SPECIAL 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	2025
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
Name of ECMWF scientist(s) collaborating to the project (if appliable)	- Jost von Hardenberg (jost.hardenberg@polito.it) - Klaus Wyser (Klaus.Wyser@smhi.se) - Twan van Noije (noije@knmi.nl) - Pablo Ortega (pablo.ortega@bsc.es - Andrea Alessandri (a.alessandri@isac.cnr.it) - Lars Nieradzik (lars.nieradzik@nateko.lu.se) - Raffaele Bernardello (raffaele.bernardello@bsc.es) - Valentina Sicardi (vsicardi@bsc.es) - Qiong Zhang (qiong.zhang@natgeo.su.se) - Sager le, Philippe (philippe.le.sager@knmi.nl) - Paolo Davini (p.davini@isac.cnr.it) - Etienne Tourigny (etienne.tourigny@bsc.es)
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)	-	-	91,000,000	25,496,150
Data storage capacity	(Gbytes)	-	-	72,900	

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)

EC-Earth4 is slower on HPC2020 than on other HPCs such as "Freja" at NSC in Sweden. We note that EC-Earth4 is faster than EC-Earth3 when OpenIFS 48r1 runs in single precision. The cause for slower execution of EC-Earth4 on HPC2020 compared to some other HPCs is not yet clear, but is under investigation and mitigation measures (such as systematically running with single precision) are being investigated.

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

Long coupled tuning and validation runs are planned with the next ESM version of EC-Earth4 to be released in July 2025. The main working resolution will be TL255 in the atmosphere and eORCA1 in the ocean. In general the aim is to arrive at the end of 2025 with a tuned version of the model which can be used for CMIP7 Fast Track experiments.

List of publications/reports from the project with complete references

No new publications not already cited in the 2022-2024 report.

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.

Status of EC-Earth4

During the period covered by this report, EC-Earth 4 has been intensively developed with a couple of releases in March 2025 and the next one coming within days (July 2025). From the long list of features and improvements, it is worth mentioning the switch from OpenIFS-43r3 to OpenIFS-48r1 (in collaboration with ECMWF OpenIFS team), with fixes for long experiments, output handled by XIOS-3 and the possibility to run this atmospheric component in double or mixed precision. A low resolution configuration is being developed (see below). Very important for climate long integration, we have added varying orbital forcing and Leaf Area Indices, CMIP6 and CMIP7 greenhouse gases and Ozone, and in the next release the CMIP7 stratospheric aerosols along the M7 aerosols scheme for a better aerosol-cloud interaction description.
On the ocean side, support for biochemistry and inert tracers has been added to NEMO. Internal wave mixing has been switched on by default. On the monitoring side, ECmean (to compute climate performance indices, https://ecmean4.readthedocs.io) was incorporated into the workflow and monitoring results can now be pushed to pages in our GitLab instance.

EC-Earth4 FAST configuration

A very low resolution version of EC-Earth4 is being developed running at TL63L3-ORCA2L31 resolution for both present-day and paleoclimatic study. Such configuration aims at coarse but efficient simulation of the Earth's climate, achieving with 256 cores more than 150 SYPD with less than 20 CHPSY. Such highly efficient configuration has been then further developed to target simulations from the DeepMIP protocol for paleo goals. To this goal, the PALEORCA grid (Sepulchre et al. 2019) has been adopted in order to perform Early Eocene simulations based on the boundary conditions from Herold et al. (2013). This requires a complete change of bathymetry and topography. The configuration is technically running although further work is required to achieve a complete setup.

Sensitivity Study of NEMO4.2.2 for EC-Earth4

The study evaluates the sensitivity of the NEMO4.2.2 ocean model in the context of EC-Earth4 development. It investigates model performance under various physical configurations, parameter settings, and atmospheric forcings, with a focus on understanding the impacts on key oceanic features, including the Atlantic Meridional Overturning Circulation (AMOC), sea surface temperature and salinity (SST and SSS), Mixed level Depth (MLD), and sea ice. All experiments began from a 372-year spin-up forced with ERA5, ensuring a well-equilibrated ocean state. The actual sensitivity phase was repeated six times between 1958 and 2019, testing two atmospheric reanalyses (ERA5 and JRA55 v1.5) and weak and standard SSS restoration methods. A common feature across the suite was the use of SSS restoring coefficients tuned to prevent unrealistic weakening of the AMOC, and the disabling of turbulent kinetic energy penetration below the mixed layer to avoid collapse of Labrador-Sea convection.

Core comparison: NEMO 4.2.1 versus 4.2.2

All the tests done indicate that upgrading from version 4.2.1 to 4.2.2 results in only marginal adjustments in AMOC strength and MLD. At the same time, the older code is systematically saltier at the surface when benchmarked against EN4 observations. Crucially, the chosen SSS-restoring strategy stabilises the overturning circulation throughout the 300-year sensitivity window in both versions. The atmospheric forcing choice matters more than the code revision: JRA55 produces a markedly smaller global sea-surface-temperature bias than ERA5, particularly in ice-covered regions.

Five experiments probed individual namelist choices:

Test Case	**Modification**	**Purpose/Impact**
TKE-NoWav	Disabled wave breaking (nn_etau = 1)	It affects SST and MLD, discarding surface wave effects.
ADV-FCT4	Higher-order advective schemes (nn_fct_h = 2)	Minor performance impact, future tests with MUSCL suggested
EC3-TKE	Lower viscosity/diffusivity values	Improves thermocline structure, especially in the equatorial Pacific
MIN-VISC	Enhanced Arctic ice growth	Using higher rn_cnd_s for Arctic ice calibration
SNOW-CND	Variation of sea ice thermodynamics	Based on literature recommendations (Lecomte et al., Döscher et al.)

Preliminary results

The strength of the AMOC at 26°N in two of the five sensitivity experiments remains consistent with estimates from the RAPID array, suggesting partial success in capturing large-scale ocean circulation (see Fig. 1). These results indicate that, among the tested parameters, the primary influence appears to be on the mixed layer depth (MLD). At the same time, the thermocline structure exerts a more dominant control on AMOC variability. However, given the complexity of the system and the limited number of test cases, additional sensitivity experiments are needed before finalising parameter choices for the EC-Earth4 configuration.

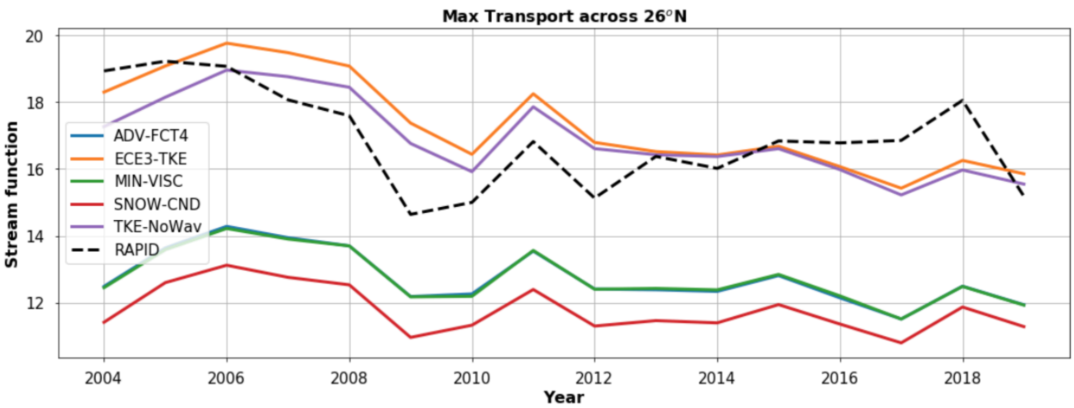

Figure 1. Time evolution of the Atlantic Meridional Overturning Circulation (AMOC) strength at 26° N in the five sensitivity experiments, compared with RAPID-array estimates black dashes.

Regarding sea surface temperature (SST), model outputs were evaluated against EN4 and HadSST observational datasets (Fig. 2). All tested configurations successfully reproduce the SST trend observed in the HadSST dataset, suggesting that the model reasonably captures the long-term surface warming signal well. However, compared to EN4, referred to as “obs” in the figure below (black line), none of the tested parameter settings fully allow the model to match the observed absolute temperature values. This mismatch suggests that, while the model can reproduce trends, structural biases in the vertical stratification or air-sea flux formulation may still affect its ability to reproduce observed SST levels accurately. Further refinement and possibly targeted tuning of surface fluxes and ocean mixing parameters may be needed to reduce this discrepancy.

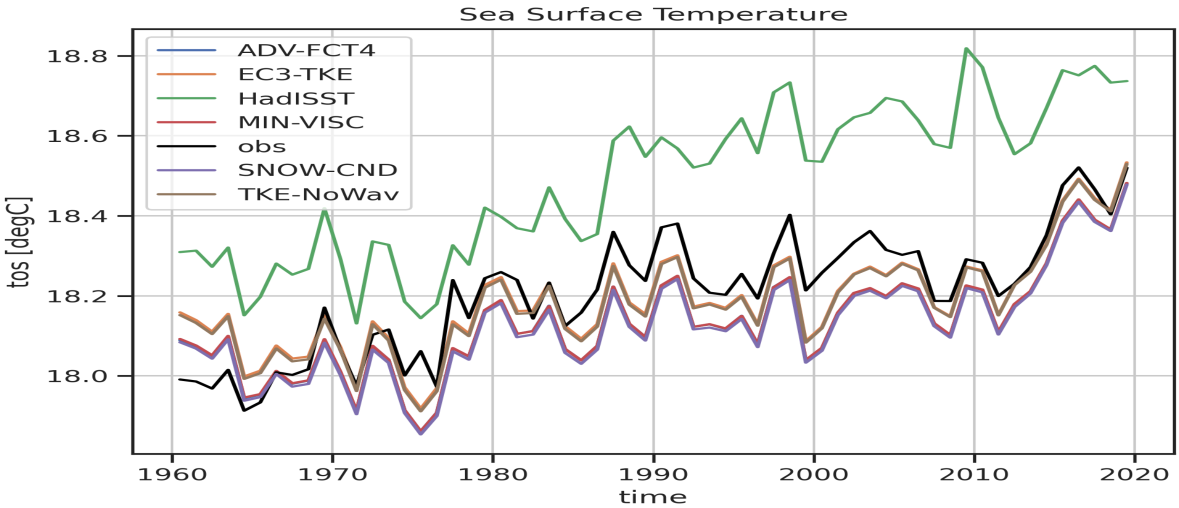

Figure 2. Annual-mean global SST bias relative to (a) HadSST (green) and (b) EN4 (black) for each sensitivity test (1958–2019).

In the case of surface salinity (Fig. 3, none of the experiments has been able to reproduce the observation, represented as EN4, in black. None of the tested parameters directly affects the salinity.

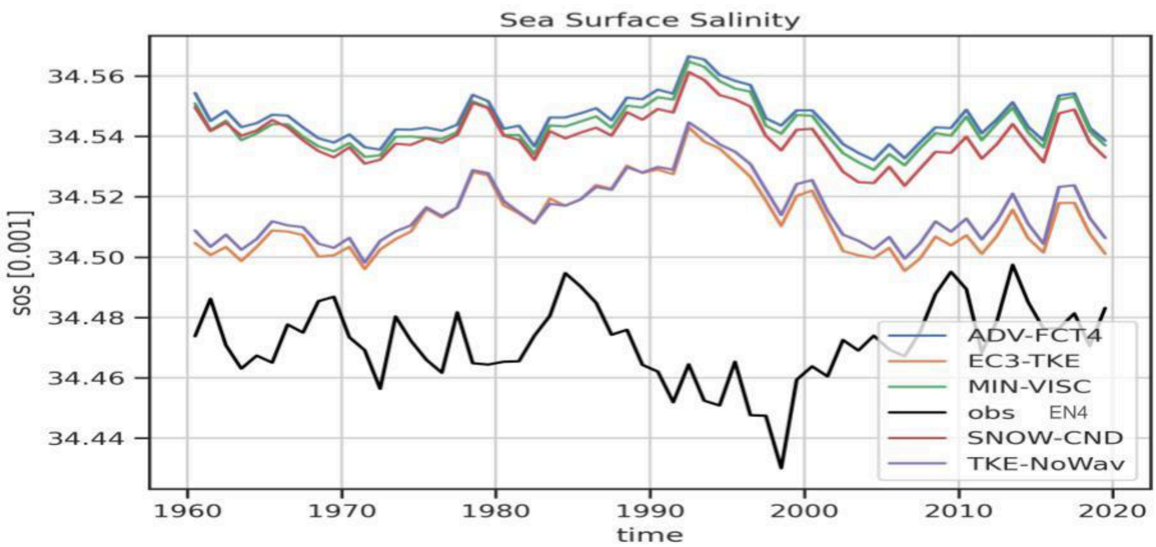

Figure 3. Annual-mean global SSS bias relative to EN4 (black line) for each sensitivity test (1958–2019).

Suppressing wave-induced mixing (TKE-NoWav) deepens the mixed layer in the Labrador Sea by ~400 m with respect to the other experiments (Fig. 4). In this case, the reference taken is the experiment with salinity restoration and forcing with ERA5. For MLD, a comparison with an observation product is necessary as long as further tests are required.

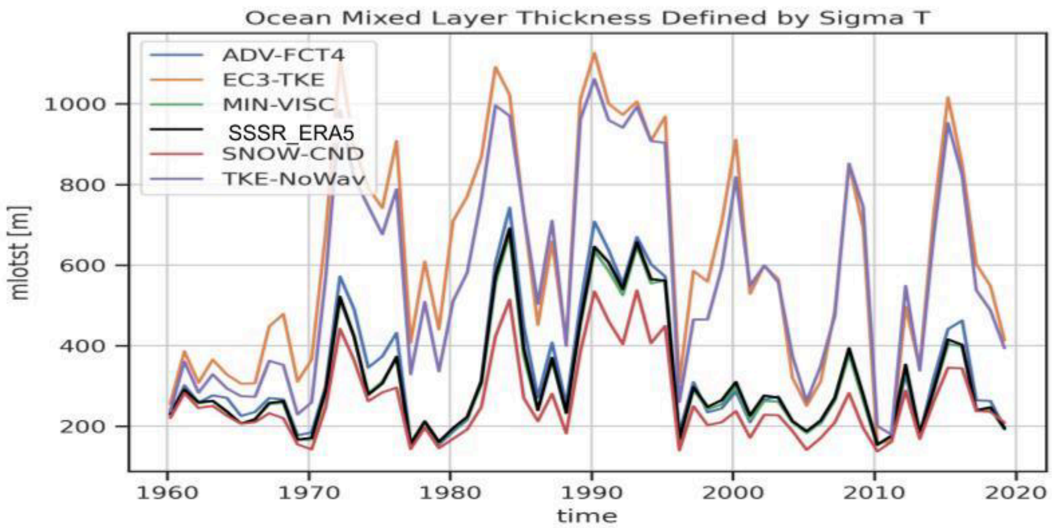

Figure 4. Labrador Sea mixed-layer depth for each experiment, averaged over 1980–2010. In this case, we used the experiment with Surface restoring, forced with ERA5, as a reference, shown in black.

The documented parameters provide a roadmap for EC-Earth tuning, focusing on mixing coefficients, wave coupling, and sea-ice conductivity, to mitigate high-latitude warm biases that were predominantly present in EC-Earth3. Future work is needed to refine the configuration of NEMO and extend these tests into the coupled EC-Earth4 version.

Paleoclimate modelling: abrupt-127k Fast Track experiment

Our paleoclimate modelling group significantly contributed to the development and enhancement of EC-Earth model capabilities, particularly in preparation for CMIP7 paleoclimate experiments. Key contributions include performing CMIP7-PMIP FastTrack simulations, such as the abrupt-127k experiment, to assess model sensitivity to orbital and boundary condition changes. The abrupt-127k Fast Track experiment will be continuously evaluated with the tuned model.

We also conducted idealized sea level sensitivity experiments using EC-Earth3 to isolate climatic impacts of elevated sea levels during the Last Interglacial. Compared to PI, the LIG experiments with or without sea level rise show significant changes in ocean circulation and surface temperature. The preliminary results imply that sea level change — through its influence on bathymetry, coastline geometry, and oceanic pathways — can substantially reshape both circulation and climate, even in the absence of changes in external forcings. Sea level must therefore be considered as a key boundary condition in paleoclimate modeling frameworks and future CMIP7 experimental designs.