

EMI R&D 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.....

Project Title: Perturbed Parameter Ensembles using the OpenIFS 48r1 atmospheric model in frame of the CleanCloud project ...
.....

Computer Project Account: SPDKULAS.....

Principal Investigator(s): Ulas Im.....
.....

Affiliation: Aarhus University, Department of Environmental Science

Name of ECMWF scientist(s) collaborating to the project (if applicable)
.....

Start date of the project: February 2025.....

Expected end date: December 2027.....

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)	70 000 000	69 771 000	70 000 000	59 257 722
Data storage capacity	(Gbytes)	100 000	30 000	200 000	40 000

Summary of project objectives (10 lines max)

About 370 (Completed) OpenIFS/AC c48r1 simulations using a perturbed parameter ensemble (PPE) framework for 1-year with 3 months spin-up. This will be used in a multi-model PPE comparison for OpenIFS (EC-Earth4) and ECHAM6-HAM2.3 analysis and publication. Results will quantify the model specific OpenIFS ERF uncertainty and the contribution of aerosol-related processes to this uncertainty.

Summary of problems encountered (10 lines max)

A previous bias was identified in spring 2026 in the earlier version of OpenIFS/AC related to the online calculation of dust and sea-salt emissions. In particular, the representation of vertical diffusion in the emission parameterisation leads to excessive emissions of both aerosol types. This results in an overestimation of the total aerosol burden in OpenIFS, which is most clearly reflected for the dust burden in comparisons of simulated aerosol optical depth (AOD) at 550 nm with satellite observations.

Furthermore, the implementation of the cloud activation scheme (Morales & Nenes, 2014) in OpenIFS applies an overly restrictive criterion for large-scale winds to enable aerosol activation. This leads to an underestimation of the aerosol–cloud interaction (ACI) contribution to the effective radiative forcing (ERF). As a consequence, the model exhibits a non-linear sensitivity of ACI responses to parameter perturbations, which must be considered when interpreting the older PPE results obtained with OpenIFS/AC.

These deficiencies have been corrected in later developments of OpenIFS this spring. These updates lead to improved agreement with observational products for our PPE analysis.

Summary of plans for the continuation of the project (10 lines max)

The continuation of the PPE work, including the exploration of additional perturbed parameters and post-processing of the simulation results, will utilize the remaining HPC resources allocated to this project for 2026 and 2027

List of publications/reports from the project with complete references

The research presented in this report, covering work conducted during 2025 and 2026, forms the basis of a manuscript currently in preparation for submission to a peer-reviewed scientific journal. The manuscript is tentatively titled “*Structural and Parametric Contributions to Aerosol Effective Radiative Forcing Uncertainty in a Two-Model Perturbed Parameter Ensemble.*”

Summary of results

The project produced two sets of 85 Perturbed Parameter Ensemble (PPE) simulations using OpenIFS/AC. Each ensemble member consists of one Present-Day (year 2010) simulation and one pre-industrial (PI: year 1850) simulation, which were used to calculate the Effective Radiative Forcing (ERF). In total, 340 simulations were performed.

The first set (170 simulations) was conducted in 2025 and partly 2026, before the model inconsistencies identified in Spring 2026, while the second set (170 simulations) was performed in

April 2026 following the implementation of the model updates. The ensemble size of 85 members was chosen to achieve an approximate ratio of six simulations per perturbed parameters seen in Table 1. This parameter selection was based on the discussions in CleanCloud project, and that has been published in early 2026 (Bhatti et al., 2026).

Table 1. List over the perturbed parameters in OpenIFS/AC with their respective PPE scaling factor for each parameter (*abs* = absolute value).

PPE Scales:	Parameter:
(abs 0.2 – 0.9)	BC im. ref. Index
(abs 0 – 0.01)	Dust im. ref. Index
(0.1 – 10)	Dry deposition Acc.
(0.01 – 10)	SO2 emissions
(0.5 – 2)	Dust emissions
(0.5 – 2)	SO2 reactions
(0.5 – 2.5)	Seasalt emissions
(abs 25 – 100 nm)	BB emission radii
(abs 15 – 45 nm)	FF emission radii
(0.5 – 2)	FF emissions
(0.25 – 4)	BB emissions
(0.33 – 3)	DMS emissions
(0.01 – 10)	Nucleation rate
(0.3 – 5)	SO4 coating
(0.5 – 2)	Wet dep. below-cloud
(0.75 – 1.25)	Wet dep. in-cloud

Additionally, we have used allocated SBU resources to train and run a Gaussian process emulator (Watson-Parris et al., 2021) for efficient exploration of parametric uncertainty for our perturbed-parameter ensemble simulations. The physical model simulations were used as the training ensemble, with the 85 OpenIFS/AC–HAM-M7 ensemble members and corresponding ECHAM-HAM ensemble output used to emulate aerosol and radiation diagnostics such as AOD550 and ERF.

Following the Earth System Emulator framework of Watson-Parris et al. (2021) shown in Figure 1, the trained Gaussian process emulators were then used to predict large synthetic ensembles of up to 1,000,000 parameter combinations, including one-at-a-time perturbation experiments for each of the 16 aerosol-related parameters following the methodology described by Bhatti et al. (2026). This allowed us to quantify parameter-driven uncertainty and model spread at a fraction of the computational cost of running the full climate model for each parameter combination.

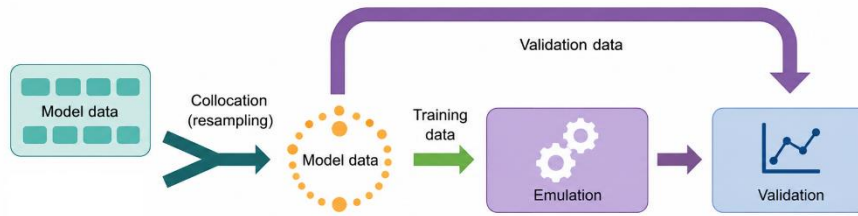


Figure 1. Workflow diagram of the ESM model data and PPE emulator. Illustration adapted from Watson-Paris et al. (2021).

Figure 2 shows the annual global aerosol optical depth (AOD) at 550 nm and its difference relative to MODIS satellite observations. The dust and sea-salt inconsistencies are clearly evident in the pre-update simulations, while the model updates result in substantially improved agreement with the observations.

Figures 3 and 4 present results from the earlier OpenIFS/AC simulations that were affected by the model bug, including the regional uncertainty contributions from the 16 perturbed parameters. The overestimation of AOD at 550 nm is again evident in Figure 3. Figure 4 illustrates the contribution of each perturbed parameter to the regional Effective Radiative Forcing (ERF). While dust is an important contributor to the uncertainty in several regions, it is not the dominant factor. These results will be repeated for the new simulations with the new model adjustments (April simulations).

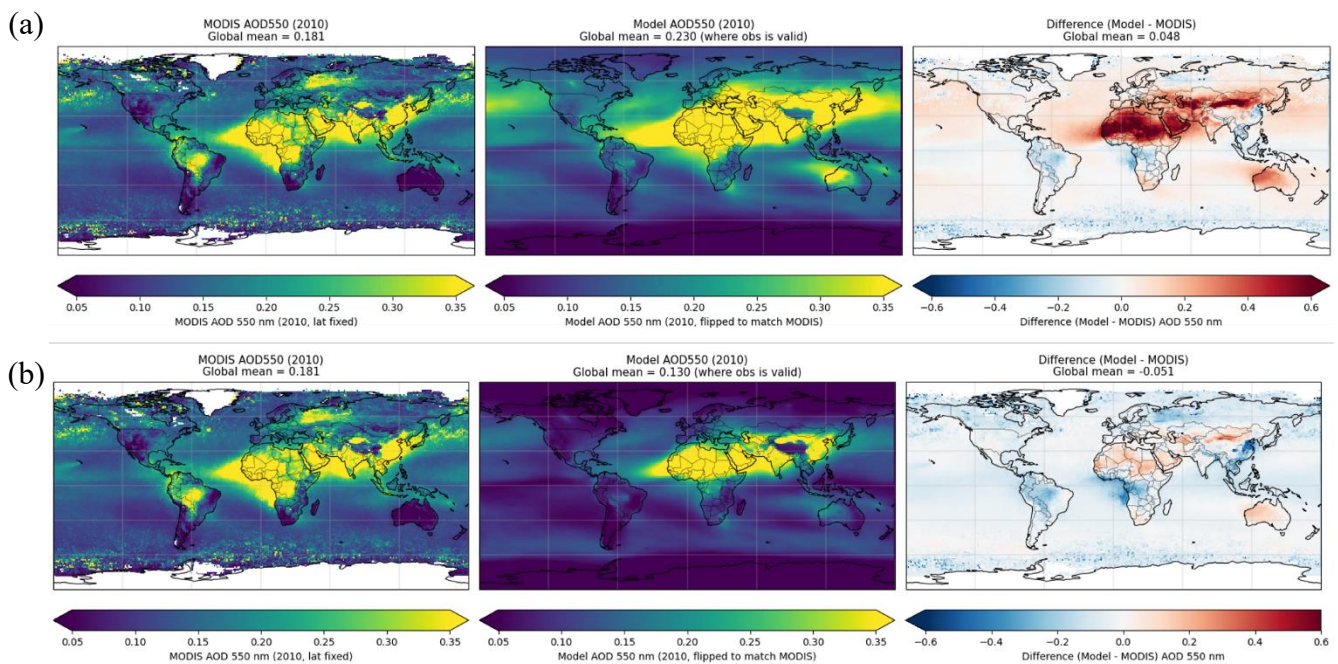


Figure 2. The annual mean OpenIFS/AC 550nm AOD from the control run versus Level 3 MODIS retrievals (a) before and (b) after the mentioned dust and sea-salt bugfix regarding the aerosol burden.

Regional mean uncertainty (30,000 members + POLDER + Control)

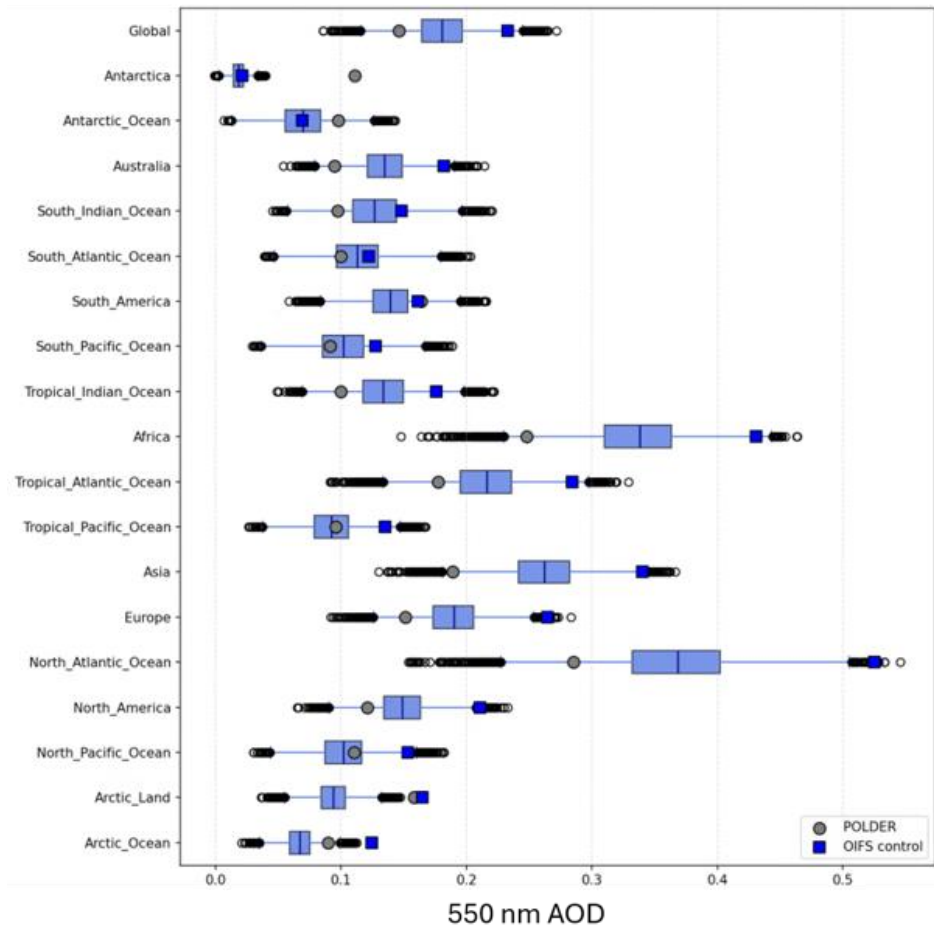


Figure 3. The regional mean of emulated PPE members simulations of OpenIFS/AC for 550 nm AOD over 2010.

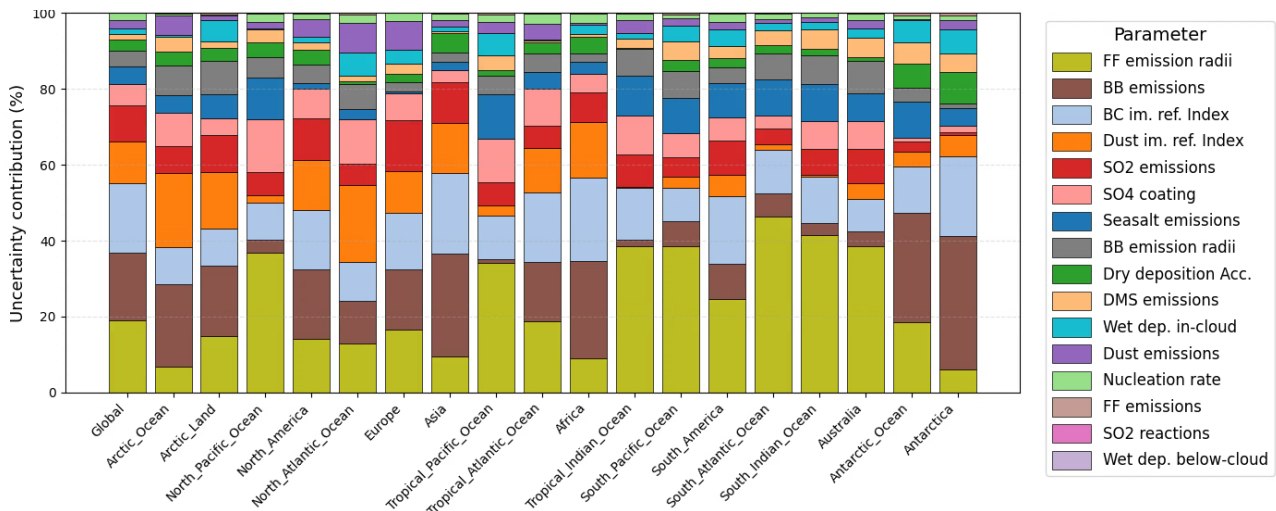


Figure 4. The regional annual mean uncertainty contribution to ERF from each parameter to the Effective Radiative Forcing (ERF) using Present Day – Pre-industrial simulations for OpenIFS/AC over 2010 based on 1 million members.