Ocean Eddy-rich Kilometre-scale Climate Simulation with IFS-FESOM

Rohit Ghosh[1], Suvarchal Kumar Cheedela[1], Sebastian Beyer[1], Nikolay Koldunov[1], Dmitry Sidorenko[1], Thomas Jung[1,2]

[1]Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremnerhaven, Germany

[2] University of Bremen, Bremen, Germany

Abstract

We present our work conducted within two computational projects, **ENHANCE** and **Stresmodes**, on the JUWELS supercomputer. For the first time on JUWELS, we have performed kilometer-scale global climate simulations on a centennial timescale. Using the global coupled climate model IFS-FESOM, with a 9 km atmospheric resolution and a minimum 5 km ocean resolution, we carried out a total of 180 years of coupled simulations. This marks the first time such an extensive km-scale simulation has been performed using a global climate model.

Introduction

- Leading European Earth System Modeling (ESM) groups are advancing km-scale climate simulations to reduce biases linked to low model resolution.
- One such effort is the EU project EERIE, which aims to develop ESMs that resolve the ocean meso-scale to improve the representation of long-term climate evolution, variability, extremes, and tipping points.
- Such effort also presents a major technological challenge to achieve high-resolution simulations with sufficient throughput for centennial-scale outputs.

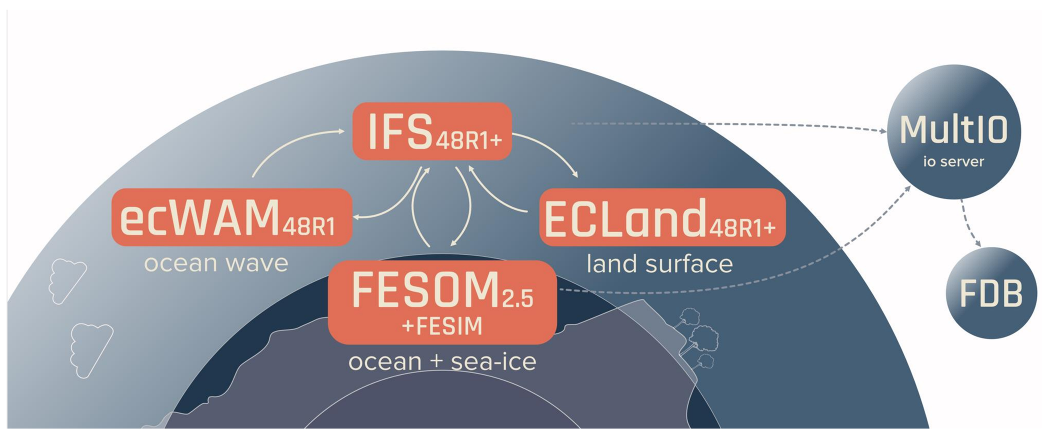

Figure 1: ***Schematic of the Coupled Model System*** *– The atmospheric model IFS (cycle 48R1) is coupled with the ocean and sea ice model FESOM2.5, the land model ECLand, and the wave model ecWAM. IFS computes air-sea fluxes using surface fields provided by FESOM2.5, with coupling achieved via a sequential single-executable strategy. Output generation utilizes the* ***MultIO*** *framework, which optimizes parallel I/O performance for high-resolution simulations. Data storage and retrieval are managed through the* ***Fields Database (FDB),*** *a high-performance, scalable object-store designed for efficient access and post-processing of model outputs.*

- Here we use the coupled model IFS-FESOM to perform km-scale ocean meso-scale eddy rich global climate simualtion.
- The atmospheric model IFS is used its Tco1279 spectral resolution which is comparable to 9km horizontal vertical lesolution and with 37 vertical levels.
- The Ocean sea ice model FESOM is used with its NG5 grid resolution which represents a horizontal resolution of 5km (13km) at the high latitudes (tropics) with 70 depth levels.
- The model employs an advanced I/O strategy to manange substantial data volumes generated by such high resolution model and implements Fields Database (FDB) for efficient data archival and retrieval. Details of the model setup can be found in Rackow et.al. 2025.

Experiments

- We conducted CMIP6 HighResMIP-style experiments, beginning with a 50-year coupled spin-up experiment. This experiment used ocean initial conditions derived from an EN4-forced standalone ocean model simulation, which was run for five years up to 1949.
- Following the 50-year coupled spin-up, we conducted a 65-year control simulation with 1950 radiative forcing, alongside a historical simulation spanning 1950 to 2014.

Results

- One primary aim of the EERIE project is to resolve ocean eddies in the climate model and assess their potential impact on the climate system. Snapshot ocean currents from the control simulations show the formation of eddies, particularly in eddy-rich regions like the Gulf Stream, demonstrating the model's capability to simulate ocean eddies (Figure 2).

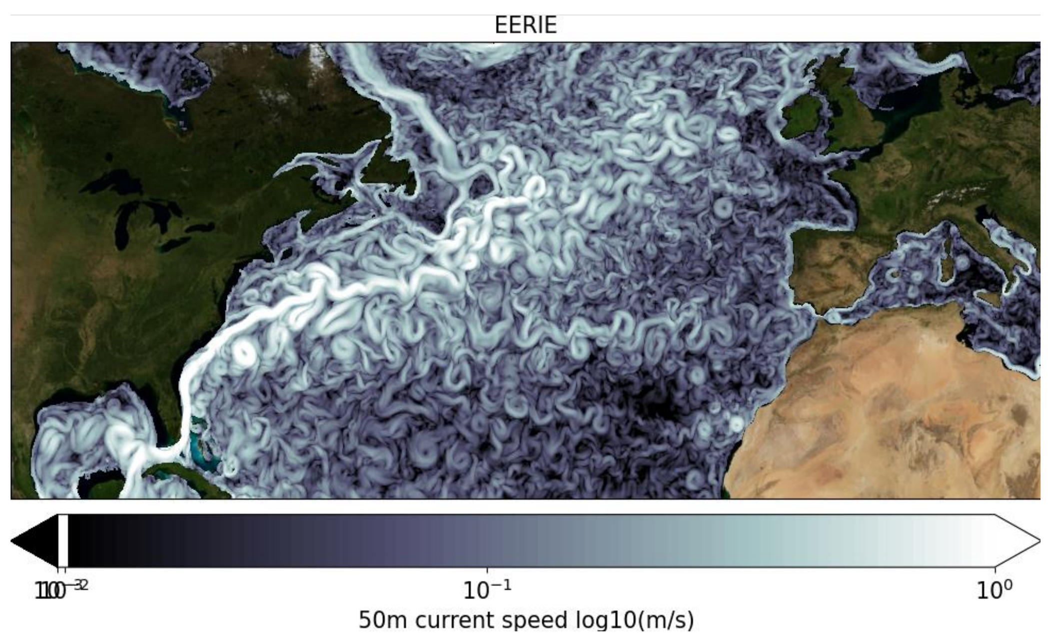

Figure 2: ***Model simulates intricate details of Ocean mesocale eddies in Ocean eddy-rich regions*** *– A snap of the speed of ocean currents at 50 m depth (m/s in logarithmic scale) on a typical day in control simulation over the North Atlantic capturing the eddies over the Gulf stream and depicting the pathway of the North Atlantic current.*

- The coupled spin-up simulation initially showed a cold drift in global mean surface air temperature (GMST), which stabilized after 10–15 years (Figure 3). Over time, the cold drift diminished, and by the end of the coupled simulation, the global mean temperature nearly returned to its initial state, from which the control and historical simulations begin.

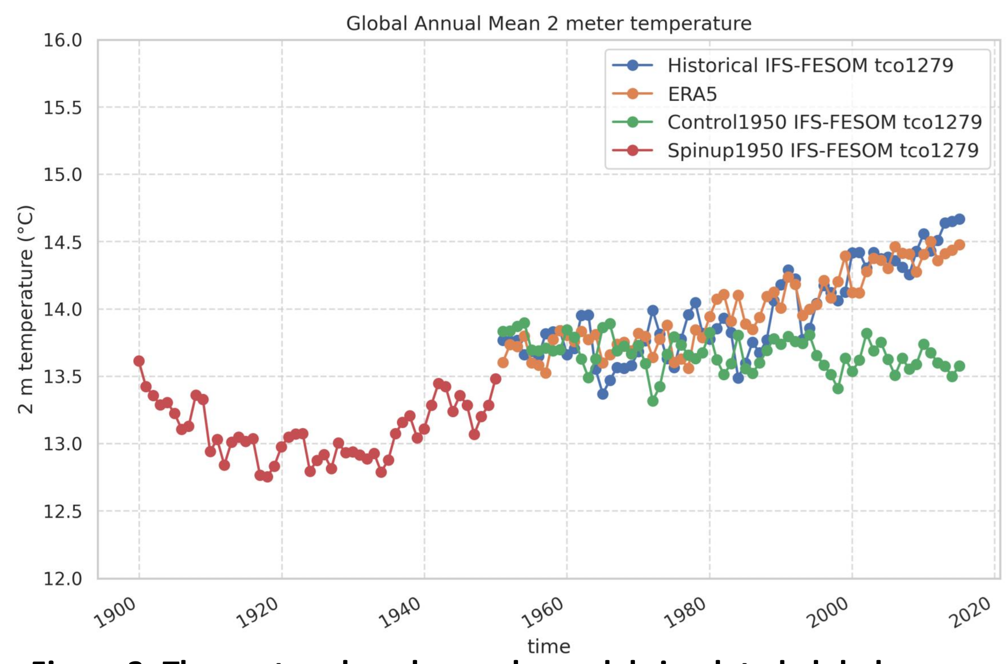

Figure 3: The century long km-scale model simulated global mean surface temperature *- Time series of global mean 2-meter temperature (in degrees Celsius) from ERA5 reanalysis (orange), Historical simulation (blue), coupled Spin-up (red), and Control simulation (green) under 1950 radiative forcing, using the IFS-FESOM model with a 9km atmosphere and 5km ocean resolution configuration.*

- Our simulation closely tracks the historical evolution of global mean 2m temperature, aligning with ERA5 (Figure 3), confirming its ability to capture observed temperature trends under ongoing anthropogenic forcing.

Results

- The model produces promising results for overall ocean eddy characteristics, closely matching eddy-rich regions (Figure 4). However, eddy activity remains underestimated in the Gulf Stream, a known challenge in climate modeling. However, overall this sets a strong foundation for our project, which will explore the impact of these eddies on the climate system.

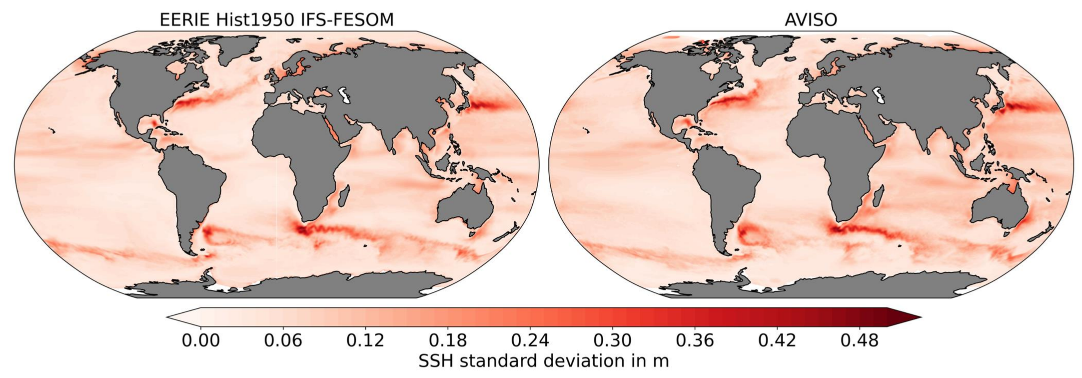

Figure 4: Capturing the global Ocean mesoscale eddy activity - *The daily SSH standard deviation over the first 20 year period in IFS-FESOM Tco1279-NG5 HighResMIP Historical simulation (top-left) and in AVISO (top-right) highlighting the ocean eddy-rich regions.*

- Spatial regression of sea surface temperature (SST) on the Niño 3.4 index reveals a strong resemblance between observed HadISST patterns and those in IFS-FESOM (Figure 5). The model effectively captures both the patterns and magnitude of ENSO signals, demonstrating its ability to represent a key driver of interannual climate variability with global regional impacts.

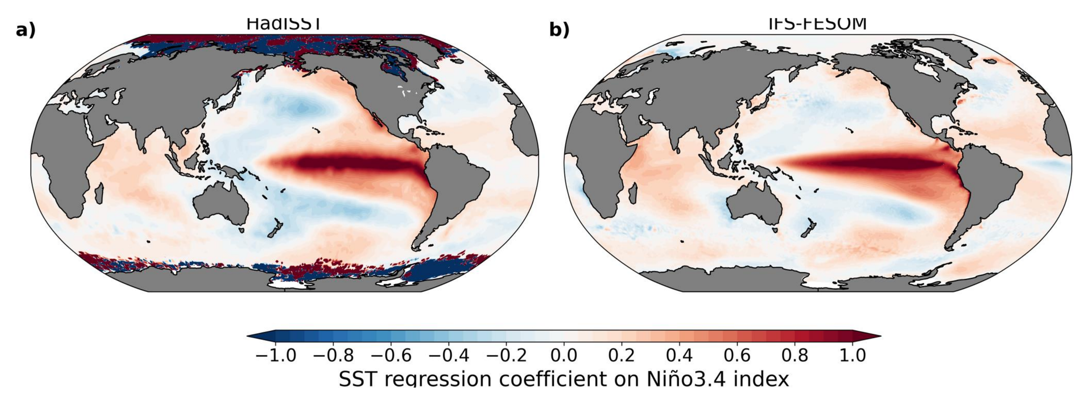

Figure 5: The ENSO, key source of global interannual variability - *The spatial regression of the sea surface temperature (SST) on the Niño 3.4 index depicting the ENSO pattern in (a) HadISST, (b) IFS-FESOM.*

- Additionally, our initial analysis shows improved representation of zonal mean temperature, surface air temperature patterns over both land and ocean, total precipitation, and cloud cover.

Summary

- To explore the impact of resolving meso-scale ocean eddies on the climate system, we conducted a centennial-scale simulation following the CMIP6 HighResMIP protocol, consisting of a 50-year coupled spin-up followed by control and historical simulations.
- Initial analysis shows promising results, with further evaluations ongoing as we extend simulations under the SSP2.4.5 scenario forcing through 2100, supported by additional ENHANCE resources.

References

Rackow, T et.al: *Multi-year simulations at kilometre scale with the Integrated Forecasting System coupled to FESOM2.5 and NEMOv3.4*, Geosci. Model Dev., 18, 33–69, https://doi.org/10.5194/gmd-18-33-2025, 2025.

Grant Agreement # 101081383

ALFRED-WEGENER-INSTITUT HELMHOLTZ-ZENTRUM FÜR POLAR- UND MEERESFORSCHUNG

Funded by the European Union

UK Research and Innovation

Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

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