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:	**EC-EARTH4: developing a next-generation European Earth System model based on ECMWF modelling systems**
Computer Project Account:	SPNLTUNE………………………………………………
Principal Investigator(s):	Shuting Yang …………………………………………
Affiliation:	Danish Meteorological Institute Lyngbyvej 100, DK-2100 Copenhagen Denmark ………………………………………………
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Start date of the project:	01/01/2025 …………………………………………
Expected end date:	31/12/2027 …………………………………………

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)	90,750,000	25,496,150	90,000,000	60,663,292

Data storage capacity	(Gbytes)	72,900		152,400	

Summary of project objectives (10 lines max)

The project aims at supporting the development of configurations of the next generation of the EC-Earth global Earth-system model: EC-Earth4, based on OpenIFS and NEMO4. In particular the project will allow model experiments to be used in the tuning process, including AMIP runs aimed at determining model sensitivity to parameter changes, validation and testing of the model following the integration of new component cycles, experiments aimed at testing new parameterizations and new configurations and long coupled equilibrium experiments at intermediate resolution to assess model biases and to tune ocean parameters. Experiments with different model resolutions and different component configurations are planned. The activity will include the implementation of a continuous testing, tuning and software validation framework.

Summary of problems encountered (10 lines max)

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

Long coupled tuning and validation with the full Earth system model version of EC-Earth4 will be continued. The main tuning efforts will be put on reducing the prominent biases in present-day climatology, such as the cold biases on high latitude continents and warm biases in the southern ocean, while keeping the net radiative budget at the top of the atmosphere in balance. The tuned model will be finalized in the autumn 2026, meanwhile, the long spin-up simulation will continue adaptively with the progress of the tuning. We plan to start the pre-industrial control simulation for CMIP7 later in 2026 and other CMIP7 DECK and ScenarioMIP experiments in the beginning of 2027.

List of publications/reports from the project with complete references

No new publications. But a number of manuscripts that are either solely or partly based on the tuning results performed under this project are under preparation. The manuscripts include: (1) The EC-Earth4 Earth system model for CMIP7: Description and evaluation; (2) Tuning of EC-Earth4; (3) EC-Earth4-FAST - A configuration for multi-century climate simulations.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

During this report period, we have continued to develop, test and tune the EC-Earth4 model intensively. To increase the computational efficiency for long climate simulations, the fully coupled model is adapted and tested in single precision mode. A new atmospheric composition and aerosol module, the HAM-M7, has been implemented into the OpenIFS in EC-Earth4 for a better aerosol-cloud interaction description. The code is debugged and tested extensively, and simulations in both double and single precision were compared and validated. Other Earth system components such as the dynamical vegetation model (LPJ-GUESS), the dynamical ice sheet model for Greenland ice sheet, and a fresh water emulator for Antarctic ice sheet melt, have been coupled in the EC-Earth4. The tuning efforts have been focused on the radiative balance at the top of the atmosphere and sensitivity of the ocean component to parameters defending various physical processes. A long spin-up of the fully coupled model is ongoing in order for the coupled model system to reach an equilibrium state. Tuning of the low-resolution (Tl159L91 and eORCA1) configuration EC-Earth4-LR were also carried out as preparation for paleo-climate studies.

Implementation and testing of the HAM-M7 aerosol module in EC-Earth4

We have continued our efforts to implement a modal aerosol module based on the Hamburg Aerosol Model (HAM) version 2.3 (Tegen et al., 2019), which is built around the microphysical core M7 (Vignati et al., 2004). Moreover, the HAM-M7 code has been combined with a new aerosol activation scheme based on the parameterization from Morales Betancourt and Nenes (2014, hereafter as MBN scheme), which provides an alternative to the Abdul-Razzak and Ghan (2000, here after as ARG scheme) activation scheme included in HAM. A number of issues were found and solved in the code interfacing the HAM-M7 module and MBN activation scheme with OpenIFS. This included a revision of the treatment of a number of cloud and precipitation variables, following their definitions in HAM. Furthermore, we have corrected the conditions for which activation is called in the MBN case. In an earlier implementation, when the large-scale vertical velocity was negative the activation was not called and a default value for the cloud droplet number concentration was assumed. In the revised code, this has been replaced by a test on the total vertical velocity, hence accounting for the effects of subgrid-scale fluctuations. This correction substantially reduced the differences with the ARG configuration and improved the comparison against CERES radiative flux estimates from satellite observations, resulting in a better global energy balance. As part of the HAM-M7 development work, the aerosol simulation has been evaluated against a range of observations data sets, including in-situ observations of surface concentrations as well as ground-based and satellite remote sensing observations of aerosol optical properties.

In addition, we have tested the computational and physical performance of the model in single precision. Initial testing with the original HAM-M7 code produced substantial divergences between single and double precision. For instance, in atmosphere-only (AMIP) mode, the net TOA flux averaged over 2001–2021 dropped from 1.1 W/m^2 in double precision to -3.3 W/m^2 in single precision. After careful revision of the code, these differences have been strongly reduced (see Figure 1).

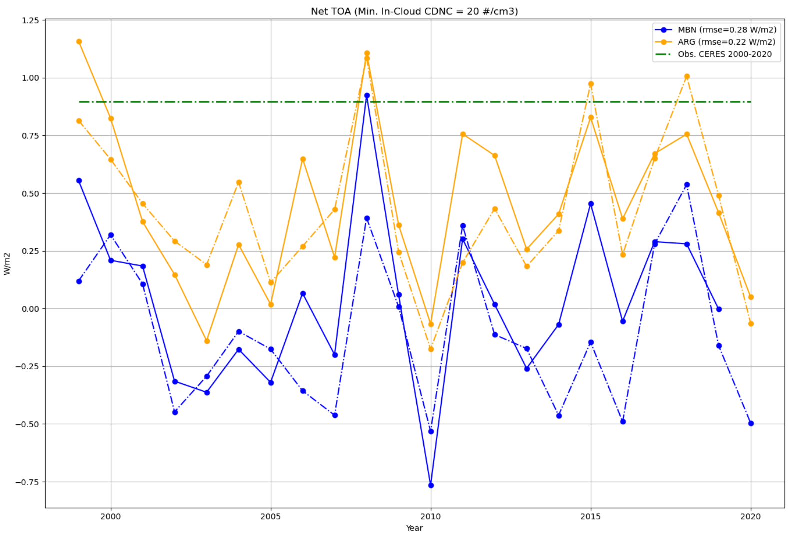


Figure 1. Time series of the global and annual mean net TOA radiative flux in AMIP simulations for the MBN (in blue) and the ARG (in orange) activation scheme, comparing results in double (solid) and single (dashed) precision. In these simulations, the minimum in-cloud droplet number concentration, which in fact is a tuning parameter of the model, was set to 20 cm^{-3}.

Initial results based on an analysis of 10 years of model output from atmosphere-only simulations indicate no clear statistically significant differences between single and double precision, except for some localized regions. As an example, Fig. 2 shows the difference maps for the net TOA flux.

Further analysis is needed to assess to what extent the remaining differences are truly random. The new aerosol module is considered ready to be used for climate change simulations of the CMIP7 Assessment Fast

Track. Meanwhile, the consortium has started efforts to retune the climate of the EC-Earth4 model with the new aerosol module, both in atmosphere-only and coupled configurations. This is work in progress.

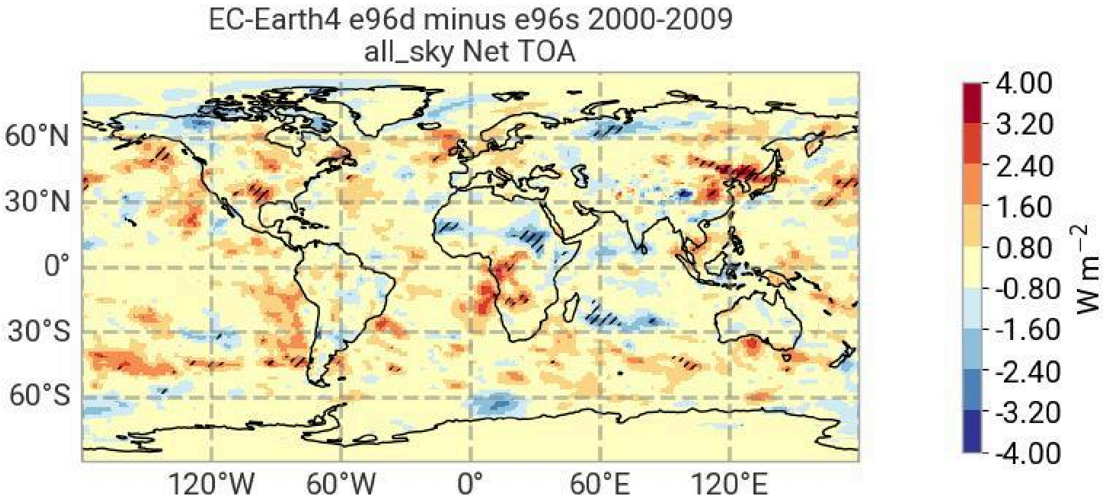


Figure 2. Map of the mean difference in the 2000–2009 mean net TOA radiative flux between double and single precision, obtained in atmosphere-only simulations with the MBN activation scheme. The hashed areas indicate the regions where the differences are statistically significant at the 5% level.

Atmospheric tuning

While implementing and testing the new HAM-M7 aerosol scheme on the OpenIFS in EC-Earth4, a new set of atmospheric simulations were carried out with EC-Earth4 release 4.1.5 (where MACv2-SP is activated by default) to examine the model responses to the CMIP7 forcing. Sensitivities of global fluxes to tuning atmospheric parameter changes have been computed with CMIP7 and 2012 fixed forcing (Figure 3). The diagnostic tool ECmean4 reference was updated in terms of observation reference period. The series of AMIP run with one parameter changed at a time and use now as sensitivity base is the k*** series. This allows improved automatic tuning of the model using the ECtuner tool.

ECtuner has been further developed in recent months and tested with spatially extended tuning (tuning the bias maps pixel-by-pixel, not only global means) are progressing.

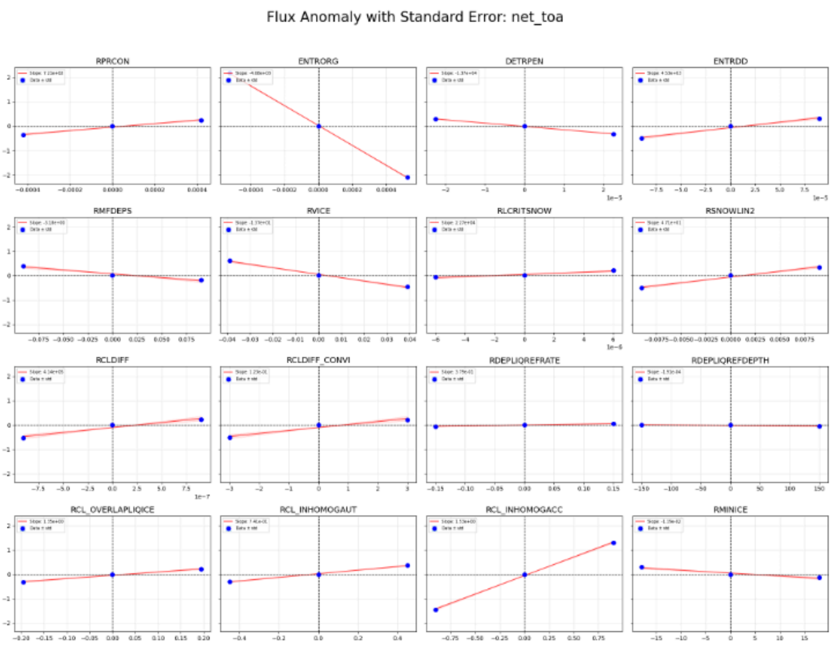
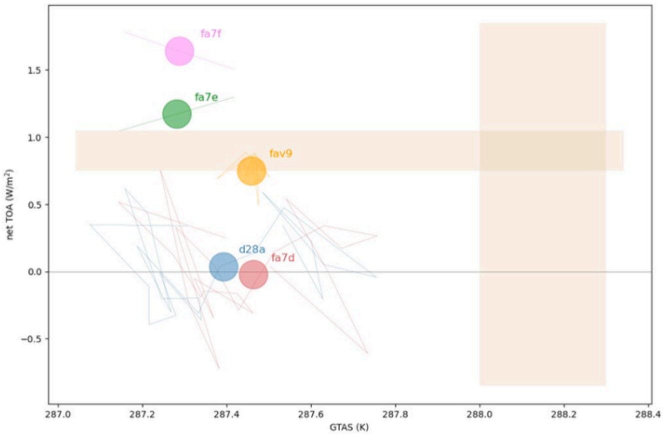


Figure 3. Atmospheric tuning parameters impact on global net top of the atmosphere (TOA) radiation.

The tuning effort continued in parallel with the development of new versions of the model to take account of the new modules that had been activated and the changes made with each release.



- fav9 (orange): tuning version v0.3 (no M7)
- d28a (blue): tuning version v0.3 + parameter RMINCDNC =30
- fa7d (pink): tuned s0d3 ù8sensitivity run for RMINCDNC)
- fa7e (green), fa7f (purple): re-tuning of fa7d

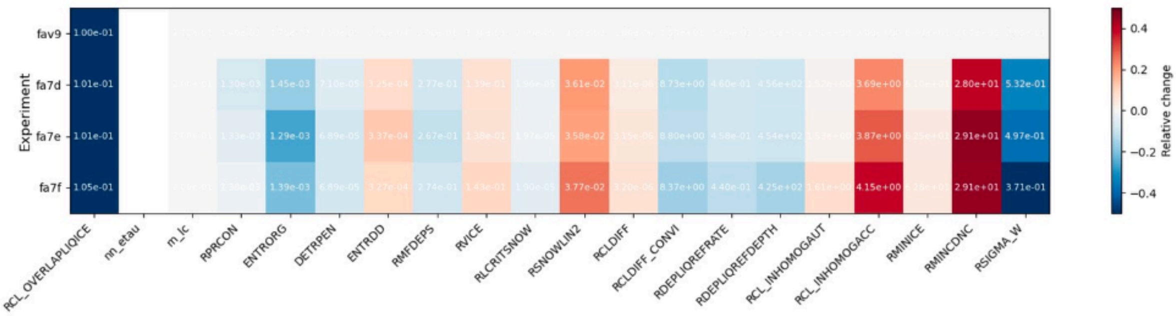


Figure 4. Top: Gregory plot comparing the latest AMIP tuning simulations carried out using version 4.1.7. The shaded bars show the observational reference. Bottom: A heat map showing how the tuning parameters considered for atmospheric tuning vary relative to the IFS reference across the different simulation set-ups.

Figure 4a shows the Gregory plot comparing the latest AMIP tuning simulations for the M7 version in DP. Figure 4b plots the corresponding diagnostics of these simulations obtained using the AQUA tool for the selected experiment. Experiment fa7e was selected as the best among the various experiments.

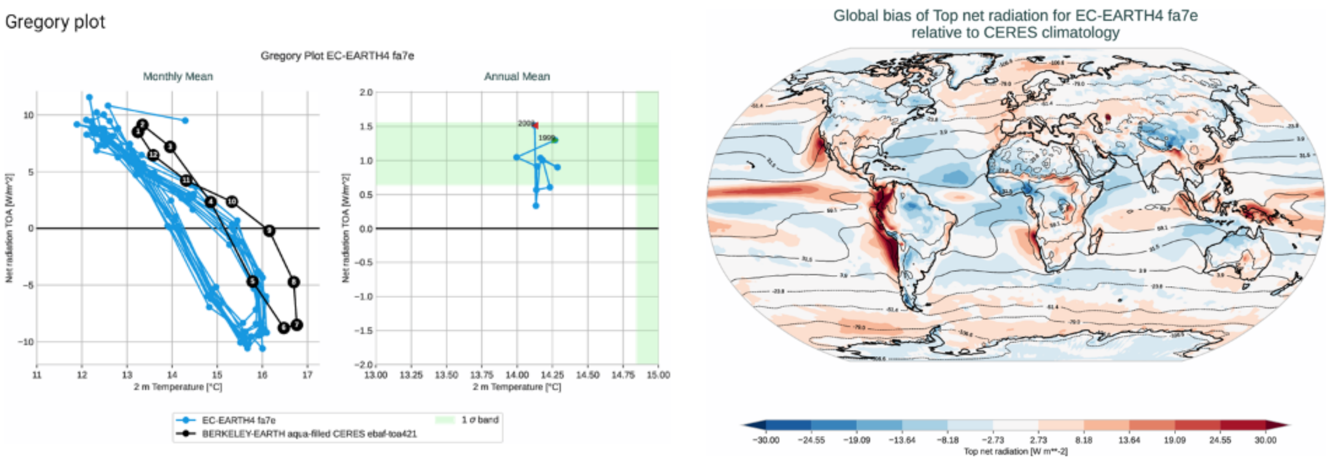


Figure 5. **Left**: the Gregory plot of EC-EARTH4 fa7e using as a reference (green shading) the BERKELEY-EARTH aqua-filled (2 m temperature) and CERES ebaf-toa421 (net TOA). The model data are averaged from 1999-01-01 to 2008-01-01. The reference 2 m temperature data are from 2001-01-01 to 2024-12-01. The reference net TOA data are from 2001-01-01 to 2024-12-01. **Right:** the spatial map of bias of top net radiation from 1999-01-16 to 2008-12-16 for the EC-EARTH4 model, experiment fa7e, with respect to CERES from 2001-01-01 to 2024-12-31 used as reference data.

Figure 5 shows the Gregory plot comparing the results with the observational reference: given that the Berkeley temperature reference tends to be warmer than ERA5, this looks rather good. The map also shows the biases in net radiation at the top of the atmosphere, from which one can still see the improvement in the Southern Ocean bias thanks both to previous and more recent tuning efforts.

NEMO Sensitivity Test

In parallel to the tuning exercises, a set of sensitivity experiments was performed with the NEMO standalone model in EC-Earth4 at eORCA1L75 resolution, the same grid used in the coupled configuration, to assess the model response to different namelist parameter settings. The sea ice model was active, while land ice was not included. These tests cover key physical processes such as vertical mixing, lateral diffusion, mixed layer eddies, tidal mixing, solar penetration, and bottom drag, and were repeated as the model evolved. The final goal is to gain knowledge that can support the coupled tuning exercise for EC-Earth4.

The table below summarizes the sensitivity ensemble members (fcXX), grouped by the physical process area being tested.

Process Area	fcXX Range	Notes / Description
Vertical physics	fc01–fc09	Eddy viscosity/diffusivity, closure & convection
TKE vertical diffusion	fc10–fc29	TKE eddy coef, dissipation, mixing length, etc.
Tidal mixing	fc30–fc31	Mixing efficiency & T/S differential
Fox-Kemper (MLE)	fc40–fc41	Mixed layer eddy parametrization
Lateral diffusion (tracer)	fc50–fc53	EIV scale & direction of diffusion
Lateral diffusion (momentum)	fc60–fc63	Eddy viscosity coefficient & viscous velocity
Solar radiation penetration	fc70–fc71	Depth of extinction
Top/bottom drag	fc80–fc81	Top/bottom drag: linear, logarithmic, etc.

As this sensitivity study is still an ongoing and evolving work, we report here only a selection of results as illustrative examples, which will guide the choice of ocean namelist parameters for the final tuning and setup of EC-Earth4.

Figure 6 shows experiments with varying eddy viscosity and diffusivity coefficients alone (fc01–fc04) has negligible impact, with members overlapping the default. In contrast, changing the vertical closure scheme to GLS (fc05) and modifying the convection scheme (fc07) produces a clear divergence in AMOC and Labrador Sea MLD, indicating that the choice of closure/convection scheme is far more influential than coefficient tuning within the default scheme.

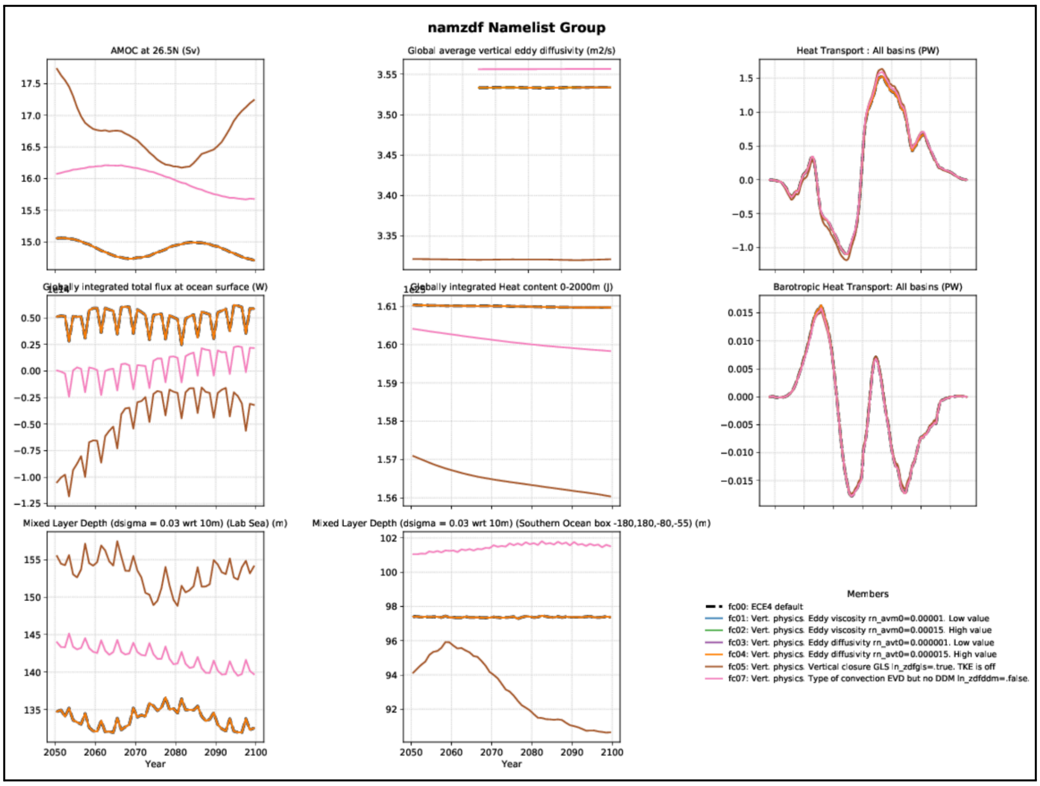


Figure 6: Namelist namzdf for Vertical physics (fc01–fc05, fc07).

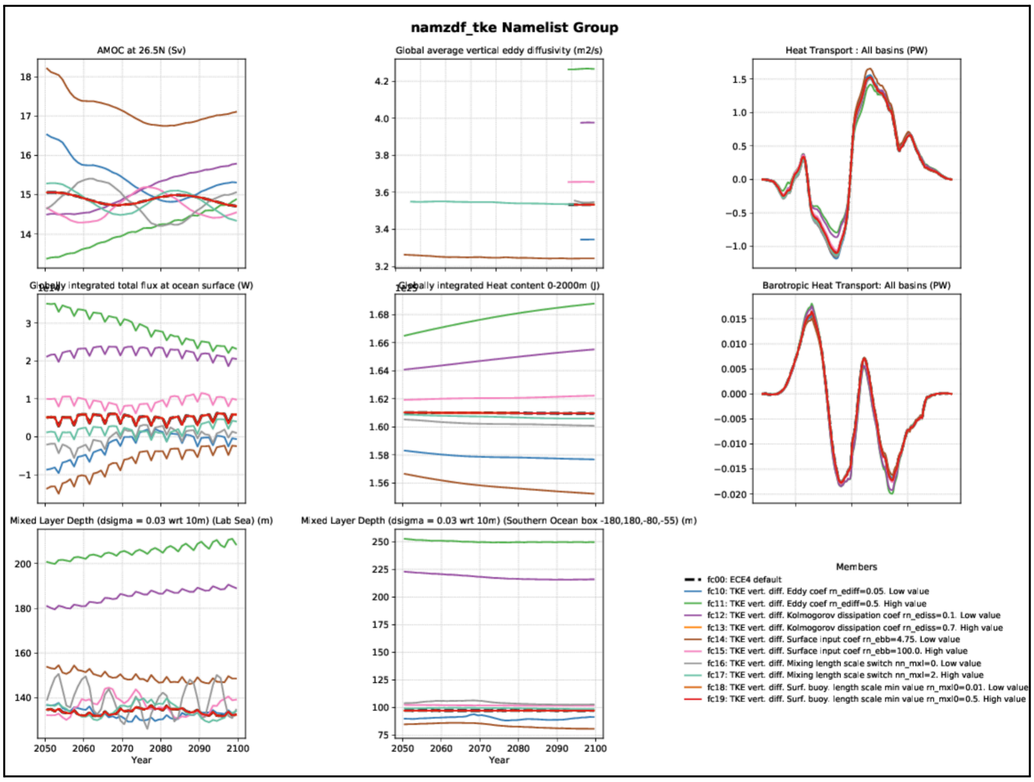


Figure 7. Namelist namzdf_tke for TKE vertical diffusion (fc10–fc19).

Figure 7 shows experiments testing the namelist group with the broadest ensemble spread, with AMOC ranging from about 14 to 18 Sv depending on parameter choice. Eddy diffusion coefficient (fc10/fc11) and surface input coefficient (fc14/fc15) settings show the largest effect on Labrador Sea and Southern Ocean MLD, confirming TKE parameters as a primary lever for deep mixing and AMOC strength.

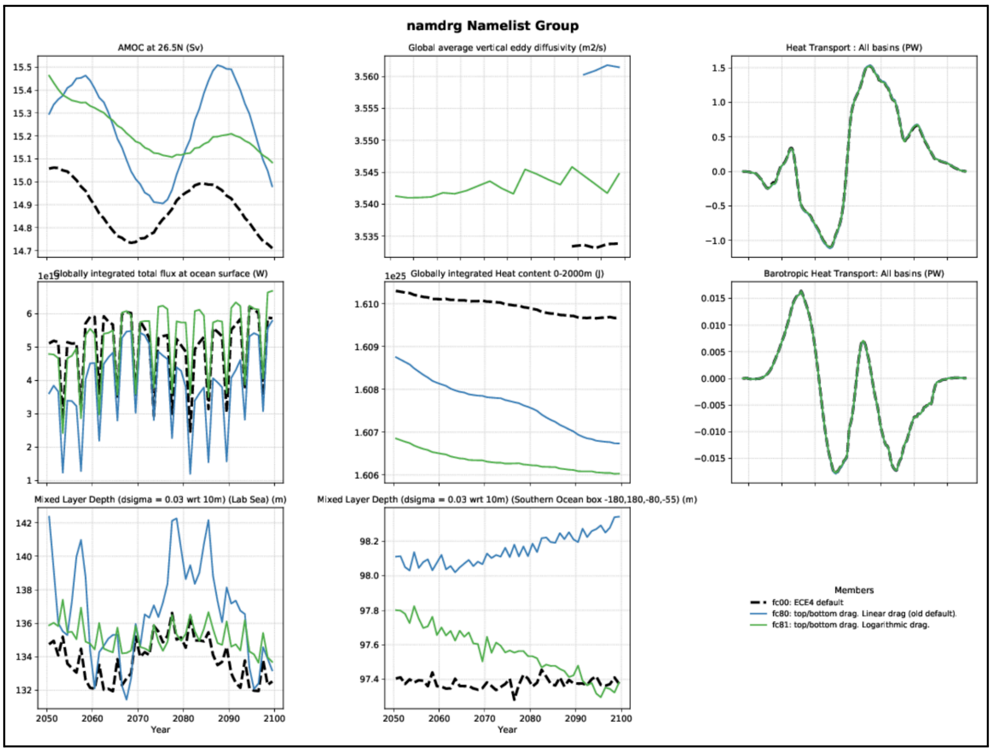


Figure 8: Namelist namdrg for Top/bottom drag (fc80–fc81)

Figure 8 shows experiments switching from linear (fc80) to logarithmic (fc81) bottom drag. This switch produces a clear and opposite-signed response in Southern Ocean MLD relative to the default, while AMOC shows a more transient difference that converges by the end of the period. This indicates bottom drag formulation mainly affects regional mixing rather than basin-scale overturning in the long run.

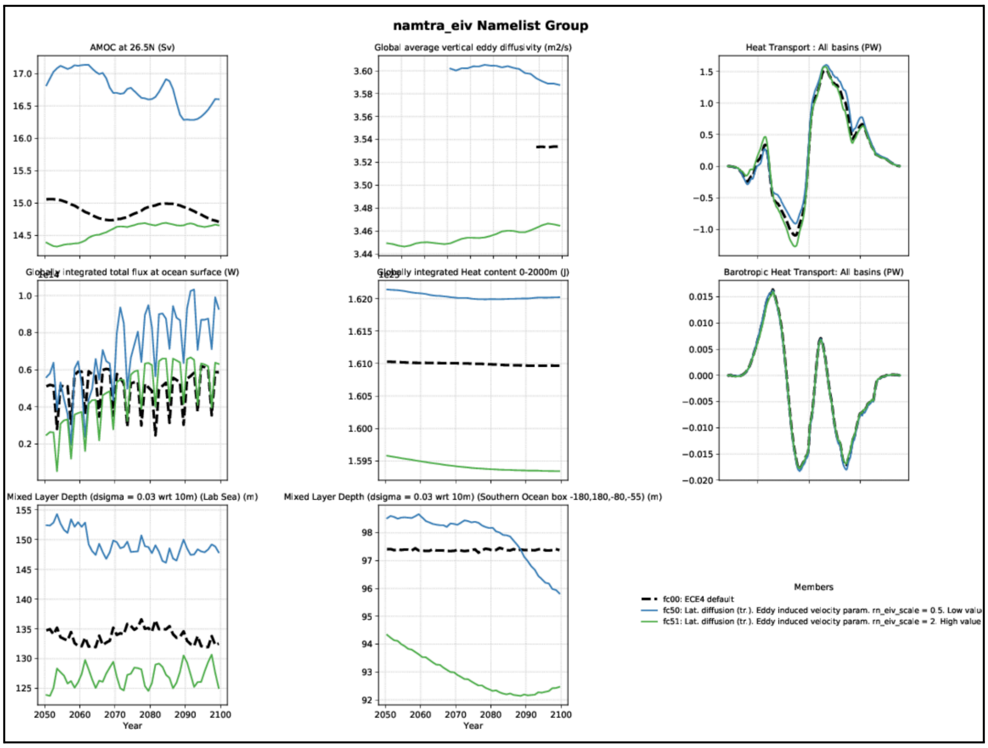


Figure 9. namelist namtra_eiv for Lateral diffusion, tracer (fc50–fc51).

Figure 9 shows experiments testing the eddy-induced velocity scale. It shows a clean, monotonic response: a low value (fc50) increases AMOC and global heat content relative to default, while a high value (fc51) decreases them, with Southern Ocean MLD diverging strongly between the two over time.

Further sensitivity tests using the same set of namelist parameters are currently being carried out in coupled mode, and results from this ongoing work will be reported in due course. It should be noted that spin-up simulations were performed for all the experiments presented here, as well as for the coupled runs, although these are not included in this report. Also, extra diagnostics are being developed to further analyse these results.

Spin-up with EC-Earth4

We have performed a continuous experiment with EC-Earth4 in coupled mode where the model simulation is restarted with each new released version. We started the simulation from a climatology of ocean observations (World Ocean Atlas 2013) and ERA5 conditions in 1990-01-01. Solar forcing and atmospheric composition is kept at pre-industrial level (i.e., at fixed year 1850 conditions) throughout the simulation. The first part of the simulation was run on the "Freja" HPC in Sweden. We then synced the restart files to ECMWF Atos and ran 3 experiments. The first experiment is a continuation of the pre-industrial control experiment but upgrading the model version from release 4.1.5 to 4.1.7 which means activating the wave model, ecWAM, the stratospheric aerosols from CMIP7, and coupling to the vegetation model LPJ-Guess. The second and third experiments are abrupt-4xCO2 (quadrouping of CO2 concentrations) and 1pctCO2 (increasing CO2 concentration by 1%/year), both run for 150 years (Figure 10).

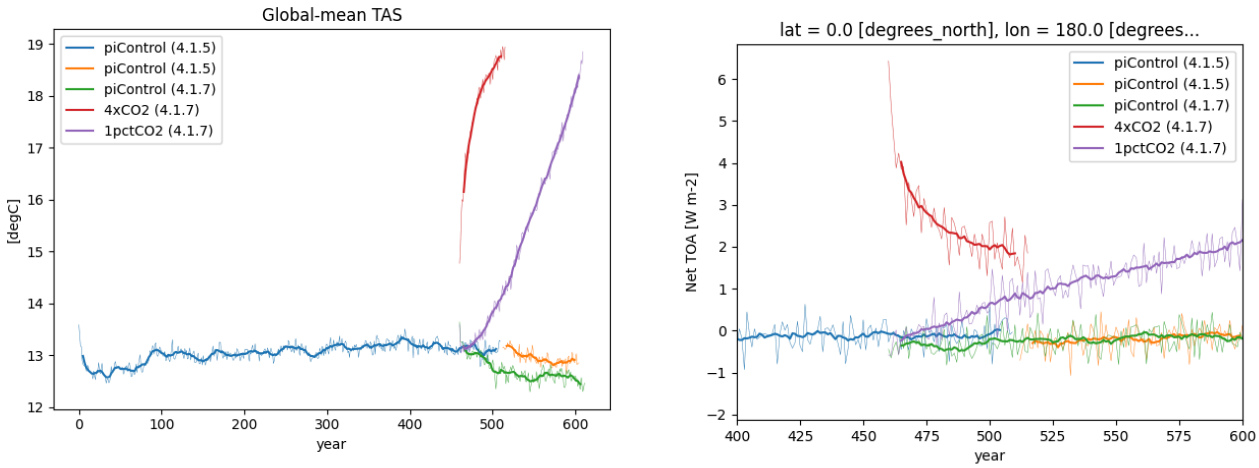


Fig 10: Global-mean 2m air temperature (TAS, left) and net top-of-atmosphere (TOA) radiative balance (right) in EC-Earth4 experiments on "Freja" HPC (v4.1.5) and ECMWF Atos (v4.1.7).

The continued experiment on ECMWF Atos (piControl v4.1.7, green line) shows a cooling of the surface climate compared to the parent experiment despite having approximately the same TOA balance near 0 W/m2. The cooling was found to most occur over the Northern Hemisphere and most over Eurasia, likely due to the vegetation model, LPJ-Guess. We suspect that the cold bias over Siberia in EC-Earth4 becomes amplified when coupling with LPJ-Guess as it drives changes in vegetation and surface albedo. We are currently continuing the experiment with the latest release of EC-Earth4, 4.1.8, and are exploring way to mitigate the cold bias.

EC-Earth4-LR tuning progress

We performed 33 sensitivity experiments for the coupled EC-Earth4-LR configuration. In these experiments, selected tuning parameters were perturbed by approximately 30% around reference values. The simulated responses of key climate metrics were used to calculate the sensitivity coefficients for EC-Tuner. These coefficients were then used to derive new parameter combinations for the following coupled tuning experiments.

The latest experiments show clear progress, with the global mean and Northern Hemisphere 2 m air temperatures moving closer to the Berkeley Earth observations. The remaining biases are mainly associated with the Southern Hemisphere, where the model is still systematically too warm (Figure 11). The next tuning experiments will focus on reducing this regional warm bias while retaining the improvements achieved in the global mean and Northern Hemisphere climate.

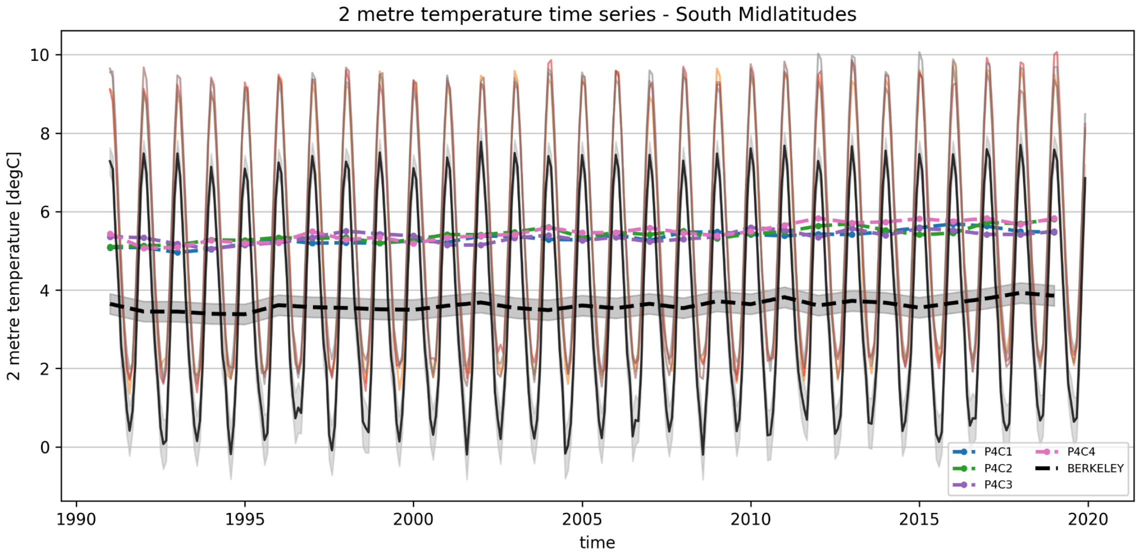


Figure 11. Time series of 2 m temperature in the Southern Hemisphere mid-latitudes.

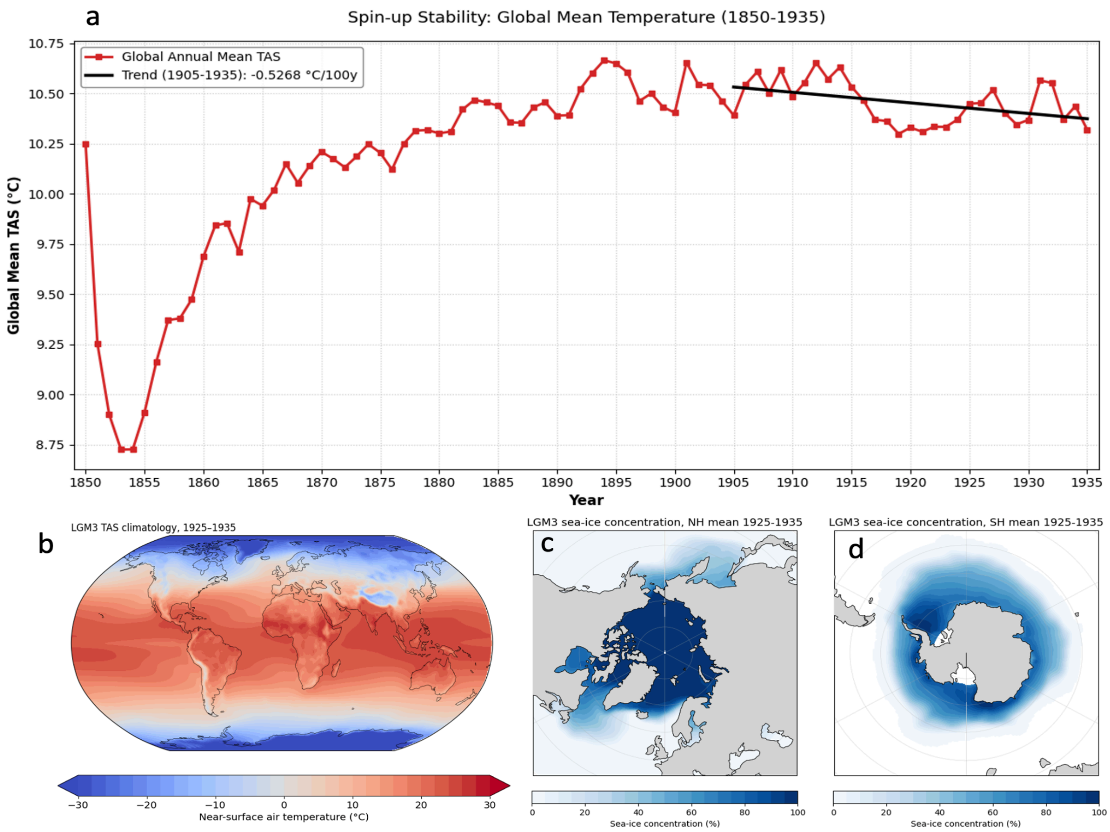


Figure 12. Results from the EC-Earth4-LR LGM-forced test experiment. (a) Global mean near-surface air temperature during the spin-up. (b) Global near-surface air temperature climatology from EC-Earth4-LR. (c) Northern Hemisphere sea-ice. (d) Southern Hemisphere sea-ice concentration.

We also performed an LGM-forced test experiment with EC-Earth4-LR using LGM boundary conditions while retaining the present-day land–sea mask and ice-sheet configuration. The simulation was initialized from a CESM LGM state. The model remained numerically stable throughout the integration without experiencing the crashes that frequently occurred in EC-Earth3 under comparable cold climate forcing (Figure 12). This represents a positive development for EC-Earth4-LR, demonstrating that the model can now be integrated under LGM-like forcing and providing a basis for further cold climate experiments.