Model and observation bias correction in altimeter ocean data assimilation in FOAM

Daniel Lea[1], Keith Haines[2] and Matthew Martin[1]

[1]Met Office, [2]ESSC, Reading

Introduction

We implement a combined online model and observation bias correction system in the UK Met Office FOAM (Forecasting Ocean Assimilation Model) OI (Optimal Interpolation) Unified Model ocean data assimilation system. The observation bias scheme is designed to estimate the error in the mean dynamic topography (MDT) that must be used for altimeter data assimilation. The mean dynamic topography field is added to the altimeter data supplied as sea-level anomalies giving the absolute sea surface height. The bias scheme separately estimates the remaining model bias in the model sea surface height field. The final unbiased estimate of the absolute dynamic topography is assimilated into the FOAM model by adjusting the subsurface density field using the Cooper and Haines (1996) scheme. Various diagnostics including the observation minus background statistics show that both model and observation bias correction schemes improve the assimilation results. Combining the schemes provides better results than either alone.

The FOAM system is now transitioning from the Unified Model (UM) ocean to a 0.25 degree global NEMO (Nucleus in European Modelling of the Ocean) system using the similar OI assimilation scheme. Some results are presented using the bias correction scheme with this new system.

FOAM system

FOAM is an operational daily open ocean analysis and forecasting system (see Matt Martin's poster S2.14-044 for details). This system assimilates real time or near real time data including satellite sea surface temperature, sea level anomaly (SLA), insitu temperature and salinity data from e.g. Argo. The along track altimeter SLA data is obtained from Collecte Localisation Satellites (CLS). The altimeter data is assimilated along with the mean dynamic topography (MDT) which is derived from model and observational estimates

Bias assimilation method

The MDT is known to have significant errors particularly on smaller scales. The launch of GOCE (Gravity field and steady-state Ocean Circulation Explorer) will improve the MDT however there will still be small scale biases of ~10 cm. In order to address this problem we augment the OI type assimilation method with an altimeter observation bias variable. Additionally to try to avoid model error contaminating the bias estimate we add an altimeter model bias variable. The scheme is described in detail in Lea et al. 2008. The assimilation problem can be expressed in terms of a cost function. The bias terms are controlled by covariance estimates. See table 1. The assimilation problem involves finding the model state and also the observation and model bias terms which minimise a cost function (1).

$$\begin{aligned} J = & (\mathbf{y} - \mathbf{H}(\mathbf{x}+\mathbf{b}))^{\mathrm{T}}\mathbf{R}^{-1}(\mathbf{y} - \mathbf{H}(\mathbf{x}+\mathbf{b})) \\ & +(\mathbf{x} - \mathbf{x}^{\mathrm{f}} + \mathbf{c})^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}^{\mathrm{f}} + \mathbf{c}) \\ & +(\mathbf{b}^{\mathrm{o}} - \mathbf{b})^{\mathrm{T}}\mathbf{T}^{-1}(\mathbf{b}^{\mathrm{o}} - \mathbf{b}) \\ & +(\mathbf{b} - \mathbf{b}^{\mathrm{f}})^{\mathrm{T}}\mathbf{O}^{-1}(\mathbf{b} - \mathbf{b}^{\mathrm{f}}) \\ & +(\mathbf{c} - \mathbf{c}^{\mathrm{f}})^{\mathrm{T}}\mathbf{P}^{-1}(\mathbf{c} - \mathbf{c}^{\mathrm{f}}) \end{aligned} \qquad (1)$$

Table 1: Variables and covariances
x – model state vector
y – observation vector
b – observation bias vector
c – model bias vector
T – observation bias error covariance
O – obs bias forecast error covariance
P – model bias forecast error covariance
R – observation error covariance
B – background error covariance
H – observation operator translates from model to observation space

The minimum to the cost function can be found analytically and is expressed below in (2). These are the standard OI analysis equations but augmented with similar equations for estimating the observation and model bias.

$$\begin{aligned} \mathbf{x}^{\mathrm{a}} &= (\mathbf{x}^{\mathrm{f}} - \mathbf{c}^{\mathrm{f}}) + \mathbf{K}_1\{\mathbf{y} - \mathbf{H}\tilde{\mathbf{b}}^{\mathrm{f}} - \mathbf{H}(\mathbf{x}^{\mathrm{f}} - \mathbf{c}^{\mathrm{f}})\} \\ \mathbf{K}_1 &= (\mathbf{B}+\mathbf{P})\mathbf{H}^{\mathrm{T}}\{\mathbf{H}(\mathbf{B}+\mathbf{P}+\mathbf{LT})\mathbf{H}^{\mathrm{T}} + \mathbf{R}\}^{-1} \\ \mathbf{b}^{\mathrm{a}} &= \tilde{\mathbf{b}}^{\mathrm{f}} + \mathbf{F}\{\mathbf{y} - \mathbf{H}\tilde{\mathbf{b}}^{\mathrm{f}} - \mathbf{H}(\mathbf{x}^{\mathrm{f}} - \mathbf{c}^{\mathrm{f}})\} \\ \mathbf{F} &= \mathbf{LTH}^{\mathrm{T}}\{\mathbf{H}(\mathbf{B}+\mathbf{P}+\mathbf{LT})\mathbf{H}^{\mathrm{T}} + \mathbf{R}\}^{-1} \\ \mathbf{c}^{\mathrm{a}} &= \mathbf{c}^{\mathrm{f}} - \mathbf{G}\{\mathbf{y} - \mathbf{H}\tilde{\mathbf{b}}^{\mathrm{f}} - \mathbf{H}(\mathbf{x}^{\mathrm{f}} - \mathbf{c}^{\mathrm{f}})\} \\ \mathbf{G} &= \mathbf{PH}^{\mathrm{T}}\{\mathbf{H}(\mathbf{B}+\mathbf{P}+\mathbf{LT})\mathbf{H}^{\mathrm{T}} + \mathbf{R}\}^{-1} \\ \tilde{\mathbf{b}}^{\mathrm{f}} &= \mathbf{Lb}^{\mathrm{o}} + (\mathbf{I} - \mathbf{L})\mathbf{b}^{\mathrm{f}} \\ \mathbf{L} &= \mathbf{O}(\mathbf{T}+\mathbf{O})^{-1} \end{aligned} \qquad (2)$$

The remaining problem is to find good estimates for the new covariances. The Rio05 MDT product comes with an estimate of the error associated with it (Fig 1). This can be used to give the variance of the observation bias error covariance matrix **T** (which controls the overall size of **b**). We find that this underestimates the spread of MDT products and therefore inflate it by a factor of 5. The correlation scale for **T** is 40 km which is thought to be the scale on which the errors in the MDT are largest. The observation bias forecast error covariance **B** which controls the change in **b** at each analysis is set to 0.01**T**. This forces to bias to change slowly preventing a noisy estimate. The model bias forecast error covariance is least well known and for this work is assumed to be uniform with a variance of 9×10^{-3} cm^2 and a correlation scale of 400 km given the main form of this error is expected to be large scale seasonal steric errors. The bias model for the observation bias is persistence since it is assumed to be constant in time. The model bias decays with a 3 month timescale.

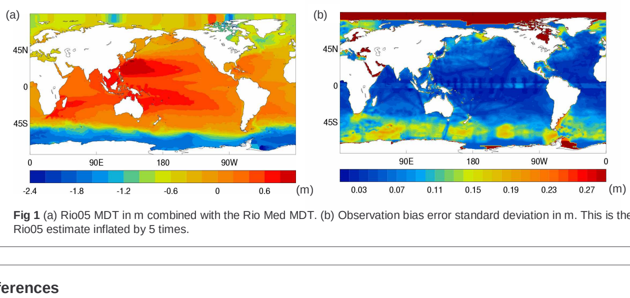

Fig 1 (a) Rio05 MDT in m combined with the Rio Med MDT. (b) Observation bias error standard deviation in m. This is the Rio05 estimate inflated by 5 times.

FOAM-UM Results

These results are from the old 1/3° Unified Model Atlantic-Arctic FOAM averaged over the whole model domain and four years. Here we show the innovations which are the observation values minus the model forecast before assimilation (model background) at the observation locations. The innovations use the bias corrected observation and model values where appropriate

	Mean innovations /cm	Standard deviation /cm
STD – no SSH bias correction	(0.317)	9.56
OBS – observation SSH bias correction	(0.150)	8.71
MOD – model SSH bias correction	(0.032)	9.10
OAM – model and observation bias	**(0.005)**	**8.56**

Table 2: Mean and standard deviation of innovations averaged overt the model domain for the last 4 years of the 5 year FOAM-UM hindcasts. The combined model and observation bias correction gives the best results.

FOAM-NEMO Results

The FOAM system is now running with the NEMO model. In this section we compare the results for the global ¼° (ORCA025) model to the nested 1/12° North Atlantic, Indian and Mediterranean models. (See Ed Blockley's poster S2.2-086) for more information on the FOAM regional models). We also compare the global model with altimeter observation bias correction to a run without altimeter bias correction (see Fig 2).

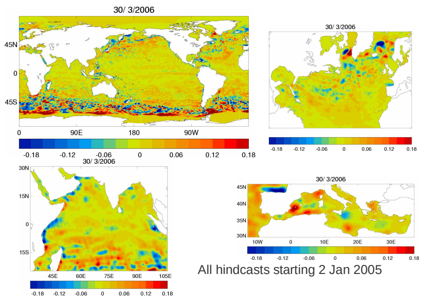

Fig 2: Instantaneous observation bias fields compared after 16 months for the global model and the nested regional models. Note that the bias field takes around 6 months to spin-up, and is subsequently fairly stable. Many features of the bias match between the global model and the regional model equivalent. The differences give an indication of resolution dependant model error. The similarities give increased confidence that some of the signal is actually observation bias rather than misidentified model bias. It should be noted that we are using the same bias covariance and the model and therefore some of the bias could be due to NEMO model errors.
A next step for exploring this may be to compare the FOAM-UM and FOAM-NEMO bias corrected MDT.

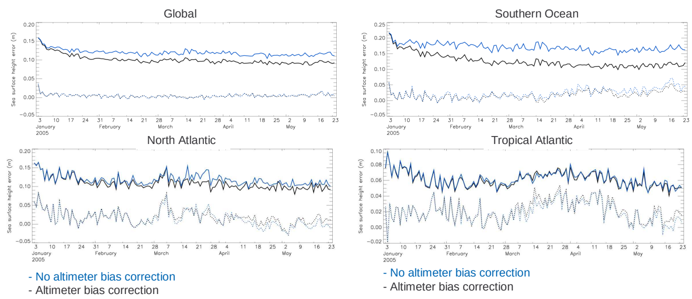

Fig 3: Comparison of SSH RMS (solid lines) and mean errors (dashed lines) of the innovations for global model assimilation experiments with and without altimeter observation bias correction. The regions are Global, North Atlantic (20°N -70°N), Southern Ocean (50°S – 90°S) and Tropical Atlantic (20°N – 20°S)

	STD: No SSH bias corr. RMS (mean)	**OBS** : SSH bias correction RMS (mean)
Global	**0.120 (0.005)**	**0.101 (0.005)**
Arctic	0.099 (0.040)	0.086 (-0.031)
North Atlantic	0.118 (0.015)	0.110 (0.018)
Tropical Atlantic	0.063 (0.019)	0.062 (0.022)
South Atlantic	0.144 (-0.001)	0.130 (0.007)
North Pacific	0.094 (0.002)	0.087 (0.002)
Tropical Pacific	0.055 (-0.021)	0.054 (-0.021)
South Pacific	0.073 (0.008)	0.068 (0.006)
Indian Ocean	0.117 (-0.017)	0.106 (-0.015)
Mediterranean	0.091 (-0.035)	0.085 (-0.036)
Southern Ocean	0.171 (0.024)	0.129 (0.018)

Table 3: Comparison of SSH RMS and mean innovations for various model regions over the period 2 Jan 2005 to 24 May 2005. (Matt Martin's poster contains a plot of the regions listed)
The bias correction gives significant Improvements in nearly all regions most significantly in the Southern Ocean region where the MDT is known to be in significant error (Fig 1b). The improvements in the Tropical Atlantic and Tropical Pacific are slight but the RMS errors are already much smaller than other regions.

The affect on the other variables in the model for example temperature and salinity profile RMS errors, is slight. However the positive effect of not assimilating bias SSH may become more evident later in the run as the bias spins up.

The observation bias correction is now standard in the new FOAM-NEMO operational system.

Discussion

We have demonstrated a useful bias correction scheme for altimeter assimilation.

Future plans are to implement the model bias correction scheme in FOAM-NEMO, implement the scheme into NEMOVAR and develop and test a more sophisticated scale selective bias error covariance (to take account of the knowledge that MDT errors are length-scale dependent). We also plan to use the new GOCE derived MDTs and error estimates when they become available as part of the GOCINO (GOCE In Ocean modelling) project.

References

Cooper, M., Haines, K. (1996) Altimetric assimilation with water property conservation. *J. Geophys. Res.,* 101(C1), pp 1059-1077
Lea, D. J., Drecourt, J.-P., Haines, K., Martin, M. J. (2008) Ocean altimeter assimilation with observational and model bias correction. *Q. J. R. Meteorol. Soc.,* In press
Martin, M. J., Hines, A., Bell, M. J. (2007) Data assimilation in the FOAM operational short-range ocean forecasting system: a description of the scheme and its impact. *Q. J. R. Meteorol. Soc.,* **133**, pp 981-995
Rio, M. H., Schaeffer, P., Hernandez, F., Lemoine, J. M. (2005) The estimation of the ocean Mean Dynamic Topography through the combination of altimetric data, in-situ measurements and GRACE geoid: From global to regional studies. In: *Proceedings of the GOCINA international workshop, Luxembourg.*

Met Office FitzRoy Road, Exeter, Devon, EX1 3PB United Kingdom
Tel: 01392 885680 Fax: 01392 885681
Email: daniel.lea@metoffice.gov.uk