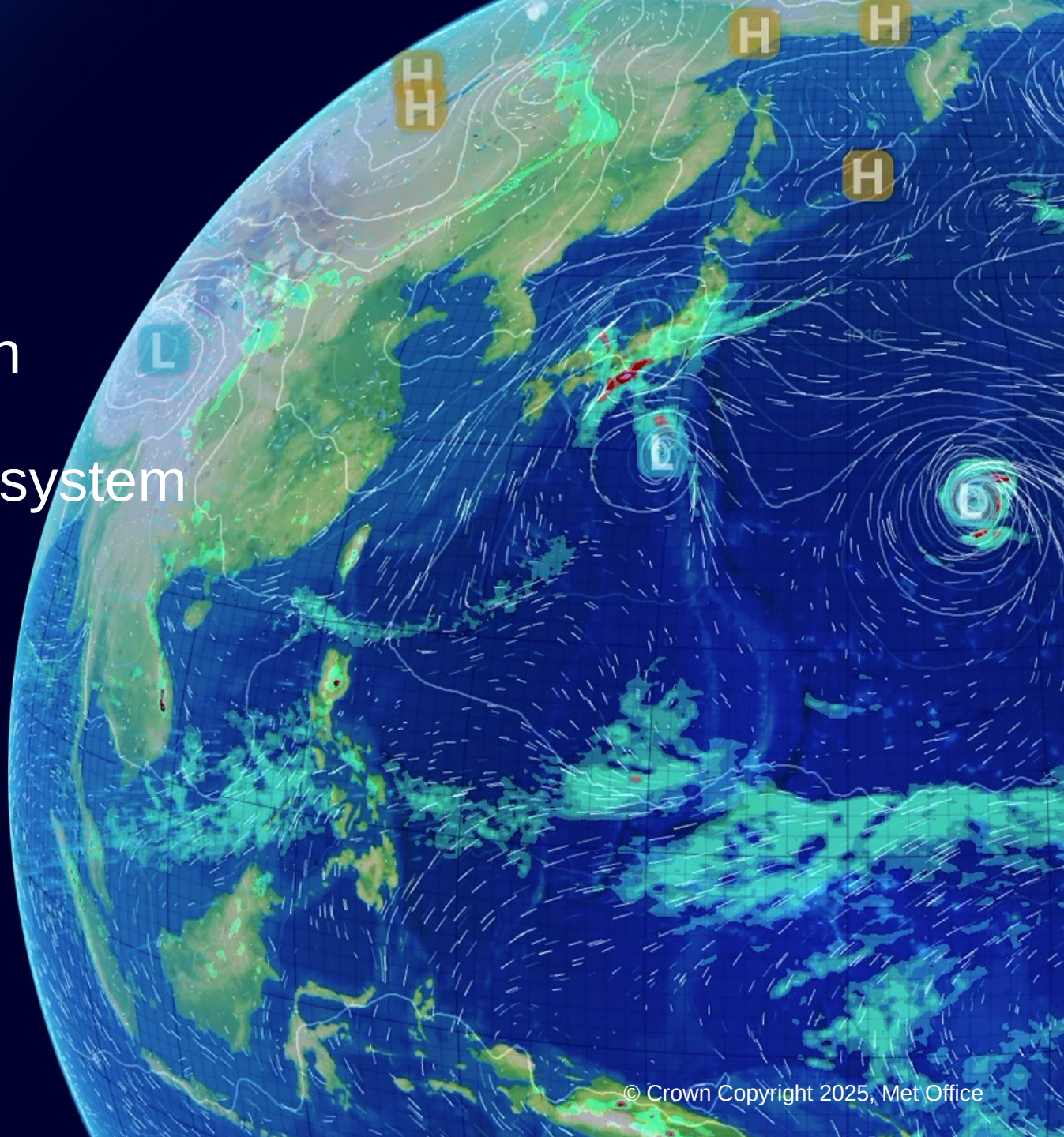
Assessing the new Met Office high resolution global ocean ensemble hybrid-3DEnVar system

Daniel Lea[1], Matthew Martin[1], Jennifer Waters[1], Davi Mignac[1], Martin Price[1]

[1]Met Office

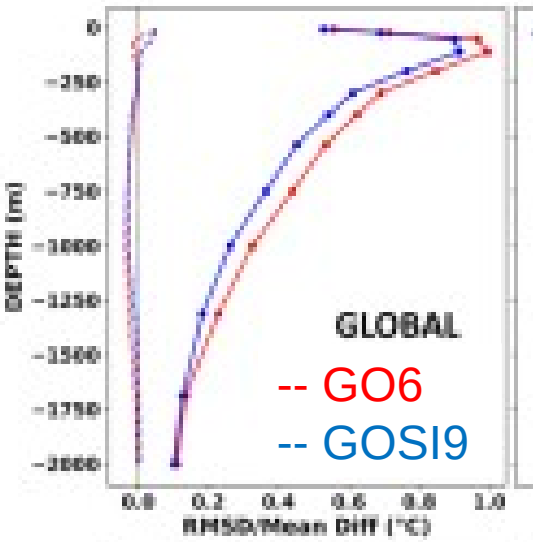


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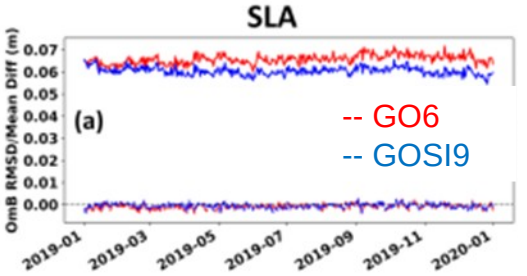
Introduction

- The Met Office global ocean forecasting system FOAM has produced daily operational ocean forecasts for many years.
- FOAM uses the NEMO ocean model and the NEMOVAR assimilation system running 3DVar assimilating along-track SLA, swath SST, profile T and S, sea ice concentration.
- This system is used to generate ocean only forecasts and as part of the coupled NWP system
- In Lea et al., 2022 we developed a FOAM based ensemble system and tested hybrid ensemble variational DA. Compared to 3DVar this gave a significant improvement in ocean DA performance.

T profile errors

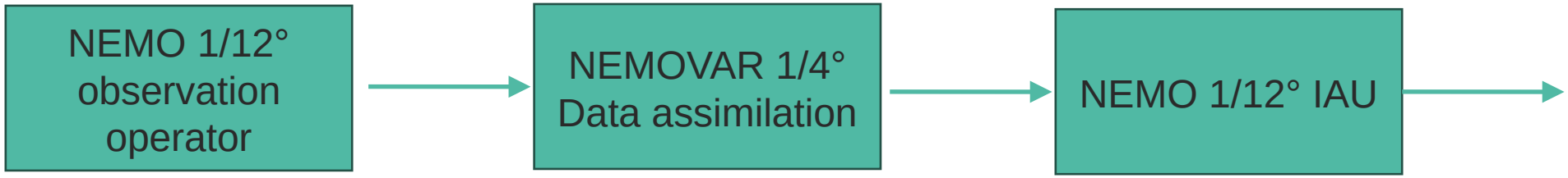


- Ensemble DA however does come with increased computational cost and it was not previously feasible for it to go operational, but it now is.
- Meanwhile the FOAM system has evolved. There have been updates to the global ocean model GO6 to GOSI9, 3DVar data assimilation improvements and an increase in model resolution from ¼° to 1/12°.
- Does ensemble DA still work as well it did previously?



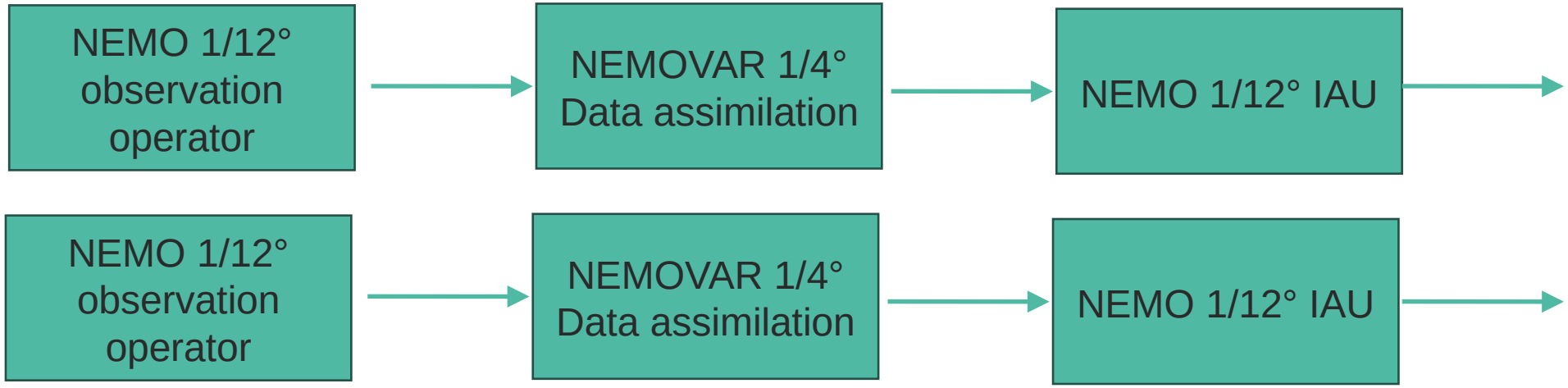
Global Ocean Ensemble system

Ensemble of separate DAs (but ensemble information can be used in the DA step).



Unperturbed member (EN000) Forcing from Met Office deterministic atmosphere. (~10km resolution)

Observation (position and value) and model perturbation schemes used.
RTPS (balance respecting) ensemble inflation. Hybrid ensemble variational DA



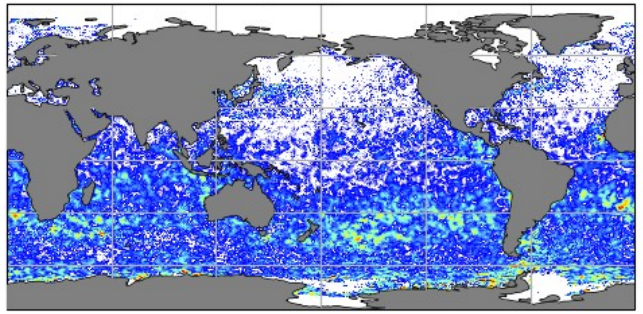
36 perturbed members
Ennn forcing from Met Office atmosphere ensemble.
(~20 km resolution currently)

NB for some of the initial testing we used ¼° NEMO as it's quicker for development purposes. (1/12° takes ~30 times HPC resources + ~10 times file sizes).

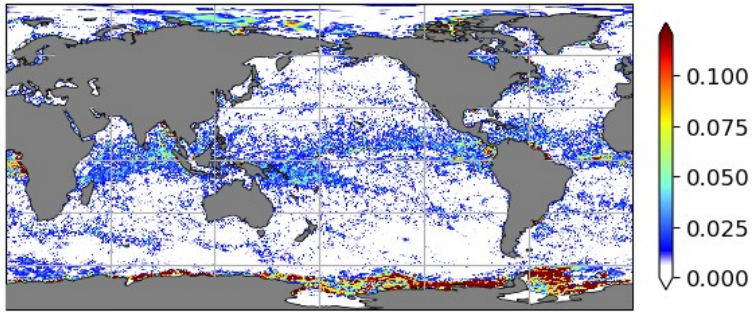
1/12° NEMO model perturbations

- The Storto et al. scheme covers various aspects of model uncertainty with SPP (Stochastic Parameter Perturbations), SPPT (Stochastic Perturbed Parameterization Tendencies), SKEB (Stochastic Kinetic Energy Backscatter) schemes.
- Some updates from the old version. New is the use of bulk formulae parameter perturbations (air-sea drag, sensible heat, evaporation).
- Model free 15 day running test impact – 2020/01/01 to 2020/01/15 increase in ensemble spread:

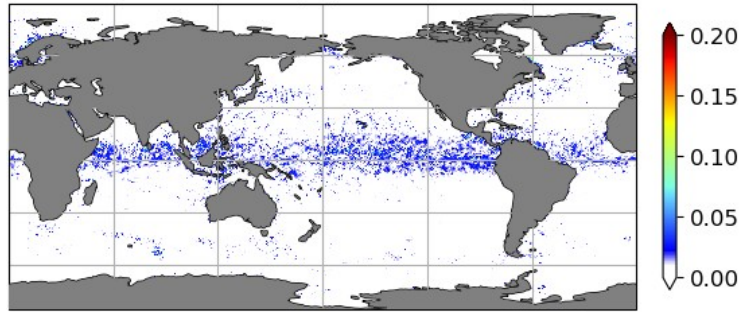
Surface Temperature



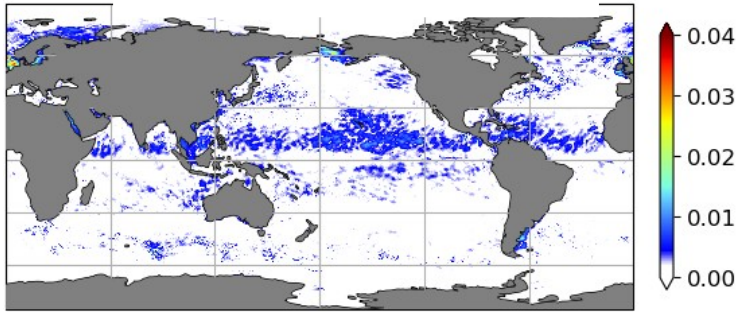
Surface Salinity



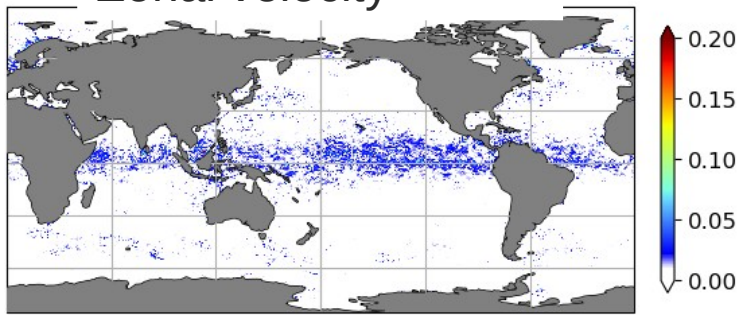
Meridional velocity



SSH



Zonal velocity



Hybrid ensemble/variational data assimilation

Ensemble based background error covariance

In an ensemble system of size N_e, the ensemble provides extra information about the forecast error covariances

$$\mathbf{X} = \frac{1}{\sqrt{N_e - 1}}(\epsilon_1 \ldots \epsilon_{N_e}) \qquad \mathbf{B_e} = \mathbf{X}\mathbf{X}^{\mathrm{T}}$$

where the ϵ_i are the differences between the background state in the i^{th} member and the ensemble mean. But we must localise to reduce sampling errors at large distances from observations.

$$\mathbf{B}_e = \mathbf{C}_L \circ \mathbf{X}\mathbf{X}^{\mathrm{T}}$$

Lengthscale 2x Rossby radius 100 km cap

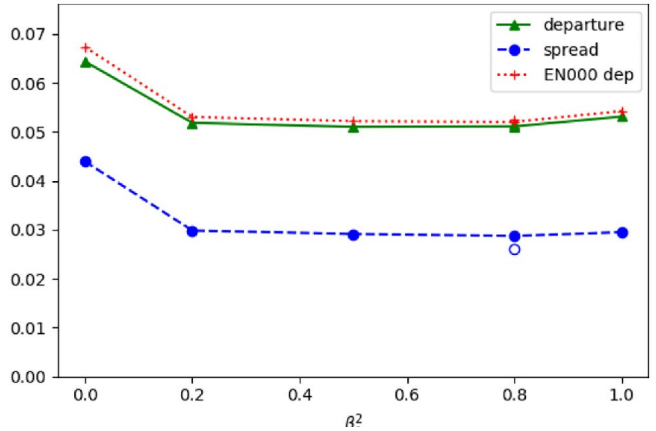
Hybrid DA where the background is a weighted sum of *modelled* $\mathbf{B_m}$, and *ensemble-based* $\mathbf{B_e}$ combines the advantages of ensemble DA with the robustness of standard 3D-Var

$$\mathbf{B}_h = \beta_m^2 \mathbf{B}_m + \beta_e^2 \mathbf{B}_e$$

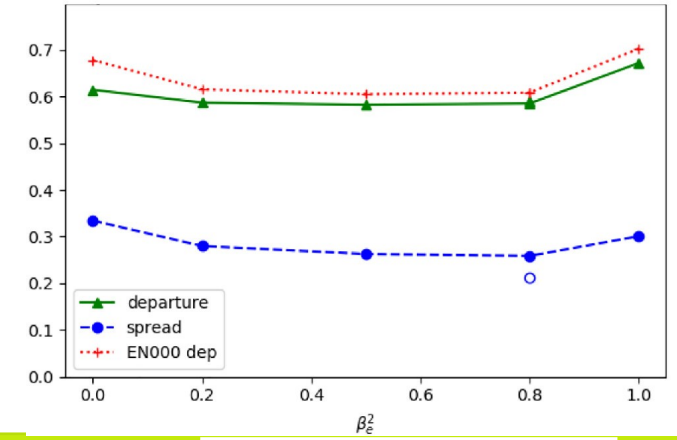
$\beta_m^2 = 1 - \beta_e^2$

$\beta_e^2 = 0.5$ for this work

SLA RMS error / m
From Lea et al. 2022



T profile RMS error / °C
From Lea et al. 2022

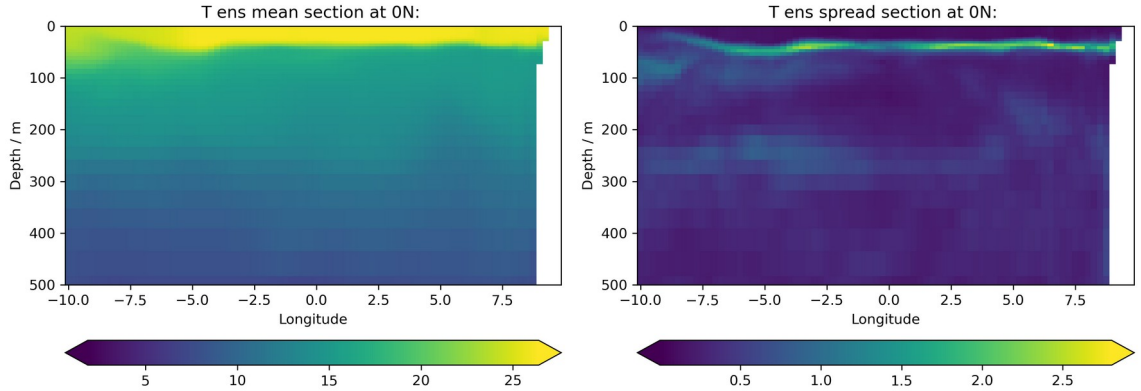


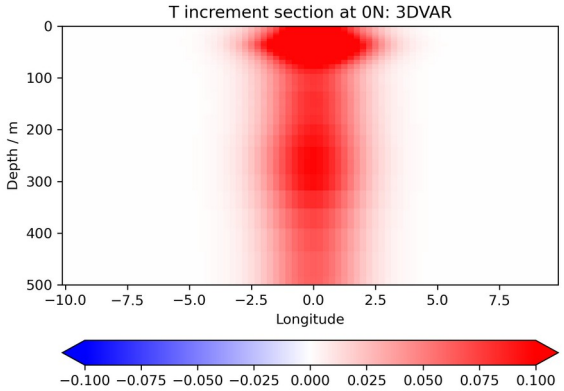
Hybrid weight, β_e^2

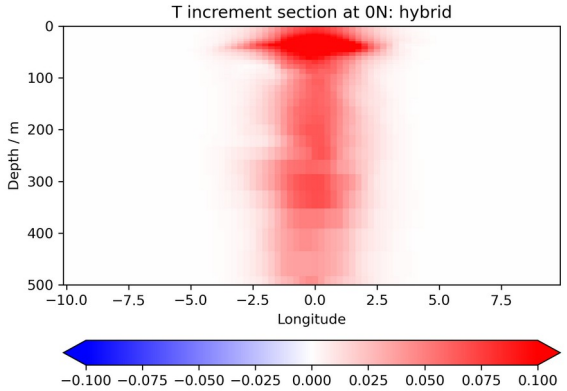
Testing hybrid DA with idealised observations

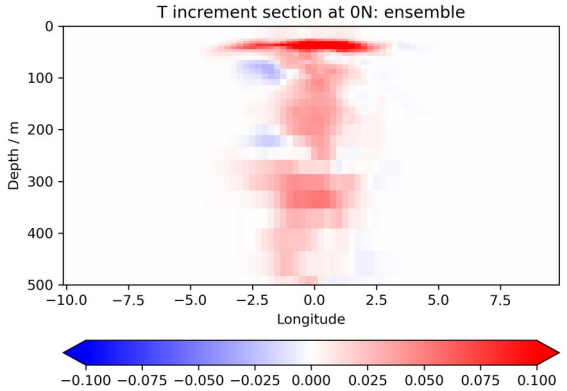
Widely spaced (SLA in this case) observations (+ve innovation). Useful to explore the error covariance structures. Can help to tune hybrid weights, localisation length scales, and to test the impact of the ensemble size.

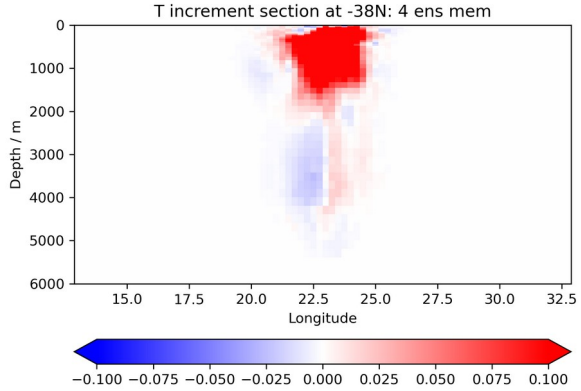
Section plots (background and increments)…

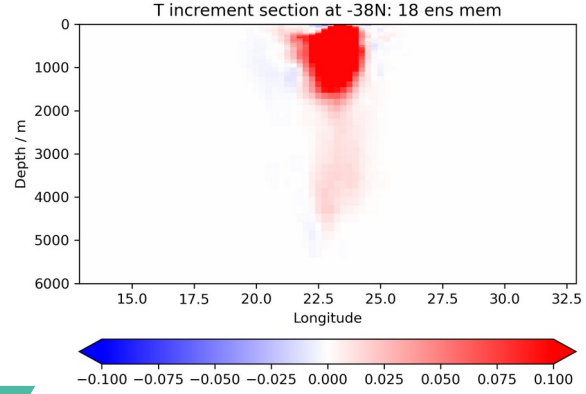


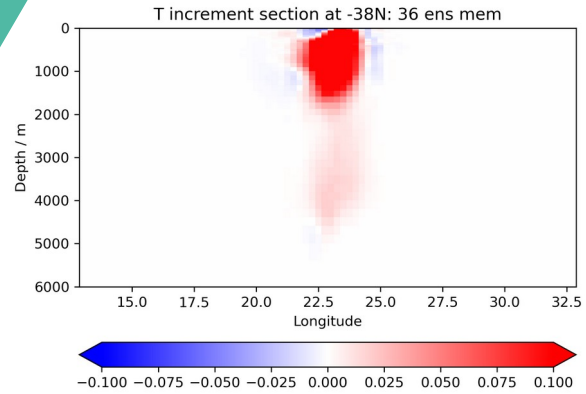




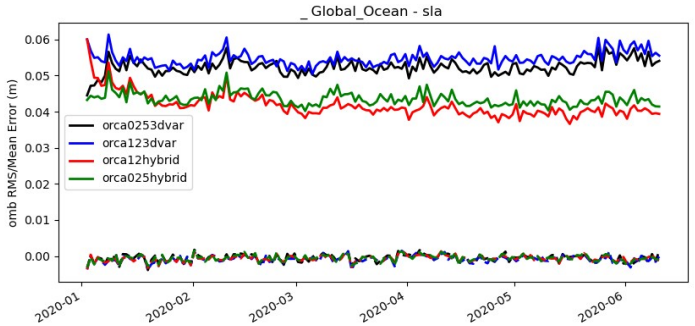


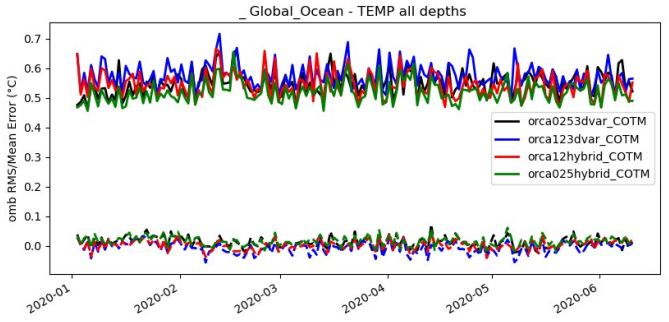


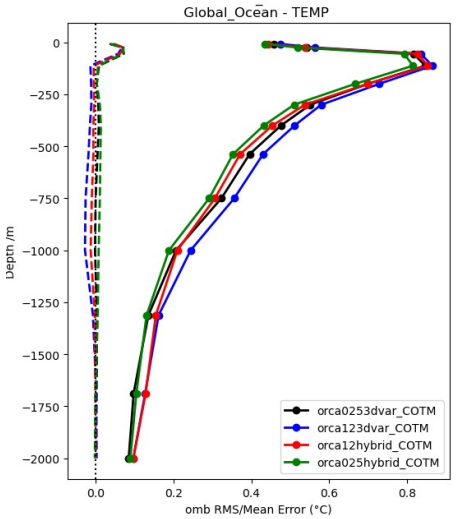


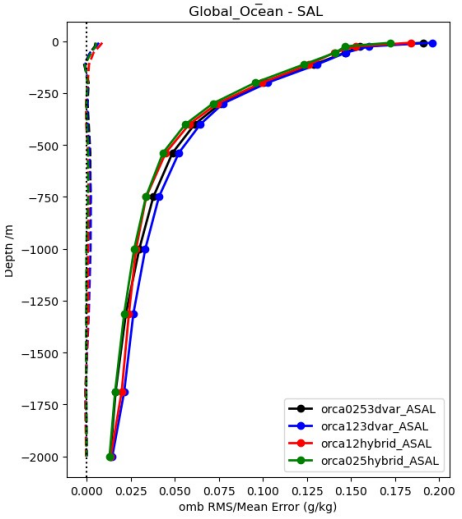


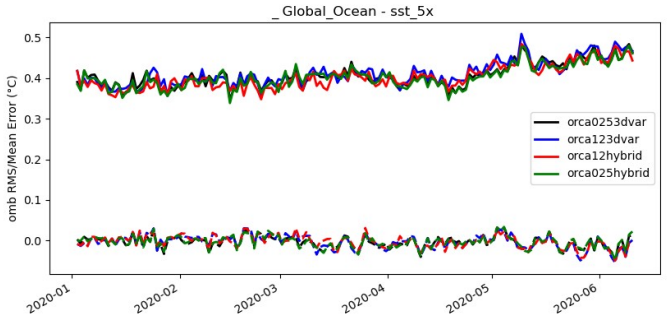
1/12 and 1/4°ensemble system observation based assessment of the unperturbed ensemble member

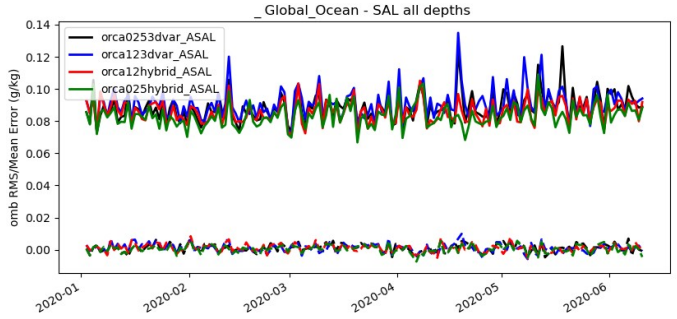












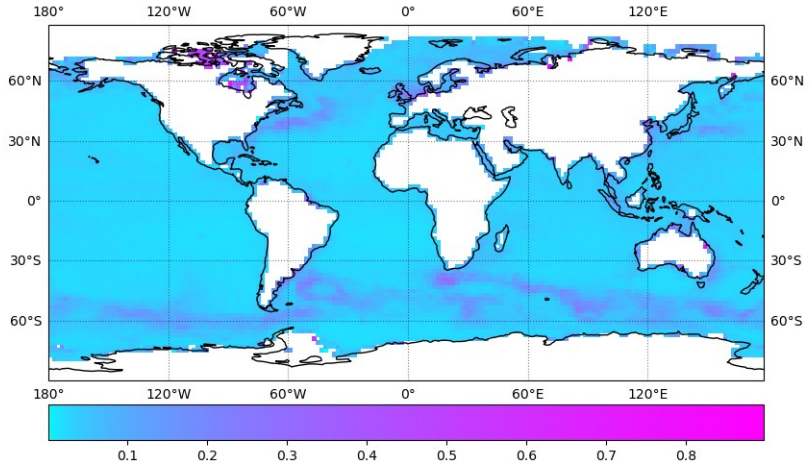
Orca025 3DVar-FGAT
Orca12 3DVar-FGAT
Orca12 Hybrid 3DEnVar
Orca025 Hybrid 3DEnVar

Hybrid DA improves results for SLA and also profile T and S

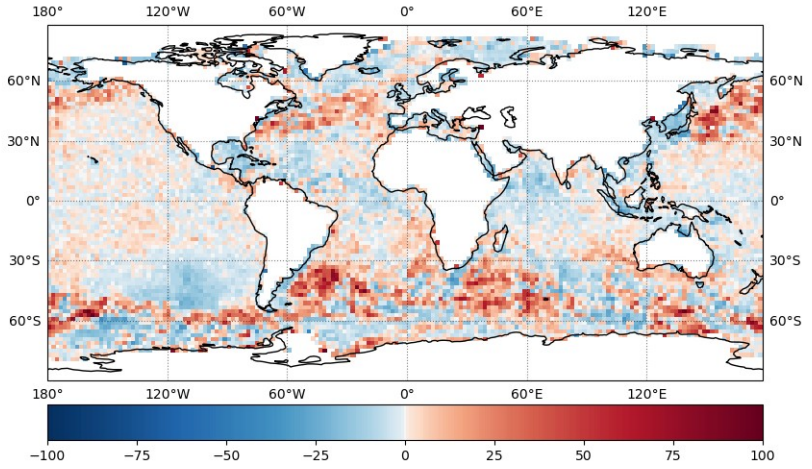
Impact on orca12 is even better than orca025 for SLA

1/12 and 1/4°ensemble system observation based assessment of the unperturbed ensemble member

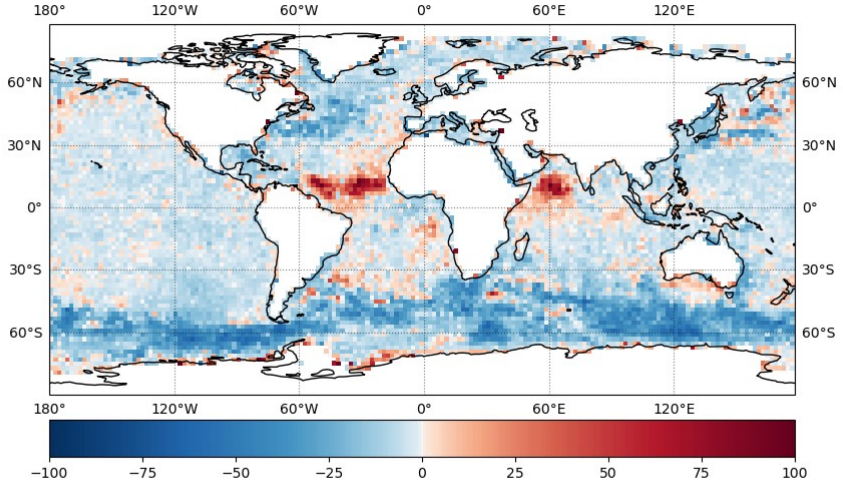
orca025_3dvar SLA:omb rms



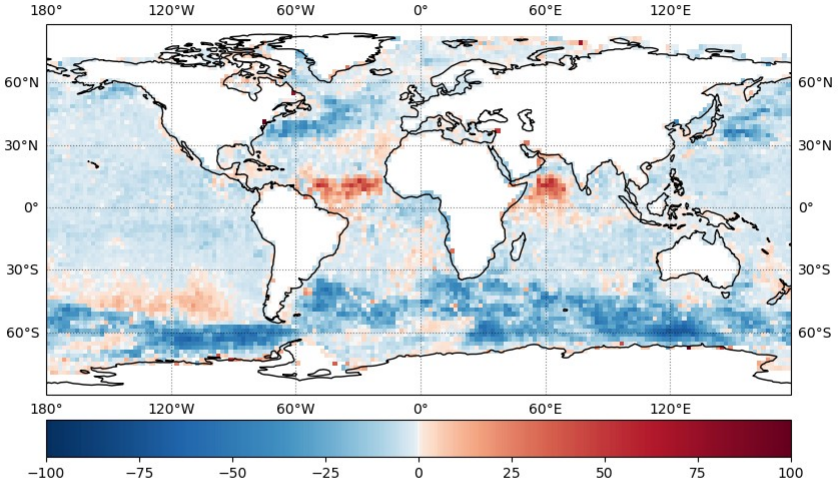
orca12_3dvar percent diff (this minus ctl)/abs(ctl) SLA:omb rms



orca12_hybrid percent diff (this minus ctl)/abs(ctl) SLA:omb rms



orca025_hybrid percent diff (this minus ctl)/abs(ctl) SLA:omb rms



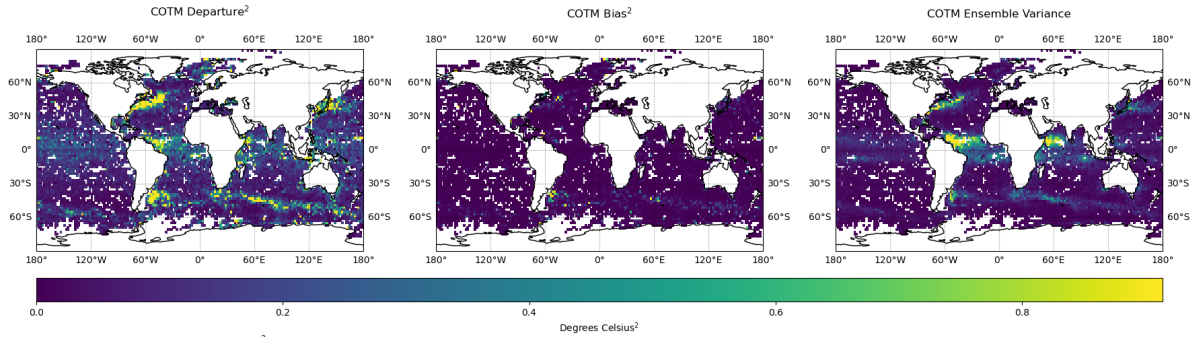
For SLA orca12 3DVar increases the errors in the mid latitude regions vs orca025 (impact of greater variability?)

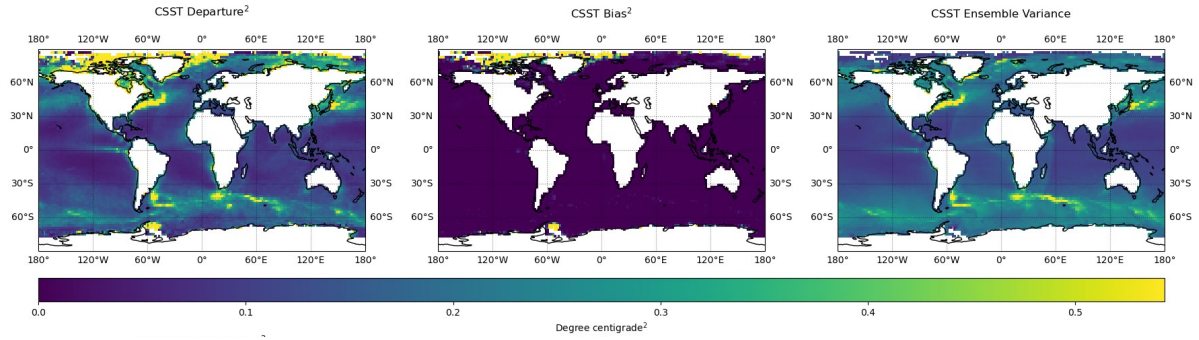
With hybrid DA in both orca025 and orca12 the errors are massively reduced (except in some tropical regions).

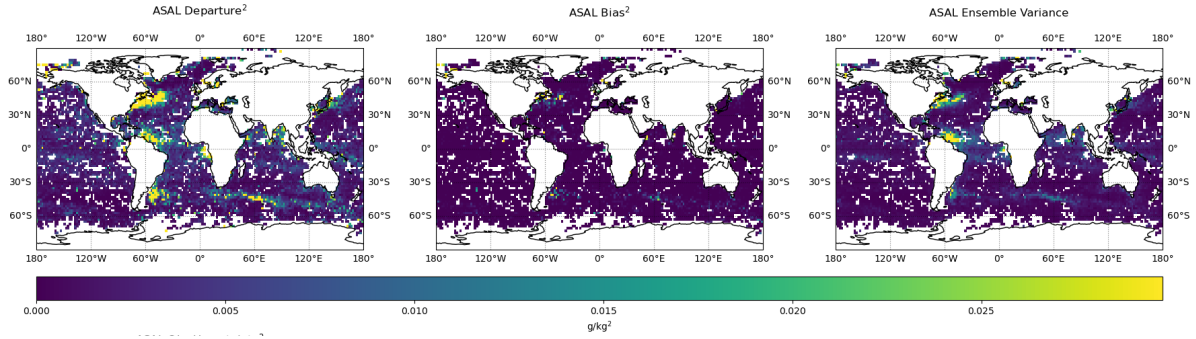
Rodwell assessment 1/12° - looking at ensemble spread

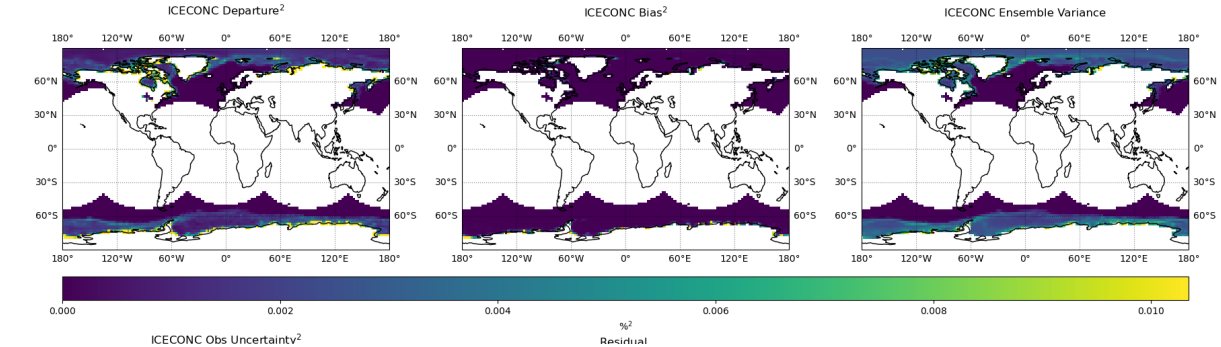
The ensemble spread should be consistent with the error of the ensemble mean vs observations

$Depar^2 = EnsVar + Bias^2 + ObsUnc^2 + Residual.$

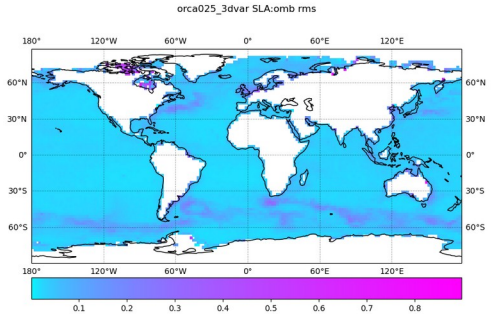


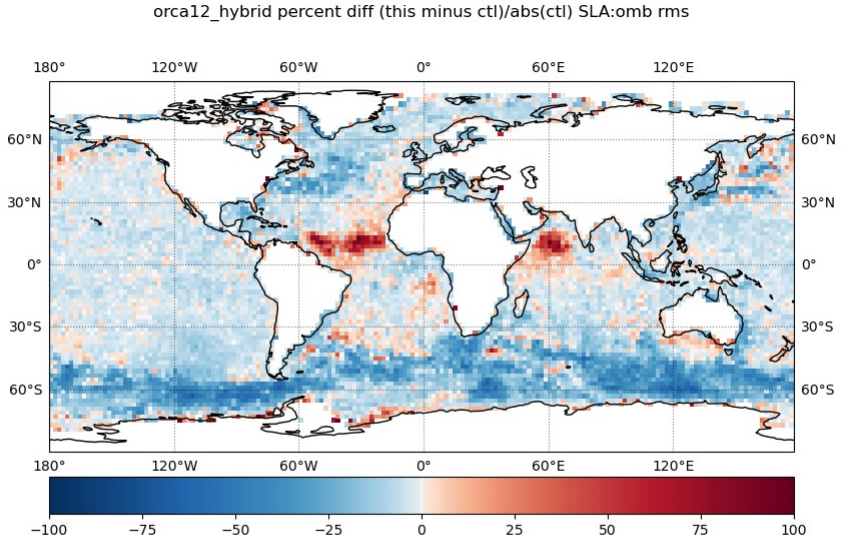


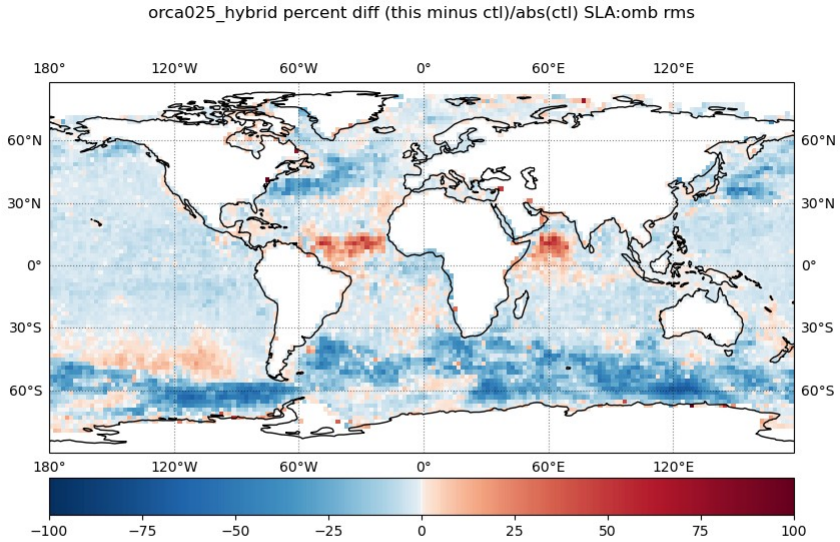




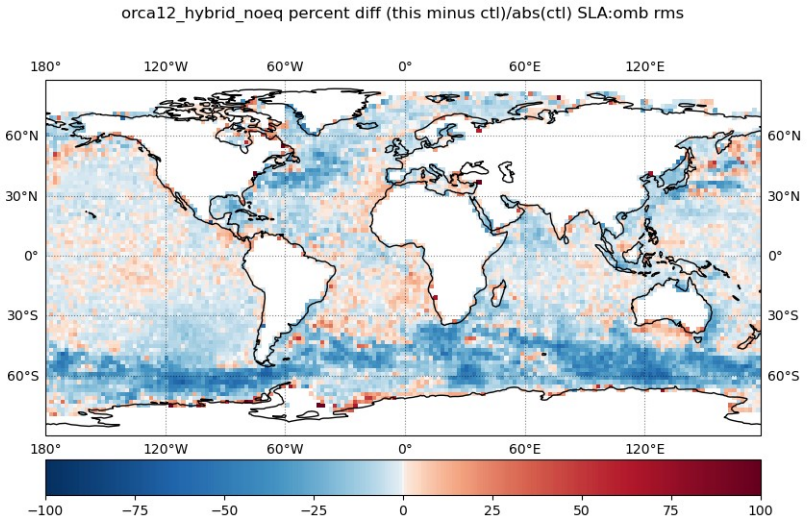
Mixed hybrid and 3DVar option

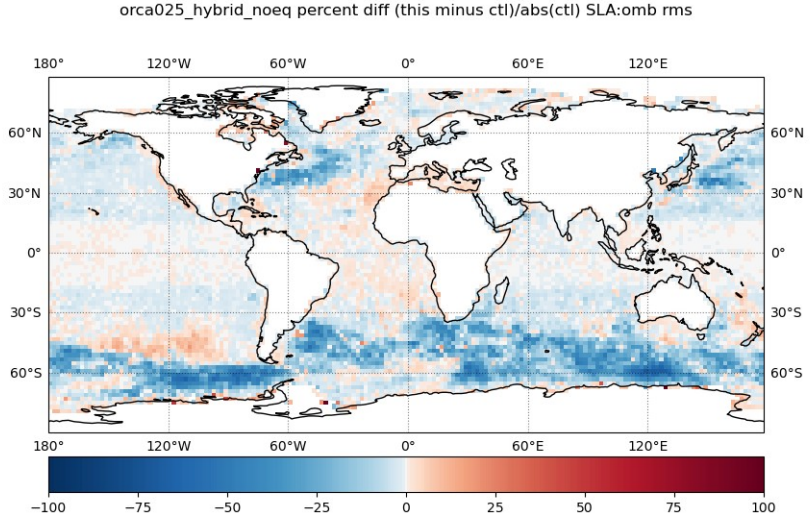




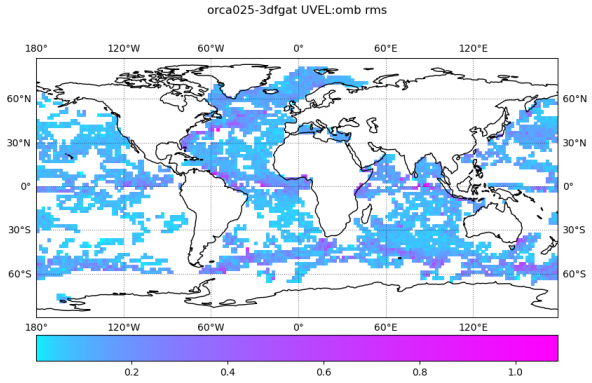


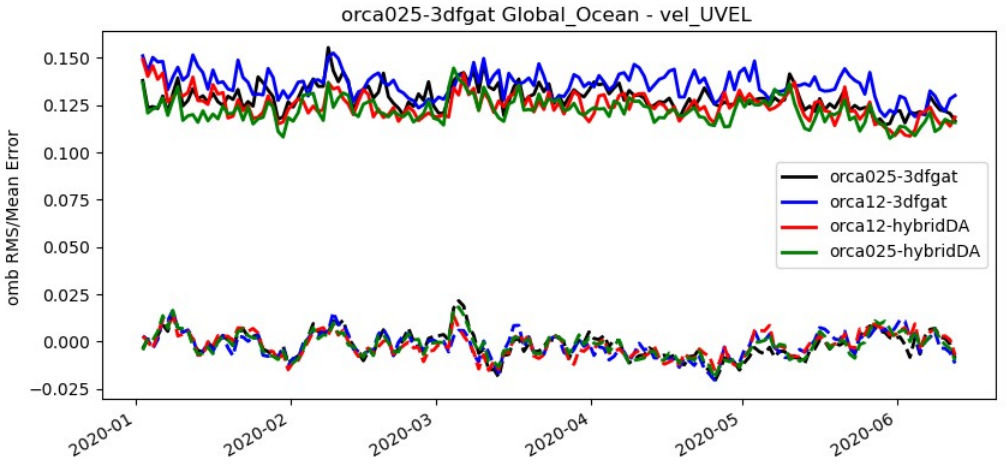
Spatially varying hybrid weights which ramp down Wgt Bens to 0 in the 15°-20° N/S of the equator.

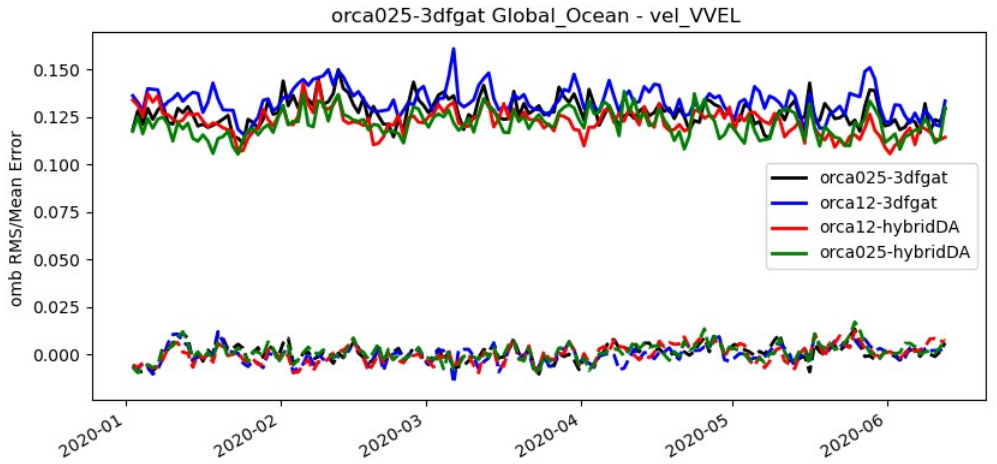




1/12° and 1/4°ensemble system assessment of the unperturbed ensemble member with drifters





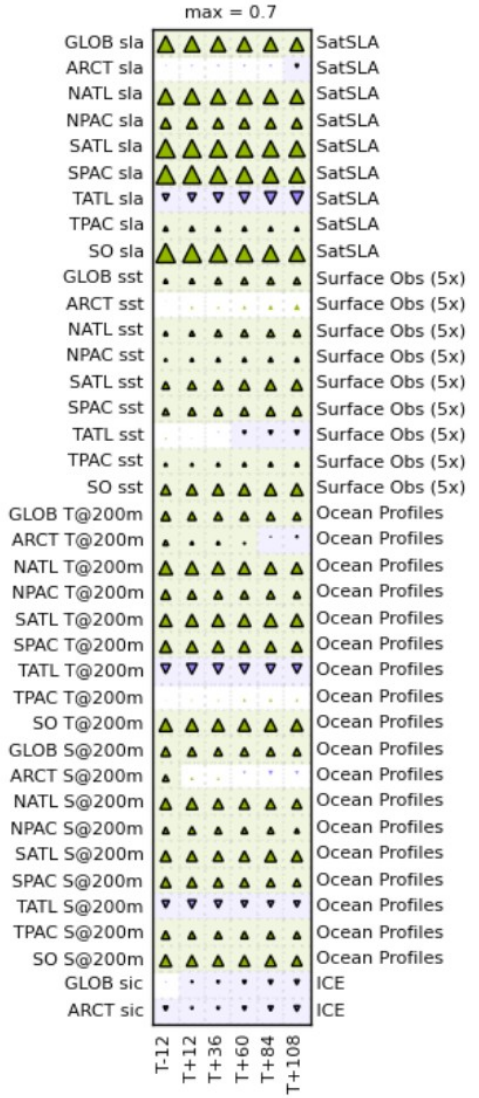


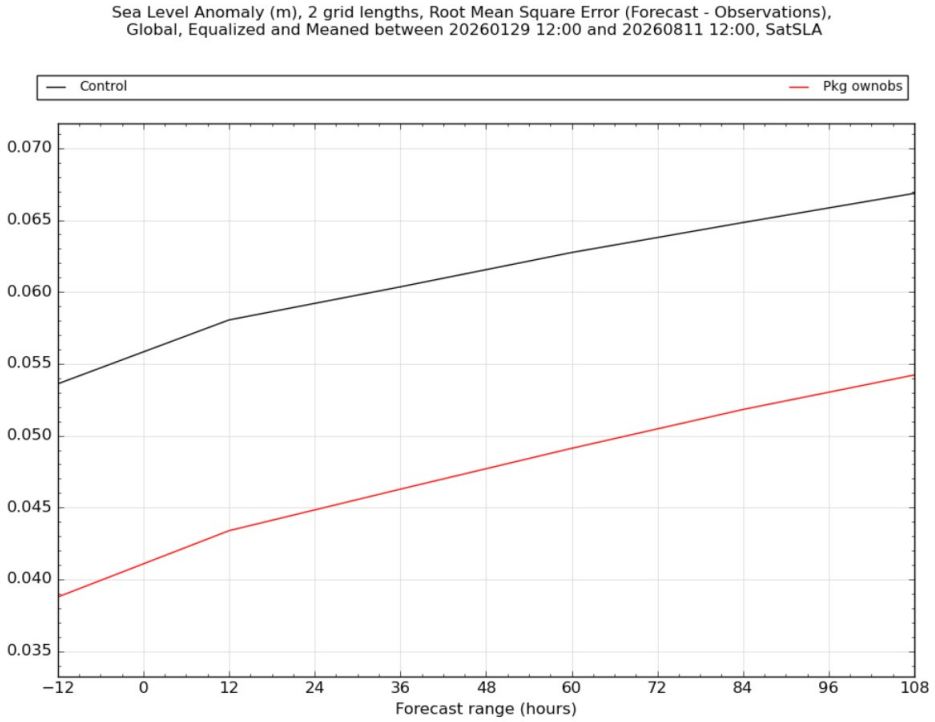
Orca025 3DVar-FGAT
Orca12 3DVar-FGAT
Orca12 Hybrid 3DEnVar
Orca025 Hybrid 3DEnVar

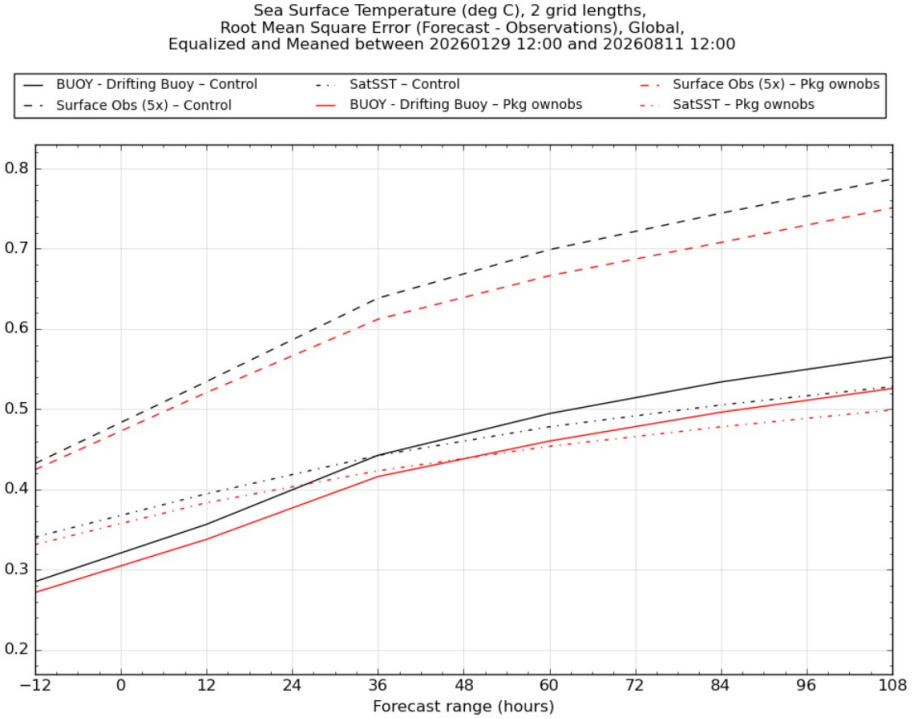
Current velocity assessment against drifter derived velocities (independent assessment)

This confirms the positive impact of hybrid DA

Orca12 – PS48 package trial vs control







Global RMS forecast lead times show good improvement in SLA (left) and SST (right). Some areas degraded specifically Arctic SLA, and SST & SLA in Tropical Atlantic

Summary

- A very large benefit is seen from hybrid DA vs 3DVar in 1/4° and 1/12° (reduction in RMS error of ~20% for SSH, and ~6% for T and S profiles). This is similar to that seen in the older version of the ensemble system (GO6) despite the many updates to the model and data assimilation system.
- The 1/12° (mixed res) ensemble system works well gives better results (for observation based comparisons) than the 1/4° system something we have not previously seen with 3DVar.
- We are not planning to run long ensemble forecasts for now - this work is mainly to improve the DA - although we will obtain “errors-of-the day” for Met Office ocean analyses for the first time.
- All being well the 1/12° ensemble system should go operational in early 2027.

- The system performs less well in parts of the tropics. Spatially varying hybrid weights is an option to deal some of these issues – other options could be explored e.g. scale selective localisation
- Longer term we will look at implementation of the ocean ensemble in the coupled NWP system (again) (after having gained valuable experience with the ocean only ensemble system).
- We also plan to work on (the not currently used) sea-ice hybrid DA in future.

Met Office

Thanks

References

Lea et al. 2022. A new global ocean ensemble system at the Met Office: Assessing the impact of hybrid data assimilation and inflation settings. Quarterly Journal of the Royal Meteorological Society 148(745). DOI: 10.1002/qj.4292.

Lea et al. 2023. Assessing the impact of including a global ocean ensemble system in the Met Office coupled Numerical Weather Prediction system. Weather Science tech report . 657.
https://www.metoffice.gov.uk/research/library-and-archive/publications/science/weather-science-technical-reports

Mignac et al. 2025. Improvements to the Met Office's global ocean–sea ice forecasting system including model and data assimilation changes. Geosci. Model Dev., 18, 3405–3425, https://doi.org/10.5194/gmd-18-3405-2025.

Spare slides

Update from previous ocean version GO6 to GOSI9

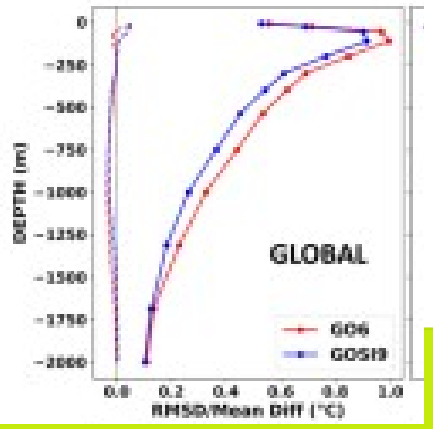
Changes to DA include:

- 1 temperature covariance (Rossby radius) length-scale but retaining 2 unbalanced salinity covariance length-scales (444 km and Rossby radius).
- Improved observation error specifications.
- Increase in number of inner loop iterations to 120 from 40

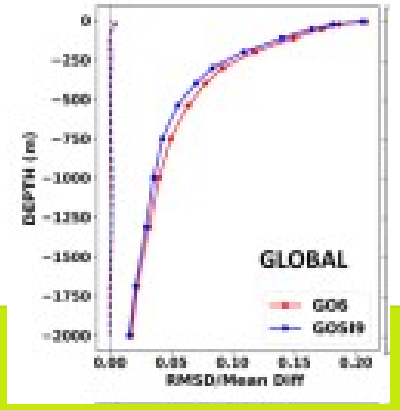
New version of NEMO (v4):

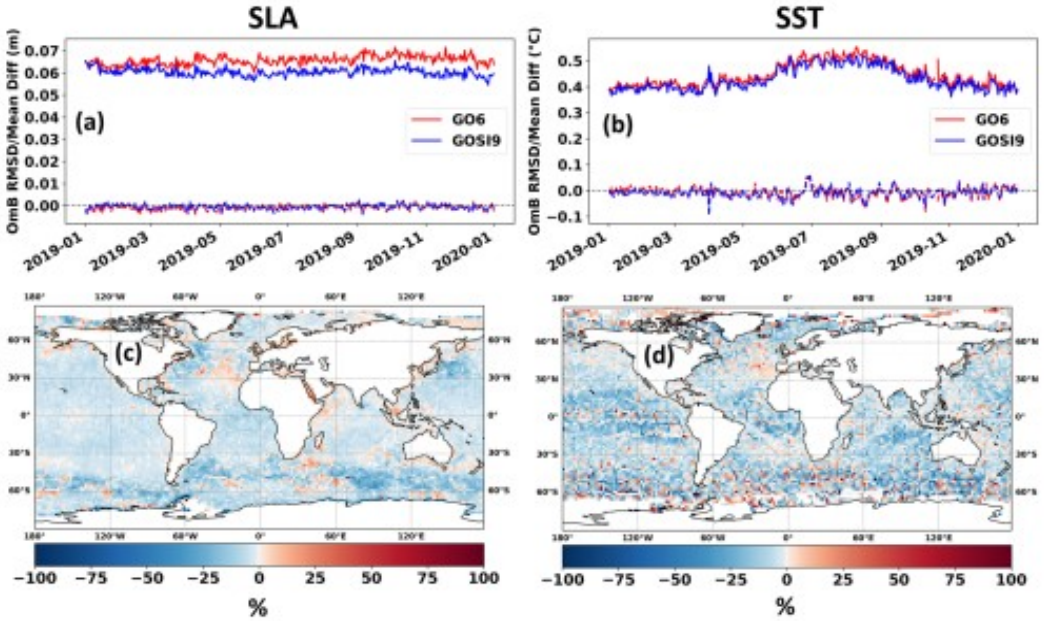
- Change in equation of state from EOS80 to TEOS-10 (conservative temperature/absolute salinity).
- New sea-ice model CICE => SI3
- Model perturbation scheme updated.

T profile errors



S profile errors





(Mignac et al., 2025)