GOCINO

GOCE in Ocean Modelling

GOCE data and recommendations on how to use GOCE data in ocean modelling

1. Background

The geoid is a “horizontal” or “level” surface, a surface which is everywhere perpendicular to the local direction of gravity. If there were no waves or currents in the ocean, it is where the sea surface would eventually settle in equilibrium. Since dynamics in the ocean make it possible for sea level to depart from the geoid, the actual vertical distance of sea surface height above the geoid is known as the ocean’s dynamic topography as illustrated in Figure 1.

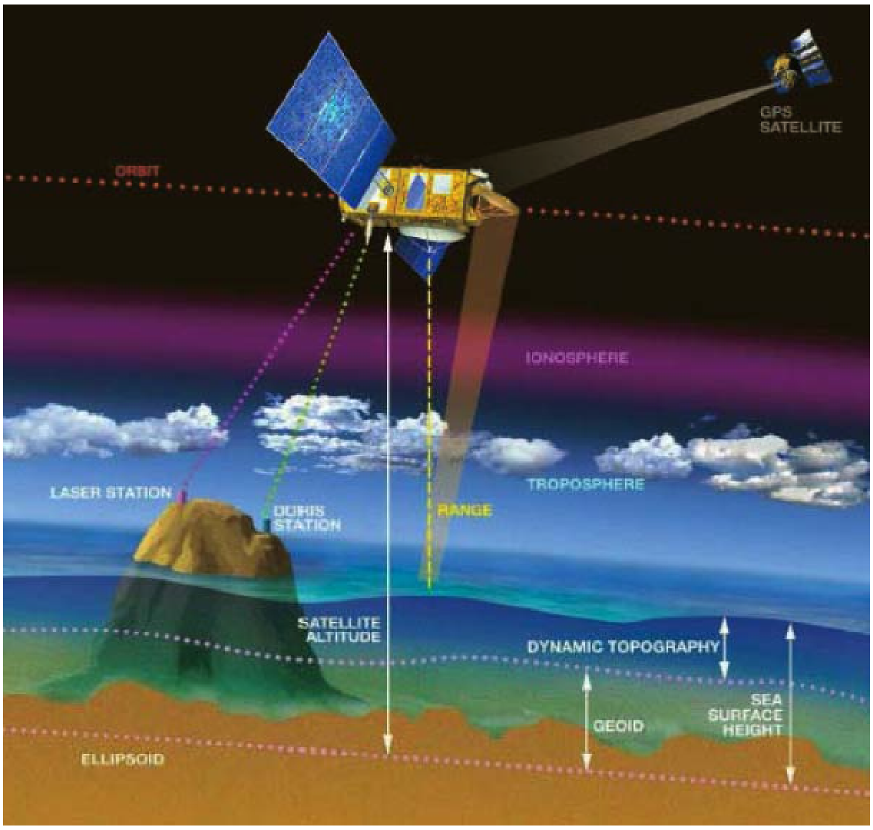

Figure 1. *Sketch showing the relationship between the geoid, the Mean Dynamic Topography (MDT – the mean value of the Dynamic Topography) and the Mean Sea Surface (MSS – the mean value of the Sea Surface Height).*

The actual shape of the geoid includes structure at all length scales. To a first approximation it is a sphere with radius about 6371 km. A closer approximation is an ellipsoid, with equatorial radius about 21.4 km longer than the polar radius. Relative to this ellipsoid, the geoid height (N) undulates by up to 100 m on the largest scales. On relatively short length scales (a few km to a few hundred km) the geoid is closely related to topography as the gravitational attraction of, for example, a seamount will pull water towards it leading to a bump in the sea surface above it (although gravity is stronger immediately above the seamount, this does not lead to a depression in sea level. Rather, it is the lateral gravitational force which pulls water from either side of the seamount, leading to a raised level above the seamount). At longer length scales, topography does not have such a large influence as the weight of mountains is balanced by low density anomalies beneath them (rather like the compensation of sea level anomalies by movements of the thermocline often observed in the ocean), as the mountains “float” like icebergs on the mantle beneath.

The geoid is not, however, simply a gravitational equipotential surface. The Earth is rotating, and in the rotating reference frame we feel a centrifugal force which must be added to the gravitational attraction to give what is usually termed “gravity”. For more details see Hughes and Bingham (2008).

A key scientific question is how new and accurate knowledge of the MDT (=MSS-N) from the GOCE satellite will improve the quantitative understanding of the ocean circulation and its transport of heat and mass. This has been investigated in several recent EU, ESA and national funded studies including GOCINA, ArcGICE, GUTS and OCTAS,projects. The expression MDT = MSS – N, simple as it looks, needs carefully consideration, as the equation is only applicable when the altimeter derived MSS and the geoid satisfy the following three conditions:

(i) The two surfaces must have the same spatial content.
(ii) The two surfaces must be given relative to the same reference ellipsoid.
(iii)The two surfaces must use the same tide system.

Once these three issues have been taken into account and once both the MSS and the N have been adequately processed, the MDT can be computed. By construction, the spectral content of the MDT is therefore limited by the spectral content of the geoid model. In the case of GOCE, the corresponding MDT will thus have centimeter accuracy at a 100 km resolution. To adequately account for the residual geoid signal having wavelengths shorter than about 100 km a filtering of the MDT values are required. The filtering required can be carried out spatially or spectrally.

In the EU FP-5 RTD project "Geoid and Ocean Circulation in the North Atlantic – GOCINA project (Knudsen et al., 2006) the mean dynamic topography (MDT) from several ocean models were collected and compared with focus on the Northeast Atlantic-Nordic Seas region (see Table 1). A composite MDT was then computed using all these available ocean models. In so doing the ocean models were corrected for the differences in averaging period using the annual anomalies computed from satellite altimetry for the 9 years period 1993-2001. In addition, the high resolution models were smoothed to be consistent with the 1*1 degree resolution. The composite MDT was thereafter derived as the mean value in each grid point. Furthermore, at each grid point the standard deviation was computed to represent the error of the mean value. The map of this composite MDT and its errors are shown in Figure 2 (left panel). The independently MDT map and associated errors estimated from the existing gravity field data is shown in the right panel of Figure 2.

MDT	Time period	Resolution
CLS v1	1993-1999	1°x1°
CLS v2	1993-1999	1°x1°
ECCO	1992-2001	1°x1°
ECMWF	1993-1995	1.4°x1.4°
FOAM	May02-May03	1/9°x1/9°
OCCAM v1	1993-1995	0.25°x0.25°
OCCAM v2	1993-1995	0.25°x0.25°

Table 1. *The ocean models, time period and model resolution used to compute the composite MDT.*

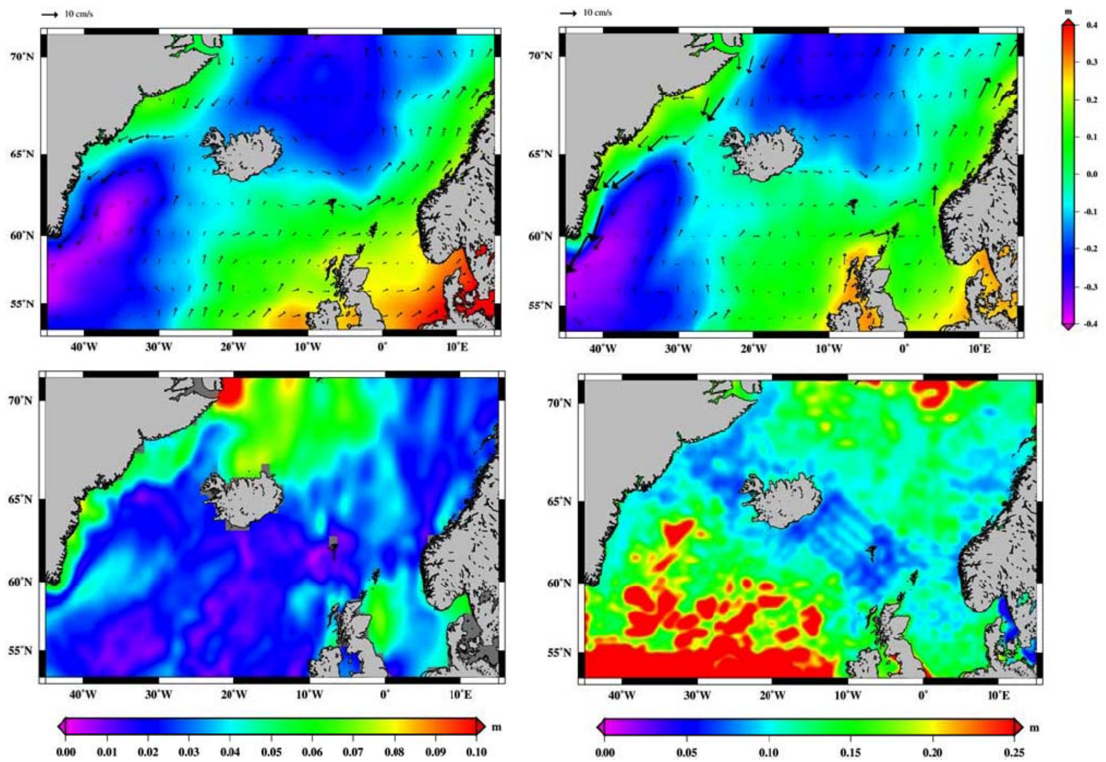

Figure 2. *(left panel) The composite MDT (upper) and the associated errors (lower). (right panel) The synthetic MDT obtained by differentiating the mean sea surface and the geoid (upper) and the associated errors based on collocation estimates (lower). Units are in m and marked by the color bars.*

2. Objectives

Capitalizing on GOCINA findings the main objective of ***GOCINO*** is to advance the readiness to integrate and exploit the new and accurate quantitative description of the geoid and the MDT. In so doing ***GOCINO*** will:

- Promote and develop strategies for implementation of the expected consistent (N, MDT, MSS) GOCE products in operational ocean models, notably together with the ECMWF and the key data assimilation systems (TOPAZ, FOAM, MERCATOR and MFS) developed and implemented under the MERSEA Integrated Project.
- Organize conferences and workshops.
- Develop and maintain a dedicated website for dissemination of information, knowledge, and experiences.

In the following this report addresses and disseminates the current state of the art regarding the planned use of GOCE data in ocean modeling in consistence with the specific content to be provided in deliverable number D1.1. It also refers to specific examples from the ESA supported GOCE User Toolbox Specification (GUTS) study for the exploitation of GOCE level-2 and ERS-ENVISAT altimetry data. The underlying main issue is how the improved GOCE geoid product combined with altimeter MSS will advance the quantitative understanding of the ocean circulation and its transport of heat and mass. The report is complemented by three individual reports (deliverables D1.2, D1.3 and D1.4) that summaries the preliminary experiences and plans for assimilation of GOCE products in operational ocean forecasting systems that assimilates altimeter data such as MERCATOR, FOAM and TOPAZ (see http://geodesy.spacecenter.dk/~gocino). A short executive summary of the experiences and plans follows below.

3. Status of experiences and plans

MERCATOR. In MERCATOR in-situ data and altimeter data are assimilated using a multivariate scheme based on a singular evolutive extended Kalman filter (SEEK) introduced by (Pham et al, 1998) and adjusted for models resolving ocean mesoscale. The preliminary impact of assimilating an improved GOCINA MDT into MERCATOR revealed no systematic behavior; e.g. slight improvements were found in some areas combined with slight degradations in other areas. The GOCINA MDT is in close agreement, albeit a little smoother, with the MDT used in the MERCATOR control run. The latter is computed from a combination of altimeter, in-situ and GRACE data, and is already an improved MDT in respect with MDT issued from model simulations.

In particular, the GOCINA runs led to a improvement in the transport computation through key sections of the Greenland-Scotland ridge. This is a very important result since the transport across this ridge, whose sum defines the largest fraction of the exchange of water and heat between the North Atlantic and the Arctic Ocean, is known to play an important role in the global circulation.

All in all the planned use of GOCE derived MDT data in MERCATOR are expected to provide high impact, notably to:

- Improve the assimilation system performance at “medium” scales (50-100km) thanks to a reduced altimeter error matrix and resulting stronger altimeter “observational” constraints. The use of a realistic MDT also allows the model to restart, at each assimilation cycle, from a state that is closer to its physics, which should improve the outputs accuracy.
- Improve the description of the basin scale-to-regional scale MDT.
- Yield increased accuracy in the MDT error field thanks to the new innovative GOCE based error matrix that, in turn, will have positive impact on the system analyses and forecast skill.

FOAM. The Met Office operational system FOAM (Forecasting Ocean Assimilation Model) uses an optimal interpolation type scheme to assimilates in-situ temperature and salinity data, and (in-situ and satellite) SST data. Along track altimeter data are assimilated after the altimeter sea level anomaly data are combined with a MDT (derived from a previous model integration combined with data from Singh and Kelly (1997) over the Gulf Stream). The resulting sea surface height (SSH) data are then assimilated into the model using the Cooper and Haines (1996) scheme, CH96 hereafter, which adjusts the subsurface density field in order to produce the required SSH increment.

The ocean model in FOAM is currently under replacement by the NEMO model. The observation and model bias correction scheme described in D1.3 is implemented in the new NEMO system. In so doing, an existing observation based MDT is used as the initial MDT along with the error estimate (based on the RIO05 estimate). In turn, the risk for initial shock in the assimilation becomes limited. The main missing factors in this context are an accurate initial MDT for the bias correction scheme and an improved MDT error estimation. Both of these are expected to be provided by the GOCE data.

All in all the planned use of GOCE derived MDT data in FOAM will capitalize on:

- Implementation of the altimeter bias correction scheme using for instance a recent observed MDT, such as RIO05. Alternatively, a model mean from another group running the ORCA025 model could be used (for example ESSC, Reading).

- Availability of reliable MDT error estimates, highly needed for accurate bias correction, which will be derived from the GOCE data.

- Investigation into the possibility to extend the bias correction scheme by direct assimilation of GOCE gravity data that will constrain the bias estimates and allow a smoother transition to new gravity data.

TOPAZ. TOPAZ uses the Ensemble Kalman Filter (EnKF) to assimilate weekly sea level anomaly maps, weekly SST maps, 3-days averaged ice concentration maps and in situ T,S profiles. The initial ensemble is sampled from a model field in which the isopycnal surfaces are randomly shifted in the vertical. An ensemble mean and standard deviation is computed from 100 ensembles.

Errors in the geoid field (slowly varying in time) have a different nature than errors in altimeter data (uncorrelated between two passes after adequate orbital correction). As a consequence, their treatment in data assimilation system should require a different approach. The differences in spatial scales of the two assimilated fields are also a challenging issue. Errors with long time autocorrelation are usually considered as bias and the consideration of a bias correction approach, like implemented for FOAM, is therefore adequate. Dee & Da Silva (1998) have examined this using an unknown bias variable with no dynamics at all.

All in all the planned use of GOCE derived MDT data in TOPAZ will provide:

- The inclusion of new independent error estimate for the assimilation. A natural way to include the uncertainty estimate with the EnKF is to simulate an ensemble of geoids, and hence an ensemble of MDT fields. This ensemble will constitute an a priori source of uncertainty on the system.

- Investigation into implementation of bias correction scheme.

4. The first GOCINO workshop: Main outcome and summary

A number of questions were discussed upon the first part of the workshop dedicated to the presentations of the individual operational center’s strategy for altimetry assimilation. In principle they capitalize on the main findings from the GOCINA project and the accumulative range of experiences and plans that are emerging in preparation of the GOCE data. They are synthesized below.

How shall the GOCE geoid height information be used? Theoretically, the quantity to assimilate is the Absolute Dynamic Topography (ADT) computed along altimeter tracks as SSH-Geoid. However this equation applies only if the geoid is known at all scales. If not the ADT will contain residual "geoid information" present in the SSH but not in the geoid (scales shorter than 100 km will not be present in the GOCE Geoid for instance). These unresolved short scales of the geoid are usually referred to as the geoid "omission error". A solution could be to filter along track altimetric heights to the same resolution as the GOCE geoid. However, the variability level of geoid height's scales shorter than 100 km (i.e. the omission error) is around 50 cm! (remarked by P. Knudsen). Thus impact of residual geoid short scales contained in the altimetric heights may be high and totally pollute the resulting absolute dynamic topography. Also we do not want to spatially filter the altimeter SSH this much because the altimetric anomaly signals are quite separable from the geoid through temporal filtering. For now, the more rigorous approach is to use the intermediate Mean Dynamic Topography information and assimilate SLA and MDT separately, as is presently done in most cases.

Careful attention must be paid when computing external MDT from GOCE data. GOCE data are produced following a number of standards and processing steps described in the GOCE data handbook. The GOCE users have to be aware of this to ensure an optimal use of the GOCE geoid to compute the MDT, e.g.:

- The reference ellipsoid and tide system used to compute the geoid model have to be the same as those used to compute the altimetric MSS to avoid unrealistic latitudinal patterns of amplitude of a few centimetres may appear. Thanks to ESA, a project is currently on-going to develop a GOCE User Toolbox (GUT) that will allow computing MDT from GOCE and altimetric data in a consistent way. This will include the addressing of the omission error problem outlined above.

- Regarding dealiasing processing applied to the GOCE geoid computation the ocean circulation contains a signal and this is dealiased using the OMCT general circulation model from Hamburg (Thomas et al, 2002). This raises the following questions. What is the impact of the ocean model choice for computing a geoid model that will then be used to compute the MDT and then the ocean mean circulation? What is the impact of the ocean model errors on the final targeted 1-2 cm accuracy of GOCE?

What are the methods to assimilate the external MDT information? When assimilating altimetric anomalies into a model, the implicit assumption is that the MDT is given by the model mean. In the context of altimetry assimilation, an "external" MDT will hereafter refer to a MDT differing from the model mean.

The use of an external MDT to assimilate altimetric anomalies has been tested in the MERCATOR, ECMWF, FOAM and MFSTEP systems. In the TOPAZ system, the MDT from the OCCAM model was tested but no offset was applied to achieve consistency between the global spatial model (TOPAZ) mean and the external model mean (based on OCCAM). This is a fundamental step before any attempt of assimilating an external MDT into a forecasting system.

In the ECMWF and FOAM operational systems, the test was done with external MDTs based on GRACE data (Mean Sea Surface minus GRACE geoid, filtered at a 400 km resolution). In both systems, strong problems arose due to large scale biases observed between the external solutions and the modelled MDT. Consequently, it could not be decided clearly if the constant offset to apply had to be computed globally, or over a particular, geographically restricted, area. Different tests led to very different results. It was therefore decided to keep a model-based MDT for further altimetry assimilation. This, however, rises a crucial issue since the GOCE mission is expected to improve the geoid knowledge at short scales but it is already known that, at scales greater than around 400 km it won't bring any further information compared to GRACE data (that are already accurate at those wavelengths at a millimetre level). Future external MDT based on the use of GOCE data (or combined GRACE/GOCE data) will still exhibit this large scale difference with ECMWF and FOAM model means. Consequently if GOCE-based external MDT is to be assimilated in these systems in the future, this large scale difference has to be explained and dealt with from now on.

Large scale difference in the MDTs looks similar to the differences observed between the GRACE-based MDT and climatological means based on hydrological data (Levitus for instance) referenced to 1500m. Apart from the different time period issue (climatological means correspond to several decades), these differences correspond to the barotropic component of the mean ocean circulation plus the deep baroclinic contribution (from 1500m to bottom). The discrepancy could therefore indicate some weaknesses in the modelled barotropic circulation which could be generated by errors in the wind fields (ERA40) used to force the model. Sensitivity studies to the wind strength are worth doing to elucidate this point. Another discrepancy source could be linked with the deep baroclinic component of the ocean circulation. . This may be resolvable now with ARGO data and perhaps some new studies focussed on recent years could be performed.

In the Mercator system, a recent external MDT based on GRACE data (Rio et al, 2005) is used without any correction to assimilate altimetry and no large scale difference between the model MDT and the external MDT has been observed. An analysis was made of the Mercator SLA residuals (analysis minus observations) in order to identify the areas where the system was not capable of using the information contained in the altimetric data. This information was therefore used to compute a so called "representativity" error that is then added to the SLA and MDT errors. Doing this, less weight is put on altimetric data in the areas where the system is not able to take them into account.

Regarding MERCATOR an external MDT improved the mean circulation of the model (analysis and forecasts) as well as the EKE field, both at the surface and at depth.

In the MFS system, the exercise of assimilating an external MDT (Rio et al, 2007) has been done and no inconsistency problem has been observed. However in that particular case, the (Rio et al, 2007) MDT computed for the Mediterranean Sea uses as first guess for integrating in-situ drifting buoy velocities a previous model mean. The large scale component of the MDT is therefore consistent with the model mean while in-situ velocity data have brought information at short scales. Additional methods have been developed to further improve the MDT using ARGO floats or drifting buoy velocities.

In the ECMWF and FOAM systems, due to the difficulties faced in assimilating an external MDT it was decided to use model-based MDTs. However, a bias estimation procedure was implemented in FOAM to improve the MDT during the assimilation. The idea is that any error on the MDT is by definition constant in time and will therefore result in a systematic bias that can be estimated and then used to correct the modelled MDT field a-posteriori and therefore produce an improved MDT. The limit of this method lies in the fact that any bias in the model or in the observations (Fabrice Hernandez quotes the case of the systematic errors discovered recently in temperature data from XBT measurements) will contribute to the bias value estimated and it can not be considered as MDT bias only. An attempt to update the method in order to estimate both the MDT bias and the model bias separately has been made in the FOAM system. For Laurent Bertino however it is very difficult to actually separate between a model bias and observation bias.

As a conclusion on this issue, David Anderson points out that difficulties in using an external MDT for altimetry assimilation should first result in attempts to understand the underlying reasons and if necessary bring corrections to the model physics or parameters. If the inconsistencies cannot be solved by modifying either the model, or the MDT, the bias estimation procedure can then be an appropriate technique.

Is the GOCE resolution sufficient (100km) or are higher resolution MDTs needed? The expected GOCE resolution may be sufficient to resolve the MDT scales of the open ocean. However, an MDT resolution higher than expected GOCE resolution (100 km) is surely needed in coastal areas or semi-enclosed basin (Mediterranean Sea).

The optimum method to obtain a higher resolution MDT should be to assimilate all available in-situ data into an ocean model and compute the model mean. This supposes however that all difficulties in assimilating GOCE-derived MDT into models have been overcome. It is going round in circles!

Alternatively, two methods can be used to compute higher resolution 'observed' MDT (not based on ocean modelling):

- ❖ The first possibility is to improve the resolution of the satellite-based geoid model that will be then subtracted from the altimetric Mean Sea Surface. This can be done using in-situ gravimetric data, as has been done in the GOCINA project. This cannot be done on a global scale due to lack of data.

- ❖ The second solution is to improve the satellite only MDT field (filtered MSSH-Geoid) using oceanographic in-situ data from which the time variable component has first been removed (using the altimetric SLA). This has been done in the past by Niiler et al, 2003 and Maximenko et al, 2005 using drifting buoys surface velocity data and by Rio et al, 2004, 2005 using drifting buoy velocities and in-situ dynamic heights.

How shall the GOCE covariance error matrix be used? What error information is needed? Accurate knowledge of the error level of all observations entering an assimilating system is a crucial issue. At the present time error on the ocean MDT (modeled or based on observations) is poorly known and particular attention has to be paid at the optimal use of GOCE data in the future.

The ESA-HPF will provide as GOCE Level-2 data the GOCE covariance error matrix. Most probably, this information will not be used directly by altimetry assimilating systems. Rather, the covariance error matrix of the MDT is needed that will depend on both the GOCE covariance error and the altimetric MSS error.

Currently, only the TOPAZ system deals with correlated observation errors. All other systems take into account only the variance errors of the observations used. However, all groups are interested in getting the full covariance error information, either for using it directly or for computing simplified covariance functions. The use of the GOCE error covariance matrix to retrieve covariance errors between points or to approximate covariance functions will be handled in the framework of the ongoing Goce User Toolbox project.

What are the best criteria to assess the impact of improved MDT on operational forecasts? The best way assess the impact is by consistent check that forecasts are actually improved. However, criteria and procedures will probably vary from group to group, eventually using independent validation data sets such as tide gauges, transport estimates across gaps and straits, etc.

Is the assimilation of time varying geoid information an issue? An issue was raised on the relevance of assimilating time varying gravity data. At the present time, only the ECCO (Estimating the Circulation and Climate of the Ocean) system takes into account the time dependent part of the gravity field provided by the monthly GRACE solution using a method described in Stammer et al (2002). However the amplitude of the seasonal field (converted into equivalent water height) is some millimetres (a maximum of 2 cm is observed in the Amazon basin). The impact of assimilating this information will certainly be negligible apart maybe in areas where errors in precipitation are high (high latitudes) or where ice melting occurs. However this issue is not relevant in the case of the GOCE mission whose objective is the computation of the static field. It may become relevant in the case of reanalysis aiming at assimilating GRACE data or in the future if the GRACE follow-on mission is launched. Note that the static gravity field is assimilated in the ECCO system as in the other systems through the computation of an intermediate MDT field (MSSH-GRACE).

5. Conclusion and Recommendation

Longer road than anticipated.

References

Dee, D.P., A.M. da Silva, 1998, Data assimilation in the presence of forecast bias. *Quarterly J. Royal Meteorological Society*, 124, pp. 269-295.

GOCINA (Geoid and Ocean Circulation in the North Atlantic) – Final Report, Danish National Space Center, Technical Report Number 5, Copenhagen, 2005, ISBN 9788791694073; ISBN 87-91694-07-8

GUTS (GOCE User Toolbox Specification) - Work Package 5000: "Summary and Tutorial Document", ESA/XGCE-DTEX-EOPS-SW-04-0001

Hughes, C. W., Bingham, R. J., 2008: An oceanographer's guide to GOCE and the geoid. *Ocean Science*, 4, 15–29, *www.ocean-sci.net/4/15/2008/*

Knudsen, Per, Ole B. Andersen, René Forsberg, Arne V. Olesen, Anne L. Vest, Henning P. Föh, Dag Solheim, Ove D. Omang, Roger Hipkin, Addisu Hunegnaw, Keith Haines, Rory Bingham, Jean-Philippe Drecourt, Johnny A. Johannessen, Helge Drange, Frank Siegismund, Fabrice Hernandez, Gilles Larnicol, Marie-Helene Rio, and Philippe Schaeffer, GOCINA Geoid and Ocean Circulation in the North Atlantic, Final Report, Danish National Space Center, Technical report No. 5, 2006.

Maximenko, N.A., and P.P. Niiler, 2005: Hybrid decade-mean global sea level with mesoscale resolution. In N. Saxena (Ed.) Recent Advances in Marine Science and Technology, 2004, pp. 55-59. Honolulu: PACON International.

Niiler, P., Maximenko, N.A. and McWilliams, J.C., 2003. Dynamically balanced absolute sea level of the global ocean derived from near-surface velocity observations. Geophysical Research Letters, 30(22): 2164-2167.

Pham, D.T., J. Verron and M.C. Rouband, 1998, A singular evolutive extended Kalman Filter for data assimilation in oceanography, *Journal of Maine Systems*, 16, 323-340.

Rio, M.-H. and F. Hernandez (2004). "A Mean Dynamic Topography computed over the world ocean from altimetry, in-situ measurements and a geoid model." Journal of Geophysical Research **109**(C12).

Rio, M.-H., P. Schaeffer, et al. (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." Proceedings of the GOCINA international workshop, Luxembourg.

Rio, M.-H., P.-M. Poulain, et al. (2007). "A Mean Dynamic Topography of the Mediterranean Sea computed from altimetric data, in-situ measurements and a general circulation model." Journal of Marine Systems **65**: 484-508

Tapley, B., Ries, J., Bettadpur, S., Chambers, D., Cheng, M., Condi, F., Gunter, B., Kang, Z., Nagel, P., Pastor, R., Pekker, T., Poole, S., Wang, F., J., 2005 : GGM02 - An improved Earth gravity model from GRACE. *Geodesy,* 79:467-478, doi:10.1007/s00190-005-0480-z.

Thomas, M., 2002: Ocean induced variations of Earth‘s rotation – Results from a simultaneous model of global circulation and tides, Ph.D. diss., 129 pp., Univ. of Hamburg, Germany, 2002

Stammer, D., C. Wunsch, R. Giering C. Eckert, P. Heimbach, J. Marotzke, A. Adcroft, C. N. Hill, and J. Marshall (2002), The global ocean circulation during 1992-1997, estimated from ocean observations and a general circulation model. J. Geophys. Res., 109(C9), 3118, doi:10.1029/2001JC000888.