USING THE GOCE MDT IN OCEAN DATA ASSIMILATION

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ABSTRACT

First results from assimilating the GOCE MDT into an operational ocean model at the Met Office are described. The method is designed to allow the MDT covariance errors to be used to adjust the MDT to better fit the other assimilated ocean data and the model constraints. In these first results the GOCE MDT covariance errors have not been used because they only represent commission errors. Bias corrections to the Rio05 and the GOCE MDTs are calculated and compared in equivalent 1 month tests experiments. Further developments are discussed.

1. INTRODUCTION

The new GOCE geoid can be combined with a Mean Sea surface (MSS) from altimeter measurements to provide ocean mean dynamic topography (hereafter MDT) with more rigorous error covariance estimates. The errors in the MDT have a quite different structure from the errors in the variable component of sea level or the sea level anomaly (hereafter SLA) obtained from time-varying altimeter data.

The best estimate of mean dynamic topography should come from combining satellite geodetic data, altimeter data, along with in situ ocean data eg. from density profiles or surface drifter measurements. However in situ ocean data are not uniformly sampled in space and time and therefore mean in situ information is hard to generate directly. The best way to combine these 2 sources of information should be through using data assimilation within a time evolving ocean model rather than trying to do the difficult task of removing transient information from each in situ ocean measurement by non-uniform averaging.

In section 2 we describe the current operational ocean assimilation system at the Met Office and section 3 describes the theoretical approach that treats MDT errors as a potential bias in the assimilated absolute dynamic topography. Section 4 we present some bias results from the operational system. In section 5 we describe the first test experiments with the GOCE MDT. We make a comparison of using the Rio05 MDT or the GOCE MDT, and compare the bias in each MDT which allows model sea level to better fit the observations using the dynamical model constraint. We show the commission errors from this GOCE MDT, although they have not been used yet in these first test experiments. Section 6 presents discussion and conclusions and ongoing work.

2. THE MET OFFICE ASSIMILATION SYSTEM

The Met Office assimilation system (FOAM) assimilates the following datasets daily:

- 1 million Sea Surface Temperature (SST) Measurements
- 1000 In Situ T and S measurements (from EN3 QCd data, Ingleby and Huddleston 2007)
- 40,000 Along-track Sea Level Anomaly (SLA) data points from Jason-1/2, Envisat from CNES-CLS/ AVISO.
- 0.8 million sea ice measurements from OSI-SAF - EUMETSAT
- Mean Dynamic Topography (MDT) externally specified

The operational forecasts use the NEMO ocean model run in a number of configurations given in Table 1,

ORCA025	Global 1/4°
ORCA1	Global 1°
NATL12	North Atlantic 1/12°
IND12	Indian 1/12°
MED12	Mediterranean 1/12°

Table 1: FOAM model configurations.

while Fig 1 shows the schematic of the data assimilation workflow.

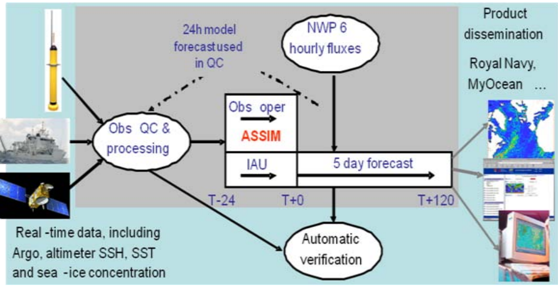

Figure 1: Schematic of the Met Office FOAM operational oceanography system.

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3. SEQUENTIAL ASSIMILATION OF MDT AS A SEA LEVEL BIAS: THEORY

This theory is based on the work of Drecourt et al 2006 and Lea et al 2008. A key challenge is to separate the MDT and its errors in order to use the new GOCE data effectively. This is achieved using a 3DVar approach where the cost function *J* below allows part of the dynamic topography error to be identified as either model bias or observation bias. The observation bias is the unknown correction to the MDT which has a known error covariance, and this bias is derived or forecast as the assimilation proceeds. The method relies on the model dynamic topography error having different space and time error covariances from that of the observations.

$$J = (\mathbf{y}-\mathbf{H}(\mathbf{x}+\mathbf{b}))^{\mathrm{T}}\mathbf{R}^{-1}(\mathbf{y}-\mathbf{H}(\mathbf{x}+\mathbf{b})) \quad \text{Model data misfit}$$
$$+(\mathbf{x}-\mathbf{x}^{f}+\mathbf{c})^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^{f}+\mathbf{c}) \quad \text{Background constraint}$$
$$+(\mathbf{b}^{o}-\mathbf{b})^{\mathrm{T}}\mathbf{T}^{-1}(\mathbf{b}^{o}-\mathbf{b}) \quad \text{Observation (MDT) bias constraint}$$
$$+(\mathbf{b}-\mathbf{b}^{f})^{\mathrm{T}}\mathbf{O}^{-1}(\mathbf{b}-\mathbf{b}^{f}) \quad \text{Observation bias evolution constraint}$$
$$+(\mathbf{c}-\mathbf{c}^{f})^{\mathrm{T}}\mathbf{P}^{-1}(\mathbf{c}-\mathbf{c}^{f}) \quad \text{Model bias forecast constraint}$$

where;
x – model state (sea level)
y – observation (MDT + SLA)
R – SLA observation error covariance
B – background error covariance
H – observation operator
b – MDT observation bias: Note we assume $\mathbf{b^o} = 0$
c – model bias
T – obs. MDT bias error covariance: (from GOCE)
O – obs. MDT bias *forecast* error covariance
P – model bias forecast error covariance.
The analysis (superscript a) solution to the above cost function minimisation wrt. **x,b** and **c** is:

$$\mathbf{x}^{a} = (\mathbf{x}^{f}-\mathbf{c}^{f}) + \mathbf{K}_1\{\mathbf{y}-\mathbf{H}\tilde{\mathbf{b}}^{f}-\mathbf{H}(\mathbf{x}^{f}-\mathbf{c}^{f})\} \quad \text{State analysis}$$
$$\mathbf{K}_1 = (\mathbf{B}+\mathbf{P})\mathbf{H}^{\mathrm{T}}\{\mathbf{H}(\mathbf{B}+\mathbf{P}+\mathbf{L}\mathbf{T})\mathbf{H}^{\mathrm{T}}+\mathbf{R}\}^{-1}$$

$$\tilde{\mathbf{b}}^{f} = \mathbf{L}\mathbf{b}^{o} + (\mathbf{I}-\mathbf{L})\mathbf{b}^{f} \quad \text{Rectified bias}$$
$$\mathbf{L} = \mathbf{O}(\mathbf{T}+\mathbf{O})^{-1}$$

$$\mathbf{b}^{a} = \tilde{\mathbf{b}}^{f} + \mathbf{F}\{\mathbf{y}-\mathbf{H}\tilde{\mathbf{b}}^{f}-\mathbf{H}(\mathbf{x}^{f}-\mathbf{c}^{f})\} \quad \text{Observation bias analysis}$$
$$\mathbf{F} = \mathbf{L}\mathbf{T}\mathbf{H}^{\mathrm{T}}\{\mathbf{H}(\mathbf{B}+\mathbf{P}+\mathbf{L}\mathbf{T})\mathbf{H}^{\mathrm{T}}+\mathbf{R}\}^{-1}$$

$$\mathbf{c}^{a} = \mathbf{c}^{f} - \mathbf{G}\{\mathbf{y}-\mathbf{H}\tilde{\mathbf{b}}^{f}-\mathbf{H}(\mathbf{x}^{f}-\mathbf{c}^{f})\} \quad \text{Model bias analysis}$$
$$\mathbf{G} = \mathbf{P}\mathbf{H}^{\mathrm{T}}\{\mathbf{H}(\mathbf{B}+\mathbf{P}+\mathbf{L}\mathbf{T})\mathbf{H}^{\mathrm{T}}+\mathbf{R}\}^{-1}$$

where **K, F** and **G** are the Kalman gains for the model state, the observation (MDT) bias and the model sea level bias respectively, each acting on the same sea level misfits {}.

4. OPERATIONAL EXPERIMENTS

In the FOAM Operational Configuration, assimilation uses high resolution models in Table 1, eg. ORCA025, and currently uses the Rio05 MDT with an error variance pattern taken to be the formal error variance but scaled up by a factor 5, shown in Figures 2a,b respectively. The Rio05 formal error variances are considered too small to represent true errors. The spatial scale associated with these error variances is assumed to be an isotropic 40km, (Knudsen and Tcherning, 2007). The model sea level error covariances are given a larger 400km scale and are also allowed to be time varying.

The error covariance information currently applied for operational forecasting is therefore given below,
$\mathbf{O} = \gamma_b \mathbf{T}$ where $\gamma_b = 0.01$ cor. scale 40 km
$\mathbf{P}$ uniform variance $9\mathrm{x}10^{-3}$ cor. scale 400 km
The MDT error covariance **T** defined how far large the observation bias field **b** can become, while **O** defines how much it can change at each assimilation time. The difference covariance scales imply that the MDT bias is dominated by smaller scales while the model bias is dominated by larger scales.

The time evolution of the Bias models: (**b** in cm) (**c** in cm/day) between assimilation time steps are also critical to separating the bias and are given by equations;
$\mathbf{b}^{f}_{i+1} = \mathbf{b}^{a}_{i}$ MDT Persistence
$\mathbf{c}^{f}_{i+1} = \beta \mathbf{c}^{a}$ Three month decay timescale.
reflecting the fact we are looking for a constant correction to the MDT, while the model error is likely to evolve seasonally.

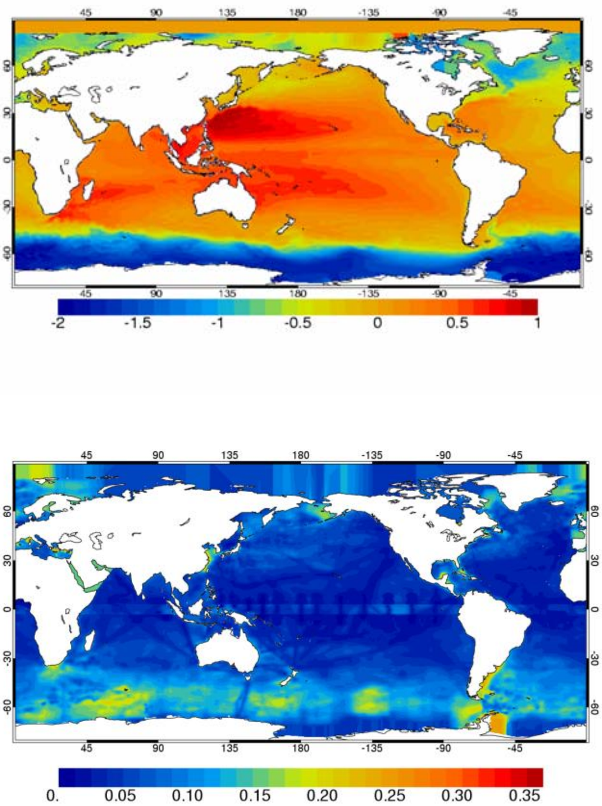


Figure 2: (a) shows the Rio05 MDT(m) and (b) the Rio05 formal error variances x 5 (m).

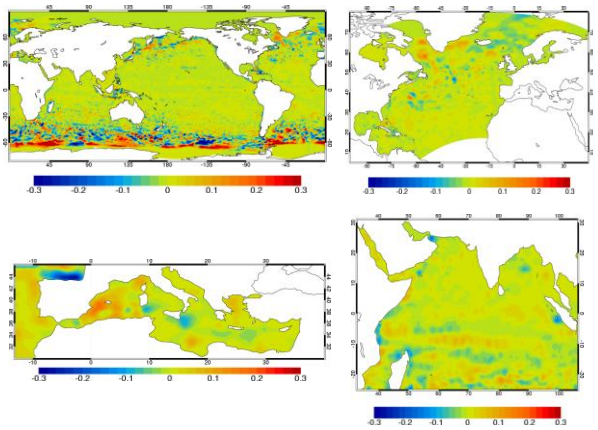


Figure 3 shows actual Operational results in 2009, showing estimated corrections to the Rio05 MDT field in different domains, in m.

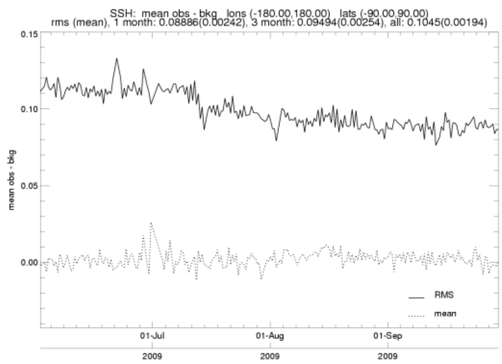


Figure 4 shows reductions in RMS Background errors in the operational system with time, as bias is identified.

Figures 3 and 4 above show MDT bias results from the operational system, with figure 4 indicating the reduction of RMS misfits to observations as the assimilation proceeds. However the error covariances being used here are generated in an an hoc manor. The GOCE MDT products should allow a more rigorous error treatment.

5. GOCE MDT ASSIMILATION EXPERIMENTS

The operational system at the Met Office will allow a first attempt to use the new GOCE MDT and its error covariances. Figure 5 shows the GOCE MDT based on the first 2 months of geoid data combined with the CLS01 mean sea surface, Hernandez and Schaeffer (2001). Figure 6 shows dominant aspects of the commission error of this product, with an error variance field and dominant meridional and zonal covariance scales all varying mainly with latitude. The original intention was to use these products for a first assimilation analysis however this error information would need to include the omission errors of the GOCE MDT product, which will be dominated by much smaller scales, as in section 4.

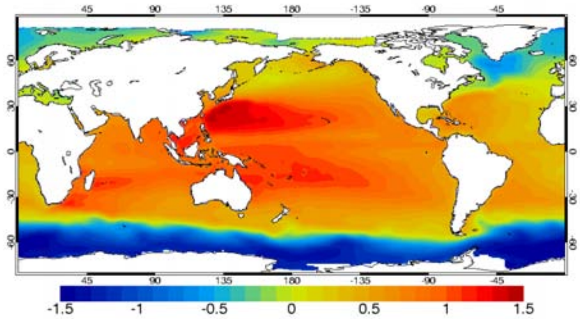


Figure 5 shows the GOCE MDT (m) based on 2 months of GOCE data (01/11/2009-11/01/2010).

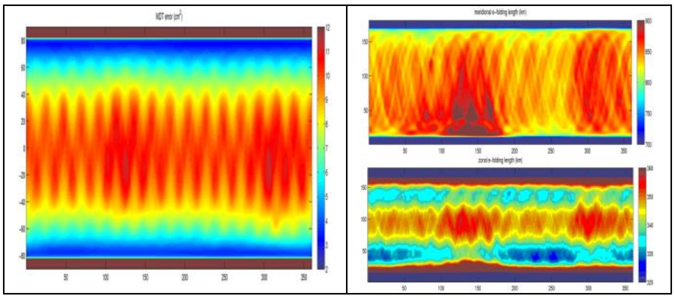
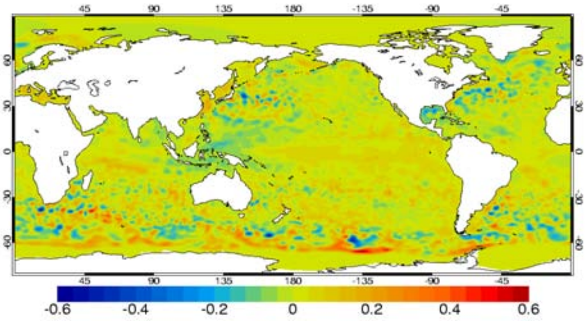


Figure 6 Left shows the error variance (cm) and (right) the meridional and zonal error covariance length scales (km) for the first month of GOCE data.

A possible methodology for generating a combined commission and omission error covariance model are discussed in section 6. For this first experiment the GOCE error information was therefore not used. The first GOCE assimilating experiment used the ORCA1 model and makes a comparison using either Rio05 or GOCE MDTs based on exactly the same simple error covariance model for both products. We assume a uniform 5cm error variance with an isotropic covariance scale 100km. The covariance scale is larger than in section 4 because the model resolution is only 1 degree. Also in these first test experiments the Model bias errors have not been used at all so the only bias product is the observational MDT bias. Runs are for a single month of Jan 2007, starting everything from the same initial conditions and, apart from the MDTs, assimilating the same ocean data.



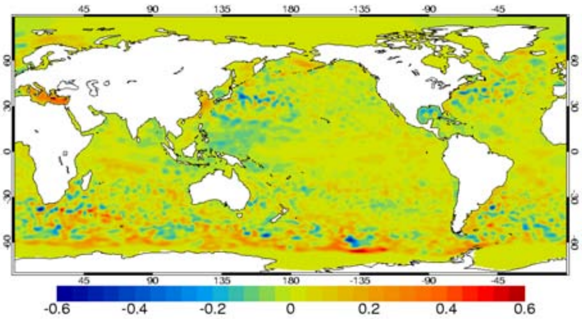


Figure 7 shows the MDT corrections to GOCE MDT (above) and Rio05 MDT (below) based on 1 month assimilation experiments in Jan 2007. Error covariances use identical RMS variance 5cm2 and scale 100km.

Figure 7 shows the bias fields calculated for each of the MDTs. Large scale differences can be seen. The GOCE MDT corrections are smaller in the Mediterranean and the western Pacific for example, but slightly larger in the eastern tropical Pacific. Many smaller scale features are similar reflecting eddy activity, however the 1 month timescale is too short to claim that these small scale MDT changes are realistic representations of small scale MDT variations.

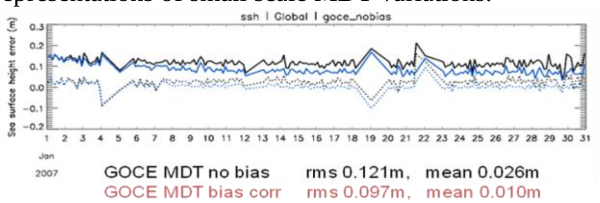


Figure 8 shows the RMS sea level errors for two GOCE experiments. Solid black; fixed GOCE MDT, solid blue; with MDT bias corrections.

Figure 8 shows that the reduction in RMS errors with bias is 50% from reduced global mean errors (dotted) and 50% due to spatial variability. This highlights a problem that still exists with the simple covariance model, because the dominant error scale currently represents a minimum scale and does not prevent bias developing on larger scales. This is in the NEMOVAR assimilation method for representing error covariances and requires further work to alter this.

6. DISCUSSION AND CONCLUSIONS

The results so far demonstrate that;

- The GOCE MDT can be used to effectively constrain ORCA1 ocean circulation.
- Comparisons with Rio05 results show differences to MDT bias corrections, however since the same error covariance model is being used these differences probably reflect the main MDT differences filtered through the error covariance model.
- Both global mean sea level errors and large scale spatial structures are modified

This last point now needs to be properly addressed. Two advances are required. (1) A total error covariance model is needed for any GOCE based MDT, taking account of both commission and omission errors. While the commission errors must be based on the geodetic data from GOCE, the omission errors can only be based on oceanographic data, providing an expectation of the amplitude of the small scale variations in mean ocean currents. (2) A more effective model for applying the error covariance information within the assimilation system which uses error covariance scales to define the maximum scale of MDT bias errors rather than the minimum scale. Ongoing work now includes these 2 main issues as well as;

- Extending application to higher resolution models eg. ORCA025 to allow smaller scales
- Testing in a 1 year run with ORCA025 with CNES-CLS 09 MDT and spatially varying bias
- Use of later GOCE MDTs based on more data with smaller commission errors

7. REFERENCES

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