REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: Italy

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Project Title: Earth system modeling of PaleOClimatic HyperthermALs (EPOCHAL)

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** …………	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2025	
Would you accept support for 1 year only, if necessary?	YES ☐	NO ☒

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	9,000,000	14,000,000	
Accumulated data storage (total archive volume)[2]	[GB]	20,000	40,000	

EWC resources required for project year:		**2025**	**2026**	**2027**
Number of vCPUs	[#]	0	0	
Total memory	[GB]	0	0	
Storage	[GB]	0	0	
Number of vGPUs[3]	[#]	0	0	

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[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.

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Extended abstract

Objectives

Within EPOCHAL we aim at investigating the characteristics of the Early Eocene climate and the mechanisms of hyperthermals making use an innovative Earth System Model configuration from EC-Earth4. Indeed, the Early Eocene undoubtedly represents one of the most intriguing paleoclimatic epochs due to its high atmospheric CO2 concentration (> 1000 ppm), which poses it as an analog for the most extreme future climate scenarios.

We will make use of the newly developed version 4 of the EC-Earth Earth System Model (ESM) and we will make use of a low-resolution, high-efficiency and computationally cheap configuration that will be able to run thousands of years at minimum computational cost, without giving up the high level of complexity and fidelity typical of an ESM.

By performing a series of 2000-year long "time slice" simulations under different greenhouse gas concentrations, orbital forcing and paleogeography it will be possible to explore the Eocene atmospheric and oceanic circulation as well as the hydrological cycle and associated extremes, at both global and continental scales. This special project will build on a currently funded PRIN (Relevant Researches of National Interest) project coordinated by P. Davini funded by the, the Italian Ministry of Education, University and Research (MIUR).

Introduction

During the Early Eocene, about 55 million years ago, the climate of the Earth was characterized by radically different conditions than today: atmospheric CO2 exceeding 1000ppm and 10-15°C higher mean global surface temperature (GST). It was also characterized by the absence of ice caps, extreme Polar Amplification and strongly reduced pole-to-equator temperature gradient (Lunt et al. 2021). Such an atmospheric and oceanic configuration, radically different from what is observed today, also had consequences on the Equilibrium Climate Sensitivity (ECS) of the Earth System, a key metric for understanding how the climate system responds to CO2 forcing (Inglis et al. 2020, Anagnostou et al. 2020).

On top of this extraordinary mean state, the Earth was struck by a series of sudden global warming events, known as hyperthermals, which lasted a few millennia and saw further GST rise by as much as 5°C. They were entirely natural climatic events and were driven by an estimated 2000-5000 Gton carbon release into the atmosphere. Hyperthermals represent the fastest carbon release in the paleoclimatic records and our comprehension of their onset and decay is still partial. Under gradual warming and orbital forcing of long (~405,000 years) and short (~100,000 years) eccentricity maxima, the climate is thought to have crossed a tipping point that triggered isotopically light carbon releases to the climate system (Lunt et al. 2011; Kirtland Turner et al. 2014). However, the validity of this driving mechanism remains in doubt, especially for the largest of the hyperthermals, known as the Palaeocene–Eocene Thermal Maximum (PETM), occurring ~56 millions of years ago.

The Eocene ECS will be compared with present-day and the impact of orbital forcing on the carbon release tipping point will be assessed. Overall, EPOCHAL will provide a large dataset:

1. to investigate the feedback, both positive and negative, that lead to hyperthermals transition,
2. to assess mismatches between model and proxy data,
3. to explore the ability of the ESM to simulate a high-CO2 world similar to what humanity may face in the upcoming centuries.

Methodology

EPOCHAL will be based on a series of "time slice" simulations to tackle the open questions for the paleoclimatic community. The run will be based on a low-setup of EC-Earth4 (ECE-FAST) that is to this day technically running. Part of the project, however, will be dedicated to make the low-resolution setup trustworthy, with the target of a stable and reliable configuration (CORE simulations) that can be exploited for the simulations of paleoclimatic interest (EPOCHAL simulations).

EC-Earth4 low resolution setup

The EPOCHAL project will make use of EC-Earth4 ESM, a full complexity ESM under development by EC-Earth consortium, successor to EC-Earth3 (Doescher et al. 2021).

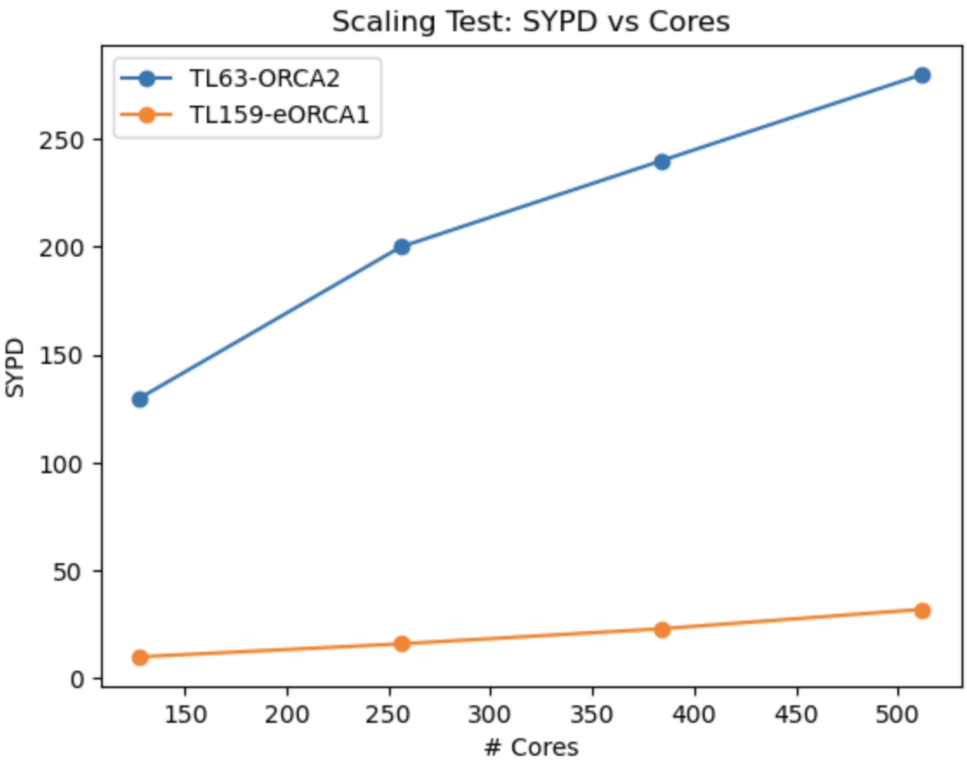

Fig. 1: Scaling test for the EC-EARTH4 TL63-ORCA2 configuration. The number of cores is in the x-axis and the number of simulated years per day is on the y-axis. ECE-FAST (the blue line) can easily run up to 250 years in single day, making long paleoclimatic runs available in less than a week.

The model has been adapted to support a low-resolution configuration (ECE-FAST) using the TL63L31 grid for the atmosphere (based on OIFS cy43) and ORCA2L31 for the ocean (NEMO v4.2). The two grids correspond roughly to a 2° horizontal resolution (specifically ~2.8° of horizontal resolution at the equator for the TL63 grid and ~2° for the ORCA2 grid). As mentioned above, the configuration is technically running, and it has already been ported on ECMWF Atos HPC2020 machine. An initial scaling on the Atos machine of the model have been performed and is shown in

Fig.1, where the scaling of the current test EC-Earth4 configuration TL159L91-eORCA1L75 is shown as a reference.

The cost of the ECE-FAST configuration is estimated to be around 50 core hours per simulated year (CHPSY) and the output of the model, thanks to the adaption of the XIOS server – developed in EC-Earth4 - is directly written into cmor-like NetCDF format, without the need of storing intermediate raw Grib data. Due to the reduced resolution of the configuration and considering a monthly output the storage (which can be considered satisfying for the type of simulations that will be performed) of the simulation is estimated in 1.3GB/year, but effort in the direction of saving only yearly output will be pursued to lighten the data analysis and reduce the occupied space.

Experiments to assess the robustness of the low-resolution configuration (CORE simulations)

The ECE-FAST configuration of EC-Earth4 is technically running but before being able to run the simulations described in this section, we need to perform validation and tuning simulations for the coupled model. This effort is shared with the EC-Earth consortium, since a similar development must be performed by the official high resolution EC-Earth configuration that will take part into the CMIP7 fast track effort. Furthermore, synergies can arise from the proposed Special Project MARTINI (coordinate by Dr. A. Sozza). However, a proper tuning of the model is extremely important for the success of the EPOCHAL project, for this reason resources dedicated to the testing/tuning are estimated in 3000-year of simulations and in 3000-year of simulations for the initial model spin-up, considering that two different spin-up will be required for the simulations following the CMIP6 protocol (Eyring et al. 2016) or the DeepMIP protocol (Lunt et al. 2017). Although we are aware that this might seem a large amount of simulation years, the ECE-FAST configuration is completely non-validated (also in the current present-day configuration) therefore complex tuning is expected to be required. Furthermore, running Eocene simulations following the DeepMIP protocol will require a modification of the orography and the bathymetry as shown in Fig. 2. Complex technical changes are expected and to obtain a stable configuration we might need a larger number of simulated years. The estimate of the time is also considering the necessity of test runs needed to validate the orography and bathymetry modifications.

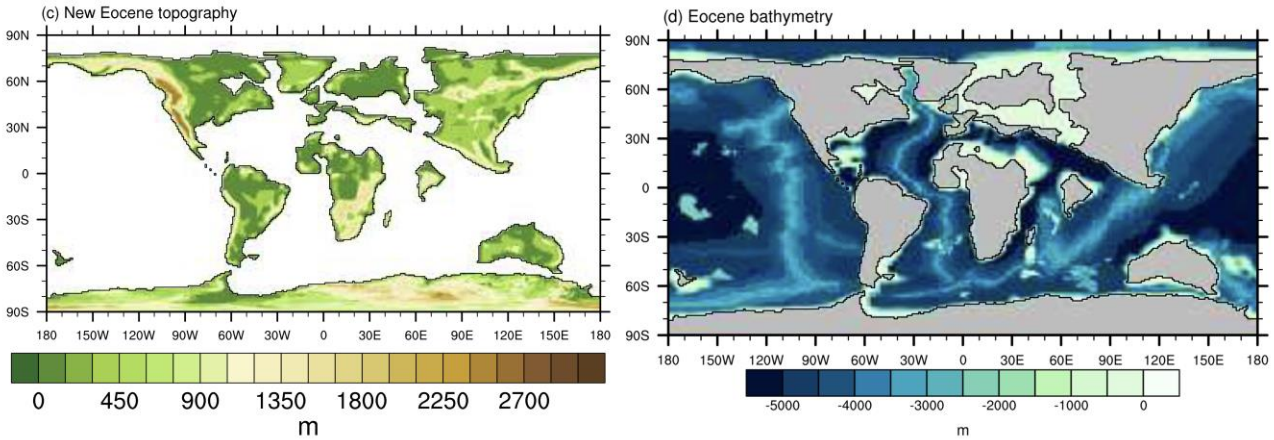

Fig. 2: Eocene topography (left) and bathymetry (right) according to Herold et al. (2014), implemented in the DeepMIP protocol by Lunt et al. (2017)

The CORE simulations are then composed of a set of development and validation simulations:

- 3000-year testing/tuning
- 3000-year spinup

Once a stable model configuration is obtained, a CMIP6 DECK simulation following the CMIP6 protocol (Eyring et al. 2016) is planned:

- 500-year pre-industrial “piControl”
- 165-year “historical”
- 165-year “abrupt4xCO2”
- 165-year “1pctCO2”

This set of simulations will allow to assess the performance of the model at the present-day climate and to compare with previous and current versions of EC-Earth at higher resolutions and as well with others CMIP6 models.

Once the model is completely validated, the first important simulation in the Eocene configuration is planned: This will be a replica of the DeepMIP protocol (Lunt et al. 2017):

- 2000-year Early Eocene pre-PETM integration, with a 3-fold CO2 concentration increase compared to pre-industrial (“deepmip-stand-3xCO2").

This simulation will provide a baseline simulation for the Early Eocene climate, with modified orography and bathymetry. We decided to have “time slices” 2000 years long because a decrease in the magnitude of the climate feedback parameter is observed at longer timescales in multi-centennial studies, and this might be something interesting to investigate given the type of simulation planned (Fabiano et al. 2024). The ECE-FAST configuration that will be used in this project will require only 8-10 days of walltime to perform such a “time slice”.

Experiments oriented to improve the understanding of the Earth System response and the PETM dynamics (EPOCHAL simulations):

Once the CORE simulations will be available, the simulations that have as purpose the understanding of ECS and PETM dynamics will be formed. They consist of:

- 2000-year with high 6xCO2 integration (“deepmip-stand-6xCO2") following the DeepMIP protocol (Lunt et al. 2017)
- 2000-year with high 12xCO2 integration (“deepmip-stand-12xCO2") following the DeepMIP protocol (Lunt et al. 2017)
- 2000-year pre-PETM (3xCO2)
- 2000-year pre-PETM (6xCO2)
- 2000-year with high 3xCO2 integration (“deepmip-stand-3xCO2") following the DeepMIP protocol (Lunt et al. 2017) and interactive vegetation if the module LPJ-GUESS will be available in the EC-Earth4 ESM
- 2 x 2000year pre-PETM integration with opposite phasing of eccentricity orbital forcing.
- 2 x 2000year with different carbon storylines

Workflow

The work will be organized as follow:

- Month 1-3: Validate the ECE-FAST configuration to be able to start the tuning procedure;

- Month 3-6: Bathymetry and Orography modification for the DeepMIP protocol and validation;
- Month 3-9: Tuning of ECE-FAST for the CMIP6 and DeepMIP protocol;
- Month 9-12: Execution of the CORE simulations and the “deepmip-stand-6xCO2" and “deepmip-stand-12xCO2" EPOCHAL simulations;
- Month 12-22: Completion of the EPOCHAL simulations, considering possible technical development for the LPJ-GUESS integration, orbital forcing modifications and carbon storylines;
- Month 9-24: Data analysis, data reduction and transfer of the reduced data to CNR-ISAC cluster machines for more detailed analysis.

Resources and technical development

Given the details of the model and the simulations that will be performed we can summarize the resources necessary to this special project.

Summing together the different planned experiments we will have that:

- CORE simulations: ~8500-years, for ~7.5 million SBU and ~15 TB of storage
- EPOCHAL simulation: ~18000-years, for ~15.5 million SBU and ~25 TB of storage

Overall, we expect to be able to produce a publication from the CORE simulations, showing a validation of the low resolution configuration of the model, and at least one peer-reviewed publication from the EPOCHAL simulations where the results from the Eocene simulations are presented.

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