameter ranges using statistical emulation and Bayesian inference.
5. Contribute a harmonized EC-Earth ensemble to the international aerosol-cloud MMPPE initiative.

Methodology

Two primary configurations will be performed:

Experiment	Year	Purpose
Present-Day (PD)	2025	Comparison with EarthCARE and PACE observations
Pre-Industrial (PI)	1850	Baseline forcing reference

Each simulation consists of a one-year control spin-up, a three-month PPE spin-up, and a 12-month production integration.

The simulations will use CMIP7-compatible forcing datasets, including CEDS anthropogenic emissions, GFED5.1 biomass-burning emissions, CMIP7 greenhouse gas and ozone forcing, and ERA5-based SST and sea-ice forcing. ERA5 reanalysis will also be used for meteorological nudging with winds-only relaxation.

Approximately 100 PPE members will be generated for each climate state (PI and PD), resulting in a total ensemble size near 200 simulations. The parameter perturbations focus on aerosol emissions, aerosol optical properties, hygroscopicity, deposition processes, aerosol activation, cloud microphysics, convection, cloud optical properties, and turbulence.

The PPE parameter combinations will be generated using Maximin Latin Hypercube Sampling (LHS), which provides statistically efficient and near-uniform sampling of high-dimensional parameter space (Collins et al., 2011; Yoshioka et al., 2019). Post-processing and uncertainty quantification will employ Gaussian-process emulators, Bayesian inference, and sensitivity analysis.

The resulting ensemble will be evaluated against EarthCARE, PACE, MODIS, and CERES observations to identify observationally constrained parameter combinations.

3. Justification of Computer Resources

Resource	Estimate	Description
PPE simulations	~200	PI and PD ensembles
Runtime per simulation	~1-2 days	EC-Earth atmosphere-only configuration
Total compute requirement	~35 million SBUs	Includes spin-up, reruns, diagnostics, and calibration
Total archive storage	~350 TB	High-frequency aerosol and cloud diagnostics

The large computational requirement arises from the need for approximately 200 ensemble integrations with high-frequency aerosol, cloud, and radiation diagnostics. The simulations will generate extensive three-dimensional aerosol and cloud fields required for aerosol forcing diagnostics, emulator training, and satellite simulator evaluation.

The MMPPE protocol requires sufficiently large ensembles to capture nonlinear aerosol-cloud interactions and parameter covariance structures. Smaller ensembles would significantly reduce statistical robustness and emulator fidelity.

Previous PPE experiments within CleanCloud and AeroCom demonstrate the feasibility of the requested resources and provide realistic estimates of runtime and storage requirements (Bhatti et al., 2025).

4. Technical Implementation

The simulations will use the EC-Earth atmospheric configuration with aerosol-cloud interaction capability and prescribed SST and sea-ice forcing.

The setup includes:

- EC-Earth atmosphere-only configuration.
- Aerosol-aware cloud microphysics.
- Aerosol activation parameterizations.
- ERA5-based nudging.
- CMIP7 forcing datasets.

The workflow consists of:

1. Parameter perturbation generation.
2. Latin Hypercube ensemble design.
3. Automated namelist generation.
4. Ensemble simulation execution.
5. Post-processing and diagnostics.

6. Emulator training.
7. Bayesian parameter constraint.
8. ERF estimation and uncertainty quantification.

Python-based workflow management tools will automate PPE generation, job submission, monitoring, and analysis. Statistical emulation will employ Gaussian-process emulators using the Earth System Emulator framework (Watson-Parris et al., 2021).

Simulation outputs will include aerosol optical properties, aerosol burdens, cloud microphysical properties, radiation diagnostics, and meteorological variables at both 3-hourly and monthly frequencies. Optional COSP diagnostics will also be produced where available.

5. Expected Outcomes and Impact

The project will deliver:

- A coordinated EC-Earth aerosol-cloud PPE ensemble.
- Quantitative constraints on aerosol and cloud process uncertainty.
- Improved understanding of aerosol effective radiative forcing.
- Observation-constrained parameter estimates.
- Reduced uncertainty in aerosol-cloud interactions.
- Improved EC-Earth parameterizations for future climate simulations.
- Harmonized datasets for AeroCom and CMIP7 analyses.
- The resulting dataset will constitute one of the largest aerosol-cloud PPE archives produced using EC-Earth and will directly support future climate model development and assessment activities.
- The project also contributes to international efforts aimed at reducing uncertainty in anthropogenic aerosol forcing, which remains one of the dominant uncertainties in climate projections (Regayre et al 2014).

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