EMI R&D PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	A new decadal prediction system based on EC-Earth3
Computer Project Account:	spdkdrew
Start Year - End Year :	2024- 2025
Principal Investigator(s)	Tian Tian
Affiliation/Address:	Danish Meteorological Institute Sankt Kjelds Plads 11 2100 Copenhagen Denmark
Other Researchers (Name/Affiliation):	Rashed Mahmood, DMI Shuting Yang, DMI

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The project aimed to develop and evaluate a new decadal climate prediction system based on EC-Earth3 using an atmosphere–ocean coupled assimilation approach. By nudging the model toward surface pressure from ERA5 and sea surface temperatures anomaly from HadISST during a multi-year spin-up period, the project sought to generate dynamically balanced initial conditions for decadal predictions. Specific objectives included establishing the assimilation workflow on ECMWF HPC systems, investigating the impact of spin-up duration on ocean adjustment and memory, evaluating key climate variability modes such as ENSO, AMV, AMOC and NAO, and assessing the feasibility of the resulting climate states for future initialized decadal predictions.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

Several practical challenges affected the implementation schedule. These were not due to limitations of ECMWF HPC infrastructure or user support, but mainly reflected the underestimated effort required to transition the EC-Earth3 workflow from the previous DMI cray xc50 with the model version EC-Earth3 v3.3.1 for the CMIP6 projects to Atos HPC2020 with an updated version EC-Earth3 v3.3.4 for CMIP6Plus projects. Considerable time was needed to make the model configuration fully functional, adapt scripts from qsub to Slurm, establish the preprocessing and post-processing pipeline, and ensure consistency between the reference and assimilation simulations. A new EC-Earth3 v3.3.4 historical reference simulation was also required, as this version includes an important correction to surface restoring under sea ice. Consequently, part of the project effort was spent on workflow development and technical validation rather than large-scale production simulations, which explains why the allocated computing resources were not fully used. With support from EC-Earth colleagues at KNMI and CNR, these issues were resolved and a robust modelling pipeline was established.

Experience with the EMI R&D Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

The EMI R&D Project framework worked very well, with clear application and reporting procedures. Communication with ECMWF staff was efficient, with prompt responses and helpful guidance throughout the project.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

1. End-to-end atmosphere–ocean coupled assimilation and decadal prediction workflow

The primary achievement of the project was the successful implementation of an end-to-end EC-Earth3 workflow for atmosphere–ocean coupled assimilation and decadal prediction on ECMWF's Atos HPC system.

To support the assimilation experiments, a new historical reference simulation was performed using EC-Earth3 v3.3.4. From this simulation, a moving 30-year model climatology was constructed and combined with observed HadISST SST anomalies to generate the SST fields used for restoring. Sea level pressure from ERA5 was used for atmoshperic nudging. These fields were applied in a continuous atmosphere–ocean coupled assimilation run for 1981–2014, from which 1 November restart files were extracted as initial conditions for decadal predictions. The prediction outputs were subsequently CMORised following CMIP6/CMIP6Plus standards and evaluated against observations using key atmosphere, ocean and sea-ice diagnostics (Figure 1).

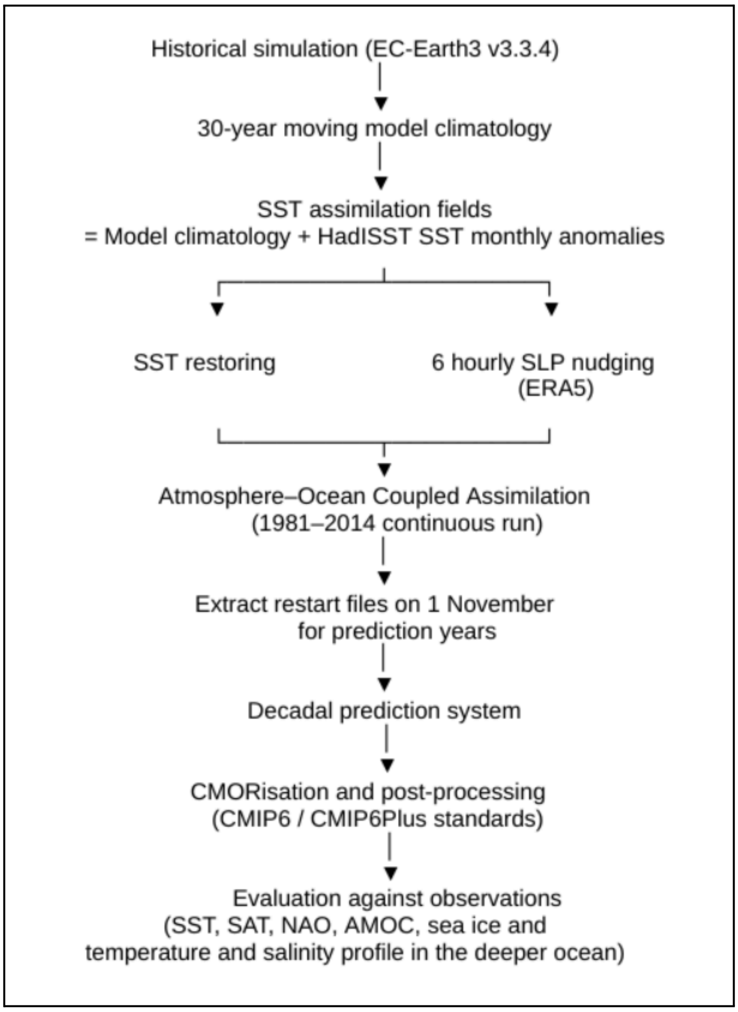

Figure 1. End-to-end workflow of the atmosphere–ocean coupled assimilation and decadal prediction system. The schematic shows the reconstruction of SST and SLP assimilation fields, the continuous coupled assimilation run, extraction of restart files for decadal predictions, and subsequent CMORisation, post-processing and evaluation of model outputs.

2. SST-restoring spin-up sensitivity experiment

The objective of this experiment was to assess how SST-restoring spin-up duration affects the realism of the assimilated ocean state. This step focused only on ocean-surface restoring and served as an intermediate test before the later comparison between ocean-only and atmosphere–ocean coupled nudging.

SST-restoring experiments were initialized in 1980, 1990 and 1995, corresponding to spin-up durations of approximately 35, 25 and 20 years before the 2004–2013 evaluation period. The simulations were evaluated against observations using regional mean SST anomalies for the globe, ENSO, AMV and the Subpolar North Atlantic (SPNA), together with global surface air temperature and AMOC strength at 26.5°N.

All restoring experiments reproduced observed SST variability reasonably well, confirming the correct implementation of the framework. They captured major modes of variability, including ENSO and AMV, as well as SPNA variability, which is particularly relevant for North Atlantic predictability. However, longer spin-up did not necessarily improve performance. The 35-year spin-up generally produced lower correlations with observed SST variability, whereas the 25-year spin-up performed best for the North Atlantic and gave the most realistic AMOC evolution. The 20-year spin-up was more effective for some tropical Pacific variability. These results indicate that the appropriate spin-up duration is region- and process-dependent, and informed the design of the subsequent atmosphere–ocean coupled assimilation experiments.

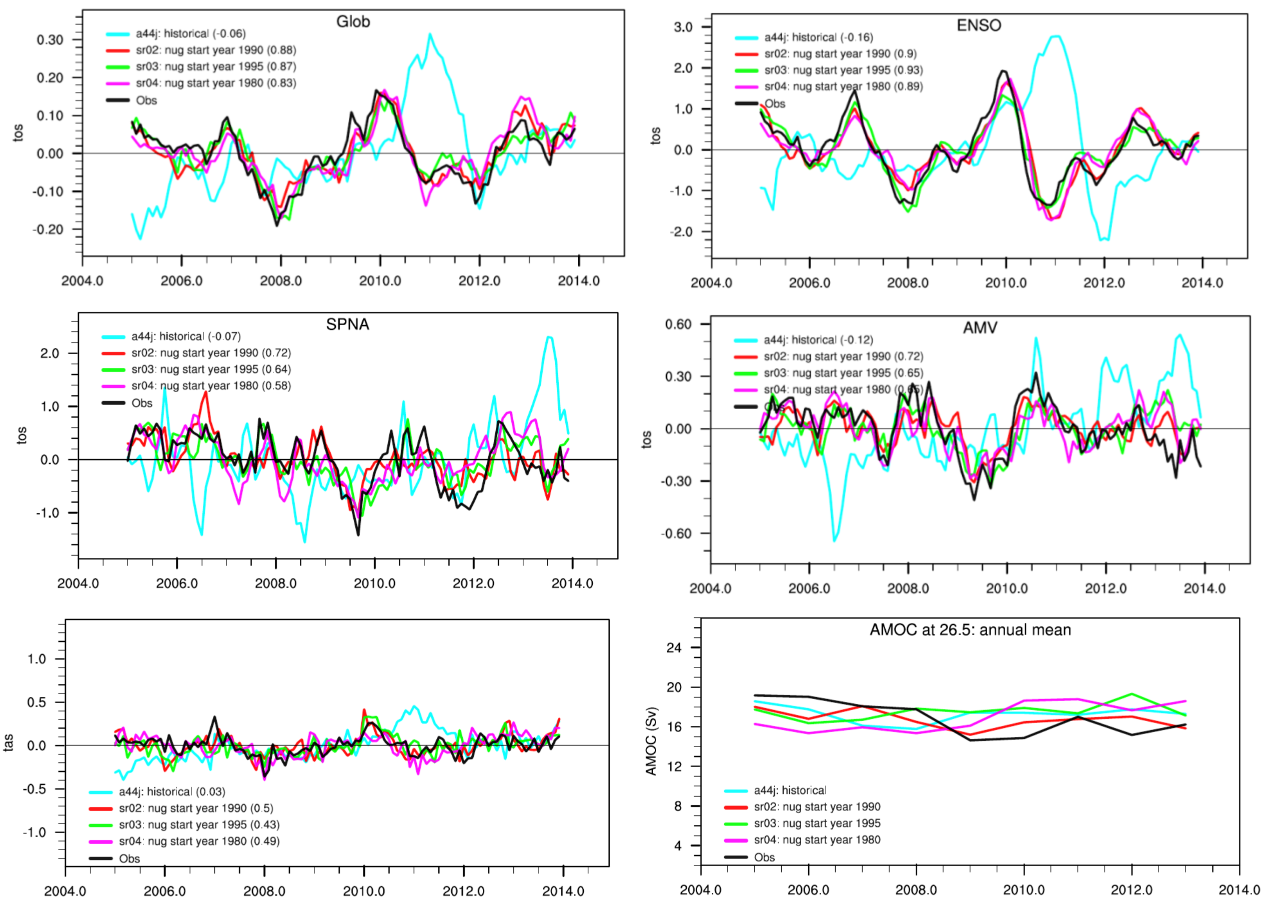

Figure 2. Sensitivity of SST-restoring experiments to spin-up duration. Time series of regional SST anomalies, global surface air temperature anomalies, and AMOC strength at 26.5°N for SST-restoring experiments initialized in 1980, 1990 and 1995. The figure shows that the restoring framework reproduces observed SST variability, while the response of regional variability and AMOC depends on the spin-up duration.

3. Benefits of atmosphere–ocean coupled nudging

Building on the SST-restoring experiments, the next step was to assess whether adding atmospheric nudging could further improve the assimilated climate state. Two test simulations were performed with EC-Earth3. The first used ocean-only assimilation, in which SSTs were restored toward observed HadISST SST anomalies superimposed on a 30-year moving model climatology. The second used atmosphere–ocean coupled assimilation, applying the same SST restoring while additionally nudging model sea-level pressure toward the 6 hourly ERA5 sea-level pressure.

The comparison shows that the atmosphere–ocean coupled assimilation produces a more realistic representation of both atmospheric and oceanic variability than SST restoring alone. Figure 3 shows the spatial correlation between simulated and observed surface air temperature. While SST restoring improves agreement mainly over the ocean, the addition of sea-level-pressure nudging leads to higher correlations over both ocean and land regions. This indicates that constraining large-scale atmospheric circulation helps the coupled system better follow observed climate variability.

The most pronounced improvement is found for the North Atlantic Oscillation (NAO), a key mode of atmospheric variability for the North Atlantic and European climate. As shown in Figure 4, the coupled assimilation reproduces the observed temporal evolution of the NAO more closely than the ocean-only assimilation. This demonstrates that SST restoring alone is insufficient to constrain large-scale atmospheric circulation, whereas combined SST restoring and SLP nudging provides a more balanced atmosphere–ocean initialisation framework for decadal prediction.

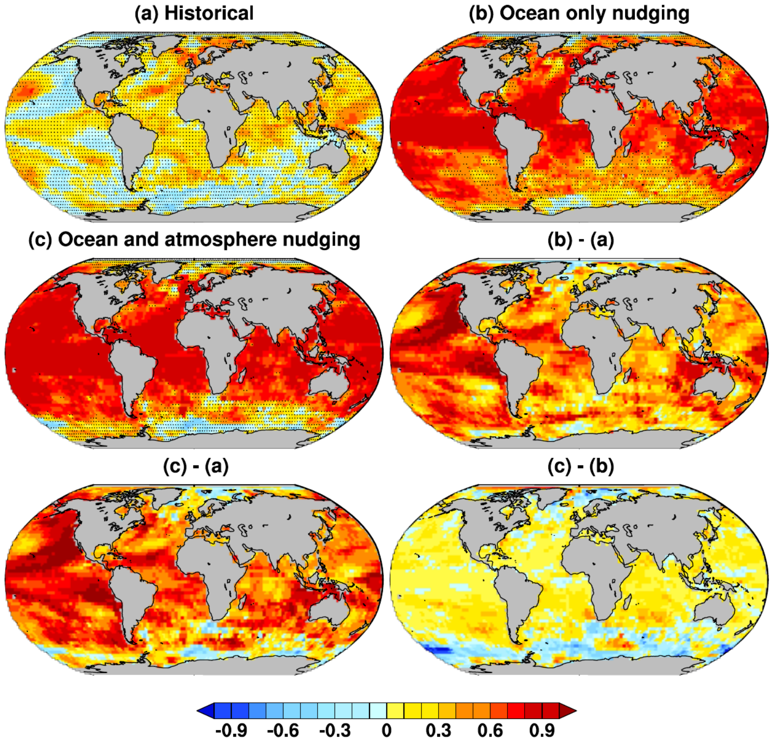

Figure 3. Surface air temperature correlation with observations. Correlation between simulated and observed surface air temperature for the historical simulation (“free-running”), the ocean-only assimilation using SST restoring, and the atmosphere–ocean coupled assimilation using SST restoring and SLP nudging. The coupled assimilation improves agreement with observations over both ocean and land regions.

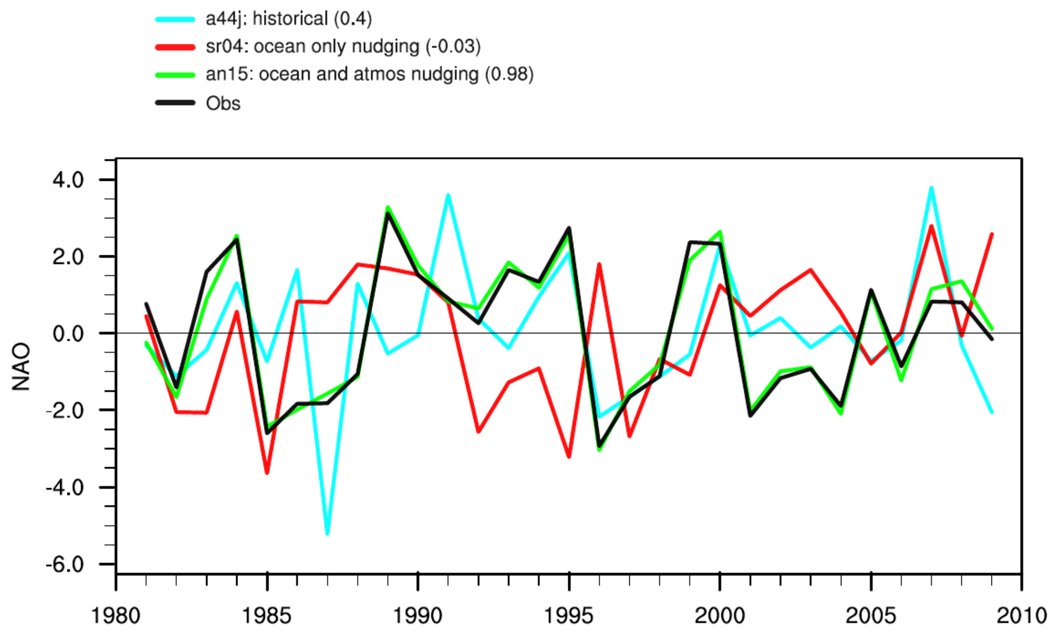

Figure 4. Representation of the North Atlantic Oscillation (NAO). Time series of observed and simulated NAO variability for the free-running historical simulation, the ocean-only assimilation, and the atmosphere–ocean coupled assimilation. The coupled assimilation provides the closest agreement with observations, demonstrating the added value of SLP nudging for representing large-scale atmospheric circulation variability.

4. Sea-ice response, DCPP-mode tests and remaining challenges

Although atmosphere–ocean coupled nudging improves many aspects of the assimilated climate state, several challenges remain. Preliminary analyses indicate that the coupled assimilation tends to produce excessive Arctic sea ice throughout much of the year and reduced Antarctic winter sea-ice extent compared with observations. In contrast, the ocean-only assimilation generally shows better agreement with observed sea-ice conditions.

These results suggest that realistic sea-ice initialization may be required in addition to atmosphere and ocean constraints. Previous studies with EC-Earth3 have demonstrated the importance of sea-ice initialization for Arctic climate prediction skill (Tian et al., 2021), and the present findings indicate that sea ice should be considered as an active component of future coupled assimilation systems rather than a passive response to atmosphere and ocean forcing.

In addition to the assimilation evaluation, first DCPP-mode hindcast tests have been initiated from the coupled nudging experiments. Two continuous coupled assimilation runs starting in January 1981 and January 1985 were used to generate restart files after different nudging lengths. Preliminary prediction experiments were then started after 5, 10 and 15 years of nudging, including start dates in November 1985, November 1990 and November 1995. These experiments represent an important transition from evaluating the assimilated climate state to assessing whether the improved atmosphere–ocean representation translates into enhanced decadal prediction skill.

Further work is still needed to understand how the SST-restoring and SLP-nudging signals propagate into the ocean interior. In particular, subsurface temperature and salinity, deeper ocean circulation, stratification and long-term ocean memory require further investigation. These diagnostics will be essential for interpreting prediction skill and for guiding the next phase of multi-ensemble DCPP production.

List of publications/reports from the project with complete references

Mahmood, R., Yang, S., and Tian, T., 2026: *Initializing climate predictions using climate states from an atmosphere–ocean coupled assimilation system*. EGU General Assembly 2026, EGU26-17142. https://doi.org/10.5194/egusphere-egu26-17142.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new EMI R&D Project.)

Building on the successful development of the atmosphere–ocean coupled assimilation framework, we have submitted a new EMI R&D Project proposal entitled ***"A new decadal climate prediction system: multi-ensemble production with EC-Earth3 and upgrade to EC-Earth4"*** (**spdktian**, 2026-2028).

The proposed project will transition from methodology development to the production of multi-member hindcasts and near-real-time forecasts, contributing to CMIP7 Decadal Climate Prediction Project (DCPP) activities and future WMO annual-to-decadal climate outlooks. Future work will also investigate explicit sea-ice initialization and the implementation of the methodology in the next-generation EC-Earth4 model.