USING ADVANCED DATA ASSIMILATION FOR ASSESSING THE CAPABILITIES AND LIMITS OF USING THE GOCE GEOID TO IMPROVE THE SHELF AND COASTAL OCEAN LOW-FREQUENCY CIRCULATIONS

Lamouroux, J.(1), De Mey, P.(2), Moreaux, G.(1), Balmino, G.(3), Le Hénaff, M.(2), Lux, M.(1), Haagmans, R.(4), Bouzinac, C.(4)

[1] ***NOVELTIS***, *Toulouse, France* http://www.noveltis.fr
[2] ***POC***, *Toulouse, France* http://poc.omp.obs-mip.fr
[3] ***GRGS/CNES***, *Toulouse, France* http://www.obs-mip.fr/grgs/
[4] ***ESA-ESTEC***, *Nordwijck, The Netherlands* http://www.esa.int/esaLP/LPgoce.html

Corresponding author: Julien Lamouroux, **julien.lamouroux@noveltis.fr**

Abstract

The study presented here aims to assess the capabilities and the limits of the use of the GOCE geoid to improve the shelf and coastal ocean low frequency circulations. The approach consists in using advanced data assimilation techniques (namely, the Ensemble Kalman Filter analysis kernel from the SEQUOIA-BELUGA data assimilation platform – De Mey, 2008, pers. comm.) in a hydrodynamic model to estimate the expected benefit of using GOCE data in addition to altimetric data. We use the SYMPHONIE 3-D free-surface model (Marsaleix *et al.*, 2008), implemented on the Bay of Biscay; the dynamics features a strong topographically-steered slope current, characterised by an associated mesoscale activity inducing strong exchanges between the shelf and the abyssal plain. In the framework of OSSEs, direct assimilation experiments of simulated altimetry and GOCE data are currently set-up with the Ensemble Kalman filter. In a first step, GOCE geoid error covariances are produced. We then look at the impact of simulated GOCE data onto the topographically-steered flow at the shelf break and its associated mesoscale and submesoscale field, and examine whether, if we assimilate GOCE data, those dynamical features and associated cross-slope transports are closer to the "truth".

Impact assessment framework

The signal associated with the slope current is small and at the limit of the ability of GOCE to detect. Coupled with the particularly large geoid omission errors over the slope, and the strong correlation between the expected sea level signal and the expected geoid error, this makes detection of the slope current a practical impossibility unless some other information can be brought to bear. That additional information can be a numerical model prediction. Thus, here, we conduct **direct assimilation experiments of simulated altimetry and GOCE data**. We look in particular at the impact of simulated GOCE data onto the topographically-steered flow at the shelf break and its associated mesoscale and submesoscale field.

The impact-testing methodology for simulated observations is generally referred to as **Observing System Simulation Experiments** (OSSEs). The most common way to perform OSSEs is to use the so-called "Twin Experiments" framework, in which observations simulated from a control run are assimilated in another run. More precisely, so-called **"Ensemble Twin Experiments"** have been performed, by the use of the Ensemble Kalman Filter (EnKF, e.g. Evensen, 2004) – what we look at then is how well a particular observing system is able to reduce the Ensemble spread when assimilated. Full EnKF has been implemented and used by POC+NOVELTIS in this work. At POC, EnKF has been previously used with success in the framework of OSSEs (as, e.g., Mourre *et al.*, 2004, 2006; Le Hénaff *et al.*, 2008a).

Modelling area

The **Bay of Biscay** (BoB, **Fig.1**) features a **strong topographically-steered slope current** (**Fig.2**), up to 100km wide, flowing in an anticlockwise manner. Because of its geographic extension, and because of the presence of tides and rich shelf dynamics, the BoB provides a valuable and unique case of study.

SYMPHONIE model (Marsaleix *et al.,* 2008) has been set up in the Bay of Biscay. This particular implementation was developed at POC during two Ph.D. theses (Pairaud and Auclair, 2005; Le Hénaff, 2008) and features a **3km-horizontal resolution**, **bulk formulae** to calculate heat fluxes, a **sigma-step vertical scheme** (41 levels max), meteorological forcings from Meteo-France **Aladin model outputs** (10 km/3h), **initial state and open boundary** fields from the **Mercator Psy2v1 model weekly data**, **rivers outflows** from the Loire, the Gironde and the Adour rivers are also modeled from in-situ data, a **period running from July to August 2004**.

The **summer period** was chosen because it is supposedly a period with lower, but significant, meteorological variability. Actually the 2004 summer has not been very nice, featuring two main low pressure events crossing the zone: on July 7, then in mid-August (separated by a calmer period). These two events are very similar in shape, and affected the entire modeled zone.

The model configuration was extensively validated during that period (Le Hénaff, Ph.D. thesis, 2008).

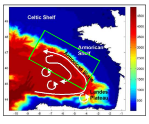

Fig.1: the Bay of Biscay modelling domain and bathymetry. The GOCE simulated observational grid domain is delineated in green. Typical dynamic features are represented with white arrows

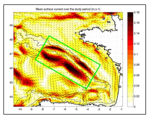

Fig. 2: mean surface currents in July-August 2004 in the reference simulation. The figure illustrates the westward-flowing slope current and eastward recirculation flowing just Southwest of it.

The slope current width is O(50km). The MDT signal is expected to be very small, O(100cm) there, at O(100km) horizontal scales in the cross-shelf direction

Observations

We want the assimilation system to be able to assimilate (1) **GOCE data** and (2) **altimetric data**. For each data type, one must be able to produce the proxy of that observation in the mode.

Problematic: the earth gravity field is not by itself a variable of an ocean model, nor can it be indirectly produced as a composite. Similarly, an ocean model has no knowledge of a reference ellipsoid or any other geodesic variable, so geoid height is not something it can produce.

➔ assimilation of **GOCE-derived Mean Dynamic Topography** (MDT) :

- Inversion of the gravity data into geoid height
- Calculation of the MDT from the geoid height and Mean Sea-Surface (MSS), as **MDT = MSS – h$_{GEOID}$**

The simulated/proxy MDT will be calculated as a running time average of DT over a fixed-size window.

The simulated/proxy MDT will also be a spatial average over a window consistent with the definition of the GOCE mission specs, in particular the GOCE commissioning space.

GOCE observational error statistics

Approach

Here we will derive typical Mean Dynamic Topography (MDT) statistics consistent with what we know of GOCE error covariances. As per the strategy chosen, MDT error statistics are directly linked to geoid height error statistics here, since in this impact assessment study we considered that the MSS was perfect.

GOCE simulated observational grid

GOCE observational errors have been simulated from a GOCE Simulated Observational Grid (hereafter SOG) nested within, and with the same resolution as, the BoB modelling domain. GOCE pseudo-observations have also been simulated over that specific area, but with a coarser resolution.

Commissioning error statistics

The commissioning error covariances have been modelled from the GOCE error covariance matrix corresponding to a simulation of GOCE spherical harmonic gravity potential of degree and order 200. These have been converted into geoid height error covariances by use of G. Balmino software.

Fig. 3 shows the first 6 commissioning error eigenvectors in the Bay of Biscay SOG, along with the corresponding eigenvalues (**Fig.4**), which give the geoid height error variance for each eigenvector. As one moves to higher modes, smaller scales, clearly attributable to the 1° grid on which the original data were expressed, appear, and at the same time the corresponding error variances appear to decrease as one moves to smaller scales. This apparent contradiction is due to the fact that those smaller error scales are not in the commissioning space, and are either artefacts of the interpolation, or scales which should instead be rejected to the omission errors. In the following, only the first eigenvector will be considered in describing commissioning errors, with its associated 2.55cm^2 error variance.

In practice…

Limitation of the ambition of our assimilation scheme: only correct those scales in the model MDT which can be adequately constrained by GOCE, i.e. the commissioning space scales.

➔ **only commission-space errors** will be considered. The omitted small scales will be considered to be absent; the only information on those small-scale MDT will have to come from the model, within its own error characteristics.

➔ **assimilation of GOCE data in commission space only**, up to degree and order 200. This is equivalent to space scales with half wavelength of the order of 20,000km/200=100km

➔ **MDTº error variance:** considered to be flat across all scales and equal to the error variance associated with the dominant eigenvector of the commission error for GOCE.

➔ **MDTº error covariance:** considered to be cross-correlated, following the isotropic function given in **Fig.5**.

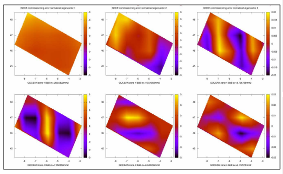

Fig. 3: First 6 GOCE commissioning error eigenvectors on the Bay of Biscay SOG

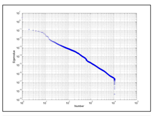

Fig. 4: Eigenvalues of the GOCE commissioning error covariance matrix on the Bay of Biscay SOG

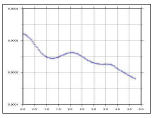

Fig. 5: GOCE commissioning error covariance function on the Bay of Biscay SOG (variance=321.022mm^2)

GOCE performance impact study in the Bay of Biscay

Abstract

Simulated altimetric SLA and GOCE MDT observations are assimilated in the SYMPHONIE Bay of Biscay free-surface 3D model using the Ensemble Kalman Filter. The performance of each array at detecting and controlling model state errors is viewed through the impact assessment diagnostics. The perturbations applied in the EnKF are chosen so as to perturb in particular the slope current vorticity and the mesoscale mass field.

Assimilation scheme

Ensemble Kalman Filter (EnKF), implemented in the BoB model by means of the SEQUOIA assimilation code (De Mey, 2007). The SEQUOIA platform has support for finite-difference and finite-element unstructured grids, and for ensemble forecasting (such as the solution of the Ensemble Kalman filter on a cluster of PCs).

Simulations

The following simulation types (summarized in **Table 1**) are carried out:

- A reference simulation (**REF**)
- A control simulation (**CONTROL**), randomly perturbed, from which all simulated observations are generated.
- A free ensemble simulation (**FREE**), where each member is randomly perturbed (➔ estimation of the model state error without assimilation by using ensemble spread)
- Two assimilated ensemble simulations (**ASSIM***), identical to the free simulation, but with assimilation of selected simulated observations.

Two types of assimilated simulations are conducted:

- ASSIM-ALTI assimilates altimetry sea-level anomaly only, using the recommended procedure explained above.
- ASSIM-ALTI-MDT assimilates both altimetry sea-level anomaly and GOCE mean dynamic topography, using the recommended procedure.

Name	*Type*	*Period*	*Assimilation data*	*Correction*
REF	Scalar	June 1 – Sept 1, 2004	None	None
CONTROL	Scalar, perturbed	June 1 – Sept 1, 2004	None	None
FREE	Ensemble	June 1 – Sept 1, 2004	None	None
ASSIM-ALTI	Ensemble, assimilated	June 1 – Sept 1, 2004	ALT_SLA (> July 1)	δSLA, δT', δS'
ASSIM-ALTI-MDT	Ensemble, assimilated	June 1 – Sept 1, 2004	ALT_SLA (> July 1) GOCE_MDT (> July 1)	δSLA, δT', δS', δMDT, δMT, δMS

Table 1: model simulations

Details

15-member ensembles were integrated

State vector : [SLA, T'(z), S'(z), MDT, MT(z), MS(z)]:

- SLA = h – MDT
  - MDT: 30-day running average of DT run through a 100-km lowpass filter
  - h: sea level variable in the model
- T'(z) = T(z) - MT(z)
  - MT(z): 30-day 100-km low-passed temperature
  - T(z): the temperature variable in the model
- S'(z) = S(z) - MS(z)
  - MS(z): 30-day 100-km low-passed salinity
  - S(z): the salinity variable in the model

Velocities are not updated but adjusted by the model itself

Observations

The observations are sampled from the CONTROL simulation to which random observational noise consistent with the observation error covariance matrix **R** is added**:**

- GOCE_MDT is calculated as a 30-day 100-km low-passed model sea level h; it is defined on the GOCE SOG
- ALT_SLA is calculated as h-GOCE_MDT. It is defined along altimetric tracks (**Fig. 6**)

Perturbation methodology

The **model state errors** in the perturbed simulations must be (1) realistic, and (2) observable and controllable by the observations.

➔ **Two types of perturbations:**

(1) Mean circulation errors, intended to be observable by MDT observations, are generated by perturbing the mean isopycnal depths **(Fig. 7)**; typically the chosen perturbations modified the mean slope current around the Bay of Biscay, as well as the recirculating anticyclonic current off the shelf break in the North (compare with **Fig.1 and Fig.2**)

(2) Mesoscale errors, intended to be observable by SLA (and possibly MDT) observations, are generated by randomly perturbing isopycnal depths (**Fig.8**).

Random generator for perturbations: *O*(20m) standard deviation vertical excursion of isopycnals between the surface layer and 800m depth.

Error covariances

- the correction is "localised" by convoluting by a special function using the influence bubble as its 2D support.
- cross-covariances between the "fluctuation" variables and the "mean" variables are forced to zero
- observational error variances :
  - (3cm)^2 for altimetry,
  - (1.58cm)^2=2.55cm^2 for GOCE_MDT
- observational error correlations:
  - ALT_SLA errors: uncorrelated
  - GOCE_MDT: following the recommendation by ESA, we used the commissioning error correlated model illustrated on **Fig. 5**.

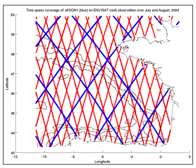

Fig. 6: Spatial coverage of JASON-1 (blue) and ENVISAT (red) in the Bay of Biscay Zone 4 domain.

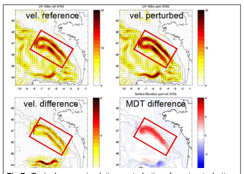

Fig.7: Typical mean circulation perturbation: from top to bottom and left to right, surface velocity reference, perturbed surface velocity, surface velocity difference, MDT difference. The GOCE SOG is delineated in red.

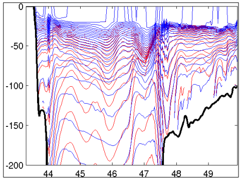

Fig.8: Vertical excursion of isopycnals for a perturbation of the mesoscale field in the Bay of Biscay, along a North-South section, after Le Hénaff (Ph.D. thesis, 2008): original (blue), perturbed (red).

Results

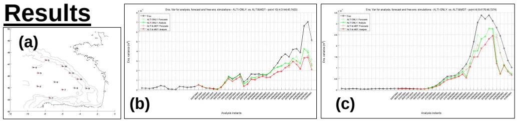

Fig. 9: Absolute sea-level ensemble variance as a function of time for the ASSIM-ALTI (green) and ASSIM-ALTI-MDT (red) simulations (b) at point 4, (c) at point 10, localized on map (a) – Dotted: forecasts; solid: analyses

Fig.9 shows at points 4 and 10 the ensemble spread as a function of time for:
ASSIM-ALTI: green curves➔the Ensemble Kalman filter is able to decrease the error when it arises, both in the context of coastal mesoscale errors and as far as the variability of the topographically-steered current is concerned
ASSIM-ALTI-MDT: red curves ➔both the forecast and analysis results are improved over the altimetry-only case, by assimilating the GOCE MDT.

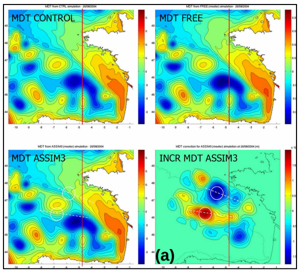

Fig.10: MDT estimates for the CONTROL ("true"), FREE ("wrong"), and ASSIM3 ("corrected") simulations on August 26, 2004, and analysis increment at the same date. Unit=m for the MDT estimates, 10^{-4}m for the MDT increment. The red line is the 4.71°W section described below.

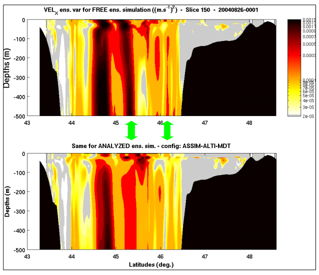

Fig.11: Comparison of FREE and ASSIM3 normal velocity ensemble variance along the 4.71°W section near point 10. The green arrows show the N and S latitudes of the recirculation loop at 4.71°W.44

Fig.10 shows the FREE, CONTROL, and ASSIM3 MDT estimates. One difference between the CONTROL and FREE simulations is the strength of the Northwestward-flowing slope current, too strong in FREE ➔ translates into a stronger cross-shelf MDT gradient in the FREE simulation.

MDT assimilation ➔ brings the MDT solution closer to the "truth" (CONTROL), within the forecast and GOCE observational errors at that time. The corrections are minute, but the results are nevertheless encouraging.

The correction MDT correction **(Fig. 10-a)** is largely anisotropic, with coherent features elongated in a way parallel to the shelf break. The N-S section (**Fig.11**) of ensemble variance of normal velocity: illustrates how the combined effect of GOCE MDT and satellite altimetry through assimilation is able to constrain the mean topographically-steered current (reducing of the error on the slope current and on the whole cyclonic recirculation loop).

Conclusions / Perspectives

As far as results are concerned, the positive impact of altimetry for the topographically-steered current and associated mesoscale field in the Zone 4 domain was evidenced. Moreover, it was shown that assimilating GOCE mean dynamic topography in addition to altimetry improves the results further, again despite the fact that the signals are very small in those regions, and the fact that the omission error is very correlated with the signal to extract. It appears that advanced assimilation with its realistic, built-in error dynamics and realistic error budgets (including correlations) was able to extract a useful signal, albeit at a relatively large scale.

Beyond this study, one could consider applying the methodology to a more realistic estimate of the MDT at smaller scales. For instance the MDTo error variance at smaller scales would be given by difference of ETOPO1 and EGM08, and the innovation projection scale would be O(1'), which would come up as almost no filtering. The methodology can also be considered as a base for a scheme which would ultimately assimilate real GOCE data and/or multisensor high-resolution MDT estimates