SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2023
Project Title:	CASCADE (Coupled regional coAStal oCeAn moDel Ensembles)
Computer Project Account:	**SPGRVER2**
Principal Investigator(s):	Vassilios D. Vervatis (1), Pierre De Mey-Frémaux (2)
Affiliation:	(1) National Kapodistrian University of Athens (UoA). (2) Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS).
Name of ECMWF scientist(s) collaborating to the project (if applicable)	Sarantis Sofianos (1), Nadia Ayoub (2).
Start date of the project:	05/04/2022
Expected end date:	31/12/2024

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		**Current year**	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(MSBU)	2,5	-	2,5	-
Data storage capacity	(TB)	2,5	-	2,5	-

Summary of project objectives (10 lines max)

The requested resources in this ECMWF Special Project are 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), submitted on March 2022 and awarded in June 2022, within the CMEMS Service Evolution framework. This ECMWF SP and the MULTICAST project aim at strengthening CMEMS in the areas of ocean uncertainty modelling, empirical ensemble consistency verification and multigrid ensemble data assimilation. Our work is based 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 (10 lines max)

Because of the migration procedures that took place last year at ECMWF premises from the old CRAY machine at Reading, UK, to the new ECMWF ATOS machine at Bologna, IT, we had to reinstall and recompile our modelling system and tools in the new environment, transferring all of our data and archives from all users, and finally reassessing the computational resources for the rest of the project (for free Ensembles, as well as for DA Ensembles).

Summary of plans for the continuation of the project (10 lines max)

This ECMWF SP supports the R&D activities of the awarded Copernicus Marine research project MULTICAST for the years 2022-2024 and therefore, we expect that we will continue the SP also for the next year 2024.

List of publications/reports from the project with complete references

Vervatis, V., P. De Mey-Frémaux, N. Ayoub, M. Ghantous and S. Sofianos, Multigrid nested ocean ensembles using stochastic modelling, 9thCOSS-TT-ICM, Montréal, Canada, 2-4 May 2023.

De Mey-Frémaux, P., 2023: Predictability of the Coastal Ocean. 2023 Coastal Ocean Dynamics Gordon Research Conference "Coastal Ocean Physics and its Connections to Marine Ecosystems", Bryant University, Smithfield, RI, USA, June 18 - 23, 2023.

Vervatis, V., 2022: MULTICAST on GitHub repository (invitation upon request) https://github.com/willverv/CMEMS-SE-MULTICAST.

De Mey-Frémaux, P., 2023: SDAP 1.7 repository on Sourceforge (multigrid version of EECA "SCRUMCAT" tools) https://sourceforge.net/p/sequoia-dap/code/HEAD/tree/branches/1.7/.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

In brief, we have developed a prototype dual-grid parent-child configuration for the Bay of Biscay named BISCAY36, derived from the IBI36 MFC grid. **Figure 1a** shows the BISCAY36 parent domain (res: 1/36° ~ 2.5 km) and **Fig. 1b** the child zoom area as a 1:3 refinement (i.e., res: 1/108° ~ 750 m) of BISCAY36. The prototype configuration has been installed at ECMWF ATOS HPC facilities, and deterministic and Ensemble runs have been performed successfully for online 1-way and 2-way nesting.

In **Table 1**, we summarize the Multi-Grid (MG) Ensemble simulations currently performed in MULTICAST. The stochastic approach of the Target Operational Protocols (TOPs) for Ensemble generation permits the investigation of physical uncertainty processes transmitted through Open Boundary Conditions (OBCs) and in response to wind forcing model errors. Interim results focus on the following ocean physics processes and their model uncertainties:

- The intrusion of the warm Iberian Poleward Current (IPC) during winter along the continental slope. This is an ocean process forced outside the parent and child areas. IPC model errors are introduced in the OBCs of the child, controlling the mesoscale eddy activity and the IPC meanders in the open ocean.
- Upper-ocean properties regulated by atmospheric fluxes and re-stratification processes, such as the shoaling of the seasonal-thermocline during spring. When the stratification is strong, wind forcing uncertainties can impact also other upper-ocean processes, such as for instance upwelling.

Table 1. Target Operational Protocols (TOPs)	
Ocean modelling	• Parent domain res. 1/36° ~ 2.5 km • Child domain res. 1/108° ~ 750 m • Ocean model physics as eNEATL36 https://github.com/immerse-project
Stochastic methods	• SPPT-AR1 u,v-wind perturbations. Common parent-child stochastic parameterizations • Ensemble members 20+1 (one member to be used for synthetic obs. in a quasi-reliable set up) • Two periods winter/spring-2017, 30-day medium-range Ensemble forecasts
Ensembles	**Parent-child coupling method & stochastic protocol**
TOP0	• Coupling: 1-way • Perturbing the wind only for the parent • Downscaled child model errors via OBC (no upscale)
TOP1	• Coupling: 1-way • Perturbing the wind for the parent and the child • Downscaled child model errors via OBC (no upscale)
TOP2	• Coupling: 2-way • Perturbing the wind for the parent and the child • Upscaled/downscaled parent/child OBC model errors

Figures 2 and 3 show the ensemble mean and spread of the SST in TOPs during winter (i.e., 20170210) and late-spring (i.e., 20170617). The key findings are:

- During winter (**Fig. 2**), when the mixed layer is deep, model errors are mainly associated with ocean processes forced outside the parent and child areas, in our experimental protocol imposed by OBCs.
    - The physical process demonstrating the SST model errors in TOPs, is the intrusion of the IPC through the western OBC of the child domain and its meanders in the open ocean interacting with the eddy mesoscale activity (**Fig. 2a-b**).

- TOPs reveal similar SST model error patterns in the child domain (**Fig. 2d,e,g**), with moderate increase in spread wrt TOP0 Ensemble (**Fig. 2d**), when local wind perturbations are activated in the child domain (i.e., in TOP1; **Fig. 2e**) and 2-way nesting is activated as well (i.e., in TOP2; **Fig. 2g**).

- A moderate increase in SST spread is observed over the Abyssal plain in the parent domain (**Fig. 2c vs. 2f**), due to upscaling in 2-way coupling (i.e., in TOP2). The increase in Ensemble variance in the parent is believed to result from the addition of the stochastic degrees of freedom of the child.

- Overall, during winter, local wind uncertainties appear to have a moderate secondary role compared to model uncertainties entering the child domain via the OBCs, the latter controlling the ocean error regimes, as demonstrated here with the intrusion of the IPC in the common parent-child area.

- During late-spring (**Fig. 3**), when the shoaling of the seasonal thermocline and upper-ocean re-stratification processes occur, the wind forcing uncertainties and the subsequent ocean model uncertainties appear to have an active role in shaping the error regimes.

    - SST child model errors are visible in the open ocean when local wind forcing errors are active in TOP1 and TOP2, with also notable differences in their error patterns because of the upscaling processes in the 2-way case (**Fig. 3e, g**).

    - In case there are no local wind perturbations in the child domain (TOP0), the SST spread is rather small, mostly visible near the boundaries where OBC model errors are downscaled ("peripheral" pattern of model uncertainties in the child). Model errors in the inner part of the child domain are minimal (**Fig. 3d**), due to local winds being identical across child members.

    - Wind forcing errors are associated with a coastal upwelling event and its model errors observed in the common parent-child coastal area (**Fig. 3c, f and 3e, g**).

    - In the 2-way case, the feedback is carried out from the child over the parent, and the information back-flux imposed by AGRIF offsets the parent dynamics and its error regimes in the common area with the child (**Fig. 3f, g**). The spread increase in the parent over the central part of the abyssal plain is present, albeit with patterns different from the winter situation (**Fig. 2**).

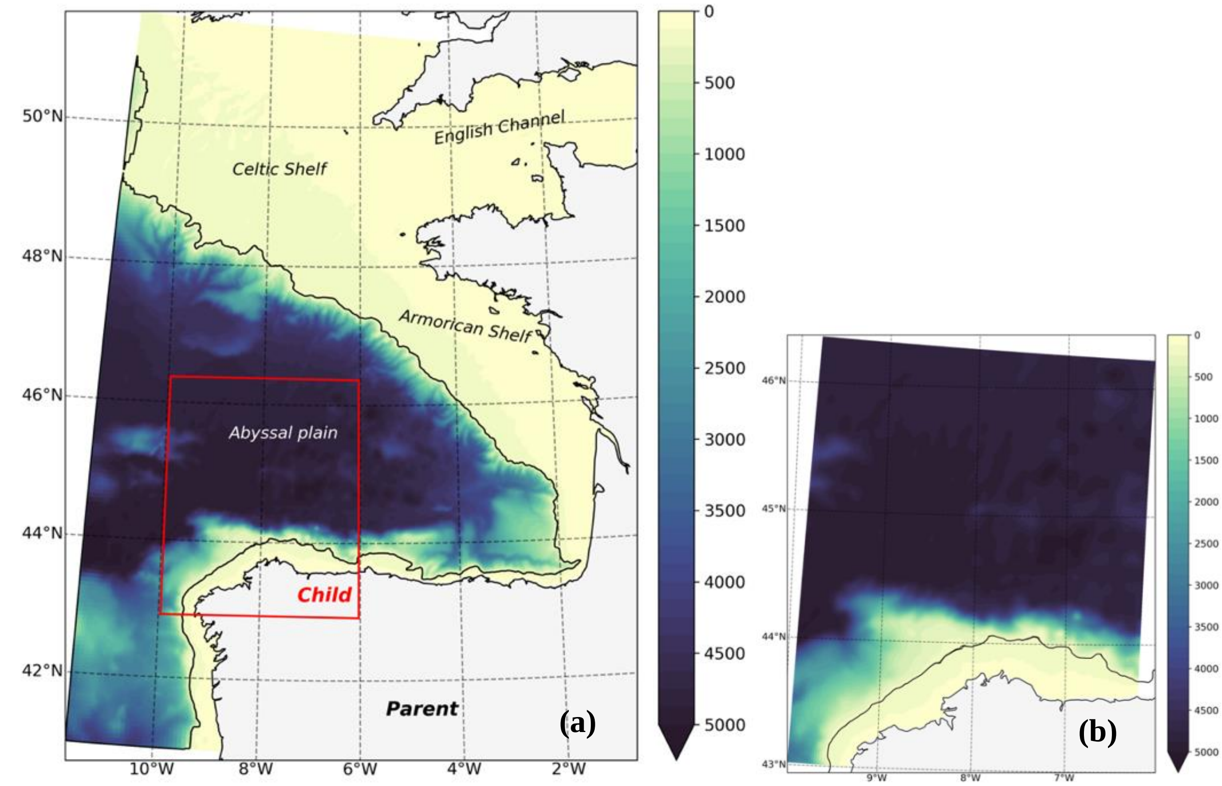

Figure 1: Ocean model "parent-child" dual-grid NEMOv4.2 configuration using the AGRIF library: (a) "parent" BISCAY36 regional domain (1/36°), (b) "child" high-resolution 1:3 refinement (1/108°).

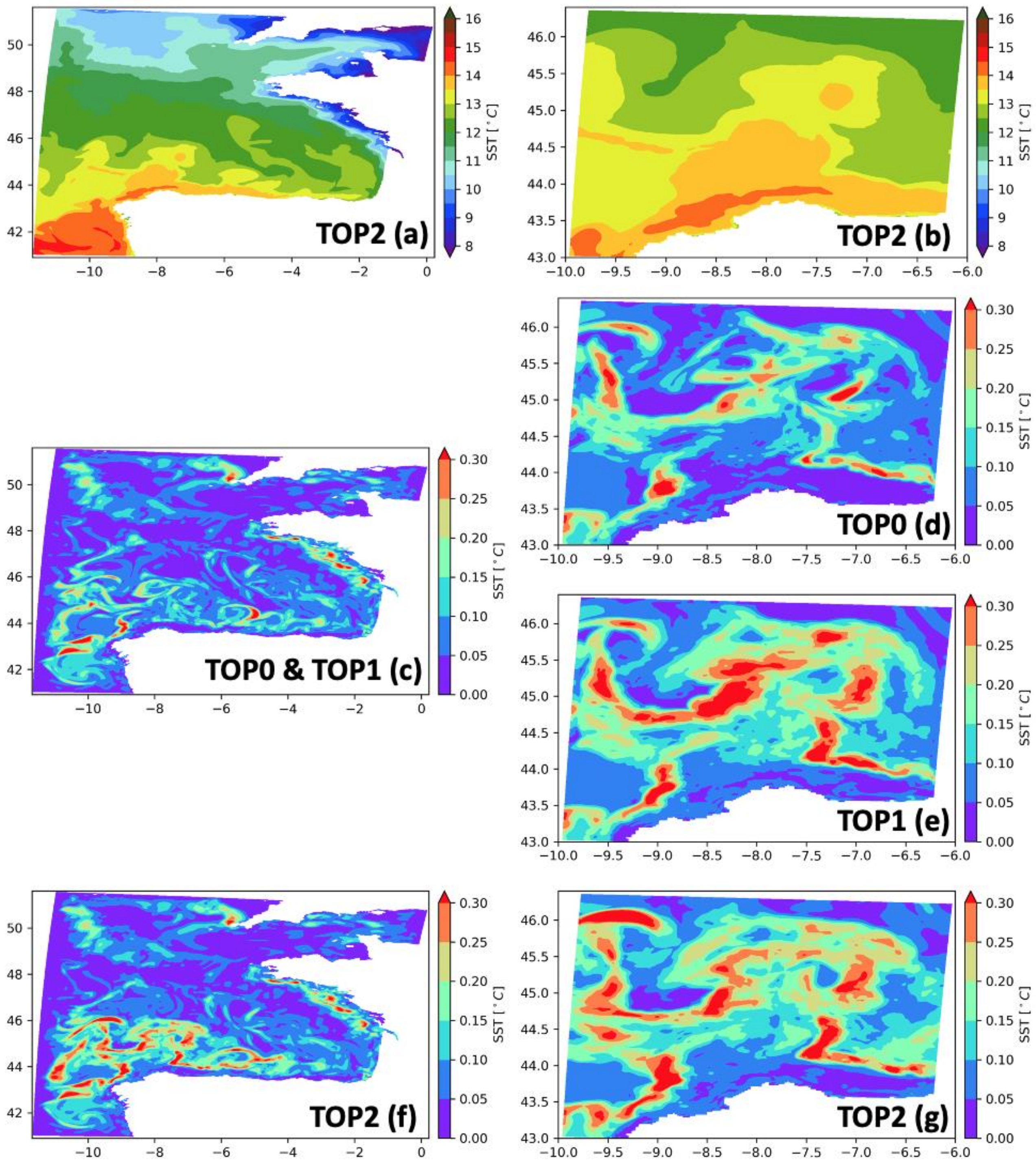

Figure 2: (a-b) parent-child TOP2 Ensemble mean SST (°C), (c-g) parent-child Ensemble spread SST (°C) in all TOPs. Winter period (date: 20170210); Ensemble forecast lead time 30 days.

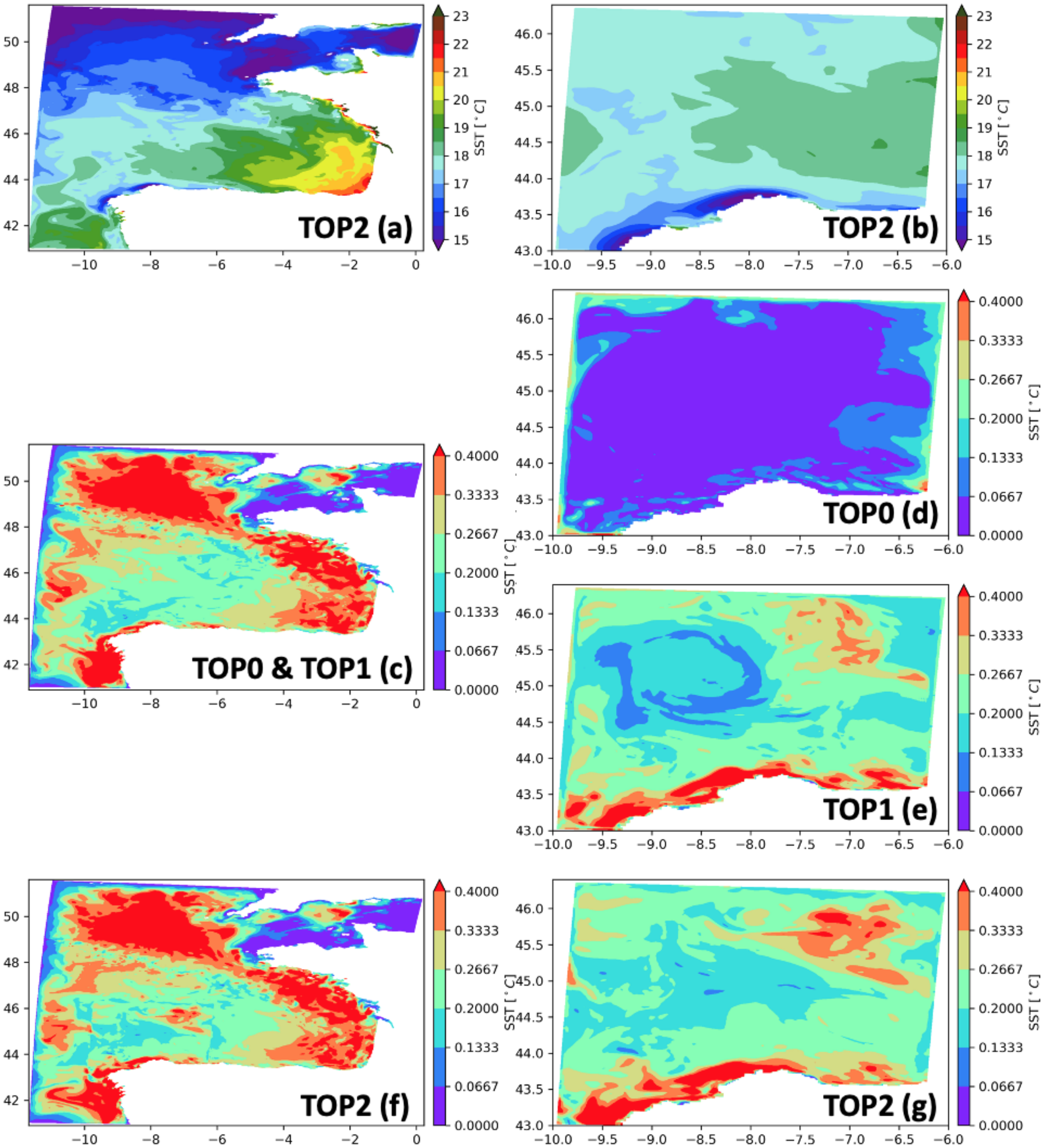

Figure 3: As in **Fig. 2**, for late-spring (date: 20170617); Ensemble forecast lead time 17 days.