THE NEW MET OFFICE GLOBAL OCEAN FORECAST SYSTEM AT 1/12° RESOLUTION

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Abstract

The Met Office has recently upgraded its operational Forecasting Ocean Assimilation Model (FOAM) from an eddy permitting 1/4° tripolar grid (ORCA025) to the eddy resolving 1/12° ORCA12 configuration. FOAM-ORCA12 uses NEMOv3.6 (GO6 configuration) coupled to CICE (GSI8.1 configuration) for the ocean and sea-ice components, respectively. It assimilates observations of sea surface temperature (SST), temperature and salinity profiles, altimeter sea level anomaly and sea ice concentration, via NEMOVAR which is a multivariate incremental 3DVar scheme that runs over a 1-day time window. Qualitatively FOAM-ORCA12 better represents the details of mesoscale features in SST and surface currents. Traditional statistical verification methods suggest that the new system performs similarly or slightly worse than the equivalent 1/4° system. However, it is known that comparisons of models running at different resolutions suffer from a double penalty effect, whereby higher-resolution models are penalised more than lower-resolution models for features that are offset in time and space. Results are shown from neighbourhood verification methods which use common spatial scales for a fairer comparison between configurations of different resolutions, applied to SST. We show that, as neighbourhood sizes increase, ORCA12 consistently has lower Continuous Ranked Probability Scores than ORCA025.

Keywords: Ocean model, eddy-resolving, ORCA12, neighbourhood verification methods

1. Introduction

The Forecasting Ocean Assimilation Model (FOAM) system (Blockley *et al.*, 2014) uses the hydrodynamic model Nucleus for European Modelling of the Ocean (NEMO) (Madec, 2016) for the ocean component and the Community Ice CodE (CICE) (Hunke *et al.*, 2015) for the sea-ice component. In September 2018, the system was updated to the UK Global Ocean configuration version 6 which uses NEMO v3.6 (GO6, Storkey *et al.*, 2018) coupled to CICE (GSI8.1 configuration, Ridley *et al.*, 2018). Initially, the adopted model grid was ORCA025 (approximately 1/4° horizontal resolution) but in December 2020, the model grid was upgraded to ORCA12 and the global ocean forecast system became eddy-resolving with 1/12° horizontal resolution. At the surface, the system is forced by boundary conditions provided by the Met Office Unified Model: 3-hourly heat and freshwater fluxes, and 1-hourly winds. The river run-off is prescribed by climatological seasonally varying estimates.

The configuration uses NEMOVAR for data assimilation (DA) over a 24 hour time-window with a 3DVar-FGAT (first guess at appropriate time) scheme and a state vector consisting of temperature, salinity, sea surface height (SSH), horizontal velocities and sea ice concentration. The assimilation includes observation bias correction schemes for sea surface temperature (SST; While and Martin, 2019) and SSH (Lea *et al.*, 2008). A diffusion operator is used to efficiently model spatial correlations in the background errors, and multivariate relationships are specified through physical balances (Weaver *et al.*, 2005). An Incremental Analysis Update (IAU) step is used to slowly add the assimilation increments into the model. Despite the 1/12° resolution of the underlying physical model, the data assimilation scheme runs at 1/4° in the present version of FOAM-ORCA12. It is common in operational systems to perform the assimilation at a lower resolution than the model run (e.g. Oke *et al.*, 2013; Lellouche *et al.*, 2018).

In order to assess the impact of changing the resolution of the model, we have carried out experiments with the 1/12° and 1/4° versions of the global FOAM system, both assimilating the same datasets, forced by the same atmospheric fields, and with the same model, with the only difference being its resolution. In the next sections we describe the experiments and an overview of the results, concluding with a summary.

2. Experiments

Two assimilation experiments have been carried out over the period 1st January 2017 to 31st December 2018. The experiment at ¼° resolution is referred to as 'FOAM-ORCA025' and the experiment at 1/12° resolution, is referred to as 'FOAM-ORCA12'. These share the same version of model and data assimilation, are forced by the same atmospheric fields and river inputs and assimilate the same observations. The only differences between the runs are the resolution of the model, some model parameter settings which are resolution-specific, and the initial conditions (which come from previous spin-up runs at the appropriate resolution which included data assimilation).

The observations come from various sources. Satellite sea-ice concentration data from SSMI/S sensors are provided by EUMETSAT. Satellite SST data are obtained from the Group for High Resolution SST (GHRSST) and includes data from AVHRR sensors on NOAA and MetOp satellites, the SEVIRI sensor on the MSG satellite, the SLSTR sensor on Sentinel-3 satellites, the AMSR2 sensor on GCOMW1 satellite and the VIIRS sensor on the Suomi NPP satellite. Along-track SLA data come from CMEMS (Copernicus

Marine Environment Monitoring Service). The *in situ* SST data are received via the Global Telecommunication System, while *in situ* temperature and salinity profiles are from the EN4 reprocessed dataset (Good *et al.*, 2013).

The hindcast trials were run over a period of two years, but here we show mainly results from the last six-months (July-December 2018). For this period, every day, we ran an analysis followed by five days of forecast.

3. Results

3.1 Surface currents

The modelled and observed surface Agulhas current, time-averaged over July-August-September 2017 is shown in Figure 1. The retroflection of the Agulhas current appears to be more coherent in FOAM-ORCA12 than in FOAM-ORCA025, and the higher resolution configuration provides a better match to the observations in terms of magnitude and meandering path followed.

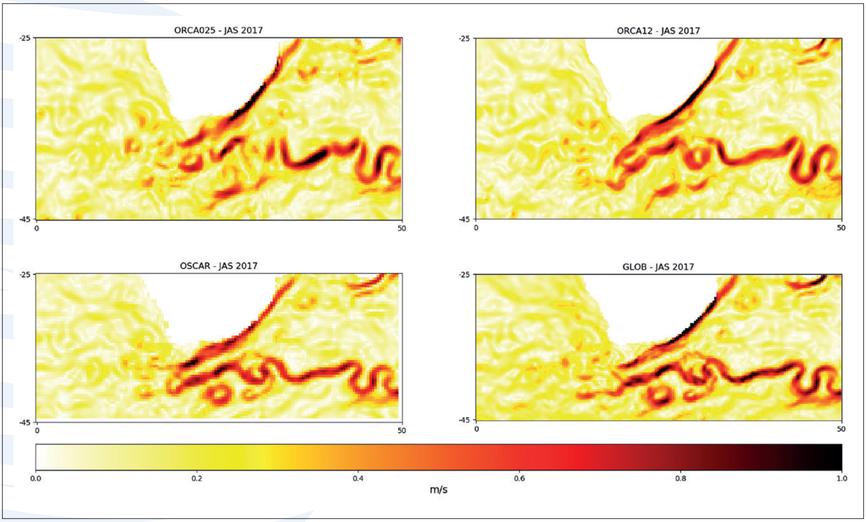

Fig. 1. Surface current [m/s] off South Africa, in the Agulhas current region. Model fields at the top with FOAM-ORCA025 on the left and FOAM-ORCA12 on the right, observed fields at the bottom with OSCAR on the left and GlobCurrent on the right.

3.2 Traditional metrics

Here we focus on the results for SST. All other variables show similar behaviour but their statistics are not presented here.

The forecast skill can be assessed on a point-to-point basis, evaluating differences between measured and simulated observations, the latter being derived from the model forecast at the nearest time and interpolated to observation locations. These differences are known as 'innovations'. The mean and RMS (Root Mean Square) of the innovations for *in situ* drifter SSTs (averaged over six-months) are presented as a function of forecast time in Figure 2. At long forecast times, the mean differences are slightly smaller for FOAM-ORCA12 than for FOAM-ORCA025 but RMS values are larger in ORCA12 at all lead times (including the analysis).

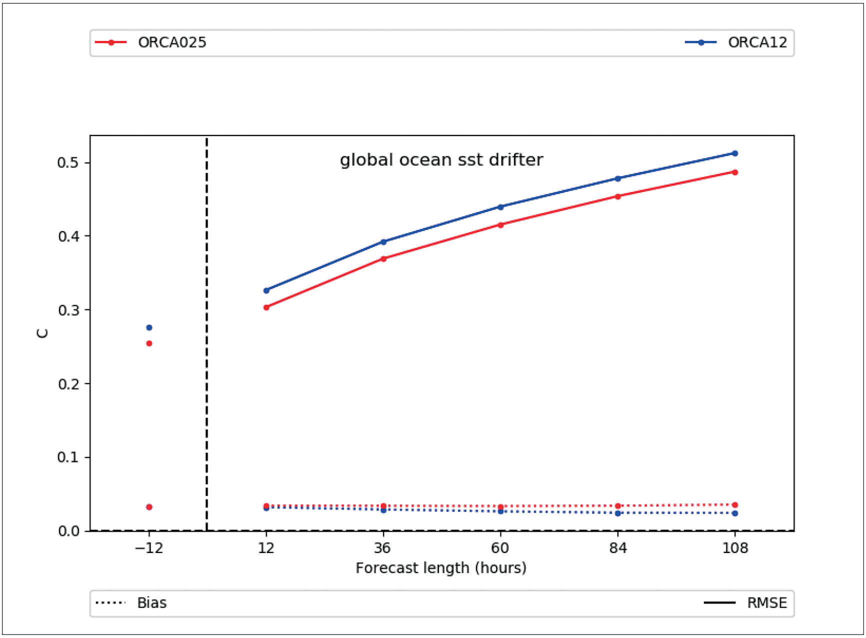

Fig. 2. Innovations for drifters' SST as a function of forecast times (-12 h is the analysis time), averages for the global ocean and over a six-month period Jun-Dec 2018. The blue lines correspond to FOAM-ORCA12 whereas the red lines correspond to FOAM-ORCA025 (control). Dotted (solid) lines represent the mean (RMS) of the innovations.

The time-series of the SST innovations for the different days of forecast (not shown) indicate that, although the error varies significantly over time, the RMS for FOAM-ORCA12 remains higher than RMS for FOAM-ORCA025 most of the time. For SLA (not shown) the degradation is slightly worse in FOAM-ORCA12 and the underlying cause is being investigated.

These results suggest that overall errors are larger in the higher resolution configuration. This counter-intuitive result arises from the fact that, when resolving finer scales, there is more chance of a time and space mismatch between simulated and observed features. Therefore, traditional point-to-point verification methods are not the most appropriate for comparing systems with very distinct resolutions.

3.3 Neighbourhood verification metrics

The High-Resolution Assessment (HiRA) method (Mittermaier and Csima, 2017) is applied here to the two resolution ocean model forecasts, following Crocker *et al.*, (2020). This makes use of ensemble and probabilistic scores to equitably compare models with regards to their accuracy and predictive skill. HiRA uses increasing size neighbourhoods to generate a pseudo ensemble which can then be compared to an observed value. It assumes that a verifying observation is the true value at its location and also representative of the characteristics of a surrounding area. For example, nine grid-cells of ORCA12 can fit in a single grid-cell of ORCA025, therefore this is the smallest neighbourhood size where a comparison of results from either configuration is valid.

Figure 3 shows the SST Continuous Ranked Probability Scores (CRPS) at different neighbourhood sizes for the two configurations. Matching line styles represent the equivalent neighbourhood sizes that should be compared. At the grid scale (neighbourhood size 1), CRPS is equivalent to mean absolute error. CRPS decreases (meaning a better forecast) with increasing neighbourhood size, suggesting that some spatial mismatches exist. Overall, the higher resolution ORCA12 consistently has lower errors than ORCA025 when equivalent neighbourhood extents are compared.

4. Summary and Future Outlook

Qualitatively, FOAM-ORCA12 better represents the details of mesoscale features. However, traditional statistical verification methods suggest that the FOAM-ORCA12 system performs similarly or slightly worse than the previous FOAM-ORCA025 system. Neighbourhood verification methods have been used to make a fairer comparison using a common spatial scale for both models and it can be seen that FOAM-ORCA12 consistently has lower CRPS than FOAM-ORCA025. CRPS measures the accuracy of the pseudo-ensemble created by the neighbourhood method and generalises the mean absolute error measure for deterministic forecasts, with lower scores indicating better forecasts.

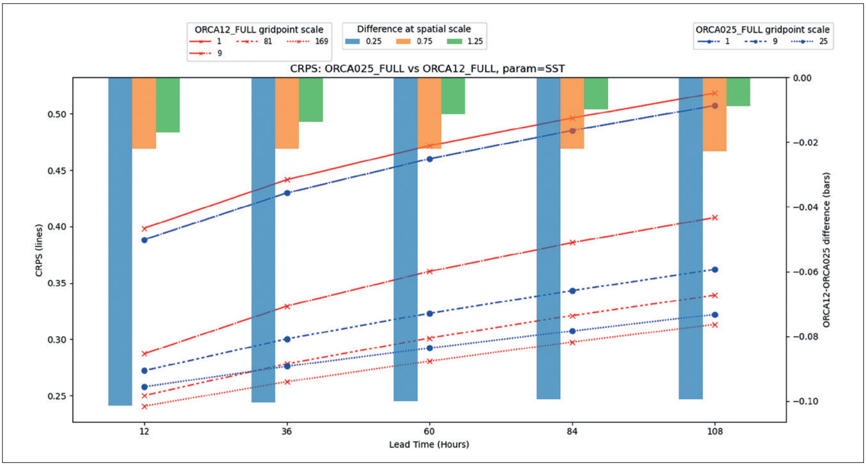

Fig. 3. Left y-axis: CRPS for drifters' SST as a function of forecast (lead) times, averages for the global ocean and over a six-month period Jun-Dec 2018. The red lines correspond to FOAM-ORCA12 whereas the blue lines correspond to FOAM-ORCA025 (control). Matching line-styles correspond to same neighbourhood lengthscales. Right y-axis: The bars represent the difference in scores 'ORCA12 minus ORCA025' and thus negative means ORCA12 is better (has a lower error). The colours correspond to different neighbourhood sizes.

Further improvements to the FOAM system are being worked on, including an update of the background-error covariances used for data assimilation (Carneiro *et al.*, 2021). In 2022, the Met Office will upgrade its main deterministic and ensemble Numerical Weather Prediction (NWP) configurations to use fully coupled atmosphere/land/ocean/sea-ice forecast systems. The ocean/sea-ice component of these will be based initially on FOAM-ORCA025 but the expectation is that this will be upgraded for the deterministic forecast model to FOAM-ORCA12 within the next few years.

Acknowledgements

Two surface current observational products were used here: 1. OSCAR (Ocean Surface Current Analysis Real-time) 5-day-averages at 1/3° resolution https://www.esr.org/research/oscar/oscar-surface-currents/; 2. GlobCurrent monthly-means at 1/4° resolution. https://resources.marine.copernicus.eu/?option=com–csw&task=results?option=com_csw&view=details&product_id=MULTIOBS_GLO_PHY_REP_015_004

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References

Blockley, E. W., Martin, M. J., McLaren, A. J., Ryan, A. G., Waters, J., Lea, D. J., Mirouze, I., Peterson, K. A., Sellar, A., and **Storkey, D.** (2014). Recent development of the Met Office operational ocean forecasting system: an overview and assessment of the new Global FOAM forecasts, *Geoscientific Model Development*, 7, 2613-2638, https://doi.org/10.5194/gmd-7-2613-2014

Carneiro, D. M., King, R., Martin, M., Aguiar, A. (2021). Short-range ocean forecast error characteristics in high resolution assimilative systems. *Met Office Weather Science Technical Report* number 645.

Crocker, R., Maksymczuk, J., Mittermaier, M., Tonani, M., and **Pequignet, C.** (2020). An approach to the verification of high-resolution ocean models using spatial methods, *Ocean Science*, 16, 831–845. https://os.copernicus.org/articles/16/831/2020/os-16-831-2020.pdf

Good, S. A., Martin, M. J. & Rayner, N. A. (2013). EN4: quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. *Journal of Geophysical Research: Oceans*, 118, 6704-6716.

Hunke, E. C., Lipscomb, W. H., Turner, A. K., Jeffery, N., and **Elliott, S.** (2015) CICE: the Los Alamos Sea Ice Model Documentation and Software User's Manual Version 5.1, LA-CC-06-012, Los Alamos National Laboratory, Los Alamos, NM

Lea, D. J., J.-P. Drecourt, K. Haines, M. J. Martin (2008). Ocean altimeter assimilation with observational- and model-bias correction. *Quarterly Journal of the Royal Meteorological Society*, 134:1761-1774.

Lellouche, J.-M., Greiner, E., Le Galloudec, O., Garric, G., Regnier, C., Drevillon, M., Benkiran, M., Testut, C.-E., Bourdalle-Badie, R., Gasparin, F., Hernandez, O., Levier, B., Drillet, Y., Remy, E. & Le Traon, P.-Y. (2018), Recent updates to the Copernicus marine service global ocean monitoring and forecasting real-time high-resolution system. *Ocean Science*, 14(5), 1093-1126.

Madec, G. (2016) NEMO Ocean Engine. Tech. Rep. 27, Pole de modelisation de IPSL. https://www.nemoocean.eu/AboutNEMO/Referencemanuals/NEMO_book_3.6_STABLE

Mittermaier, M. P., & Csima, G. (2017). Ensemble versus deterministic performance at the kilometer scale, *Weather and Forecasting*, 32(5), 1697-1709.

Oke, P. R., Sakov, P., Cahill, M. L., Dunn, J. R., Fiedler, R., Griffin, D. A., Mansbridge, J. V., Ridgway, K. R. and **Schiller, A.** (2013). Towards a dynamically balanced eddy-resolving ocean reanalysis: BRAN3. *Ocean Modelling*, 67, 52-70.

Ridley, J.K., Blockley, E.W., Keen, A.B., Rae, J.G.L., West, A.E. and **Schroeder, D.** (2017). The sea ice model component of HadGEM3 GC3.1. *Geoscientific Model Development*. 11, 713–723. https://doi.org/10.5194/gmd_11_713_2018

Storkey, D., Blaker, A.T., Mathiot, P., Megann, A., Aksenov, Y., Blockley, E.W., Calvert, D., Graham, T., Hewitt, H.T., Hyder, P., Kuhlbrodt, T., Rae, J.G.L. and **Sinha, B.** (2018) UK Global Ocean GO6 and GO7: a traceable hierarchy of model resolutions. *Geoscientific Model Development*, 11, 3187– 3213. https://doi.org/10.5194/gmd_2017 263

Weaver, A.T., Deltel, C., Machu, E., Ricci, S. and **Daget, N.** (2005) A multivariate balance operator for variational ocean data assimilation. *Quarterly Journal of the Royal Meteorological Society*, 131, 3605 – 3625. https://doi.org/10.1256/qj.05.119

While, J., Martin, M. J. (2019). Variational bias correction of satellite sea surface temperature data incorporating observations of the bias. *Quarterly Journal of the Royal Meteorological Society*, 145: 2733– 2754. https://doi.org/10.1002/qj.3590