REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: Italy

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Project Title: Deep ocean heat uptake on equilibrating time scales (DEEPNESS)

To make changes to an existing project please submit an amended version of the original form.)

If this is a continuation of an existing project, please state the computer project account assigned previously.	/	
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	

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	12,200,000	15,350,000	/
Accumulated data storage (total archive volume)[2]	[GB]	16,900	38,350	/

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

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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

1. Introduction

1.1 Background and motivation

Since the industrial revolution, human activities have altered Earth's climate through changes in atmospheric composition and surface properties (i.e. land-use influencing albedo). Both these effects represent radiative forcings and are responsible for the radiative imbalance observed at the top of the atmosphere (TOA). The planet then tries to reach a new equilibrium state by changing its surface temperature, modulated by radiative feedback whose strength influences the final state of the system (Intergovernmental Panel on Climate Change (IPCC), 2023).

Huge research efforts have been devoted to estimating how the climate system will adapt to such perturbations. A widely used metric is the Equilibrium Climate Sensitivity (ECS), the globally averaged surface temperature anomaly observed at equilibrium after a doubling of CO2 concentration. Usually, an idealized framework is used to estimate ECS with climate models, which involves abrupt quadrupling of the CO2 concentration. This idealized framework is chosen as it helps isolate the signal from greenhouse gases emissions, excluding aerosol and other effects. To further enhance this signal, the concentration is usually quadrupled, dividing the result by a factor two at the end.

To reach a final equilibrium condition, millennium-length simulations would be necessary but, especially if a comprehensive state-of-the-art Earth System Model is used, the final computational cost could be substantial. This is why it is customary practice to use the 150 years required by Coupled Model Intercomparison Project (CMIP) protocols and extrapolate to zero the radiative unbalance at the TOA, assuming a constant feedback parameter and a linear relationship between radiation and surface temperature changes (Gregory et al. 2004). However, it has been shown that the estimates obtained focusing only on this brief time window could be misleading, as the total equilibrating response comes from the combination of fast and slow modes (Rugenstein et al. 2020). The latter component of the response is primarily due to the long-term redistribution of the added heat into the ocean, according to deep ocean circulation timescales. Indeed, due to its large thermal inertia, the ocean has absorbed almost 90% of the radiative imbalance to date. Divergent pathways of ocean circulation evolution or base states can redirect different amounts of heat towards the surface or deep ocean and thus influence the surface warming pattern (Gjermundsen et al. 2021; Bellomo and Mehling 2024). This effect, on the other hand, could induce a change in the relative strengths of different climate feedback mechanisms, especially water vapor, lapse rate, and cloud ones, through the so-called pattern effect, influencing the stabilizing strength of the atmosphere, and eventually a lower or higher ECS (Andrews et al. 2015).

Multi-centennial simulations better allow to see the effect of ocean circulation changes and deep ocean heat storage. Millennium-length equilibrating simulations have been performed using Coupled Global Climate Models (GCMs), as collected by the LongRunMIP project (Rugenstein et al. 2019), or intermediate-complexity models (Rugenstein et al. 2016), in this case extending up to 10000 years. While the latter are sufficiently long to capture the warming even of the deepest layer, the former are expected to comprehend more processes and better describe the changes in the global circulation that can influence the pathways of ocean heat uptake. Overall, when the focus is on the deepest layers of the ocean (i.e. below 2000 m), a huge uncertainty remains. A 6000-year simulation run with a CMIP3 low-resolution model shows how the system can reach an equilibrium condition, but the interpretation is limited as just one model and one forcing level is available (Li et al. 2013).

An additional degree of complexity to this problem is the fact that the response of the system depends non-linearly on the forcing. Linearity is usually assumed in the standard framework, which still captures the key mechanisms behind future projections (Good et al. 2016). Indeed, applying increasingly higher CO2 concentrations influences both global properties and warming patterns in a non-linear fashion (Rugenstein et al. 2016; Bloch-Johnson et al. 2021; Fabiano et al. 2024). Some simulations, on the other hand, also suggest the possibility of a non-monotonic response (Mitevski et al. 2023). Furthermore, many processes contribute to the heat redistribution at depth - for example, diffusive processes connected with the ocean stratification and captured by the pycnocline depth (Newsom et al. 2023; Oh et al. 2024) - but not all of them are explicitly resolved in the models. The areas of major interest are the Atlantic basin, strongly influenced by the strength of the Atlantic Meridional Overturning Circulation, and the Southern Ocean, a key region for global ocean heat uptake (Lago et al. 2019; Gjermundsen et al. 2021; IPCC AR 6).

A better understanding of the role of the deep ocean in absorbing the added heat might help tackling the uncertainty about the values of ECS. Moreover, although sometimes neglected, understanding nonlinear responses associated with extreme warming can be helpful in many ways. Among the others, it can help in tuning energy balance models to better study the dependence of feedback parameters or assessing impacts through pattern scaling techniques (Good et al. 2016).

1.2 Scientific goals

In this project we plan to perform long equilibrating simulations to answer the following scientific questions regarding the state-dependence of climate change.

Q1) Is the equilibrium response of the deep ocean heat uptake linear to CO2 forcing?

Fabiano et al. (2024) found that, over 1000 years, the deep ocean behaves independently from the forcing level, while more spread is observed in the intermediate and surface ocean. The latter simulations have been conducted branching from SSP5-8.5 and modifying both GHG and aerosol concentrations. In this project, we will apply a further ideal forcing, to isolate the CO2 effect on equilibrium conditions.

Q2) What is the role of ocean circulation and ocean stratification in determining the deep ocean uptake?

Previous studies have identified the Northern and Southern high latitudes as regions more subjective to non-linear warming patterns (Rugenstein et al. 2016; Poletti et al. 2024). Moreover, these regions are the ones associated with the formation of water masses contributing to the Meridional Overturning Circulation. Ad-hoc experiments of water hosing are a consolidated exercise to evaluate the effects of changes in the ocean stratification and therefore the Meridional Overturning Circulation and associated heat transport, both in the North Atlantic (Jackson et al. 2023; Mitevski et al. 2023; Bellomo and Mehling 2024) and the Southern Ocean (Armour et al. 2016; Phipps et al. 2016; Rye et al. 2020).

2. Proposed activities

2.1 Model

We plan to conduct the experiments using EC-Earth4, a state-of-the-art Earth System model, whose development by the EC-Earth consortium started in 2020 (see https://ec-earth.org/ec-earth/ec-earth4/ for further details, SPLTUNE ECMWF Special Project by S. Yang, 2022). For the scope of this research, we are interested in using EC-Earth4 in the AOGCM configuration, including the atmospheric (OpenIFS) and ocean (NEMO4) components of the model, with the sea-ice model SI^3. To balance simulation length and computational cost, a low-resolution of the model will be used, with TL63L31-ORCA2Z31 grid. This configuration will have approximately 2.8° x 2.8° grid resolution for the atmosphere and 2° x 2° for the ocean, with 31 vertical levels.

Since the previously mentioned model version is still under development, it may not be ready for the planned experiments during the first project year. In that case, we plan to perform the simulations using SPEEDY-NEMO. SPEEDY-NEMO (Kucharski et al. 2016; Ruggieri et al. 2024) is an intermediate complexity model, which combines the Simplified Parametrizations primitivE-Equation Dynamics model for the atmosphere (SPEEDY) with model NEMO version 3 for the ocean, using LIM2 for sea-ice. The atmosphere will be run in the T30L8 configuration, while the ocean grid will have a resolution of almost 2°. Although the atmospheric model SPEEDY is simplified with respect to OpenIFS, the ocean configuration is similar in terms of spatial resolution and physical parametrizations. It should be able to reproduce the main oceanic mechanisms while retaining a low computational cost, such as decreasing of the AMOC strength and Antarctic Bottom Water (AABW) formation rate in response to CO2 concentration increase.

2.2 Simulations

To answer question *Q1*, we plan to perform idealized abrupt simulations, starting from pre-industrial conditions, at different forcing levels in the first year. Abrupt simulations, contrary to transient ones, allow for a better separation of short and long timescales. Specifically, we will perform 5 simulations, in addition to the pre-industrial control. The first four forcing levels will be respectively 0.5x, 2x, 4x, 8x. The last simulation will be performed under the abrupt4xto1x protocol of NonLinMIP (Good et al. 2016).

- *AbruptNxCO2*, N=0.5, 2, 4, 8: CO2 concentration is abruptly N-fold increased, then held constant up to the end of the simulation. The combination of these simulations allows us to diagnose a possible non-linear response.
- *Abrupt4xto1x*: the simulation is initialized from year 100 of the abrupt4xCO2, then CO2 concentrations are abruptly returned to pre-industrial levels and held constant up to the end of the simulation. This simulation will count as 1xCO2, further allowing us to explore a role for the direction of the forcing change.

To simplify comparison between the different experiments, all simulations will be run for 5000 years. Experiment length will eventually change depending on the effective achievement of a stable climate condition.

To answer question *Q2*, we plan to perform sensitivity experiments to enlighten the role of changes in the Meridional Overturning Circulation in the second year. We select the abrupt4xCO2 described in the previous step as reference perturbed state. Then, we would like to apply the same procedure followed by Bellomo and Mehling (2024), implementing a reversed water-hosing experiment to prevent the decrease of the Atlantic Meridional Overturning Circulation (AMOC), while perturbing CO2 concentrations. To artificially keep the AMOC strength at values comparable to the preindustrial ones, a uniform virtual positive salinity flux is added in the Atlantic and Arctic Oceans. The simulation will be compared to the reference 4xCO2 to assess the impact of the AMOC decline on the deep ocean response. An analogous experiment will be performed in the Southern Ocean to artificially control the formation of AABW and counterbalance the effects of CO2 increase.

Lastly, we will test if other transport mechanisms could be relevant in determining the efficiency of the heat transport, considering the parametrized components of advection and diffusion. This takes inspiration from studies regarding the tuning of the atmospheric model component, with a particular focus on cloud parametrizations (Mauritsen et al. 2012; Golaz et al. 2013; Fabiano et al. in prep). The experiments will be characterized by an abrupt quadrupling of CO2 concentration and a perturbation of one ocean model parameter, to compare with the previously mentioned abrupt4xCO2 run. Preliminary tests will be necessary to see the effect of parameter changes and to select the proper magnitude of the perturbation, big enough to observe a change in the dynamics, while avoiding the generation of profoundly unphysical worlds. 4 runs will be performed, perturbing 2 parameters in the opposite directions.

3. Justification of the requested computer resources

A proper scaling test for the low-resolution version of EC-Earth4 has not yet been carried out, but preliminary runs on 256 cores show that almost 450 SBU are needed for each simulated year with the TL63L31-ORCA2Z31 configuration. In terms of outputs, 600 MB for the ocean and 50 MB for the atmosphere are needed per simulated year, for a total of 650 MB of monthly values.

On the other hand, on the Atos machine, it is already possible to run simulations with SPEEDY-NEMO, requiring almost 100 SBU per simulated year (ECMWF Special Project BONSAI by A. Bellucci, 2022). We request enough computational resources and storage space to be able to perform the more demanding EC-Earth simulations. If simulations will be run with SPEEDY-NEMO, the leftover hours will be needed to set up and test the hosing experiments, as it will be the first time performing them with this model. An extra number of hours is requested for testing.

	Experiments	**Duration (years)**	**SBU**
Year 1	Pre-industrial control	1000	450,000
	Abrupt0.5xCO2	5000	2,250,000
	Abrupt2xCO2	5000	2,250,000
	Abrupt4xCO2	5000	2,250,000
	Abrupt8xCO2	5000	2,250,000
	Abrupt4xto1x	5000	2,250,000
	Testing	-	500,000
Model years Year 1			26000
SBU Year 1			12,200,000
Storage after Year 1			16,900 GB
Year 2	FixedAMOC-Abrupt4x	5000	2,250,000
	FixedAABW-Abrupt4x	5000	2,250,000
	Parameter testing	150*20= 3000	1,350,000
	Perturbed-Abrupt4x	5000*4= 20000	9,000,000
	Testing	-	500,000
Model years Year 2			33000
SBU Year 2			15,350,000
Storage after Year 2			21,450 GB
Total SBU			27,550,000
Total Storage			38,350 GB

References

Andrews, Timothy, Jonathan M. Gregory, and Mark J. Webb. 2015. “The Dependence of Radiative Forcing and Feedback on Evolving Patterns of Surface Temperature Change in Climate Models.” Journal of Climate 28 (4): 1630–48. https://doi.org/10.1175/JCLI-D-14-00545.1.

Armour, Kyle C., Marshall, John, Scott, Jeffery R., Donohoe, Aaron and Newsom, Emily. 2016. “Southern Ocean warming delayed by circumpolar upwelling and equatorward transport.” Nature Geosci 9, 549–554. https://doi.org/10.1038/ngeo2731

Bellomo, Katinka, and Oliver Mehling. 2024. “Impacts and State-Dependence of AMOC Weakening in a Warming Climate.” Geophysical Research Letters 51 (10): e2023GL107624. https://doi.org/10.1029/2023GL107624.

Bloch-Johnson, Jonah, Maria Rugenstein, Martin B. Stolpe, Tim Rohrschneider, Yiyu Zheng, and Jonathan M. Gregory. 2021. “Climate Sensitivity Increases Under Higher CO2 Levels Due to Feedback Temperature Dependence.” Geophysical Research Letters 48 (4): e2020GL089074. https://doi.org/10.1029/2020GL089074.

Fabiano, Federico, Paolo Davini, Virna L. Meccia, Giuseppe Zappa, Alessio Bellucci, Valerio Lembo, Katinka Bellomo, and Susanna Corti. “Multi-Centennial Evolution of the Climate Response and Deep-Ocean Heat Uptake in a Set of Abrupt Stabilization Scenarios with EC-Earth3.” *Earth System Dynamics* 15, no. 2 (April 30, 2024): 527–46. https://doi.org/10.5194/esd-15-527-2024.

Fabiano, Federico, Chiara Ventrucci, Paolo Davini, Jost von Hardenberg and Susanna Corti "Impact of model tuning on the climate sensitivity of the EC-Earth3 climate model", in prep.

Gjermundsen, Ada, Aleksi Nummelin, Dirk Olivié, Mats Bentsen, Øyvind Seland, and Michael Schulz. 2021. “Shutdown of Southern Ocean Convection Controls Long-Term Greenhouse Gas-Induced Warming.” Nature Geoscience 14 (10): 724–31. https://doi.org/10.1038/s41561-021-00825-x.

Golaz, Jean-Christophe, Larry W. Horowitz, and Hiram Levy II. 2013. “Cloud Tuning in a Coupled Climate Model: Impact on 20th Century Warming.” *Geophysical Research Letters* 40 (10): 2246–51. https://doi.org/10.1002/grl.50232.

Good, Peter, Timothy Andrews, Robin Chadwick, Jean-Louis Dufresne, Jonathan M. Gregory, Jason A. Lowe, Nathalie Schaller, and Hideo Shiogama. 2016. “nonlinMIP Contribution to CMIP6: Model Intercomparison Project for Non-Linear Mechanisms: Physical Basis, Experimental Design and Analysis Principles (v1.0).” Geoscientific Model Development 9 (11): 4019–28. https://doi.org/10.5194/gmd-9-4019-2016.

Gregory, J. M., W. J. Ingram, M. A. Palmer, G. S. Jones, P. A. Stott, R. B. Thorpe, J. A. Lowe, T. C. Johns, and K. D. Williams. 2004. “A New Method for Diagnosing Radiative Forcing and Climate Sensitivity.” Geophysical Research Letters 31 (3). https://doi.org/10.1029/2003GL018747.

Intergovernmental Panel on Climate Change (IPCC), ed. 2023. “The Earth’s Energy Budget, Climate Feedbacks and Climate Sensitivity.” In Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 923–1054. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157896.009.

Jackson, Laura C., Eduardo Alastrué de Asenjo, Katinka Bellomo, Gokhan Danabasoglu, Helmuth Haak, Aixue Hu, Johann Jungclaus, et al. 2023. “Understanding AMOC Stability: The North Atlantic Hosing Model Intercomparison Project.” *Geoscientific Model Development* 16 (7): 1975–95. https://doi.org/10.5194/gmd-16-1975-2023.

Kucharski, Fred, Farah Ikram, Franco Molteni, Riccardo Farneti, In-Sik Kang, Hyun-Ho No, Martin P. King, Graziano Giuliani, and Kristian Mogensen. 2016. “Atlantic Forcing of Pacific Decadal Variability.” Climate Dynamics 46 (7): 2337–51. https://doi.org/10.1007/s00382-015-2705-z.

Lago, Véronique, and Matthew H. England. 2019. “Projected Slowdown of Antarctic Bottom Water Formation in Response to Amplified Meltwater Contributions.” Journal of Climate 32, no. 19: 6319–35. https://doi.org/10.1175/JCLI-D-18-0622.1.

Li, Chao, Jin-Song von Storch, and Jochem Marotzke. 2013. “Deep-Ocean Heat Uptake and Equilibrium Climate Response.” Climate Dynamics 40 (5): 1071–86. https://doi.org/10.1007/s00382-012-1350-z.

Mauritsen, Thorsten, Bjorn Stevens, Erich Roeckner, Traute Crueger, Monika Esch, Marco Giorgetta, Helmuth Haak, et al. 2012. “Tuning the Climate of a Global Model.” *Journal of Advances in Modeling Earth Systems* 4 (3). https://doi.org/10.1029/2012MS000154.

Mitevski, Ivan, Yue Dong, Lorenzo M. Polvani, Maria Rugenstein, and Clara Orbe. 2023. “Non-Monotonic Feedback Dependence Under Abrupt CO2 Forcing Due To a North Atlantic Pattern Effect.” *Geophysical Research Letters* 50 (14): e2023GL103617. https://doi.org/10.1029/2023GL103617.

Newsom, Emily, Laure Zanna, and Jonathan Gregory. 2023. “Background Pycnocline Depth Constrains Future Ocean Heat Uptake Efficiency.” Geophysical Research Letters 50 (22): e2023GL105673. https://doi.org/10.1029/2023GL105673.

Oh, Ji-Hoon, Jong-Seong Kug, Soon-Il An, Fei-Fei Jin, Michael J. McPhaden, and Jongsoo Shin. 2024. “Emergent Climate Change Patterns Originating from Deep Ocean Warming in Climate Mitigation Scenarios.” Nature Climate Change 14 (3): 260–66. https://doi.org/10.1038/s41558-024-01928-0.

Poletti, A. N., D. M. W. Frierson, and K. C. Armour. 2024. “Why Do CO2 Quadrupling Simulations Warm More Than Twice as Much as CO2 Doubling Simulations in CMIP6?” Geophysical Research Letters 51 (10): e2023GL107320. https://doi.org/10.1029/2023GL107320.

Rugenstein, Maria, Jan Sedláček, and Reto Knutti. 2016. “Nonlinearities in Patterns of Long-Term Ocean Warming.” Geophysical Research Letters 43 (7): 3380–88. https://doi.org/10.1002/2016GL068041.

Rugenstein, Maria, Jonah Bloch-Johnson, Ayako Abe-Ouchi, Timothy Andrews, Urs Beyerle, Long Cao, Tarun Chadha, et al. 2019. “LongRunMIP: Motivation and Design for a Large Collection of Millennial-Length AOGCM Simulations.” Bulletin of the American Meteorological Society 100 (12): 2551–70. https://doi.org/10.1175/BAMS-D-19-0068.1.

Rugenstein, Maria, Jonah Bloch-Johnson, Jonathan Gregory, Timothy Andrews, Thorsten Mauritsen, Chao Li, Thomas L. Frölicher, et al. 2020. “Equilibrium Climate Sensitivity Estimated by Equilibrating Climate Models.” Geophysical Research Letters 47 (4): e2019GL083898. https://doi.org/10.1029/2019GL083898.

Ruggieri, Paolo, Muhammad Adnan Abid, Javier García-Serrano, Carlo Grancini, Fred Kucharski, Salvatore Pascale, and Danila Volpi. 2024. “SPEEDY-NEMO: Performance and Applications of a Fully-Coupled Intermediate-Complexity Climate Model.” Climate Dynamics 62 (5): 3763–81. https://doi.org/10.1007/s00382-023-07097-8.

Rye, Craig D., Marshall, John, Kelley, Maxwell, Russell, Gary, Nazarenko, Larissa S., Kostov, Yavor, Schmidt, Gavin A., and Hansen, James. (2020). Antarctic glacial melt as a driver of recent Southern Ocean climate trends. Geophysical Research Letters, 47. https://doi.org/10.1029/2019GL086892