# REQUEST FOR AN EMI R&D PROJECT 2027–2029


**Country/Organisation:** Italy

**Principal Investigator**[1]**:** Renata Coppo

**Affiliation:** Consiglio Nazionale delle Ricerche, Istituto di Scienze dell'Atmosfera e del Clima (CNR-ISAC)

**Address:** Corso Fiume 4, 10133, Torino, Italy

**Other researchers:**
Paolo Davini (CNR-ISAC)
Federico Fabiano (CNR-ISAC)
Virna Meccia (CNR-ISAC)
Jost Graf Von Hardenberg (Politecnico di Torino)
Marianna Albanese (Politecnico di Torino)


**Project Title:**

Eocene Thermal optimum with EC-Earth4: paleoclimatic Reconstruction and Numerical AnaLysis (ETERNAL)

| | | |
|---|---|---|
| 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.) | 2027 | |
| Would you accept support for 1 year only, if necessary? | YES ☐ | NO ☒ |

| **Computer resources required for project year:** | | **2027** | **2028** | **2029** |
|---|---|---|---|---|
| High Performance Computing Facility | [SBU] | 8,500,000 | 12,000,000 | |
| Graphics Processing Unit Cluster-A | [GBU] | 0 | 0 | |
| Graphics Processing Unit Cluster-B | [GBU] | 0 | 0 | |
| Accumulated data storage (total archive volume)[2] | [GB] | 6,000 | 22,000 | |

[1] The Principal Investigator will act as contact person for this EMI R&D 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.

**EWC resources required for project year:**

| | | 2027 | 2028 | 2029 |
|---|---|---|---|---|
| Number of vCPUs | [#] | 0 | 0 | |
| Total memory | [GB] | 0 | 0 | |
| Storage | [GB] | 0 | 0 | |
| Number of vGPUs[3] | [#] | 0 | 0 | |

*Continue overleaf*

**Principal Investigator:** Renata Coppo

**Project Title:** Eocene Thermal optimum with EC-Earth4: paleoclimatic Reconstruction and Numerical AnaLysis (ETERNAL)

# Extended abstract

## Introduction

The early Eocene (~56–48 Ma), and particularly the Early Eocene Climatic Optimum (EECO; ~53–49 Ma), represents one of the warmest intervals of the Cenozoic, with global mean temperatures were 10–17 °C above preindustrial levels, atmospheric $CO_2$ concentrations were near 1500 ppm, polar regions were ice-free, and the equator-to-pole temperature gradient was significantly reduced (Cramwinckel et al., 2018; Anagnostou et al., 2020; Lunt et al., 2021). As an analogue for future high-$CO_2$ climates, it provides a key benchmark for evaluating equilibrium climate sensitivity (ECS) and model performance (Zhu et al., 2019; Lunt et al., 2026). Reproducing these conditions remains a major challenge for climate models and constitutes one of the central scientific questions addressed by the Deep-Time Model Intercomparison Project (DeepMIP). During its first phase (DeepMIP-Eoc-p1; Lunt et al., 2017, 2021), DeepMIP established a coordinated framework for model–data comparison across several early Eocene climate states, including the EECO and the Paleocene Eocene Thermal Maximum (PETM; ~56 Ma).

Despite recent advances, climate models continue to underestimate high-latitude warmth and fail to reproduce proxy-derived meridional temperature gradients (Lunt et al., 2021), a long-standing discrepancy known as the Eocene equator-to-pole temperature paradox, that highlights major uncertainties in the representation of climate feedbacks, ocean heat transport, cloud processes, and climate sensitivity under greenhouse conditions (Lunt et al., 2021; Zhang et al., 2022; Kelemen et al., 2023), remaining one of the most important challenges in deep-time paleoclimate modelling.

ETERNAL builds on the ECMWF special project EPOCHAL, which developed the first low-resolution atmosphere-ocean Global Climate Model (GCM) configuration, EC-Earth4 (EC-Earth4-FAST-P), for the early Eocene (Coppo et al., 2026), successfully simulating multi-centennial boundary conditions following DeepMIP-Eoc-p1. Preliminary results suggest high ECS values for EC-Earth4 compared to other DeepMIP models (Fig. 1). ETERNAL will support EC-Earth4's first participation in DeepMIP-Eocene Phase 2 (DeepMIP-Eoc-p2), which focuses on a comprehensive exploration of EECO climate states and model sensitivity experiments, through a systematic exploration and tuning of model parameters under early Eocene boundary conditions. Particular emphasis will be placed on improving the simulation of meridional temperature gradients.

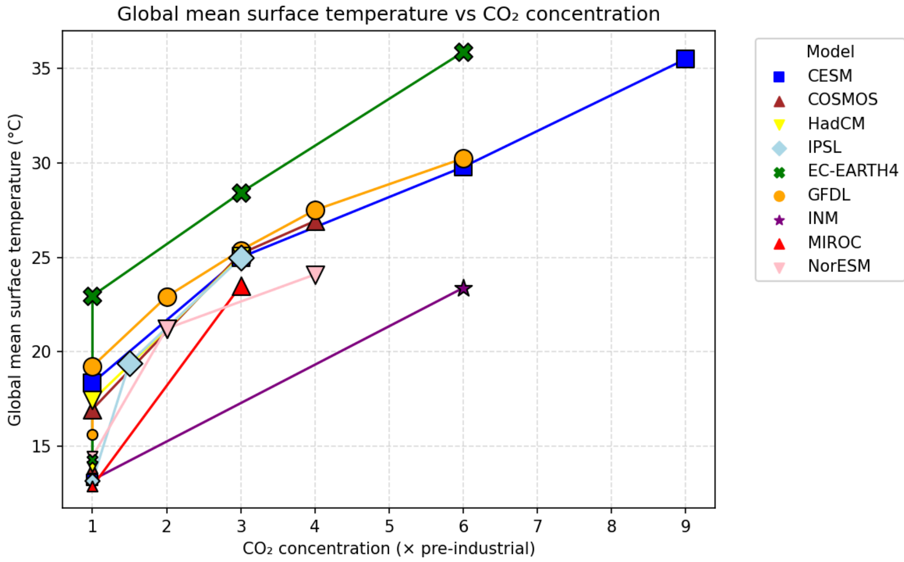


*Figure 1 - Global annual mean near-surface (2-metre) air temperature in the EC-Earth4 (green crosses) and DeepMIP ensemble, as a function of atmospheric $CO_2$. Large symbols show the Eocene simulations, while smaller symbols show the associated preindustrial controls. Models that have run Eocene simulations at more than one $CO_2$ concentration are joined by a line. (derived from Lunt et al., 2021).*

Beyond its paleoclimate applications, ETERNAL provides a unique framework for evaluating the performance of the OpenIFS atmospheric model within EC-Earth4 under an extreme greenhouse climate state. By testing model behaviour outside modern climate conditions and comparing simulations with geological evidence (e.g., Hollis et al., 2019), the project will help assess the robustness of physical parametrizations, identify structural model biases, improve confidence in climate projections, and contribute to both the scientific objective of DeepMIP and the continued development of EC-Earth4 modelling within the ECMWF community.

## Objectives

ETERNAL aims to investigate the dynamics of the early Eocene greenhouse climates and the mechanisms responsible for reduced equator-to-pole temperature gradients under extreme $CO_2$ conditions. The project combines the development of a next-generation Earth System Model with process-based climate investigations to improve our understanding of ECS and Earth-system feedback during one of the warmest intervals of the Cenozoic.

Building on the PRIN 2022 EPOCHAL project, ETERNAL will use the EC-Earth4-FAST-P configuration to support EC-Earth4's first participation in the DeepMIP-Eoc-p2. A systematic exploration of key model parameters will be undertaken to optimize simulations under EECO boundary conditions, with particular emphasis on reproducing proxy-derived meridional temperature gradients. A suite of simulations will evaluate the model's ability to reproduce greenhouse climates and investigate the oceanic and atmospheric processes, including heat transport and deep-water formation, that sustain them.

In parallel, the project will develop a carbon-cycle-enabled configuration of the EC-Earth4 Earth System Model specifically designed for deep-time applications (EC-Earth4-FAST-P-ESM). By incorporating dynamic vegetation and ocean biogeochemistry while maintaining high computational efficiency, this framework will enable multi-millennial simulations under EECO boundary conditions. The DeepMIP-Eoc-p2 protocol will then be repeated using this fully coupled ESM configuration.

Ultimately, ETERNAL will deliver a set of validated early Eocene EC-Earth4 configurations, provide quantitative constraints on climate sensitivity and climate-carbon feedback, improve the integration of proxy and model evidence, and establish EC-Earth4 as a European reference infrastructure for paleoclimate research.

## Methodology

**Modelling tools: EC-Earth4**

The project's core is EC-Earth4, a full-complexity ESM under development by the EC-Earth consortium (Kelsson et al., in prep.), successor to EC-Earth3 (Doescher et al. 2021), which has been part of the CMIP6 effort (Eyring et al. 2016). CNR-ISAC and Politecnico di Torino are among the main contributors to the EC-Earth Consortium, and CNR-ISAC is part of the Steering Committee.

In ETERNAL, we start from the low-resolution EC-Earth4-FAST-P configuration (T63L31 atmosphere and PALEORCA2L31 ocean, i.e., horizontal resolution of about 2.5° in the atmosphere and 2° in the ocean), adapted for deep-time simulation through the work of EPOCHAL. This setup is fast and computationally efficient, achieving ~150 simulated years per day (SYPD) in Eocene configurations, with a cost of less than 50 core hours per simulated year (CHPSY), potentially allowing for multi-millennial integrations (Fig. 2). The output of the model, thanks to the adaptation of the XIOS server (developed for EC-Earth4), is directly written into cmor-like NetCDF format. Due to the reduced resolution of the configuration and considering a monthly output (which can be considered satisfying for the type of simulations that will be performed), the storage required is estimated at 1.5GB/year, while it could be 33% more in the case of the EC-Earth4-FAST-P-ESM configuration (~2GB/year). Efforts in the direction of saving only yearly output will be pursued to lighten the data analysis and reduce the occupied space.

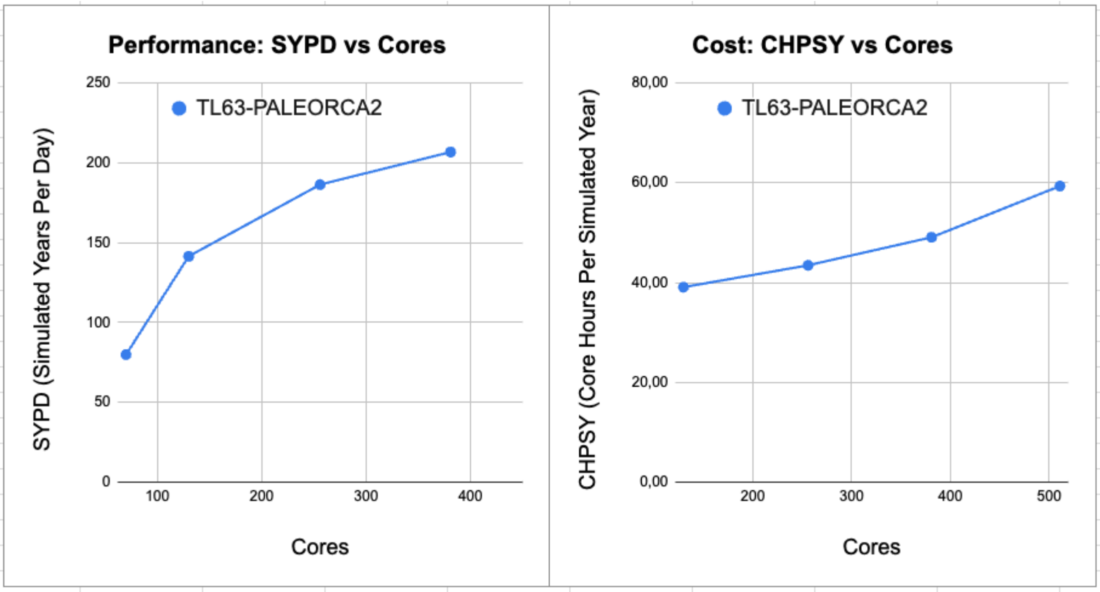


*Figure 2 – Performance and cost analysis of the EC-Earth4-FAST-P configuration on the ECMWF HPC2020 platform. The panel on the left shows the Simulated Years Per Day (SYPD), while the right panel displays the cost in Core Hours Per Simulated Year (CHPSY). All metrics are plotted as a function of the number of cores.*

**Development of EC-Earth4-FAST-P-ESM**

While concentration-driven GCM experiments provide a baseline, a comprehensive understanding of EECO dynamics requires a fully coupled ESM to resolve carbon-cycle feedbacks affecting ocean carbon uptake and global heat transport. ETERNAL will integrate the LPJG dynamic global vegetation model and the PISCES biogeochemical ocean model under EECO boundary conditions in the EC-Earth4-FAST-P architecture, developing an ESM configuration hereafter named EC-Earth4-FAST-P-ESM. Adapting modern EC-Earth4 configurations to a ~50 Ma environment requires a dedicated effort to reflect early Eocene biodiversity and paleogeography. This elevates the model to a predictive tool capable of capturing greenhouse-world feedbacks. For achieving this, two sets of simulations are planned to support the development and  to test both configurations (EC-Earth4-FAST-P and EC-Earth4-FAST-P-ESM):

- ~10 TEST-GCM simulations of ~30 years: test simulations under DeepMIP-Eoc-p2 boundary conditions
- ~30 TEST-ESM simulations of ~30 years: test simulations under present-day and DeepMIP-Eoc-p2 boundary conditions

**Participation in Eocene DeepMIP**

To address the participation of EC-Earth4 in the Eocene DeepMIP framework, ETERNAL will implement the EECO DeepMIP-Eoc-p2 protocol. DeepMIP Phase 2 brings updated boundary conditions from newer proxies, increasing $CO_2$ to 5x-preindustrial, a new paleogeographic reconstruction centred at ~51 Ma (centred on the EECO), and a new vegetation reconstruction based on a dynamical model. Simulations will be performed using both the GCM and ESM configurations of EC-Earth4-FAST-P.

A first set of **spin-up simulations** will be run for all configurations:

- 500-year **piControl-GCM-spinup**: Modern geography, vegetation, and preindustrial $CO_2$ (280 ppm), with the EC-Earth4-FAST-P model configuration.
- 500-year **deepmip-GCM-spinup**: Eocene geography and vegetation with preindustrial $CO_2$, with the EC-Earth4-FAST-P model configuration.
- 500-year **piControl-ESM-spinup**: Modern geography, vegetation, and preindustrial $CO_2$ (280 ppm), with the EC-Earth4-FAST-P-ESM model configuration.
- 500-year **deepmip-ESM-spinup**: Eocene geography and vegetation with preindustrial $CO_2$, with the EC-Earth4-FAST-P-ESM model configuration.

Then, the four **standard DeepMIP-Eoc-p2 experiments** (run for both GCM and ESM models) are:

- 1000-year **present-day piControl**: Modern geography, vegetation, and preindustrial $CO_2$ (280 ppm) serve as the benchmark.
- 1000-year **present-day abrupt-4×$CO_2$**: Instantaneous $CO_2$ quadrupling under modern geography to isolate ECS from paleogeography.
- 1000-year **deepmip-p2-stand-5×$CO_2$:** Standardized EECO run; primary proxy-comparison run to evaluate extreme warmth.
- 1000-year **deepmip-p2-stand-1×$CO_2$:** Eocene geography and vegetation with preindustrial $CO_2$, isolating the specific warming effects of EECO boundary conditions from greenhouse gas concentrations.

**EC-Earth4 tuning for Eocene**

While DeepMIP provides a vital multi-model framework, current Earth System Models often suffer from "present-day bias" due to parameterizations tuned to modern observations. To address this issue, ETERNAL will explore the model parameter space to optimize a configuration specifically for early Eocene boundary conditions. Using the ECtuner tool (Albanese et al. 2026, https://github.com/jhardenberg/ECtuner) and the ECmean global diagnostic tool (https://github.com/oloapinivad/ecmean), short simulations aimed at systematically retuning the model for Eocene conditions will be conducted. Tuning targets are a reduced meridional temperature gradient and higher proxy-data fidelity than default DeepMIP versions.

For this, a new set of **standard DeepMIP-Eoc-p2 simulations** will be run:

- ~50 tuning simulations of ~20 years: test simulations to retune the GCM model for early Eocene conditions.
- 500-year piControl-EC-Earth4-tuned-spinup: Modern geography, vegetation, and preindustrial CO2 (280 ppm), with the EC-Earth4-FAST-P model configuration re-tuned.
- 500-year deepmip-EC-Earth4-tuned-spinup: Eocene geography and vegetation with preindustrial $CO_2$, with the EC-Earth4-FAST-P model configuration re-tuned.
- 1000-year present-day piControl with the re-tuned model: Modern geography, vegetation, and preindustrial $CO_2$ (280 ppm) serve as the benchmark.
- 1000-year present-day abrupt-4×$CO_2$ with the re-tuned model: Instantaneous $CO_2$ quadrupling under modern geography to isolate ECS from paleogeography.
- 1000-year deepmip-p2-stand-5×$CO_2$ with the re-tuned model: Standardized EECO run; primary proxy-comparison run to evaluate extreme warmth.
- 1000-year deepmip-p2-stand-1×$CO_2$ with the re-tuned model: Eocene geography and vegetation with preindustrial $CO_2$, isolating the specific warming effects of EECO boundary conditions from greenhouse gas concentrations.

## Workflow

The work will be organized as follows:

- Months 1-3: Integration of DeepMIP-Eocene Phase 2 boundary conditions; TEST-GCM simulations
- Months 4-10: Biogeochemical (PISCES) and vegetation (LPJ-GUESS) components integration for carbon cycle closure; TEST-ESM simulations
- Months 3-5: piControl-GCM-spinup and DeepMIP-GCM-spinup
- Months 5-7: Standard DeepMIP-Eoc-p2 simulations with GCM
- Months 11-12: piControl-ESM-spinup and DeepMIP-ESM-spinup
- Months 12-14: Standard DeepMIP-Eoc-p2 simulations with ESM
- Months 12-17: Deep time tuning; tuning test simulations
- Months 17-19: piControl-GCM-spinup and DeepMIP-GCM-spinup for the tuned version

- Months 19-21: Standard DeepMIP-Eoc-p2 simulations with the GCM-tuned version
- Months 21-24: Completion of the ETERNAL simulations, considering possible technical development for the EC-Earth4 model
- Months 10-24: 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 model's details and the simulations to be performed, we can summarize the resources necessary for this special project.

Summing together the different planned experiments, we will have:

- TEST-GCM simulations: ~300 years, for ~282 thousand SBU, no long-term storage needed
- TEST-ESM simulations: ~300 years, for ~1.3 million SBU, no long-term storage needed
- GCM spinup simulations: ~1000 years, for ~1.4 million SBU, no long-term storage needed
- GCM simulations: ~4000 years, for ~3.7 million SBU and ~6 TB of storage
- ESM spinup simulations: ~1000 years, for ~1.4 million SBU, no storage needed
- ESM simulations: ~4000 years, for ~5.6 million SBU and ~8 TB of storage
- Deep time tuning test simulations: ~1000 years, for ~1.4 million SBU and ~1.5 TB of storage
- GCM-Tuned spinup simulations: ~1000 years, for ~940 thousand SBU, no storage needed
- GCM-Tuned simulations: ~4000 years, for ~3.7 million SBU and ~6 TB of storage

The project team combines complementary expertise in climate modelling, paleoclimate dynamics, Earth system model development, model tuning, and data–model comparison, enabling an efficient and parallelized distribution of tasks across all project components.

The requested computational resources are distributed across the two project years according to the planned model development and production phases. During 2027, activities will focus on model testing, spin-up simulations, and the first long-scale experiments with DeepMIP-Eoc-p2 using the EC-Earth4-FAST-P configuration. These tasks require approximately 8.5 million SBU and generate a limited volume of archived output (~6 TB), as most test and spin-up simulations do not require long-term storage.

During 2028, the project will transition to the systematic parameter-space exploration required for early Eocene tuning and to the production of large-scale simulations using both the tuned GCM and the newly developed carbon-cycle-enabled EC-Earth4-FAST-P-ESM configuration. The higher computational demand (~12 million SBU) reflects the increased complexity of the ESM, the need for multi-millennial integrations, and the execution of sensitivity experiments. The accumulated storage requirement will increase to ~22 TB as output from ESM simulations, deep-time tuning experiments, and tuned GCM simulations will be archived for analysis, model intercomparison, and contribution to the DeepMIP framework.

## References

**Albanese**, M., Fabiano, F., and von Hardenberg, J.: ECtuner: a semi-automatic GCM tuning tool and its application to the EC-Earth4 model, EGU General Assembly 2026, Vienna, Austria, 3–8 May 2026, EGU26-12785, https://doi.org/10.5194/egusphere-egu26-12785, 2026

**Anagnostou**, E., John, E. H., Babila, T. L., Sexton, P. F., Ridgwell, A., Lunt, D. J., ... & Foster, G. L. (2020). Proxy evidence for state-dependence of climate sensitivity in the Eocene greenhouse. *Nature communications*, *11*(1), 4436. https://doi.org/10.1038/s41467-020-17887-x

**Coppo,** R., Sozza, A., Nurisso, M., Meccia, V., Fabiano, F., and Davini, P.: Unlocking Multi-Millennial Eocene Simulations with a New EC-Earth4 Configuration, EGU General Assembly 2026, Vienna, Austria, 3–8 May 2026, EGU26-10249, https://doi.org/10.5194/egusphere-egu26-10249, 2026

**Cramwinckel**, M. J., Burls, N. J., Fahad, A. A., Knapp, S., West, C. K., Reichgelt, T., ... & Inglis, G. N. (2023). Global and zonal‐mean hydrological response to early Eocene warmth. *Paleoceanography and Paleoclimatology*, *38*(6), e2022PA004542. https://doi.org/10.1029/2022PA004542

**Döscher,** R., Acosta, M., Alessandri, A., Anthoni, P., Arneth, A., Arsouze, T., ... & Zhang, Q. (2021). The EC-earth3 Earth system model for the Climate Model Intercomparison Project 6. Geoscientific Model Development Discussions, 2021, 1-90. https://doi.org/10.5194/gmd-15-2973-2022

**Eyring,** V., Righi, M., Lauer, A., Evaldsson, M., Wenzel, S., Jones, C., ... & Williams, K. D. (2016). ESMValTool (v1. 0)–a community diagnostic and performance metrics tool for routine evaluation of Earth system models in CMIP. Geoscientific Model Development, 9(5), 1747-1802. https://doi.org/10.5194/gmd-9-1747-2016

**Hollis**, C. J., Dunkley Jones, T., Anagnostou, E., Bijl, P. K., Cramwinckel, M. J., Cui, Y., ... & Lunt, D. J. (2019). The DeepMIP contribution to PMIP4: Methodologies for selection, compilation and analysis of latest Paleocene and early Eocene climate proxy data, incorporating version 0.1 of the DeepMIP database. *Geoscientific Model Development*, *12*(7), 3149-3206. https://doi.org/10.5194/gmd-12-3149-2019

**Kelemen**, F. D., Steinig, S., de Boer, A., Zhu, J., Chan, W. L., Niezgodzki, I., ... & Ahrens, B. (2023). Meridional heat transport in the DeepMIP Eocene ensemble: Non‐CO2 and CO2 effects. *Paleoceanography and Paleoclimatology*, *38*(8), e2022PA004607. https://doi.org/10.1029/2022PA004607

**Lunt**, D. J., Huber, M., Anagnostou, E., Baatsen, M. L., Caballero, R., DeConto, R., ... & Zeebe, R. E. (2017). The DeepMIP contribution to PMIP4: Experimental design for model simulations of the EECO, PETM, and pre-PETM (version 1.0). *Geoscientific Model Development*, *10*(2), 889-901. https://doi.org/10.5194/gmd-10-889-2017

**Lunt**, D. J., Bragg, F., Chan, W. L., Hutchinson, D. K., Ladant, J. B., Morozova, P., ... & Otto-Bliesner, B. L. (2021). DeepMIP: Model intercomparison of early Eocene climatic optimum (EECO) large-scale climate features and comparison with proxy data. *Climate of the Past*, *17*(1), 203-227. https://doi.org/10.5194/cp-17-203-2021

**Lunt**, D. J., Wright, N. M., Vaes, B., Salzmann, U., Rae, J. W., Hickler, T., ... & Baatsen, M. (2026). DeepMIP-Eocene-p2: Experimental design for Phase 2 of the early Eocene component of the CMIP7/PMIP7 Deep-time Model Intercomparison Project (DeepMIP-Eocene). *EGUsphere*, *2026*, 1-30. https://doi.org/10.5194/egusphere-2025-6135

**Zhang**, Y., de Boer, A. M., Lunt, D. J., Hutchinson, D. K., Ross, P., van de Flierdt, T., ... & Huber, M. (2022). Early Eocene ocean meridional overturning circulation: The roles of atmospheric forcing and strait geometry. *Paleoceanography and Paleoclimatology*, *37*(3), e2021PA004329. https://doi.org/10.1029/2021PA004329

**Zhu**, J., Poulsen, C. J., & Tierney, J. E. (2019). Simulation of Eocene extreme warmth and high climate sensitivity through cloud feedbacks. *Science advances*, *5*(9), eaax1874. DOI: 10.1126/sciadv.aax1874