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: ……Improving the ORAS5 Global Ocean Reanalysis using a Smoother Algorithm
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Computer Project Account: ………spgbdong………………………………….

Principal Investigator(s): ………Bo Dong, Keith Haines…………….……
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Affiliation: ………University of Reading

Name of ECMWF scientist(s) collaborating to the project
(if applicable) …… Hao Zuo
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Start date of the project: ………1/1/2023……………………….……

Expected end date: ………31/12/2025……….……

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	(units)	N/A	N/A	200,000	0
Data storage capacity	(Gbytes)	N/A	N/A	1,200	0

Summary of project objectives (10 lines max)

We have developed a reanalysis smoothing method (DHM smoother, Dong et al. 2021), which makes use of historically stored increment data to produce a more physically plausible time-evolving ocean state, with smoother temporal adjustments towards the available observations. We have tested this new method in the Lorenz 1963 model, as well as the Met Office FOAM ocean analysis. Both systems show that the errors have been reduced effectively (Dong et al. 2021). In the work proposed here we will explore how the smoother works when longer assimilation time windows are being used as in the ECMWF ORAS5 system. We also hope to gain from the improved treatment of bias that has been applied in ORAS5 which should allow the smoothing timescales in the subsurface ocean to be extended for longer periods than we have used before.

Summary of problems encountered (10 lines max)

Not any so far. For the first half year of the project we've been developing theoretical foundation of the smoothing method by linking the temporal decay assumption to the cross-time error covariance of the traditional Kalman smoother. Our paper on this work has been accepted for publication in Geoscientific Model Development.

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

For the 2nd half of year 1, we plan to apply this smoother on the ECMWF ORAS5 reanalysis, for temperature and salinity field. The experiments will be run on the Atos clusters.

List of publications/reports from the project with complete references

Dong, B., Bannister, R., Chen, Y., Fowler, A., and Haines, K.: Simplified Kalman smoother and ensemble Kalman smoother for improving reanalyses, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-337, 2023

Summary of results

We relate the DHM smoother algorithm presented in Dong et al. (2021) to a traditional Kalman smoother by showing that the cross time error covariance can be simplified as the Kalman filter error covariance multiplied by the DHM decay parameter γ. The simplified smoother solution at time k can be therefore be written as the following formula

$$\mathbf{x}_k^s \approx \mathbf{x}_k^a + \sum_{\ell=1}^{L} \gamma^\ell \mathbf{K}_{k+\ell}^a (\mathbf{y}_{k+\ell} - \mathcal{H}_{k+\ell}(\mathbf{x}_{k+\ell}^f))$$

where future timesteps l are influencing the earlier timestep k. The sum above is therefore defined entirely in terms of filter increments which are commonly stored, and the smoother can therefore be applied as a post-processor. The smoother posterior uncertainty is also approximated as;

$$\mathbf{P}_k^s \approx \mathbf{P}_k^a - \sum_{\ell=1}^{L} \gamma^{2\ell} \mathbf{IP}_{k+\ell}$$

where again IP represent error covariance increments that could be stored during filtering. Such simplification also works in the ensemble Kalman smoother, so that the ensemble mean smoother solution can be similarly expressed in the ensemble Kalman smoother framework with simplified cross time Kalman gain, as

$$\overline{\mathbf{x}_k^s} \approx \overline{\mathbf{x}_k^a} + \sum_{\ell=1}^{L} \gamma^{\ell} \mathbf{K}_{k+\ell}^a (\mathbf{y}_{k+\ell} - \mathcal{H}_{k+\ell}(\overline{\mathbf{x}_{k+\ell}^f}))$$

Details of the equation derivations are referred to Dong et al. (2023)

We simulate the simplified Kalman smoother (MKS), extended Kalman filter (ExtKF), and extended Kalman smoother (ExtKS) in the Lorenz 1963 model. Each experiment is carried out with a 100-member ensemble run. The RMSEs for each of the methods are presented in Fig.1.
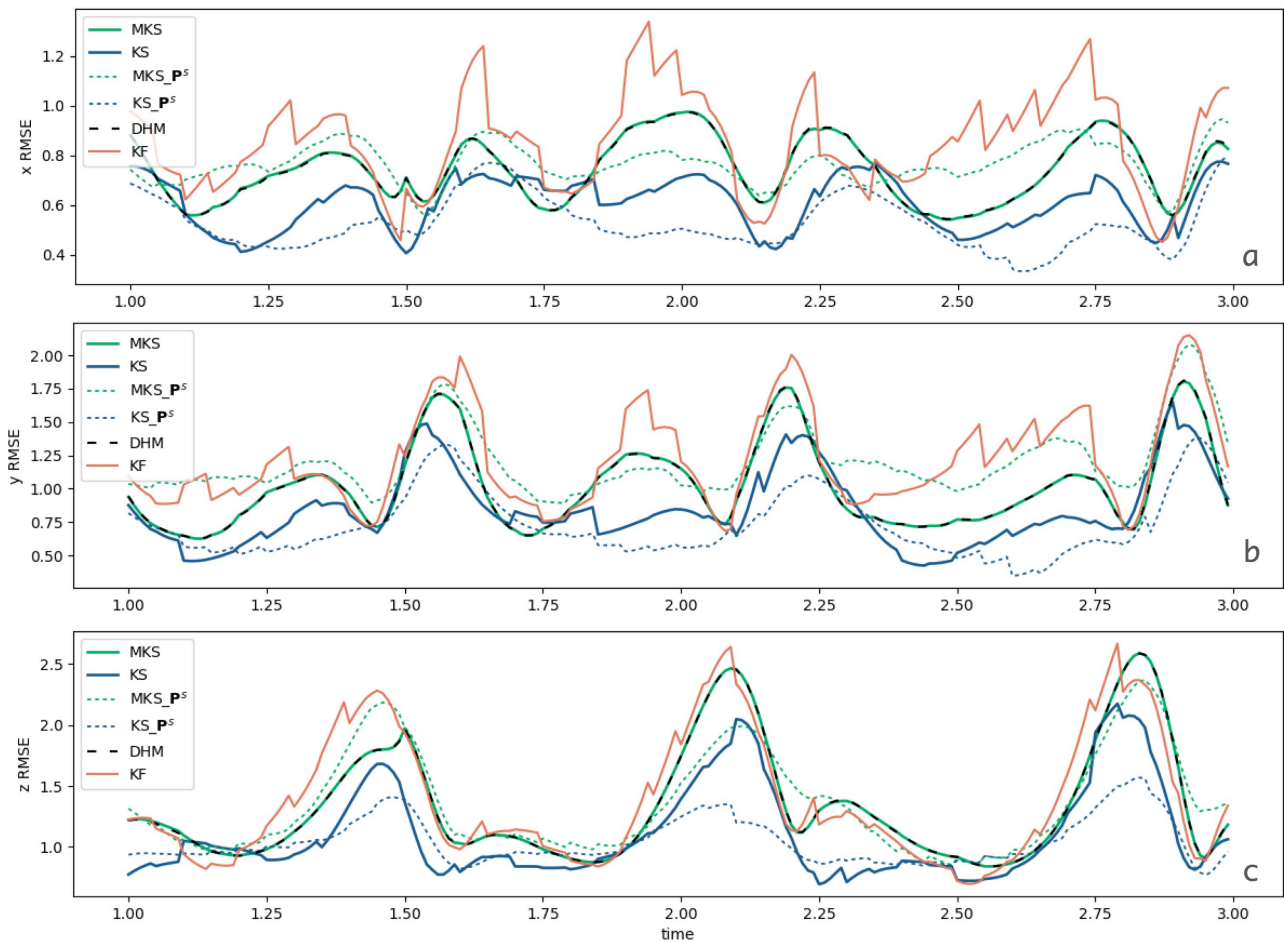

Fig.1 adapted from Dong et al. (2023). The RMSE timeseries against the truth for the ExtKF and ExtKS along with the MKS and the simplified DHM smoother in the L63 system for (a) x, (b) y and (c) z. Green lines and blue lines are the posterior uncertainty standard deviation estimates for the MKS and ExtKS respectively.

For most timesteps the KF errors are larger than the smoother errors. The full ExtKS has the smallest errors, however the DHM and MKS are almost identical and lie in between those for the

KF and KS. Also on Figure 1 are dashed lines representing the average of the smoothed standard deviation (STD) uncertainty estimates for the ExtKS runs and MKS runs respectively. It should be emphasised that these uncertainty estimates are calculated entirely independently of the actual truth values themselves, which would not be known in a real assimilation problem. The level of agreement between these uncertainty estimates and the RMSE against truth is remarkable.
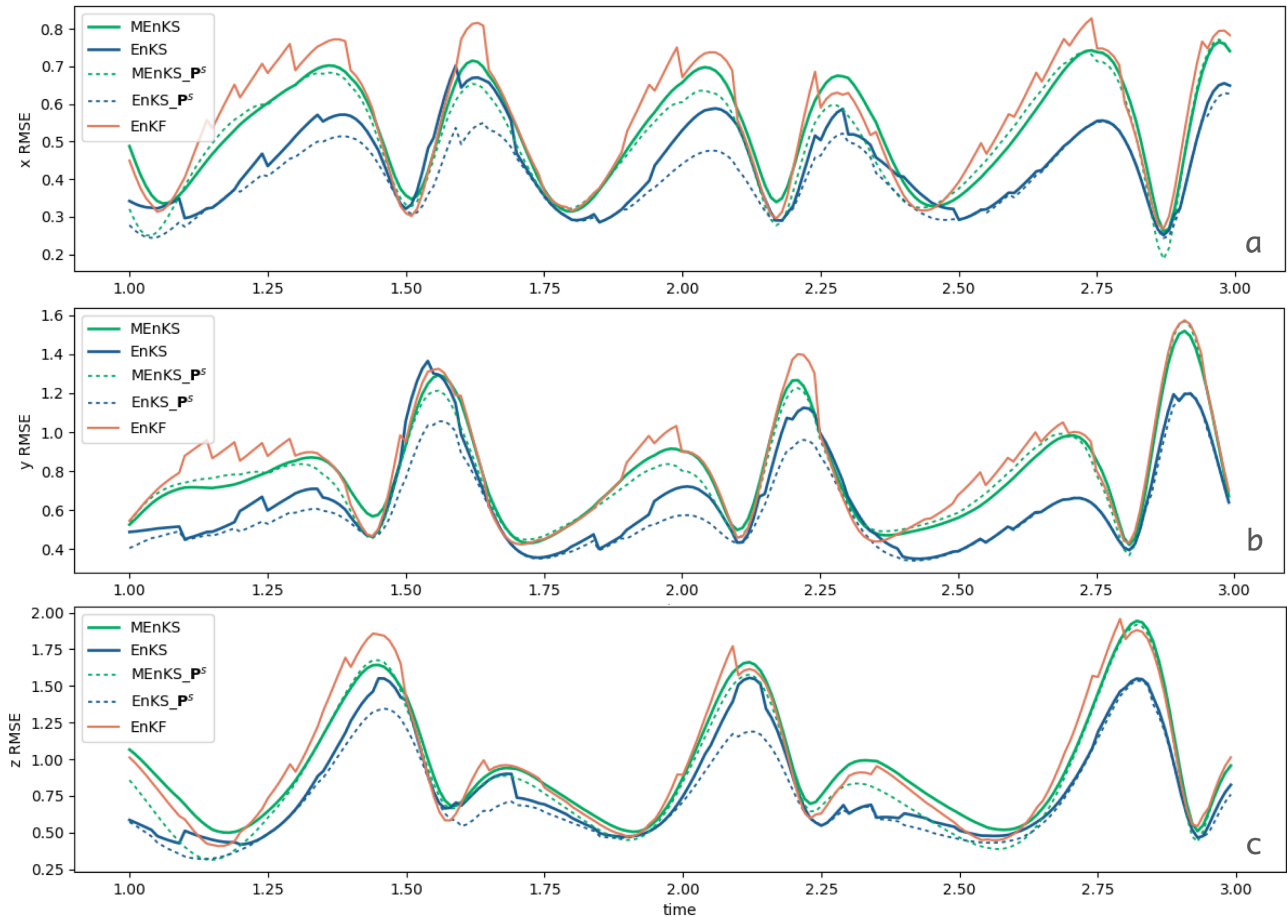

Fig.2 adapted from Dong et al. (2023). As in Fig. 1 but for EnKF, EnKS and MEnKS.

The simplified smoothing method is also shown to work well in ensemble assimilation system (Fig. 2). The RMSE for simplified ensemble Kalman smoother (MEnKS) is smaller than the ensemble Kalman Filter (EnKF) for most timesteps, and larger than the full EnKS as expected.

With this theoretical foundation, we are confident that the simplified smoother would work well in most of the sequential assimilation systems that are based on Kalman filtering or 3DVar. We've completed supervising an MSc student summer project for testing the smoother algorithm on the ORAS5 reanalysis for a 3-month period. Sample outputs are shown in Fig.3 and Fig.4 below. We plan to run this smoother on the Atos clusters for longer period, for the 2nd half of year 1 of this special project.
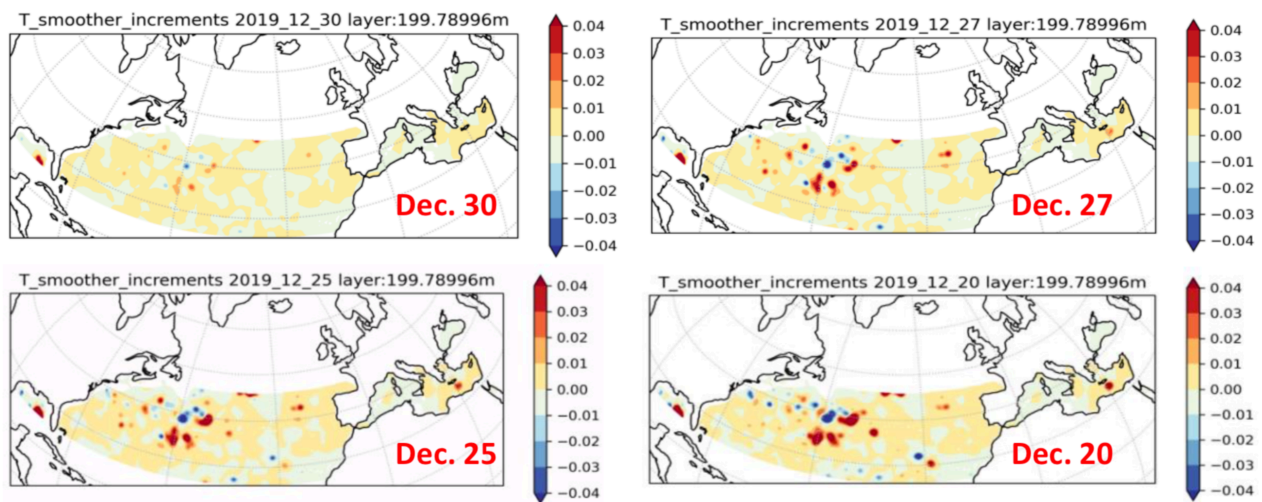
Fig. 3. Smoother increments in 200 m temperature field for selected days in December 2019. The decay parameter γ=0.936 which is equivalent to ~15 days decay time (e-folding time).
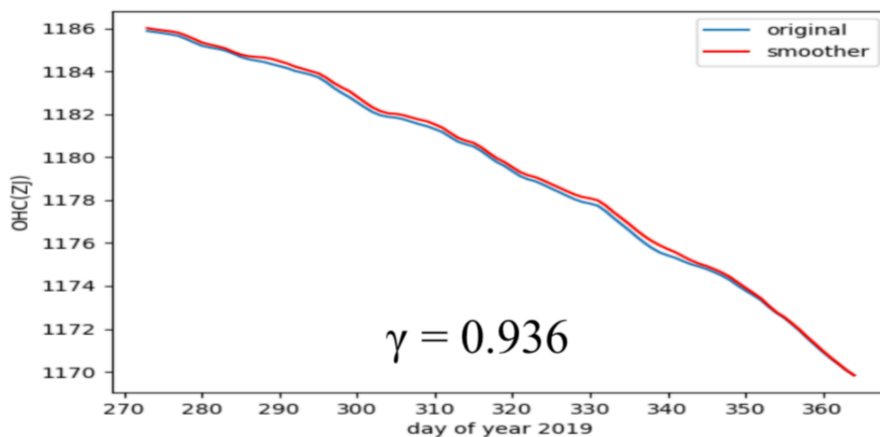

Fig. 4. North Atlantic 0-2000m OHC time series from October to December 2019 in ORAS5 reanalysis (blue) and smoother reanalysis (red).

Reference:

Dong, B., Haines, K., and Martin, M.: Improved high resolution ocean reanalyses using a simple smoother algorithm, Journal of Advances in Modeling Earth Systems, 13, e2021MS002 626, 2021.

Dong, B., Bannister, R., Chen, Y., Fowler, A., and Haines, K.: Simplified Kalman smoother and ensemble Kalman smoother for improving reanalyses, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-337, 2023