

# SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

|                                                  |                                                                                                                                       |
|--------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| <b>Project Title:</b>                            | CASCADE (Coupled regional coAStal oCeAn moDel Ensembles)                                                                              |
| <b>Computer Project Account:</b>                 | spgrver2                                                                                                                              |
| <b>Start Year - End Year :</b>                   | 2022 - 2024                                                                                                                           |
| <b>Principal Investigator(s)</b>                 | Vassilios D. Vervatis (1), Pierre De Mey-Frémaux (2)                                                                                  |
| <b>Affiliation/Address:</b>                      | (1) National Kapodistrian University of Athens (UoA)<br>(2) Laboratoire d'Etudes en Géophysique et<br>Océanographie Spatiales (LEGOS) |
| <b>Other Researchers<br/>(Name/Affiliation):</b> | Sarantis Sofianos (1), Nadia Ayoub (2)                                                                                                |

The following should cover the entire project duration.

## Summary of project objectives

(10 lines max)

The ECMWF Special Project resources were used to support the R&D activities of the University of Athens (Greece) and LEGOS/CNRS (France) teams, in a joint research Copernicus Marine project named MULTICAST (<https://marine.copernicus.eu/about/research-development-projects/2022-2024/MULTICAST>), within the CMEMS Service Evolution framework. The project aimed at strengthening CMEMS in the areas of ocean uncertainty modelling, consistency verification and multigrid ensemble data assimilation. The work focused on the development of an ensemble ocean data assimilation system, using two-way coupled high-resolution parent-child nested domains for the Bay of Biscay, as a case study for the CMEMS SE and the future capabilities of CMEMS Modelling and Forecasting Centers (MFCs).

## Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

The only minor problem we encountered was the migration procedures that took place at ECMWF premises from the old CRAY machine at Reading, UK, to the new ECMWF ATOS machine at Bologna, IT. During that period, we reinstalled and recompiled our modelling system in the new environment, transferring all our data and archives from all users. We are thankful to the ECMWF technical and scientific advisory committee for their help during the project, solving promptly all issues.

## Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

The use of the ECMWF HPC Facilities was very important, to complete successfully the joint CMEMS research project mentioned above. All administrative issues were easy to follow.

## Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

In this section, we give a short summary of the project. For a more detailed description the reader is referred to the previous SP reports, and to the [Zenodo Documents and Science Repositories provided at the end of this report](#).

The project addresses, in a parent-child 1-way and 2-way nested dynamical model configuration, the assessment of the forecasting skill as well as the formulation of the multigrid control vector for data assimilation. In a first step, we set up a dual-grid configuration to generate Ensembles, using appropriate hypotheses for sources of error in the wind forcing and the Open Boundary Conditions (OBCs). The dual-grid resolutions considered here are  $1/36^\circ$  for the Bay of Biscay parent domain and  $1/108^\circ$  for the child domain. In a second step, we define Ensemble-based forecasting metrics aimed at assessing the added value of downscaling and local grid refinement for nested high-resolution forecasting. In a third step, we focus on data assimilation methods, performing incremental analysis to assess the added value of multigrid Ensemble covariances for analysis and forecasting.

Overall, the most important findings of the project are:

- Among the configuration elements that could possibly make discrimination non-conclusive between various experiments, are the size, dispersion and reliability of the Ensembles, the variables considered, and the dependence on the regime.

- Identifying an Ensemble as under/over-dispersive it is not entirely related to the Ensemble size. Whatever the cause of the weak dispersion, Richardson (2001)<sup>1</sup> gives an estimate of the CRPS sampling error due to ensemble size.
- When downscaling perturbations in a 1-way or 2-way nested Ensemble DA system, we find that domain scale parent uncertainties are not sufficient to generate enough spread in both grids, for reasons possibly specific to the Bay of Biscay dynamics, as well as to the AGRIF configuration.
- The optimal stochastic perturbation strategy is to generate local uncertainties in both grids. We adopt the same d.o.f's in both grids, eliminating the problem of having discontinuities in the child boundaries.
- We were able to show that a meaningful benefit of 2-way nested DA could be conclusively identified over the first week of the forecast, confirmed by the analysis of the CRPS and the RMSD trends.
- The Ensemble DA with the best performance, for both the parent and the child, is the 2-way nesting configuration with AGRIF and observations on both grids, and simultaneous multigrid assimilation with multigrid covariances and control vector.
- Another result is that, in the 2-way nested system where the parent assimilates, the benefit of the child assimilating its own observations is clearly felt for both the child and the parent.

## List of publications/reports from the project with complete references

The most recent communications of the SP final year (acknowledging the ECMWF SP resources) are:

### Journals

Edwards, C.A., P. De Mey-Frémaux, et al., (2024). Assessing the impacts of observations on ocean models in coastal and shelf sea environments, *Front. Mar. Sci.* 11:1458036, <https://doi.org/10.3389/fmars.2024.1458036>.

Vervatis, V., P. De Mey-Frémaux, et al., (2025). Regional ocean model uncertainties using stochastic parameterizations and a global atmospheric ensemble, *Ocean Modelling*, 194:102501, <https://doi.org/10.1016/j.ocemod.2025.102501>.

### Conferences

De Mey-Frémaux, P., V. Vervatis, B. Lemieux-Dudon, (2025). Coupled multi-grid stochastic modelling and data assimilation and their impact on regional/coastal forecasting in the Bay of Biscay, 10<sup>th</sup> COSS-TT International Coordination Meeting meeting, Ifremer, Brest-Plouzané, 17-20 June, 2025, <https://oceanpredict.org/archived-events/op-task-team-meetings/coss-tt-meetings/coss-tt-meeting-june-2025/#section-overview-and-meeting-objectives>.

### Zenodo Documents & Science Repositories

*(this section includes links to Zenodo documents with details for the assimilation approach, complementing the information provided in this SP final report)*

De Mey-Frémaux, P., and V. Vervatis, (2024). MULTICAST Tools Quick Reference Sheet and Users Guide (v1.0). Zenodo. <https://doi.org/10.5281/zenodo.11067905>.

De Mey-Frémaux, P., and V. Vervatis, (2024). MULTICAST Configurations and Tuning Quick Reference Sheet (v1.0). Zenodo. <https://doi.org/10.5281/zenodo.11073137>.

<sup>1</sup> Richardson, D.S., (2001). Measures of skill and value of ensemble prediction systems, their interrelationship and the effect of ensemble size. *Q.J.R. Meteorol. Soc.*, 127: 2473-2489. <https://doi.org/10.1002/qj.49712757715>.

De Mey-Frémaux, P., (2024). Multigrid analysis implementation in SDAP 1.7 (v1.0). Zenodo. <https://doi.org/10.5281/zenodo.12771900>.

SDAP public code: (licenses: GNU-GPL v3 and CeCill v2) <https://sourceforge.net/p/sequoia-dap/code/HEAD/tree/branches/>.

MULTICAST (private repository; access upon request), including NEMOv4.2-AGRIF configuration files, scripts to run SDAPv1.7 `scrumcat` tools and python notebooks for visualisation: <https://github.com/willverv/CMEMS-SE-MULTICAST.git>.

## Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

We plan to continue our work on stochastic ocean modelling in coastal and regional domains, since we participate in the Working Group entitled “*Machine Learning and Uncertainty Modelling for NEMO*”.