SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Enhancing regional ocean data assimilation in high and mid-latitude European seas
Computer Project Account:	spitstor
Start Year - End Year :	2022 - 20.24
Principal Investigator(s)	Andrea Storto
Affiliation/Address:	CNR ISMAR Via del Fosso del Cavaliere 100, 00133 Rome, Italy
Other Researchers (Name/Affiliation):	Chunxue Yang Vincenzo de Toma Davide Cavaliere Giovanni Nunziante

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The project develops along with four main research topics that are summarized below: i) Stochastic physics formulation and experiments, mostly using a North Atlantic-Arctic-Mediterranean configuration of NEMO at multiple resolutions (1/4°, 1/12°, and 1/36°) or the global ORCA configuration of NEMO (at 1° or ¼°); ii) Altimetry data assimilation at high latitudes, focussing on the use of high sampling rate (5Hz) altimetry datasets; iii) coupled data assimilation algorithms, using as a target configuration a regional Earth system model; iv) weak-constraint four-dimensional data assimilation algorithms and testing.

Summary of problems encountered

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

The a* clusters have been found stable and robust; no major problems have been encountered. The compilation of NEMO with XIOS has worked only using the Intel compilers + IntelMPI (the OpenMPI or other implementations did not seem to work); however, this issue has not been investigated further, nor has support to ECMWF analysts been asked, namely there may be easy fixes that we are not aware of.

Experience with the Special Project framework

The Special Project framework works nicely and smoothly and is a fundamental resource for Member States. We have limited in-house computational facilities, and the ECMWF SP is crucial to allow us advancing in our research objectives. Perhaps, the misalignment between the reporting period at the end of June and the duration of the project year (Jan-Dec) could be minimized.

Summary of results

Stochastic physics

We have run 2-year NEMO experiments at multiple resolutions (1/4°, 1/12°, and 1/36°) to estimate the sub-grid variability ("mesoscale" and "submesoscale" like variability), for further use in the tuning of stochastic physics schemes. The three configurations have been run freely and share the same model configuration (except for the scaled diffusivity and viscosity coefficients) and surface and lateral boundary conditions, representing an important dataset to assess the ocean subgrid variability in the North Atlantic and Arctic regions. Basic sea surface subgrid variability has been calculated as well for use in several follow-up experiments. Next, we run four four-member ensemble experiments to assess the impact of different atmospheric forcing perturbation strategies: i) using the ERA5 EDA ensemble members to generate time-varying forcing perturbation consistent with the ERA5 ensemble system; ii) using a reformulated SPPT scheme, where the wind stress and the solar and non-solar heat fluxes are perturbed collinearly to their time-varying tendencies; iii) an SPP scheme, where the air-sea transfer coefficients (for wind stress, evaporation, and sensible heat) are perturbed with a log-normal distribution; iv) a coarse-grained perturbation scheme, where the subgrid variability, estimated from the high-resolution runs, is used to mimic high-resolution bulk formulas, and then the fluxes are upscaled to the nominal model resolution through simple subgrid averaging, to simulate the effect of the subgrid variability of the sea surface on the resulting fluxes. Results indicate that the schemes, in general, can significantly improve some verification skill scores (e.g. against drifter current speed, SST analyses, and hydrographic profiles) and, in some cases, enhance the mesoscale activity and weaken the large-scale circulation. The response, however, is different depending on the specific scheme, whose choice thus depends on the target application, as detailed in the paper. The detailed assessment is contained in Storto and Yang (2023).
Additionally, we have extended the code to include several new SPP parameters and a new random field generation algorithm based on Perlin Noise. We have so far run several short sensitivity tests, and we plan to run more extensive tests if the project continuation will be granted.

Altimetry data assimilation at high latitudes

For this activity, we have assessed the impact of assimilating 5Hz altimetry data in a series of experiments and compared it with standard (1Hz) altimetry. The extensive assessment in ongoing and we plan to submit a manuscript before the end of 2024 on this topic. Results show that the mesoscale activity is enhanced in some areas (Norwegian Sea) leading in turn to larger northward heat transport at high latitudes when 5Hz altimetry is assimilated (experiment A02) compared to 1 Hz altimetry (experiment A03) or no altimetry case (A01). The figure below shows 3-year averaged meridional heat transports for the experiments indicated earlier, for the winter and spring seasons.

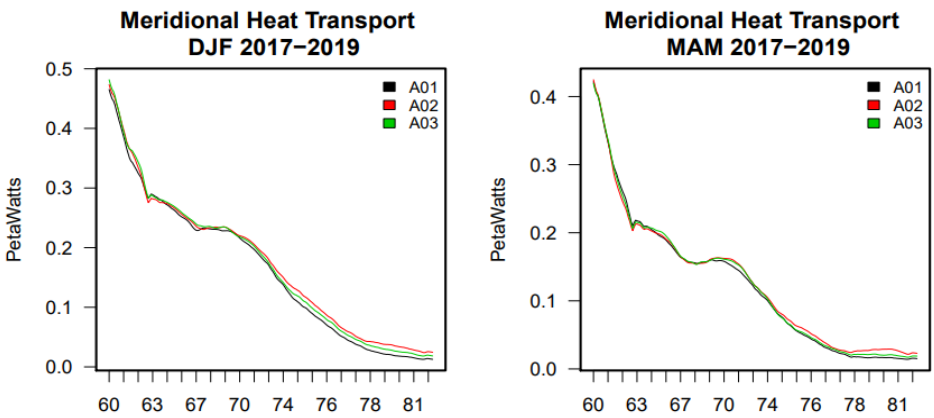

Figure 1. Meridional Heat Transports in the Atlantic Ocean in the experiments presented in the text.

Coupled Data Assimilation algorithms

For this line of activity, we have extensively used the SP resources to assess the best weakly coupled data assimilation strategy for the MESMAR system. Results are documented in detail in Storto et al., (2023), which show the benefit of a setup that combines variational data assimilation in the ocean and spectral nudging in the atmosphere, to improve several skill score metrics and represent the track and intensity of several medicane events.

Additional experiments were devoted to assessing the relative merits of atmosphere coupling and ocean data assimilation to improve several ocean skill metrics, not only including RMSE of near-surface parameter but also levels of Eddy Kinetic Energy and deep-water formation in the modeling system.

Weak-Constraint Data Assimilation

This line of investigation has slightly changed from the initial proposal, and we have focussed our research on bias correction methodologies for long-term simulations. Two approaches were investigated: i) using climatologically averaged analysis increments to correct systematic ocean model errors; ii) using neural networks to correct air-sea heat fluxes, whose systematic error is assumed to be state-dependent. The first approach has been tested in detail in conjunction with other bias correction schemes, it is now part of CIGAR reanalysis system (http://cigar.ismar.cnr.it/) and documented in Storto and Yang (2024). A large part of the HPC resources has been used to retune these schemes and run pilot reanalysis experiments. Secondly, we have started preliminary experiments towards the neural network-based correction of air-sea heat fluxes for long ocean model simulations.

Initial results are promising, and indicate the success of the online inference to correct air-sea heat flux, as in SST data-assimilating experiments (see the figure below). We plan to extend these experiments in the remaining months of 2024, and continue this line of research if the project continuation is granted.

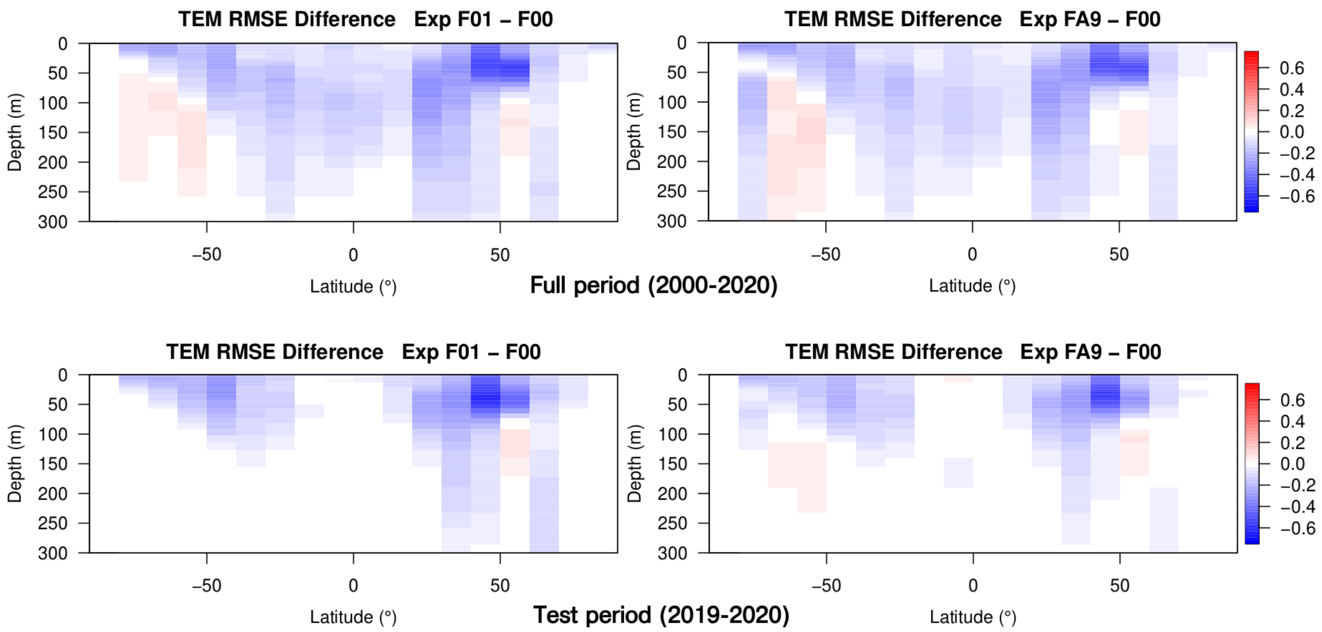

Figure 2. Temperature RMSE decrease (calculated from in-situ profiles) with respect to a control control experiment (F00, no assimilation) in case of SST assimilation (F01) or neural network-based air-sea heat flux correction (FA9), for the full period 2000-2020, and the period 2019-2020 fully independent from the training phase.

List of publications/reports from the project with complete references

de Toma, V., Ciani, D., Hesham Essa, Y., Yang, C., Artale, V., Pisano, A., Cavaliere, D., Santoleri, R., and Storto, A.: Skin Sea Surface Temperature schemes in coupled ocean-atmosphere modeling: the impact of chlorophyll-interactive e-folding depth, Geosci. Model Dev. Discuss. [preprint], https://doi.org/10.5194/gmd-2024-13, in review, 2024.

Storto, A., Yang, C. Acceleration of the ocean warming from 1961 to 2022 unveiled by large-ensemble reanalyses. Nat Commun 15, 545 (2024). https://doi.org/10.1038/s41467-024-44749-7

Storto, A., Hesham Essa, Y., de Toma, V., Anav, A., Sannino, G., Santoleri, R., and Yang, C.: MESMAR v1: a new regional coupled climate model for downscaling, predictability, and data assimilation studies in the Mediterranean region, Geosci. Model Dev., 16, 4811–4833, https://doi.org/10.5194/gmd-16-4811-2023, 2023.

Storto A and Yang C (2023) Stochastic schemes for the perturbation of the atmospheric boundary conditions in ocean general circulation models. Front. Mar. Sci. 10:1155803. doi: 10.3389/fmars.2023.1155803

Bonaduce, Storto, P Raj, Bertino, Xie, Counillon (2022): Exploitation of high-resolution datasets for sea level studies in the Nordic Seas and Arctic Ocean, 2022/10, 2022 Ocean Surface Topography Science Team Meeting, doi:10.24400/527896/a03-2022.3238

Storto, et al., 2023: Assimilation of high-sampling rate altimetry for sea level studies in the Nordic Seas and Arctic Ocean. OceanPredict Data Assimilation Workshop, Rome 9-11 May 2023. Available at: https://oceanpredict.org/docs/Documents/Task%20Teams/DA-TT/Meetings/RomeMay-2023/Presentations/3.2_20230510_1105_Storto.pdf

Storto, et al., 2023: Reconstructing historical ocean heat content from reanalyses: an uncertainty assessment. OceanPredict Data Assimilation Workshop, Rome 9-11 May 2023. Available at: https://oceanpredict.org/docs/Documents/Task%20Teams/DA-TT/Meetings/Rome-May2023/Presentations/6.3_20230511_1145_Storto.pdf

Future plans

We have submitted a continuation of the SP to continue investigating and extending the previous research topics.