REQUEST FOR A SPECIAL PROJECT 2024–2026

MEMBER STATE: ………………Italy………………………………………………

Principal Investigator[1]: ……………Chunxue Yang……………………………

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Project Title: The Impact of stochastic physics in the North Atlantic Climate

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.	**SP** …………..	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2024	
Would you accept support for 1 year only, if necessary?	YES ☐	NO ☒

Computer resources required for project year:		**2024**	**2025**	**2026**
High Performance Computing Facility	[SBU]	9M	9M	12M
Accumulated data storage (total archive volume)[2]	[GB]			

EWC resources required for project year:		**2024**	**2025**	**2026**
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

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.
[3]The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

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1. Executive Summary

Because of the limitation of earth observations, especially the observation discontinuity and gaps in the deep ocean, numerical models are important tools for ocean and climate studies. However, the computational constraints require reasonable spatial resolution applied in numerical models. For this reason, most ocean models used in climate model projections (such as the CMIP6 models) are still configured at an eddy-permitting resolution (e.g. 1/4° of horizontal resolution), which in turn hampers the eddy population and lifecycle to be fully resolved by the model at mid and high latitudes. To accurately represent these unresolved physical processes, different methods such as multiphysics and perturbed parameter ensembles have been developed, showing that the implementation of these methods can also successfully reduce model biases.

Stochastic physics is an alternative approach that has been developed in atmospheric models to improve the representation of sub-grid processes, namely those processes not explicitly resolved by numerical models due to their limited spatial resolution. Results show that the model biases and forecast errors are reduced, and climate signals such as El Niño Southern Oscillation are better represented with the implementation of stochastic physics. In recent years, the development of stochastic physics is emerging to improve the representation of sub-grid physical processes in the ocean. For example, Juricke et al., 2017 have developed stochastic perturbation schemes to enhance vertical mixing, showing that the representation of low-frequency climate variability is improved.

Recently a stochastic ocean physics package (STOPACK, Storto and Andriopoulos, 2021) has been developed, including three schemes: stochastically perturbed parameterization tendencies (SPPT), stochastically perturbed parameters (SPP) and stochastic kinetic energy backscatter (SKEB) schemes. The implementation of STOPACK in a regional ocean model shows an increase of eddy kinetic energy and a reduction of warm biases in the thermocline layer, due to enhanced vertical mixing.

The North Atlantic Ocean is a critical region for regional and global climate change. The objective of this project is to assess the potential impact of stochastic physics on the North Atlantic climate variability by implementing STOPACK in an eddy-permitting resolution of ocean model, NEMO, with two resolution configurations. In the North Atlantic Ocean, the deep convection in the Labrador Sea plays a significant role in the change of North Atlantic Meridional Overturning circulation (AMOC) which is an essential element in the North Atlantic and global climate. Additionally, the Gulf Stream is located at the eddy active areas and the accurate representation of eddies in ocean models could improve the Gulf Stream path and penetration. The inclusion of stochastic physics in the ocean model could potentially improve the representation of deep convection in the Labrador Sea and Gulf Stream path which are closely related to changes of North Atlantic Ocean dynamics (e.g. AMOC and gyre circulations).

The outcome of the sensitivity experiments performed in this project will advance our understanding of the impact of stochastic ocean physics in the North Atlantic climate change. Meanwhile, the direct and indirect impacts of stochastic ocean physics will be explored by analysing the sensitivity experiments. The scientific findings of this project will benefit the ocean and climate communities not only for the assessment of the importance of stochastic ocean physics in the numerical models, but also to advance our knowledge of the North Atlantic climate dynamics.

2. Research Objectives

2.1 Scientific framework

Due to the limitation of observation technology (e.g. spatial coverage and temporal continuity, deep ocean observations) especially in the ocean, numerical models including ocean general circulation model (OGCM) and Earth system climate models are essential tools for ocean and climate studies. In the last few years, owing to the advancement in computer technology and capacity, the spatial resolution of the numerical models and observations has been increasing to resolve meso-scale eddies (e.g. higher than 1/10° global ocean model) in the ocean. Some global ocean models have resolved submesoscale processes as well. However, due to the high cost of simulations especially for long term simulations for climate studies, most ocean and climate models still do not fully resolve mesoscale and submesoscale processes explicitly. Instead, these unresolved physical processes are usually parameterized. To accurately represent subgrid-scale ocean processes by parameterization is still one big challenge, in both the ocean and climate model communities. Consequently, uncertainties related to parameterized processes remain in the ocean and climate models. In order to account for these uncertainties, several methods have been developed such as multiphysics (Berner et al., 2011) and perturbed parameter ensembles (Murphy et al. 2004).

Another alternative is stochastic parameterization which has been extensively used in atmospheric models to provide forecast errors and uncertainties (Palmer et al., 2005). The implementation of stochastic physics in seasonal forecast models shows an improved representation of unresolved physical processes and a reduction of forecast errors. In terms of climate signals, the implementation of stochastic physics has alternated the mean state and improved the representation of El Niño Southern Oscillation in climate-coupled models (Christensen et al., 2015; Yang et al, 2019).

Recently the development of stochastic parameterization has also emerged in the ocean model (Juricke et al., 2017; Storto et al., 2021). The implementation of these schemes in a stand-alone ocean model (Nucleus for European Modelling of the Ocean, NEMO at 1° resolution) shows that the representation of low-frequency variability has been improved. In particular, Storto and Andriopoulos, 2021 have developed a new STochastic Ocean physics PACKage (STOPACK) implemented in NEMO. Three schemes have been included in STOPACK, which are stochastically perturbed parameterization tendencies (SPPT), stochastically perturbed parameters (SPP), and stochastic kinetic energy backscatter (SKEB) schemes. Sensitivity experiments show that the implementation of the SPPT and SKEB schemes in the model reduces the warm biases near the thermocline owing to the enhancement of upper ocean vertical mixing.

In a previous Special project (spitstor) we focussed on the tuning and extension of the STOPACK stochastic physics package for the CREG025 configuration.

Here, we plan to add a stochastic configuration for the CREG12 configuration and assess in detail the effect of stochastic physics in multi-resolution ensemble experiments, which was not achieved in the spitstor special project for the sake of a lack of resources. Additionally, we will run a short simulation in a corresponding 1/36 configuration (CREG36) as a benchmark for mesoscale resolving / submesoscale permitting ocean model realization.

Up to now, the stochastic ocean physics schemes are implemented either on the regional scale (Storto and Andriopoulos, 2021) or low-resolution stand-alone ocean model (Juricke et al., 2017). Evaluating the impact of stochastic ocean physics on the low-frequency climate variability within higher resolution configurations of ocean and climate models is still lacking. The objective of this project is thus to study the impact of ocean stochastic physics on climate variability focusing on the North-Atlantic-Arctic region by implementing STOPACK developed by Storto and Andriopoulos, 2021 in both ocean stand-alone model (NEMO)

2.2 Project objectives

The North Atlantic-Arctic-Mediterranean ocean is an essential area for regional and global climate change. The ocean's physical processes such as the deep convection (vertical mixing) in the Labrador Sea and the subpolar gyre, and the eddy representation in the Gulf Stream play a crucial role in modulating the North Atlantic Ocean circulations (e.g. North Atlantic Gyre circulation and Atlantic Meridional Overturning Circulation, AMOC) that are crucial for the North Atlantic and global climate. Representing these physical processes accurately in ocean and climate models could improve our analysis and prediction skills of local and global climate variability and climate change.

Currently, the enhanced vertical mixing in the deep convection area of the Labrador Sea is still parameterized and the submesoscale processes in the Gulf Stream region are still not well represented. As previous studies (Juricke et al., 2017 and Storto and Andriopoulos, 2021) have shown, the subgrid-scale variability is enhanced, and the mean state will be alternated with the inclusion of stochastic physics in the ocean model. The implementation of STOPACK in the ocean and climate-coupled models could potentially improve the vertical mixing in the Labrador Sea and subpolar gyre, and submesoscale processes in the Gulf Stream. The change of AMOC plays a significant role in the North Atlantic climate change at the regional scale and the global climate change in general (Buckley and Marshall, 2016; Zhang et al, 2019; and references therein), and the strength of the AMOC is closely related to the deep convection in the Labrador Sea and the change of the Gulf Stream Path. Consequently, the improved representation of subgrid physical processes could potentially improve the representation of AMOC transport.

Previous studies show that the change of the Gulf Stream path has a potential influence on the wintertime North Atlantic storm track and jet variability (Joyce et al., 2019; Reilly et al., 2017). Therefore, the improvement of the Gulf Stream with the inclusion of stochastic physics could have impacts on the atmosphere circulation as well.

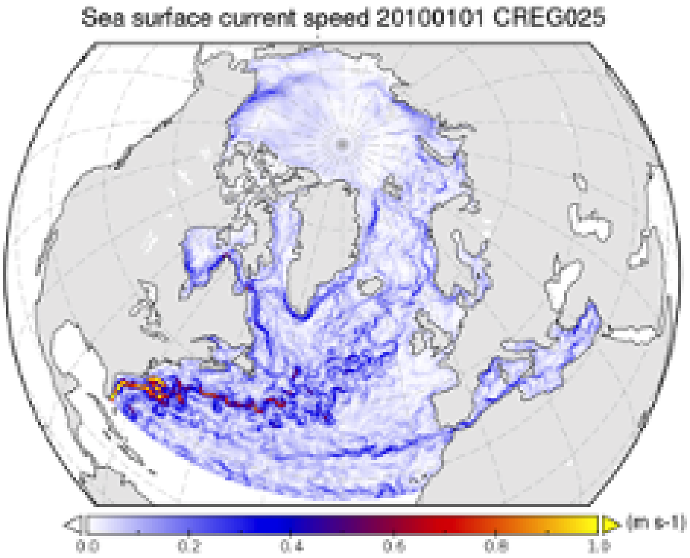

Figure 1. A snapshot of surface current speed from the CREG025 configuration, showing its computational domain covering the North Atlantic (north of 26°N), the Mediterranean and the Arctic Seas (bounded by the Dardanelles and the Bering Strait, respectively)

2.3 List of milestones

M1 Identification of best-performing domain decomposition through scalability tests in the NEMO configuration (M2)
M2 Assessment and evaluation of ensemble experiments performed with CREG025 (M24)
M3 Assessment and evaluation of CREG12 experiment (M30)
M4 Extension of CREG36 experiment (M36)

2.4 Theoretical and computational methods employed

NEMO is a primitive equation ocean model that prognoses sea surface height, ocean currents, and temperature and salinity fields. It is coupled to a dynamic-thermodynamic sea-ice model, SI3, which is formulated with multiple categories of sea-ice, and embeds elasto-visco-plastic sea-ice rheology. NEMO is a state-of-the-art ocean model featuring advanced options, such as complete TKE equations for the vertical mixing closure, non-linear free surface formulation, time-varying coordinate systems, advanced surface and boundary condition options, high order numerical schemes, advanced I/O management and many more. Please see https://forge.ipsl.jussieu.fr/nemo/chrome/site/doc/NEMO/manual/pdf/NEMO_manual.pdf for a complete list of available options and parametrizations.

2.5 List of the applications to be used and their performance on parallel architectures

NEMO has been run since long on parallel architectures, and have been ported onto all the main HPC centres. Scalability tests and performance assessment are publicly available.
For instance, Ticco et al. (2020,https://prace-ri.eu/wp-content/uploads/WP295-Keeping-computational-performance-analysis-simple-An-evaluation-of-the-NEMO-BENCH-test.pdf) reports a performance assessment of NEMO for different global configurations (including the 1/4° and 1/12° configurations. Maisonnave

and Masson (2019, https://cerfacs.fr/wp-content/uploads/2019/01/GLOBC-TR_Maisonnave-Nemo-2019.pdf) report also recent enhancements of NEMO4 to decrease the MPI communication latency in global configurations of NEMO. Note that our grids CREG025 and CREG12 do not require periodic conditions at the North Pole, unlike the global NEMO configurations; this means that such grids are more efficient than the global ones, potentially providing better scalability skills.

2.6 Scalability and load-balancing

We have previously performed tests of scalability of the same NEMO configurations on the ECMWF HPC (cca cluster), running an Intel Xeon cluster. These scalability tests indicated that CREG025 and CREG12 can be run with 216 and 576 cores, respectively, without significant speedup losses, which is the number of cores used at ECMWF to run such configurations. We switched on hyper-threading, as this allows us a larger number of land domain elimination without changing the number of physical cores (the larger is the number of domains, the larger is the proportion of domains falling inland and thus eliminated).

Load-balancing in NEMO is optimized through a dedicated runtime routine. The ocean model indeed embeds a procedure to set up the optimal domain decomposition, with elimination of domains on land, which for a given number of cores finds the best configuration in terms of i) maximum land domains eliminated; ii) minimum memory requirements. More information is provided in the NEMO manual, available at https://forge.ipsl.jussieu.fr/nemo/chrome/site/doc/NEMO/manual/pdf/NEMO_manual.pdf.

3. Computational Approach
3.1 Computation Approach
In terms of computation approach, we will use one numerical ocean model and the details are below.

The numerical ocean model used within the project is NEMO (https://www.nemo-ocean.eu/), in its version 4. NEMO stands for "Nucleus for European Modelling of the Ocean ''. It is a state-of-the-art modelling framework for research activities and forecasting services in ocean and climate sciences, developed by a European consortium. NEMO solves the primitive equations of the ocean and includes a sea-ice dynamical-thermodynamic model as well (SI3). It supports distributed parallelism through the classical horizontal domain decomposition. It has been efficiently ported onto any HPC architecture, including the Intel Xeon clusters.

3.2 Application Packages
The application packages we need for this project are HDF5 parallel and NetCDF4 (with parallel support), which are used by XIOS, the I/O manager used within the NEMO ocean model.

3.3 List of Experiments

Computational costs for the CREG configurations (on cca/ccb) are as follows: 11 650 SBU and 0.01 TB of output data per 1 year of simulation of the CREG025 configuration; 81 600 SBU and 0.1 TB of output data per 1 year of simulation of the CREG12 configuration; 580 000 SBU and 1TB of output data per 1 year of simulation of the CREG36 configuration.

We plan to perform the following experiments:

1) CREG025 10 members 27 years (1993-2020) = 3 146 000 SBU
2) CREG12 10 members 27 years (1993-2020) = 22 000 000 SBU
3) CREG36 1 member 8 years (2013-2020) = 4 640 000 SBU

The total request is therefore 29 786 000 SBU, which we round to 30M SBU. The raw data produced will be around 40 TB, which will be gradually downloaded into the CNR ISMAR local storage facility.

With this set of experiments, we will be able to assess the effect of stochastic physics, and enhanced eddy representation, on the multi-decadal variability of the North Atlantic Ocean. We will also be able, for a shorter period (8 years), to compare the ensemble experiments with a very high-resolution configuration.

References

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