REQUEST FOR A SPECIAL PROJECT 2026–2028

MEMBER STATE: Denmark……………………………………………………………………………………

Principal Investigator[1]: Ulas Im…………………………………………………………………………………………

Affiliation: Aarhus University, Department of Environmental Science…………………

Address: Frederiksborgvej 399, 4000, Roskilde, Denmark………………………………

…………………………………………………………………………………………………

Other researchers: Carl Svenhag……………………………………………………………………………

…………………………………………………………………………………………………

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

…………………………………………………………………………………………………

…………………………………………………………………………………………………

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** DKULAS………….	
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 X☐

Computer resources required for project year:		**2026**	**2027**	**2028**
High Performance Computing Facility	[SBU]	25 000 000	25 000 000	
Accumulated data storage (total archive volume)[2]	[GB]	200 000	200 000	

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

[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.

Principal Investigator: Ulas Im……………………………………………………………………

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

Extended abstract

Aerosol-cloud interactions (ACI) remain the largest source of uncertainty in past, present, and future radiative forcing, impeding credible climate projections. ACI effects are expected to change dramatically as we enter a post-fossil world, characterized by strong reductions in anthropogenic aerosol emissions but with increasingly larger impacts from natural aerosols. Although we expect cleaner clouds compared to today, ACI in this post-fossil state may considerably differ from preindustrial conditions, owing to shifts in climate and changes in sources region characteristics. The Horizon Europe funded CleanCloud project (Grant Agreement 101137639) will address the major gaps impeding robust ACI assessments, improve their representation in current and next generation kilometer-scale climate models , quantify and understand their regional and temporal effects, and how they will evolve in the transition to the post-fossil regime. To accomplish this, CleanCloud will

1) carry out targeted field experiments in European climate hotspots;

2) develop state-of-the-art algorithms and analysis tools to obtain new proxies and diagnostics for key ACI-related processes;

3) contribute to the calibration and validation of upcoming satellite missions in coordination with the satellite community;

4) *improve and better constrain kilometer- and large-scale climate models using advanced machine learning, data assimilation and model calibration, confronting perturbed physics ensembles with existing and new satellite and in-situ data*;

5) assess the role of aerosols in the life cycle of convective systems, focusing on precipitation formation and the impacts on the hydrological cycle, and

6) enhance the exploitation of data centres, measurement programs, international campaigns, laboratory studies, and models.

With these, CleanCloud will profoundly strengthen European Research on climate change, significantly contribute to upcoming climate assessments, and benefit society through models that enable improved weather and seasonal predictions. CleanCloud runs from January 2024 to January 2027, and is coordinated by Dr. Im, who is also the PI for this special project.

In order to constrain the uncertain processes in Earth system models (ESMs), and to reduce the uncertainties in climate projections, it is important to integrate observations from multiple sources with models. CleanCloud will follow the perturbed parameters ensemble (PPE) approach (Collins et al., 2011: Johnson et al., 2018; Yoshika et al., 2019: Figure 1) to constrain the improved CleanCloud target models, including EC-Earth4. The PPE approach involves perturbing the values of uncertain parameters within a single model structure, with the choice and range for the perturbed parameters determined. In some cases, different variants of physical schemes may also be switched in and out as well as parameters in those alternative schemes being varied. Any number of experiments that are routinely performed with single models can then be produced in "ensemble mode" subject to constraints on computer time.

The key strength of the PPE approach is the ability to produce a large numbers of ensemble members in a relatively easy way. It is possible to control the experimentation and systematically explore uncertainties in processes and feedbacks. For example, it is possible to produce a set of ensemble experiments where the input forcing data (e.g. in a twentieth century simulation) is the same in each experiment, but the parameters which control, say, the aerosol-cloud interactions, are varied. Thus, the different sources of uncertainty can be isolated. It is also possible to explore a wide range of feedback processes in the model by "de-tuning" it, potentially revealing the impact of previous compensating errors.

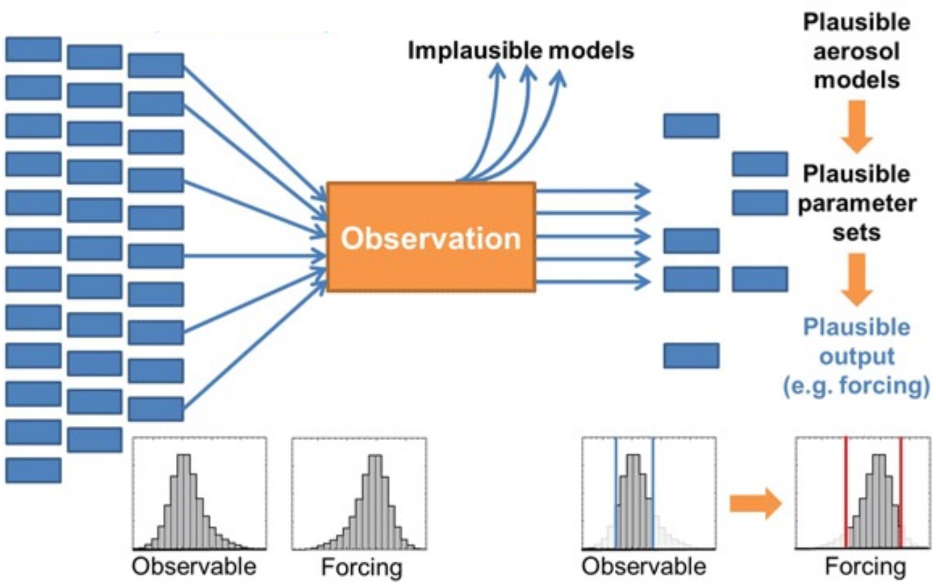

Figure 1. PPE flow chats adopted from Johnson et al. (2018).

The uncertain parameter space in CleanCloud will be constrained by new and/or improved satellite observations, of aerosol properties (e.g. CCN, size distribution, absorption, water fraction), cloud properties (e.g. droplet number concentrations, cloud phase), and precipitation from EarthCARE, METOP-SG, and PACE (Figure 2 & 3). For this, we will use existing instrument simulators that will be adapted for new observations where needed. We will also perform PPEs for selected sub-domains and periods over selected convective systems using the improved climate models, focusing on key microphysical parameters including updraft variance, secondary ice production, and liquid and solid precipitation initiation. PPEs are particularly suited for constraining model process parameters (Regayre et al., 2014). CleanCloud uses PPEs as data assimilation, which does not create optimal initial conditions as done in traditional data assimilation (e.g. 4DVAR, ensemble Kalman filter/smoother), focusing more on optimizing concentrations/properties or emissions, but obtains an optimal constraint on model parameterizations, revealing their strengths, limitations, and best configuration, which are much more important to constrain for climate predictions than initial conditions. We will apply Bayesian inference to constrain scheme parameters and model structure using cloud and precipitation observations rigorously and systematically (Partridge et al., 2012).

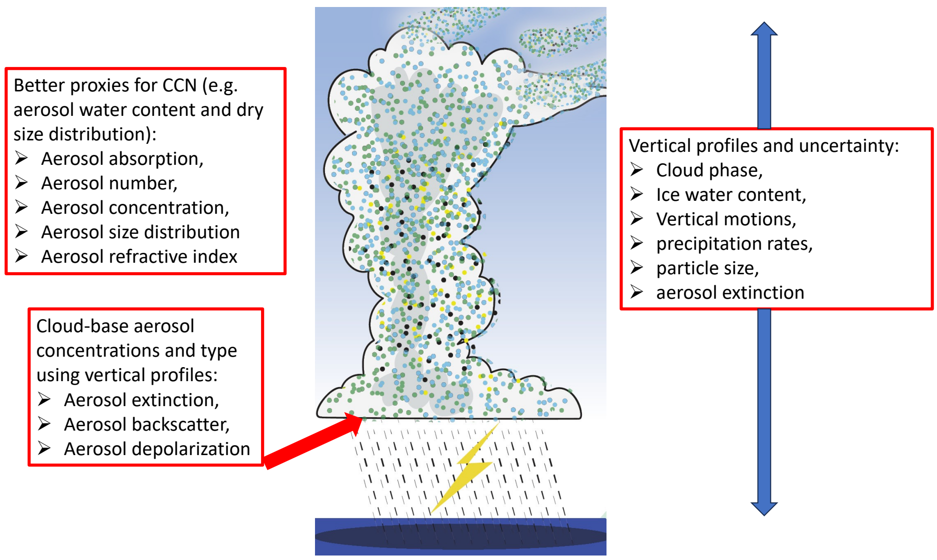

Figure 2. The parameters of interest for the PPE design.

In this special project, we will use the OpenIFS/AC cycle CY48R1, which is part of the EC-Earth4 Earth system model (ESM), to perform PPE simulations, focusing on aerosols. We will perturb more than 20 parameters including emissions of individual aerosols and precursors (e.g. black carbon, sulfate, dust, and sea-salt), size distribution, wet and dry removal, etc. (Figure 3).

OpenIFS/AC cycle CY48R1 is ECMWF's global numerical weather prediction model accessible to research institutes and universities. The OpenIFS/AC version incorporates new modules for atmospheric composition (AC) based on the CB05, CB05-BASCOE, and AER tropospheric chemistry scheme with OpenIFS dynamics. Details on OpenIFS/AC (version CY43R3) of this model is described in Huijnen et al. (2022), including runtime, pre- and post-processing scripts. The model requires the ecCodes GRIB library from ECMWF for input and output. The model uses input from the CAMS reanalysis input dataset of GRIB files and emissions from a set of various established CMIP6 standardized emissions inventories. Further OpenIFS CY48R1 documentation and can be found at: https://confluence.ecmwf.int/display/OIFS/Release+notes+for+OpenIFS+48r1#ReleasenotesforOpenIFS48r1-ModelDocumentation.

The first phase of the PPE simulations will focus on the year 2010, where previous PPEs are available from other models, such as in the AEROCOM PPEs. The second phase will focus on the year 2025, which will be the first complete EarthCARE year, providing additional constraints on aerosols and clouds, including their vertical distributions and types. Both phases will consist of two sets of simulations, one set for the pre-industrial (PI) period (1850), and one set for the actual “present day” period, which is either 2010 or 2025 depending on the phase. The PI simulations are necessary to estimate the effective radiative forcing, which is aimed to be constrained by the PPE. The first phase simulations for the PI are being setup and will start in 2025. We will perform AMIP-type simulations, where sea surface temperatures and sea-ice concentrations are prescribed, and winds are nudged towards ERA5 reanalyses.

We estimate around 200 simulations. Assuming 2 days per a year simulation on one node, 200 simulations amount to 21 000 000 SBUs. We therefore ask for 25 000 000 SBUs/year to be on the safe side, such as additional parameters that can come in later in the ensemble design or repeating some simulations due to technical reasons. We estimate 600 Gb space per year per simulation. Therefore, for 200 simulations we need a lot of space and therefore ask for 200 000 GB/year disk space. We will transfer all the outputs to local servers to keep the space as empty as possible.

1. **Control**

2. SCALE_EMI_DMS *(SCALE: 0.33 -> 3)*
3. SCALE_EMI_FF (SCALE: 0.5 -> 2)
4. SCALE_EMI_ANTH_SO2 *(SCALE: 0.6->1.5)*
5. SCALE_EMI_DUST (SCALE : 0.5 -> 2)
6. SCALE_EMI_SSA (SCALE 0.5 -> 2.5)
7. SCALE_EMI_BB (SCALE: 0.25 -> 4)
8. SCALE_EMI_BF (SCALE: 0.25 -> 4)
   - Scale the emissions

9. EMI_CMR_BF(30) (ABS: 25-> 100nm)
10. EMI_CMR_FF(30) (ABS: 15 -> 45 nm)
11. EMI_CMR_BB(75) (ABS: 25 – 100nm)
    - Scale the emission count median radius. The default radius is in brackets.

12. BC_RAD_NI(0.71) (ABS 0.2 -> 0.9)
13. DU_RAD_NI(0.001) (ABS 0 -> 0.01)
    - Scale the imaginary refractive index for BC and DUST.
14. SO2_CHEMISTRY (SCALE: 0.5 -> 2)
    - Scaling all sulfate chemical reactions, including aqueous-phase (e.g. SO2 + OH, DMS + OH)

15. NUC_FT (SCALE: 0.01 -> 10)
16. CDNC_Min(40) (1 -> 40)
    - Scaling the CDNC min fixed.
17. Vertical updraft: (SCALE: 0.5 -> 2)
18. WETDEP_IC (SCALE 0.75-> 1.25)
19. WETDEP_BC (SCALE 0.5 -> 2)
    - In-cloud (ic), below-cloud (BC)

20. DRYDEP_ACC (SCALE: 0.1->10)
21. DRYDEP_COA (SCALE: 0.15 -> 5)
22. DRYDEP_AIT (SCALE: 0.2 -> 2)

23. SO4_COATING (ABS 0.3 – 5 monolayers)
24. CLOUD_PH (ABS pH of: 4.5 -> 7)
    - Baseline cloud water pH

25. Kappa SS (ABS: 0.5 -> 1.2)
26. Kappa SO4 (ABS 0.4 -> 0.8)

Figure 3. Example of PPE parameters from the ECHAM-HAM model in the CleanCloud project.

After the PPE simulations are completed, we will use the Gaussian Process (GP) emulator from Earth System Emulator package (ESEm; Watson-Parris et al., 2021). GP is a powerful non-parametric tool often used to emulate climate models to provide robust uncertainty estimates, particularly with limited training data (Eidhammer et al., 2024; Yoshioka et al., 2019). We will use this emulator to statistically represent over 1 million model outputs across the 20-dimensional parameter space, all bounded by their minimum and maximum limits. ESEm will produce annual mean data for each model grid cell (when comparing to observations, only taking into account co-located data in space and time). These samples allow a sensitivity analysis to quantify the variance of each component (Lee et al., 2011).

References

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

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

Eidhammer, T., Gettelman, A., Thayer-Calder, K.,Watson-Parris, D., Elsaesser, G., Morrison, H., van Lier-Walqui, M., Song, C., and McCoy, D.: An extensible perturbed parameter ensemble for the Community Atmosphere Model version 6, Geoscientific Model Development, 17, 7835–7853, https://doi.org/10.5194/gmd-17-7835-2024, publisher: Copernicus GmbH, 2024.

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

Lee, L. A., Carslaw, K. S., Pringle, K. J., Mann, G. W., and Spracklen, D. V.: Emulation of a complex global aerosol model to quantify sensitivity to uncertain parameters, Atmospheric Chemistry and Physics, 11, 12 253–12 273, https://doi.org/10.5194/acp-11-12253-2011, publisher: Copernicus GmbH, 2011.

Partridge, D. G., Vrugt, J. A., Tunved, P., Ekman, A. M. L., Struthers, H., and Sorooshian, A.: Inverse modelling of cloud-aerosol interactions – Part 2: Sensitivity tests on liquid phase clouds using a Markov chain Monte Carlo based simulation approach, Atmos. Chem. Phys., 12, 2823–2847, https://doi.org/10.5194/acp-12-2823-2012, 2012.

Regayre, L. A., K. J. Pringle, B. B. B. Booth, L. A. Lee, G. W. Mann, J. Browse, M. T. Woodhouse, A. Rap, C. L. Reddington, and K. S. Carslaw (2014), Uncertainty in the magnitude of aerosol-cloud radiative forcing over recent decades, Geophys. Res. Lett., 41, 9040–9049, doi:10.1002/2014GL062029.

Watson-Parris, D.,Williams, A., Deaconu, L., and Stier, P.: 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.

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