REQUEST FOR A SPECIAL PROJECT 2025–2027

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

Principal Investigator[1]**:** ………Paolo Mauriello………………………

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Project Title: Eddy Predictability and Detection-Tracking models for mesoscale eddies in North Atlantic

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.)	2026	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2026-2028: (To make changes to an existing project please submit an amended version of the original form.)		**2026**	**2027**	**2028**
High Performance Computing Facility	(SBU)	12 M	12 M	12 M
Accumulated data storage (total archive volume)[2]	(TB)	15	25	40

[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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1.Motivation

Numerical forecasts of ocean dynamics are inherently affected by errors that grow with the forecast lead time. Typically, deterministic ocean forecasts remain skilful only up to about **7–10 days**, beyond which errors become too large, rendering predictions less informative than climatological conditions. Mesoscale ocean eddies, characterized by horizontal scales from tens to hundreds of kilometers and timescales from weeks to months, dominate the ocean's energy budget and critically influence the transport of heat, salinity, momentum, and biogeochemical tracers. The current generation of ocean forecasting models is taking two complimentary approaches to improve the quality of the ocean forecasts:

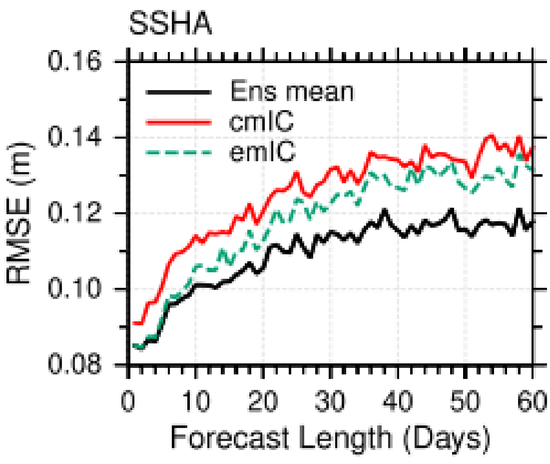
(1) Improving realism of the ocean models, such as increasing model resolution beyond the mesoscale20, inclusion of tides, and coupling between ocean and atmosphere.

(2) Directly accounting for uncertainty in the ocean initial conditions and forecast evolution by using ensembles of model forecast.

Higher resolution models, while providing a more realistic representation of ocean features at scales smaller than the mesoscale, cannot be sufficiently constrained due to sparse observations available to provide necessary coverage. As a consequence, the source of error from the unconstrained scales could lead to larger forecast errors owing to growing dynamical instabilities. Thoppil et al (2021) demonstrated a significant improvement in the ocean forecast can be attained by accounting for uncertainty in the initial conditions: using of a suite of coupled lower resolution (1/12.5°), high-resolution model (1/25°), and ensemble model forecast (1/12.5°), in order to examine the role of each of these model enhancements in improving the ocean forecast.

Recently, however, ensemble (probabilistic) forecasting methods have shown great potential in extending the predictability horizon of mesoscale eddies beyond traditional deterministic limits and studies by Thoppil et al. (2021) and Leroux et al. (2022), who demonstrated that properly configured probabilistic forecasting systems can skilfully predict **mesoscale variability up to approximately 20–40 days**, significantly **surpassing the deterministic forecast limit.**

So, for these reasons, we aim to obtain an **accurate long-range prediction of these eddies is thus crucial for improving operational ocean forecasting and climate projections.**



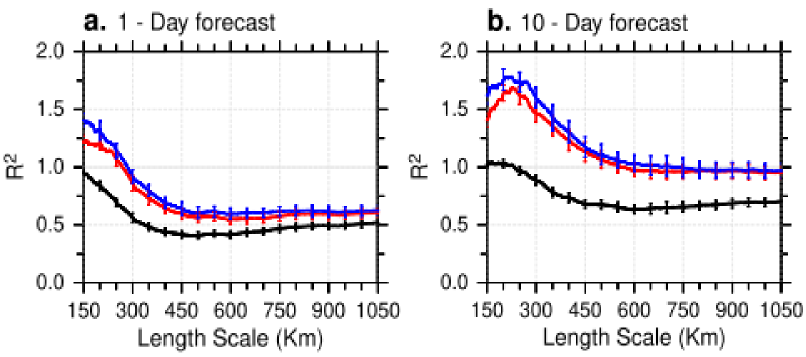
[10] Thoppil et al., 2021

Figure 1. *Divergence of the RMSE for sea surface anomalies (SSHA) between deterministic and ensemble forecasts. Initially (until the deterministic threshold) the ensemble-driven deterministic forecast (emIC, dashed line) presents errors similar to the ensemble forecast itself (black line),*

thanks to the filtering of unpredictable scales. However, as the forecast time progresses, the deterministic error increases rapidly, aligning with the typical error of standard deterministic forecasts (cmIC, red line). The ensemble instead maintains a lower RMSE thanks to the explicit representation of uncertainty (Thoppil et al., 2021).

Ensemble forecasts explicitly account for uncertainty in initial conditions and model parameters, effectively filtering out dynamically unconstrained scales that would otherwise rapidly amplify forecast errors. As illustrated by Figure 1, ensemble forecasts maintain lower root mean square errors (RMSE) over extended periods compared to deterministic forecasts, due to their ability to represent the uncertainty inherent in mesoscale ocean dynamics. Initially, deterministic forecasts initialized from the ensemble mean (emIC) exhibit errors similar to ensemble forecasts, yet rapidly diverge towards higher error values, aligning with typical deterministic model behavior (cmIC) as forecast lead time increases.

Furthermore, the spectral analysis (Figure 2) demonstrates how ensemble forecasts effectively constrain ocean dynamics at scales typically unresolved by deterministic systems. Initially, both deterministic and ensemble systems capture large-scale features adequately, but deterministic systems quickly lose predictive skill at scales below approximately 300 km. The ensemble mean remains skilful across a broader range of spatial scales due to its intrinsic capability to account for uncertainties at smaller scales, preventing error growth from cascading upwards into the larger, dynamically significant mesoscale eddies.



[10] Thoppil et al., 2021

Figure 2. *Spectral analysis (R^2 statistic) highlighting the skill divergence across spatial scales. Ensemble forecasts (black line) maintain predictive skill (R^2<1) at scales significantly smaller than deterministic forecasts (red and blue lines), which fail to adequately constrain mesoscale and submesoscale variability due to initial uncertainties. (Thoppil et al., 2021).*

Building upon these insights, this project aims to comprehensively investigate optimal methods for generating ensemble forecasts and their effectiveness in extending the predictability horizon of mesoscale eddies. The goal is to systematically evaluate how different resolutions, ensemble generation strategies, and stochastic parameterizations contribute to improving long-range forecasts of mesoscale structures in the North Atlantic region using the **NEMO (4.0.7 version)** ocean model.

Our analyses will employ satellite altimetry data (AVISO DUACS, AVISO SWOT MIOST) and advanced statistical techniques, such as spectral error analysis, object-based eddy detection (py-eddy-tracker; Mason et al., 2014), and probabilistic forecast skill metrics (CRPS, RMSE).

In this context, this project proposes to critically assess and optimize ensemble forecasting strategies for mesoscale eddy predictability. Through targeted numerical experiments using the NEMO ocean model across a hierarchy of resolutions (CREG025, CREG12, and CREG36), and by leveraging state-of-the-art validation tools (py-eddy-tracker, CRPS metrics, eddy-matching algorithms), we aim to quantify the gain in forecast skill and the extended predictability range afforded by ensemble systems.

2. Objectives

2.1 Scientific Framework

The predictability of mesoscale ocean eddies is fundamentally limited by nonlinear growth of initial errors arising from uncertainties in initial conditions and unresolved subgrid-scale processes. Deterministic high-resolution ocean models, despite resolving mesoscale dynamics explicitly, typically exhibit rapid degradation in forecast accuracy after about 7–10 days due to chaotic dynamics and insufficient observational constraints, particularly in subsurface regions (Thoppil et al., 2021).

Ensemble forecasting addresses these limitations by providing a probabilistic approach to prediction, capturing uncertainties through perturbed initial conditions and stochastic parameterizations. Leroux et al. (2022) demonstrated through regional ocean ensemble experiments that introducing stochastic perturbations significantly improves the ensemble spread, progressively filtering out unconstrained smaller scales and enhancing the accuracy of mesoscale forecasts over extended time periods.

Using NEMO 4.0.7 at different nested resolutions (CREG025, CREG12, and CREG36), the project will explore how spatial resolution and stochastic methods contribute to forecast skill and mesoscale predictability. The validation framework will rely on advanced feature-based verification methods using the py-eddy-tracker software (Mason et al., 2014), (Pegliasco et al., 2022) and satellite altimetry data (AVISO DUACS, AVISO SWOT MIOST Science), enabling systematic and objective evaluation of forecast performance. This project seeks to:

1. Identify and optimize ensemble configurations that maximize the predictive skill of mesoscale eddies.
2. Evaluate the role of model resolution in influencing ensemble forecast accuracy and uncertainty quantification.
3. Utilize advanced feature-based verification methods, employing the py-eddy-tracker software (Mason et al., 2014) and satellite-based observations (AVISO, SWOT), to systematically validate ensemble forecasts.
4. Ultimately, the scientific framework developed here will quantify the extent to which ensemble approaches can reliably predict mesoscale eddies beyond traditional deterministic forecasting horizons. Results will provide critical guidance for future developments in operational ocean prediction systems, enabling more accurate, reliable, and extended forecasts of mesoscale ocean variability.

The project's central aim is to evaluate how different ensemble strategies—based on perturbed initial conditions, even stochastic physics, and varying model resolutions—contribute to the forecast skill and predictability of mesoscale eddies. So, we will try to suggest that advancements in ensemble analysis and forecasting should complement the focus on high-resolution modelling of the ocean.

2.2. Validation and Verification Strategy

In order to evaluate in a rigorously way the model performance, we will use the open-source tool **Py-Eddy-Tracker** (Mason et al., 2014), (Pegliasco et al., 2022) which allows automated detection and tracking of eddies in both model output and observational datasets (e.g., AVISO DUACS and AVISO SWOT MIOST Science).

The validation framework will include:

- One-to-one matching between modeled and observed eddies (Smith et al., 2022);
- Metrics based on eddy characteristics (position, amplitude, radius, lifetime);
- Probabilistic verification (e.g., CRPS, location scores, spread-skill diagnostics), following the methodology of Leroux et al. (2022), to assess the degradation of forecast skill over time.

This evaluation will allow us to quantify how ensemble spread and structure relate to forecast reliability, and how ensemble strategies can extend the effective prediction range of eddy-resolving systems. To further evaluate the capability of different model resolutions (CREG configurations) in representing mesoscale eddies, we will employ advanced diagnostic tools such as spectral error analysis and feature-based validation.

3. Computational Approach

3.1 Computational Approach

The numerical core of this project will be based on the **Nucleus for European Modelling of the Ocean (NEMO)**, version 5.0 NEMO solves the primitive equations for ocean circulation and includes advanced modules for sea-ice (SI3), vertical mixing (TKE closure), sub-grid scale parameterizations, and surface fluxes, to explicitly represent mesoscale eddies and their predictability, three configurations will be employed over the North Atlantic domain:

- **CREG025** (1/4° resolution, eddy-permitting)
- **CREG12** (1/12° resolution, eddy-resolving)
- **CREG36** (1/36° resolution, submesoscale-permitting benchmark)

The project's central aim is to evaluate how different ensemble strategies—based on perturbed initial conditions, stochastic physics, and varying model resolutions—contribute to the forecast skill and predictability of mesoscale eddies.

The output diagnostics will be handled via the **XIOS I/O server**, using parallel NetCDF and HDF5 libraries.

Each model configuration will be integrated as a probabilistic ensemble to sample uncertainty in eddy initialization. Ensemble forecasts will be initialized from perturbed initial conditions, complemented by stochastic tendencies during integration to capture growth of forecast error at mesoscale scales.

The project adopts the verification framework developed in recent studies (Leroux et al., 2022; Smith et al., 2022; Mason et al.,2014) to **quantify eddy predictability**:

- **Eddy detection** with Py-Eddy-Tracker (Mason et al., 2014) on both model and satellite SLA data (AVISO DUACS, AVISO SWOT MIOST Science).
- **Eddy matching algorithms** to directly pair model-predicted eddies with observed structures.
- **Skill metrics** including position error growth, amplitude forecast skill, lifetime predictability, survival probability, and location-dependent predictability horizons.

These probabilistic diagnostics allow for a direct quantification of the mesoscale eddy forecast horizon, beyond deterministic skill metrics, and enable an objective assessment of ensemble forecast performance.

3.2 Scalability and HPC Approach

NEMO's scalability on HPC systems, especially in high-resolution configurations, remains largely controlled by the cost of MPI communications. Several scalability studies have demonstrated that the most limiting factor arises from the frequent **halo exchanges and global collective communications**, which dominate runtime at high core counts. In particular Maisonnave & Masson (2019) systematically identified the MPI communication bottlenecks in NEMO 4.0.7 using code instrumentation, highlighting:

- The major role of **North Polar folding exchanges** (tri-polar grid topology) on communication overhead, especially for ORCA025 and ORCA12 grids.

- The imbalance of computation across MPI ranks due to the extra work in polar regions.
- Significant gains in scalability (up to 40%) can be achieved through optimizations such as reduced halo exchanges, grouping of collective communications, and more efficient handling of SI3 sea-ice communications.

Although many of these improvements are being progressively integrated in the NEMO main branch, this proposal will benefit from the most recent optimizations for load balancing, land masking, halo exchange minimization, and parallel I/O performance.

Benchmarking results indicate:

- **CREG025** has been benchmarked at ~200–250 cores.
- **CREG12** shows good scalability up to ~600 cores.
- **CREG36** can efficiently exploit 1000+ cores, depending on domain decomposition and halo size.

The ensemble structure will fully exploit ECMWF's parallel architecture, minimizing I/O bottlenecks via XIOS with NetCDF4-HDF5 parallel output.

3.3 Computational Costs and Data Storage

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.

To support long-range, ensemble-based experiments with flexibility for sensitivity analyses and resolution scaling, we request the following computing resources:

Configuration	**Years**	**Ensemble Members**	**SBUs**	**Output Data**
CREG025	27 years (1993–2020)	10	3,146,000 SBU	0.01 TB/year
CREG12	27 years (1993–2020)	10	22,000,000 SBU	0.1 TB/year
CREG36	8 years (2013–2020)	1	4,640,000 SBU	1 TB/year

- Total estimated computing resources over 3 years: ~30.0 million SBUs
- Total expected archived data volume: ~40 TB, but only 3.5 TB for model output dataset.

To accommodate experimental margins and contingency, the request is intentionally set 20% above minimum requirements, ensuring room for ensemble extensions, parameter tuning, and test re-runs.

While only 3.5 TB will be archived long-term, the raw data produced during simulations is expected to reach ~40 TB. These data will be downloaded progressively to CNR-ISMAR's local HPC storage infrastructure, ensuring long-term accessibility for reanalysis and eddy verification studies.

Assumptions: evenly distributed simulations, with an acceleration in the first 12–18 months (e.g. CREG025 and part of CREG12), and completion of the bulk by the second year. Output of the third year is mainly for CREG36 and final analyses.

This setup will enable:

- Quantification of the impact of physics and resolution on eddy statistics and North Atlantic variability;
- Comparison between multi-member ensembles and a high-resolution benchmark (CREG36) over a shared 8-year period (2013–2020).

3.4 Software and Libraries

- NEMO 4.0.7 ocean model (https://www.nemo-ocean.eu/)
- Py-Eddy-Tracker (https://github.com/AntSimi/py-eddy-tracker)
- STOPACK stochastic physics module
- Parallel I/O: NetCDF4 + HDF5 + XIOS.

4.References

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12. Yang, C., Bricaud, C., Drévillon, M., Storto, A., Bellucci, A., & Santoleri, R. (2022). The role of eddies in the North Atlantic decadal variability. *Frontiers in Marine Science, 9*, 781788. https://doi.org/10.3389/fmars.2022.781788

The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

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.

Following submission by the relevant Member State the Special Project requests will be published on the ECMWF website and evaluated by ECMWF as well as the Scientific Advisory Committee. The evaluation of the requests is based on the following criteria: Relevance to ECMWF's objectives, scientific and technical quality, disciplinary relevance, and 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 asking for 1,000,000 SBUs or more should be more detailed (3-5 pages). Large requests asking for 10,000,000 SBUs or more might receive a detailed review by members of the Scientific Advisory Committee.