REQUEST FOR A SPECIAL PROJECT 2023–2025

MEMBER STATE: Spain

Principal Investigator[1]**:** Etienne Tourigny

Affiliation: Barcelona Supercomputing Center

Address: Plaça Eusebi Güell, 1-3
08034 Barcelona (Spain)

Other researchers: Yohan Ruprich-Robert, Martí Galí, Joan Llort, Andrea Orihuela, Vladimir Lapin, Saskia Loosveldt, Valentina Sicardi, Eleftheria Exarchou, Raffaele Bernardello, Elif Yilmaz, Etienne Tourigny, Miguel Castrillo

Project Title: Organic Particle Export, Remineralization and Advection in the North Atlantic mesopelagic layer

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SPESICCF**	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2023	
Would you accept support for 1 year only, if necessary?	YES x	NO ☐

Computer resources required for 2023-2025: (To make changes to an existing project please submit an amended version of the original form.)		**2023**	**2024**	**2025**
High Performance Computing Facility	(SBU)	65M	0	0
Accumulated data storage (total archive volume)[2]	(GB)	20000		

Continue overleaf

[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.

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Extended abstract

All Special Project requests should provide an abstract/project description including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used. The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

Following submission by the relevant Member State the Special Project requests will be published on the ECMWF website and evaluated by ECMWF and its Scientific Advisory Committee. The requests are evaluated based on their scientific and technical quality, and the justification of the resources requested. Previous Special Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests exceeding 5,000,000 SBU should be more detailed (3-5 pages).

Motivation

This activity takes place in the context of the Spanish National MICINN project OPERA (Organic Particle Export, Remineralization and Advection in the North Atlantic mesopelagic layer). The resources requested in this ECMWF special computing project will enable us to perform all the simulations planned in the OPERA project.

The mesopelagic layer of the oceans extends between ~200 and 1000 m depth, making it one of the largest ecosystems on Earth [1]. It plays a pivotal role in global biogeochemical cycles and climate [2–5], and hosts a massive biomass of zooplankton and small fish [1]. However, scientific understanding and predictive capacity of biogeochemical processes in the mesopelagic zone are still in their infancy [3–8]. This lack of quantitative understanding has societal and economic costs. Most prominently, it introduces uncertainty in estimates of oceanic carbon storage [2] (which inform policies for the reduction of carbon dioxide emissions), and might soon hamper sustainable management of mesopelagic biological resources that are threatened by imminent exploitation [1].

Mesopelagic functioning depends on the biological transformation and physical transport of organic matter produced by photosynthesis in the overlying sunlit layer of the ocean [4,6]. Every year, around 10 Pg C (10x10^15 g C) enters the mesopelagic zone through gravitational particle sinking, vertical migration of zooplankton, vertical mixing and water mass subduction [6]. Around 90% of this export production flux is consumed by mesopelagic organisms following two main pathways [3,4,7]. A major fraction is degraded by bacteria, consuming oxygen and releasing carbon dioxide and inorganic nutrients [2–5]. A smaller fraction is assimilated by zooplankton and transferred up the detrital food web [3–4], ultimately sustaining larger organisms like fish. Only the remainder of the export flux, around 1 Pg C / year, can sink to deeper layers where carbon can be locked away from atmospheric exchange for centuries [2]. The balance between these competing pathways in the mesopelagic layer influences the redistribution of carbon, as well as nutrients and trace metals essential to marine life, among ocean basins through intermediate-depth waters. Therefore, slight changes in this balance carry important consequences for global climate and ocean productivity [2–5].

However, the carbon flux estimates provided in the previous paragraph suffer from a large uncertainty, possibly >50% [3]. Previous attempts to balance mesopelagic carbon budgets have failed. In particular, estimates of organic carbon consumption generally exceed inputs, sometimes by an order of magnitude or more [3–4], which is physically incompatible with mass conservation. Previous studies suggested that this imbalance might result from insufficient observations. Another source of uncertainty is the poor knowledge of the fluxes and transformations of small suspended particles (smaller than 100 micrometers) [7,8]. Particle transformations and transports occur in a wide range of spatio-temporal scales that are technically impossible to fully observe. In this context, ocean biogeochemistry models informed by the available observations are the best tool at hand to gain detailed understanding of mesopelagic carbon budgets.

Advances in observation of ocean particles with autonomous robots (biogeochemical Argo boats) [9] and a recent key development in the representation of small particles in a state-of-the-art ocean biogeochemistry model (PISCESv2) [7] now enable comprehensive estimates of mesopelagic particulate organic carbon (POC) cycling pathways. The aim of the OPERA project is to quantify mesopelagic POC budgets and constrain their sources of uncertainty, including (1) biological processes represented in PISCESv2, (2) meteorological forcing of upper-ocean mixing and temperature, which exert a strong control on plankton productivity, and (3) the long-neglected role of the horizontal advection of suspended particles. To this end, we will exploit the synergies between model simulations (PISCESv2 coupled with the ocean circulation model NEMO4) and a wide array of POC data collected from ships, satellites, and novel high-resolution observations from biogeochemical Argo boats. OPERA research focuses on the North Atlantic, a region that features wide latitudinal, seasonal and interannual variations in ocean dynamics [10]. The relatively abundant observations of ocean circulation, biogeochemistry and ecosystem functioning make the North Atlantic an ideal testbed for our project.

The OPERA project is linked to the ongoing H2020 projects TRIATLAS (Tropical and South Atlantic climate-based marine ecosystem prediction for sustainable management) and 4C (Climate-Carbon Interactions in the Coming Century) as well as the LaCaixa Junior Leader Fellowship ReSPonSe (Climate predictions performed with a mean bias corrected numerical climate model, with a main focus on the North Atlantic ocean)

Computational Activity proposed

The general objective of the OPERA project is to quantify POC (particulate organic carbon) budgets of the mesopelagic layer of the North Atlantic Ocean, and to constrain their sources of uncertainty. To reach this goal, several numerical experiments with the NEMO4-PISCESv2 model will be performed. The first experiment follows the standard protocol defined in the Ocean Model Intercomparison Project (OMIP2-Tier2) [11]. This will serve as reference for the whole project. It consists in a global simulation of ocean biogeochemistry performed with NEMO4-PISCESv2 (1° resolution - ORCA1 gridand 75 vertical levels) forced by the JRA-55 atmospheric reanalysis (1958-2019). The OMIP protocol requires that the chronology of the observed atmospheric forcing is repeated 5 times to equilibrate the ocean physics (NEMO) and the outputs from a sixth cycle are considered. Here, we couple the ocean physics to ocean biogeochemical fields (PISCES), which can interact with the ocean physical properties (e.g. through sunlight penetration). Ocean biogeochemical fields are slower to equilibrate than physical fields. Simulations performed with the previous version of the model (NEMO3.6- PISCESv1) reached an equilibrium after 20 cycles. Therefore, we plan the need of 26 cycles (20 equilibration plus 6 OMIP2) for the reference simulation of our project, that is a total of 26 cycles x 62 years = 1612 years of NEMO4-PISCESv2 simulation. The last 62 years of the reference simulation will be compared to available observations to evaluate the performance of our model.

As models do not represent all the observed physical and biogeochemical processes, we expect that our model will present biases. To reduce those biases, we will re-run the last 62-year cycle of the reference simulation during which we will constrain the surface POC field of the model to match the observed one using restoring techniques. Two different techniques will be tested to correct for either mean surface POC bias only or both interannual variability and mean state biases. Therefore, for those experiments we will perform a total of 2 cycles x 62 years = 124 years of simulations. By construction, the imposed surface constraint will reduce the surface model biases. We also foresee a reduction of the sub-surface biases through ocean downward vertical transport and mixing. The effectiveness of our bias correction techniques will be evaluated by comparing those restored simulations to our reference simulation and to observations.

Previous research and results from the BSC's ORCAS project (led by one of the contributing scientists in this special project) indicate that the POC residence time in the mesopelagic layer of the ocean depends on the interplay between POC sinking speed, POC degradation by microorganisms ("remineralization"), and interception of sinking POC by zooplankton ("flux-feeders"). Due to a lack of direct observations of those different processes, large uncertainties exist about their relative importance. To quantify their importance, we will perform sensitivity experiments by perturbing these processes in our model within a range of realistic observed values. To do so, we will multiply their model parameter by 0.5 or 2 and sample all the possible combinations, making a total of 26 combinations. For each parameters combination, we will re-run the last cycle of the reference simulation. Therefore, we will perform a total of 27 cycles x 62 years = 1674 years of simulations. Thanks to those thorough sensitivity tests, we will assess the biogeochemical processes that control the mesopelagic carbon content and its turnover times. One of the main working hypotheses of the OPERA project relies on the importance of horizontal advection of mesopelagic POC and on its effects on other biogeochemical fields. To quantify the role of this horizontal advection, we will additionally perform an idealized simulation similar to the reference one but in which the horizontal transport of mesopelagic POC will be suppressed. This experiment consists of one cycle of 62 years = 62 years of simulation.

Finally, the OPERA project aims to quantify the inter-annual variability of the mesopelagic POC. In particular, we assess the role played by the main atmospheric mode of variability, namely the North Atlantic Oscillation (NAO). In this context, several five-year long simulations will be performed in which additional canonical NAO surface heat fluxes (heat, freshwater, and momentum) are added to the JRA-55 historical atmospheric forcing during the first winter and then integrated as for the reference simulation. To take into account the internal variability of the climate system dynamics, 58 ensemble members will be performed from both the positive and the negative phases of the NAO. Therefore, although all members will share the same additional NAO forcing anomalies during the first winter, each member will differ by their initial conditions taken from different dates of the reference simulation and by their full atmospheric forcing, matching the reference simulation period. The ensemble mean of each NAO experiment will be compared to the corresponding period's mean of the reference simulation. The differences will inform us on the mean mesopelagic POC response following on NAO forcing. In total those experiments will require: 5 years x 58 dates x 2 ensembles = 580 years of simulations.

In summary, the experiments planned for the OPERA project require a total of 4052 years of simulation with the NEMO4-PISCESv2 coupled model with a 1° of horizontal resolution and 75 vertical levels. From performance tests, we quantified that 1 year of simulation with this model requires 700 CPU hours. This results in 4,052 x 700 = 2,836,400 CPU hours. Adding a 10% overhead to account for failing jobs that may need to be repeated, we obtain a total of 3,120,040 CPU hours, which corresponds to approximately 60M SBU on the new ATOS machine. Since this is a new machine on which NEMO4-PISCESv2 has not yet been fully tested we would request an additional 5M SBU for testing and optimization. We therefore request a total of 65M SBU for 2023 only.

References:
[1] Martin, A., et al. Nature 580, 26-28 (2020)
[2] Kwon, E. Y., et al. Nat. Geosci. 2, 630–635 (2009).
[3] Burd, A. B. et al. Deep Sea Res. Part II Top. Stud. Oceanogr. 57, 1557–1571 (2010).
[4] Giering, S. L. C. et al. Nature 507, 480 (2014).
[5] Marsay, C. M. et al. Proc. Natl. Acad. Sci. 112, 1089–1094 (2015).
[6] Boyd, P. W., et al. Nature 568, 327 (2019).
[7] Aumont, O. et al. Biogeosciences 14, 2321–2341 (2017).
[8] Alonso-González, I. J. et al. Geophys. Res. Lett. 37, 1–5 (2010).
[9] Claustre, H., et al. Annu. Rev. Mar. Sci. 12, 1–26 (2020).
[10] Henson, S. A., et al. Geophys. Res. 114, (2009).
[11] Tsujino, H., et al. Geosci. Mod. Dev. 13, 1-65 (2020).

Computational algorithms and codes outline

NEMO4-PISCESv2 is composed of NEMO4 (Nucleus for European Modelling of the Ocean, ocean physics component) and PISCESv2 (Pelagic Interactions Scheme for Carbon and Ecosystem Studies volume 2; ocean biogeochemistry component). These two components are interfaced through TOP (Tracers in Ocean Paradigm), which manages the transport of PISCES biogeochemical tracers (chemical and biological variables) according to the physical dynamics (ocean currents and mixing) calculated by NEMO. NEMO4-PISCESv2 fully supports a parallel environment. The model generates outputs in NetCDF formats through XIOS 2.5 (XML Input/Output Server). Restarts are generated at the end of each simulation in a NetCDF format. Bash and Perl are essential for configuring and building the model executable through the Autosubmit workflow manager, thus ensuring bit-to-bit reproducibility of complex experiments. NEMO4-PISCESv2 supports several configurations which have already been tested on various supercomputing platforms, MareNostrum4 among them. In this activity we will use the ORCA1 configuration, which corresponds to a spatial resolution of ~100km in the ocean. In order to store sources and initial data, the experiments require at least 40GB of disk space.

Relevant publications from contributing scientists

Galí, M., Falls, M., Claustre, H., Aumont, O., Bernardello, R. Bridging the gaps between particulate backscattering measurements and modeled particulate organic carbon in the ocean. Under review in Biogeosciences Discussions. https://doi.org/10.5194/bg-2021-201
Falls, M., Bernardello, R., Castrillo, M., Acosta, M., Llort, J., Galí, M. Use of genetic algorithms for ocean model parameter optimisation. Under review in Geoscientific Model Development. https://doi.org/10.5194/gmd-2021-222
Llort, J., Lévy, M., Sallée, J. B. & Tagliabue, A. Nonmonotonic response of primary production and export to changes in mixed-layer depth in the Southern Ocean. Geophys. Res. Lett. 46, 3368–3377 (2019).
Tsujino et al. (including Y. Ruprich-Robert, V. Lapin, V. Sicardi, E. Exarchou, R. Bernardello). Evaluation of global ocean–sea-ice model simulations based on the experimental protocols of the Ocean Model Intercomparison Project phase 2 (OMIP-2), Geosci. Model Dev., 13, 3643– 3708 (2020). https://doi.org/10.5194/gmd-13-3643-2020
Jackson et al. (including Y. Ruprich-Robert). Impact of ocean resolution and mean state on the rate of AMOC weakening. Clim Dyn, 1711–1732 (2020). https://doi.org/10.1007/s00382-020-05345-9