GOCINO

Contract N° SSA5-CT-2006-030756

GOCINO

GOCE in Ocean Modelling

Specific Support Action

Final Activity Report

Start date of project: 1 June 2007	Date of preparation: 14 March 2010
Project coordinator name: Per Knudsen	Duration: 30 months
Project coordinator organisation name: DTU Space	Revision: First Draft.

Table of content

1. PROJECT EXECUTION

1.1. Executive summary

The Gravity and Ocean Circulation Experiment – GOCE satellite mission is a new type of Earth observation satellite that measures the Earth gravity and geoid with unprecedented accuracy. Combining GOCE geoid models with satellite altimetric observations of the sea surface height (see Figure 1) substantial improvements in the modelling of the ocean circulation and transport are foreseen.

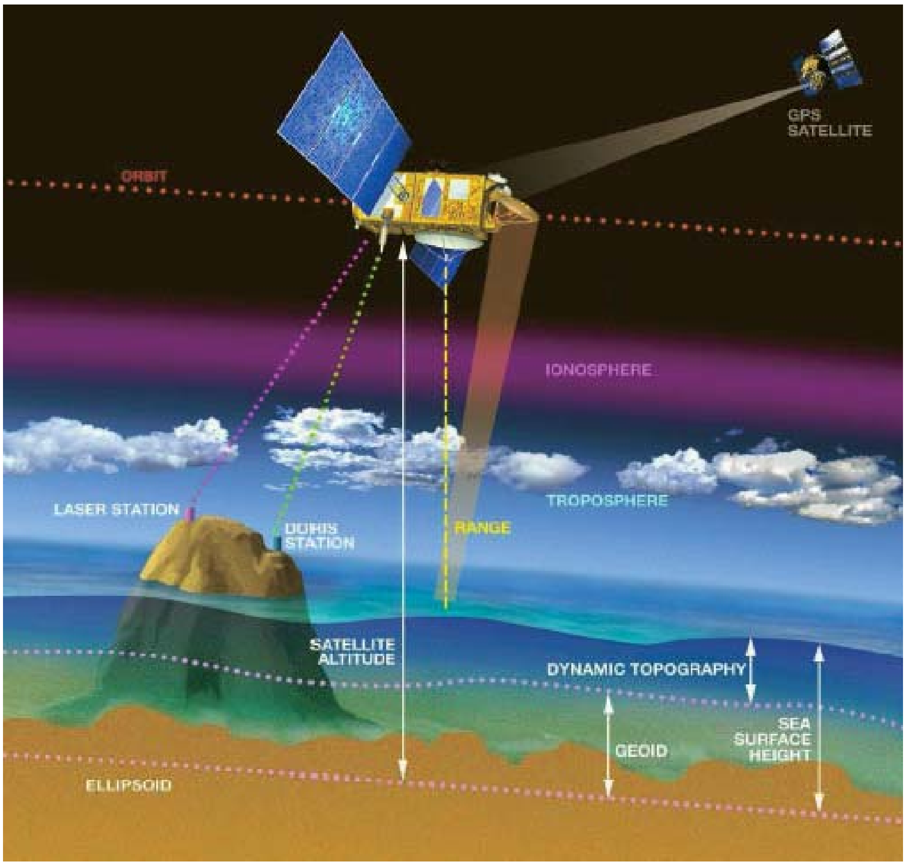


Figure 1: *Sketch showing the relationship between the geoid, the Mean Dynamic Topography (MDT – the mean value of the Dynamic Topography) and the Mean Sea Surface (MSS – the mean value of the Sea Surface Height). If the oceans were motionless the MDT would be zero and the geoid and the MSS would coincide. However, the oceans are not motionless, and the MDT provides the absolute reference surface for the ocean circulation.*
Improved geoid models from GOCE and MSS from ENVISAT is expected to improve the performance of operational ocean and seasonal forecasting models. The determination of the mean circulation will, in turn, advance the understanding of the role of the ocean mass and heat transport in climate change.

The ***GOCINO*** project actively contributed to reach the pre-operational capability in ocean modelling for GMES utilizing data from this ESA satellite mission GOCE that was launched in March 2009. In ***GOCINO*** an effort was made to further promote and facilitate the transfer of knowledge and the exploitation of GOCE data. The project used specific scenarios for the integration of GOCE data products into four major operational oceanography systems, notably MERCATOR, MFS, FOAM and TOPAZ, and into the seasonal forecasting system at ECMWF.

GOCINO (an EU FP-6 Specific Support Action) supported the advance of the capabilities in exploitation of EO data from the satellite mission GOCE in oceanographic services of GMES through the following networking activities: 1) Dissemination of the scientific results from the EU FP-5 RTD project “Geoid and Ocean Circulation in the North Atlantic – GOCINA” and applying GOCINA products and recommendations to develop strategies for implementation of GOCE products in operational ocean models together with the ECMWF, TOPAZ, FOAM, MERCATOR, and MFS operational centres, 2) Organizing conferences and workshops to facilitate the interaction and communication between the GOCE data processing consortium and the oceanographic users and to promote the exploitation of GOCE data in the operational centres, and 3) Developing and maintaining the ***GOCINO*** web pages for dissemination of information, knowledge, and experiences, so that the knowledge and expertise build up through the research in the GOCINA as well as in the ***GOCINO*** projects are kept together and fully made accessible for operational GOCE data users in the period up to the release of the first GOCE data.

Main achievements

In ***GOCINO*** a series of reports describing the scientific results from the EU FP-5 RTD project “Geoid and Ocean Circulation in the North Atlantic – GOCINA” were prepared. Subsequently, a workshop was planned and held with participation of the relevant ocean centres. A synthesis of the discussion that arose during the workshop was prepared mainly addressing challenges in implementing GOCE data in the ocean modelling systems. Those are:

1. How shall the GOCE geoid height information be used?
2. What are the methods to assimilate the external MDT information?
3. Is the GOCE resolution sufficient (100km) or is higher resolution MDTs needed?
4. How shall the GOCE covariance error matrix be used? What error information is needed?
5. What are the best criteria to assess the impact of improved MDT on operational forecasts?
6. Is the assimilation of time varying geoid information an issue?

Based on the outcome from the 1st ***GOCINO*** workshop***,*** the project partners prepared a series of reports describing the strategies for implementation of GOCE products in operational ocean models together with the ECMWF, TOPAZ, FOAM, MERCATOR, and MFS operational centres. A second workshop was held with participation of the invited ocean centres. The outcome of the workshop formed the basis for the finalisation of those strategies. Subsequently, the ***GOCINO*** conference was held to disseminate and transfer the implementation strategies to the MyOcean partners to follow up and coordinate the further implementation of GOCE data into the marine component of GMES. Also, a GOCE workshop was held to facilitate interaction and communication between the GOCE data processing consortium and the oceanographic users.

Strategy for combining GOCE geoid and altimetry: The practical task of computing a Mean Dynamic Topography (MDT) from a mean sea surface (MSS) and a geoid is conceptually very simple, however there are some issues that must be considered in order to obtain a good MDT product. First, both the MSS and the geoid must be represented relative to the same reference ellipsoid and tidal system. Then, it is important that the altimetry used for the MSS in the MDT calculation has the same corrections applied as the altimetry that is used for the computation of the sea level anomalies. Finally, it is vital that when a MDT is calculated and used to reference time varying sea level anomaly data, the time periods defining the MDT and the sea level anomalies do correspond. Subsequently, the separation of the MDT from the MSS and the geoid require a proper filtering of the differences to eliminate the short scale geoid signal present in the MSS to obtain the MDT. This may be carried out in either the space domain, where the MSS is usually represented, or in the spectral domain where global geoid models are usually represented. Both methods have their advantages and their disadvantages. In both cases, it may be recommended to augment the GOCE spherical harmonic series using other higher degree harmonic expansions of the gravity field to reduce the magnitude of the short scale geoid signal in the MSS.

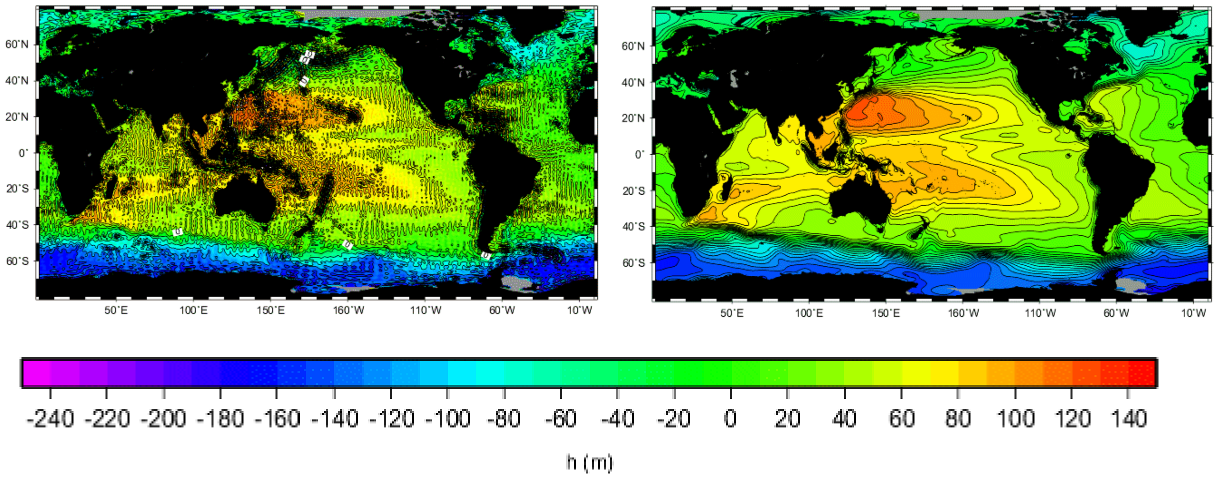


Figure 1: MDT computed from MSS CLS01 and EIGEN-GL05S filtered at 133 km (left) and filtered at 500km (right).

<u>The ECMWF model system</u>: Altimeter data assimilation was included for the first time in April 2006 in the operational ECMWF System 3 seasonal forecasting system. An analysis of a model MDT showed that an MDT based on a MSS and a GRACE geoid is higher in the Atlantic that the model MDT and lower in the Pacific. The reason for this discrepancy is partly model errors. More sophisticated schemes are needed to use observation-based MDTs. Including bias correction schemes to correct the model or correct the MDT so it is more compatible with the model. ECMWF may still need to adopt the altimeter bias correction scheme to deal with any large scale discrepancy due to model errors. ECMWF plan to operationally implement a system based on NEMOVAR. The Met Office and ECWMF will both be working on the NEMOVAR so it is likely that there will be close collaboration on the technical development of bias correction schemes in NEMOVAR. It will be very important that ECMWF thoroughly test any assimilation scheme using a GOCE based MDT to confirm that forcing the model large scale circulation to match does improve the system and forecast results.

<u>The TOPAZ model system</u>: The TOPAZ system covering the North Atlantic Ocean, Nordic Seas and the Arctic Ocean is presently running its third version (TOPAZ3) in real-time. A nearly identical copy is also exploited in real-time by the Norwegian Meteorological Institute. The assimilation system in TOPAZ3 relies on an Ensemble Kalman Filter (EnKF) and the HYCOM ocean model. Experiments have showed that the efficiency of the EnKF assimilation in taking up the MDT biases are regionally dependent. This means that the differences in the adjustment of the MDT are linked with the different physical processes predominantly acting in the tropics and mid-latitudes. The results above are produced in a case of severe bias in MDT. Nevertheless the results imply that the impact of GOCE data might be expected to be regionally and temporally dependent. In view of the strategy for assimilating GOCE derived MDT the TOPAZ3 system will be employed. When it comes to the observation errors and the account for the slow-varying geoid error covariance an ensemble of GOCE based MDTs will be generated, which average is the best MDT estimate. Each of those realizations will be affected to one ensemble member. This will include a MDT error term in the observation errors.

<u>The FOAM model system</u>: The UK Met Office operational system FOAM (Forecasting Ocean Assimilation Model) uses an optimal interpolation type scheme to analyse temperature, salinity, currents and sea ice in the open ocean. The system provides daily analysis and 5 day forecasts using a range of nested models from a ¼ degree global to a 1/12 degree limited area. Recently the observation bias method has been introduced and results are shown below. The full bias code, including model biases, has not yet been implemented operationally, however. If we use a new combined MDT or a direct MDT it will be important to use the altimeter bias correction method to correct for or specify the small scale components of the MDT only. With respect to implementation

of a GOCE MDT the work has started at the Met Office on testing the 3D-Var NEMOVAR assimilation scheme within the FOAM system. Within the timescales for producing GOCE based MDT it is likely that we will be testing NEMOVAR for operational implementation so we may transition both to using a GOCE MDT and NEMOVAR at the same time. Any new scale selective bias correction scheme will be implemented and tested directly in NEMOVAR. It is expected that by correcting the model MSS on the large scale using a GOCE based MDT and the MDT on the small scale using bias correction we should obtain maximum benefit from altimeter data assimilation.

The MERCATOR model system: In the MERCATOR system, the observed Mean Dynamic Topography used to assimilate altimetric Sea Level Anomalies is built from two main steps. The first step consists in estimating a large scale ocean Mean Dynamic Topography from the subtraction and further filtering of an altimetric Mean Sea Surface and a geoid model. This large scale MDT solution can be compared to 'synthetic' estimates of the mean computed combining ocean in-situ measurements and altimetric Sea Level Anomalies, which provide an insight onto the shortest scales of the mean field. The strategy developed at MERCATOR for assimilating the future GOCE data consists in combining spatial and in-situ data so as to estimate the ocean Mean Dynamic Topography at the highest resolution for further assimilation into the operational forecasting system. Data from the GOCE mission will allow resolving the geoid at spatial scales down to 100km with centimetric accuracy. Areas will be identified where the 100km resolution permitted by GOCE won't be sufficient to fully resolve the mean circulation (mainly in coastal areas or in strong western boundary currents) so that further combination with synthetic heights is needed. In this combination step, the covariance error information from the GOCE data will be very useful. On the other hand, the assimilation scheme from the MERCATOR system does not need at the moment the MDT covariance error information.

The MFS model system: A 3D-VAR assimilation scheme has been recently developed to be integrated into the MFS forecasting system. The estimation of the Mean Dynamic Topography is particularly difficult in the Mediterranean Sea due to the short characteristic spatial scales of the Mediterranean circulation. A strategy has been developed to take benefit of and improve the existing Mean Dynamic Topography of the Mediterranean Sea, as well as to prepare for the future use of GOCE data into the MFS forecasting system. The strategy is based on the assumption that the error in the MDT field appears in the assimilation system as a temporally constant and spatially variable observational bias. At the present time, no covariance information is used. When available (together with the GOCE geoid information), it will be used for constructing the MDT. In the future, GOCE observations may be used in a variational scheme to further improve the MDT of the Mediterranean Sea.

*The **GOCINO** web pages* were developed for dissemination of information, knowledge, and experiences, so that the knowledge and expertise build up through the research in the GOCINA as well as in the ***GOCINO*** projects are kept together and fully made accessible for operational GOCE data users in the period up to the release of the first GOCE data.

GOCINO Partners

DTU Space
Department of Geodesy
2100 Copenhagen Oe
Denmark
Att: Per Knudsen (coordinator)

Collecte Localisation Satellites
Space Oceanography Division
31526 Ramonville St. Agne
France
Att: Marie-Helene Rio

Nansen Environmental and
Remote Sensing Center
N-5006 Bergen
Norway
Att: Johnny Johannessen

University of Reading
Environmental Systems Science Centre
RG6 6AL Reading
UK
Att: Keith Haines

UK Meterological Office
Fizroy Road
Exeter
EX1 3PB Devon
UK
Att: Daniel Lea

MORE INFO:
Per Knudsen
DTU Space
pk@space.dtu.dk

GOCINO website:

http://www.gocino.dk

1.2. Progress and results

1.2.1. Dissemination of GOCINA findings

A series of reports were prepared based on GOCINA results describing the analysis of the impact of using an improved Mean Dynamic Topography (MDT) on the ocean circulation. In so doing the results of the initial tests on assimilating the GOCINA MDT model into MERCATOR, FOAM and into TOPAZ were assessed. The reports compiled the relevant information on how an improved geoid product from the GOCE mission together with altimetric sea surface heights can be combined in ocean modelling, notably advancing the quantitative knowledge of ocean circulation.

The overall findings and achievements using the expected GOCE derived new geoid and hence MDT field in the data assimilation system can be summarized as:

MERCATOR. In MERCATOR in-situ data and altimeter data are assimilated using a multivariate scheme based on a singular evolutive extended Kalman filter (SEEK). The preliminary impact of assimilating an improved GOCINA MDT into MERCATOR revealed no systematic behaviour. 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 with respect to MDT derived 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 state, which should improve the modelling 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. This 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 over the Gulf Stream. The resulting sea surface height (SSH) data are then assimilated into the model using the Cooper and Haines CH96 scheme, 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). 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 MDT (i.e., RIO05). Alternatively, a model mean from another group running the ORCA025 model could be used (for example UREAD, 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.

The differences in spatial scales of satellite altimetry and GOCE geoid fields are 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.

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.

Summary of findings:

The investigations from this study shows that 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.

It was also pointed out at the first workshop 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 might potentially become an appropriate technique.

Accurate knowledge of the error level of all observations entering an assimilating system is a crucial issue. Presently, the error in the ocean MDT (modelled or based on observations) is poorly known at the spatial scales of around 100-200 km and shorter. It is therefore expected that the GOCE data will therefore shed new and important light on this issue.

1.2.2. Conferences and workshops

A workshop with participation of the operational centres of ECMWF, TOPAZ, FOAM, MERCATOR, and MFS was organised to present the GOCINA results of the initial tests on how to assimilate GOCE information into the operational models and to discuss the developments of operational strategies. One of the main discussions at the first workshop was designing the criteria of how to best assess the impact of the improved MDT on operational forecasts. This workshop 1st ***GOCINO*** workshop was organized and took place in ECMWF, Reading, on January, 7-8th, 2008 gathering together representatives from ECMWF, TOPAZ, FOAM, MERCATOR, and MFS.

A synthesis of the discussion that arose during the workshop was prepared mainly addressing challenges in implementing GOCE data in the ocean modelling systems. Those are:

7. How shall the GOCE geoid height information be used?
8. What are the methods to assimilate the external MDT information?
9. Is the GOCE resolution sufficient (100km) or is higher resolution MDTs needed?
10. How shall the GOCE covariance error matrix be used? What error information is needed?
11. What are the best criteria to assess the impact of improved MDT on operational forecasts?
12. Is the assimilation of time varying geoid information an issue?

The synthesis served as a starting point to the development of strategies for assimilating GOCE data into the operational model systems. Later, a second workshop was organised with participation of the involved operational centres (ECMWF, TOPAZ, FOAM, MERCATOR, and MFS) to discuss the developed operational strategies. The main ***GOCINO*** conference was organized as planned at the end of the project to present the developed strategies on how to assimilate GOCE information into the operational models of ECMWF, TOPAZ, FOAM, MERCATOR, and MFS. Finally, a GOCE post-launch workshop was held with participation from the ***GOCINO*** project as well as representatives from the GOCE HPF (High level Processing Facility) to discuss the latest updates on the GOCE mission status and on the quality of the first GOCE measurements.

1.2.3. Strategy developments

The ***GOCINO*** project reviewed the procedures and challenges that must be considered when using geoid data derived from the Gravity and steady-state Ocean Circulation Explorer (GOCE) mission in order to constrain the circulation and water mass representation in an ocean general circulation model. It covers the combination of the geoid information with time-mean sea level information derived from satellite altimeter data, to construct a mean dynamic topography (MDT), and considers how this complements the time-varying sea level anomaly, also available from the satellite altimeter. The further steps needed for assimilating the resulting dynamic topography information into an ocean circulation model are described using three different operational forecasting and data assimilation systems. Results from the use of GRACE geoid information in the operational oceanography community are described and discussed as well as the future potential gains that we may be obtained from a new GOCE geoid. Based on those guidelines the ***GOCINO*** partners developed assimilation strategies for each of the model systems in collaboration with the operational centres.

Strategy for combining GOCE geoid and altimetry

The practical task of computing a MDT from a mean sea surface (MSS) and a geoid is conceptually very simple, however there are some issues that must be considered in order to obtain a good MDT product. First, both the MSS and the geoid must be represented relative to the same reference ellipsoid and tidal system. Then, it is important that the altimetry used for the MSS in the MDT calculation has the same corrections applied as the altimetry that is used for the computation of the sea level anomalies. Finally, it is vital that when a MDT is calculated and used to reference time varying sea level anomaly data, the time periods defining the MDT and the sea level anomalies do correspond.

The separation of the MDT from the MSS and the geoid may be carried out in either the space domain, where the MSS is usually represented, or in the spectral domain where global geoid models are usually represented. Each methodology has issues where care is needed. The “space domain methods” where the geoid is calculated in physical space from the set of harmonic coefficients and subtracted from the MSS, require a proper filtering of the differences to eliminate the short scale geoid signal present in the MSS to obtain the MDT. The “spectral domain methods” require that the MSS is expanded into spherical harmonics to carry out the differencing using the coefficients of the geoid and the MSS. The fundamental problem in applying spectral domain methods is that the MSS and MDT are not defined over land, hence hampering the global spherical harmonic expansion. In both cases, it may be recommended to augment the GOCE spherical harmonic series using other higher degree harmonic expansions of the gravity field to reduce the magnitude of the short scale geoid signal in the MSS.

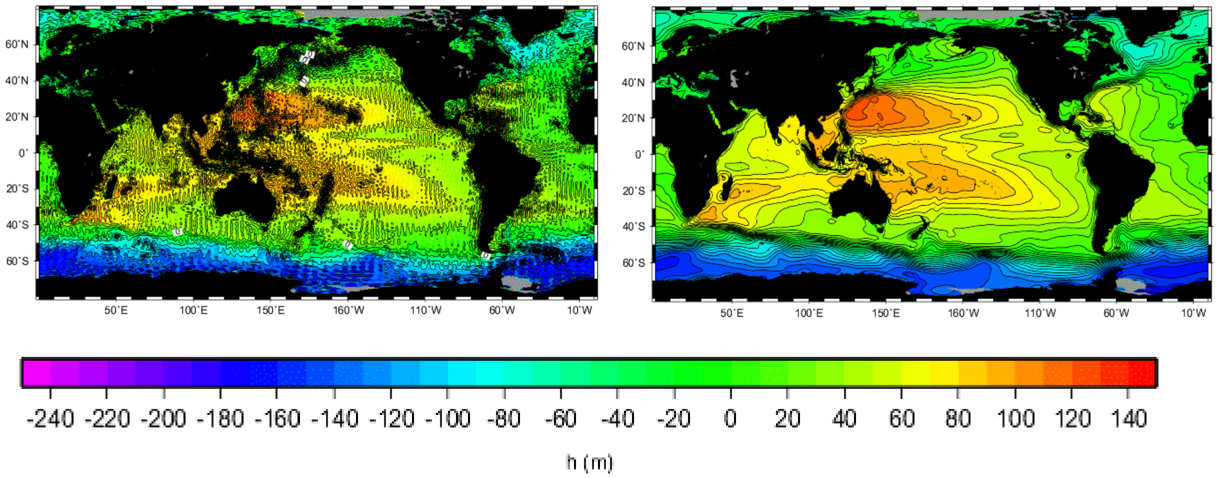


Figure 1: MDT computed from MSS CLS01 and EIGEN-GL05S filtered at 133 km (left) and filtered at 500km (right).

Table describing model systems and their characteristics.

Model system	**Area**	**Model type**	**Assimilation scheme**
ECMWF	Global	HOPE with 29 layers. Resolution 111 km	Optimal Interpolation (Cooper&Haines)
TOPAZ	Nordic Seas	HYCOM with 22 layers. Resolution 20-30 km	Ensemble Kalman Filter
FOAM	European coasts	Hadley Center with 20 layers. Resolution 12 km	Optimal Interpolation (Cooper&Haines)
MERCATOR	European coasts	OPA (Ocean Parallelise) with 43 layers. Resolution 5-7 km	Optimal Interpolation (Reduced - SOFA)
MERCATOR (Prototype)	Global	OPA9 (Ocean Parallelise) with 43 layers. Resolution 6-26 km	Optimal Interpolation (Reduced - SOFA)
MFS	Mediterranean Sea	OPA (Ocean Parallelise) with 31 layers. Resolution 7 km	Optimal Interpolation (Reduced - SOFA)

The ECMWF model system

Altimeter data assimilation was included for the first time in April 2006 in the operational ECMWF System 3 seasonal forecasting system. The operational ocean analysis scheme (system 3 or S3) provides initial conditions for seasonal and monthly forecasts (in contrast to FOAM which focuses on 5 day forecasts). The system produces global analyses on 1 degree grid, increasing to 1/3 degree meridionally at the equator. The assimilation method is OI and the model used is the HOPE (Hamburg Ocean Primitive Equations) model. The scheme assimilates subsurface temperature and salinity and altimeter data. SST is relaxed to maps produced separately. Altimeter assimilation was implemented for the first time with S3. Maps of 1/3x1/3 Sea Level Anomaly data provided by Ssalto/DUACS are assimilated. Combining the SLA with an MDT, a 2D analysis of sea surface heights (SSH) is produced. This is applied to the model using the CH96 (as in FOAM).

An analysis of a model MDT is derived from the mean SSH of a 7-year integration of the model and an observed MDT such as Rio05 showed that the Rio05 MDT is higher in the Atlantic that the model MDT and lower in the Pacific. The reason for this discrepancy is partly model errors. Attempting to correct this bias risks doing more harm than good. Therefore it was decided to use the model mean SSH, recognizing that possibility of correcting the mean circulation is lost. Using more sophisticated schemes may allow the use of observation-based MDTs. Including bias correction schemes to correct the model or correct the MDT so it is more compatible with the model.

A new GOCE based MDT will be accurate to 100 km for a 1 degree model this may mean that ECMWF can use a direct MDT based on the difference between the altimeter observed mean sea surface height and the GOCE measured geoid without needing to use a merged direct and synthetic geoid like Rio05. However ECMWF may still need to adopt the altimeter bias correction scheme to deal with any large scale discrepancy due to model errors. ECMWF plan to operationally implement a system based on NEMOVAR. The Met Office and ECWMF will both be working on the NEMOVAR so it is likely that there will be close collaboration on the technical development of bias correction schemes in NEMOVAR. It will be very important that ECMWF thoroughly test any assimilation scheme using a GOCE based MDT to confirm that forcing the model large scale circulation to match does improve the system and forecast results.

The TOPAZ model system

The TOPAZ system covering the North Atlantic Ocean, Nordic Seas and the Arctic Ocean is presently running its third version (TOPAZ3) in real-time as illustrated in Figure 2. A nearly identical copy is also exploited in real-time by the Norwegian Meteorological Institute. The assimilation system in TOPAZ3 relies on an Ensemble Kalman Filter (EnKF) and the HYCOM ocean model. The EnKF is a Monte Carlo technique that attempts to emulate the system errors in order to compute the forecast error covariance at the time of the analysis.

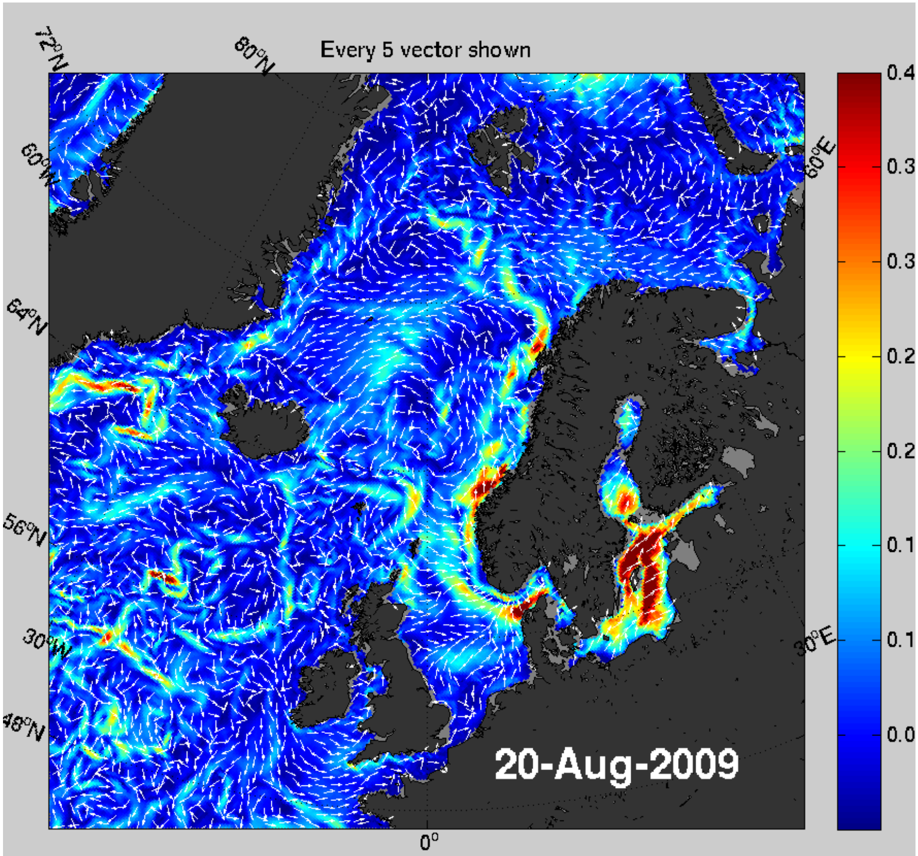


Figure 2. TOPAZ surface current field for the closed-up coverage of the Northeast Atlantic and Nordic Seas for 20 August 2009.

To test the ability to change MDT information an external MDT was taken from a global 1/4th deg OCCAM reanalysis. After sufficiently spun-up, the initial and model errors produce differences in sea-surface heights between members. It was noted that the MDT presented quite large deviations from the free running HYCOM model dynamic topography (about 30 cm), but this can be expected when comparing MDTs from different models. However, there is no source of error in the system that is related to uncertainties in the geoid, so the success of the assimilation of an exogenous MDT is not guaranteed. Thus, by precaution, the MDT assimilated so far in TOPAZ was produced by the HYCOM ocean model. The experiment showed that the efficiency of the EnKF assimilation in taking up the large MDT bias is regionally dependent. The input statistics of the three EnKF prior error terms (initial error, model error and measurement errors) have uniform values over the model domain, but the ensemble propagation in the model develops flow-dependent – and thus regionally different – forecast error covariances. This means that the differences in the adjustment of the MDT are linked with the different physical processes predominantly acting in the tropics and mid-latitudes.

The results above are produced in a case of severe bias in MDT. Nevertheless the results imply that the impact of GOCE data might be expected to be regionally and temporally dependent. In view of the strategy for assimilating GOCE derived MDT the TOPAZ3 system with assimilation of altimeter maps, SSTs, ice concentrations, ice drift and Argo Temperature and Salinity profiles will be employed. When it comes to the observation errors and the account for the slow-varying geoid error covariance an ensemble of GOCE based MDTs will be generated, which average is the best MDT estimate. Each of those realizations will be affected to one ensemble member. This will include a MDT error term in the observation errors. Moreover, the inclusion of GOCE data needs to be synchronous with the development plan for TOPAZ.

We will schedule the inclusion of the latest Rio MDT from CLS at the start of assimilation runs of TOPAZ4. The first validated GOCE data can be expected in Summer 2010. This means that it may come just in time for the TOPAZ4 1989-2002 reanalysis. It should also be included in the TOPAZ4 real-time runs undertaken at met.no as part of the MyOcean modelling and forecasting of the high latitude and Arctic region. We expect similar challenges when assimilating real GOCE based MDT data as when assimilating the exogenous Rio MDT.

The FOAM model system

The UK Met Office operational system FOAM (Forecasting Ocean Assimilation Model) uses an optimal interpolation type scheme to analyse temperature, salinity, currents and sea ice in the open ocean. The system provides daily analysis and 5 day forecasts using a range of nested models from a ¼ degree global to a 1/12 degree limited area. See Martin et al (2007) for a recent detailed description of the FOAM system. Recently the system was upgraded to use the NEMO system. The system assimilates in-situ temperature and salinity, (in-situ and satellite) SST and sea ice concentration data. Along track altimeter data obtained from Collecte Localisation Satellites (CLS) is also assimilated. To assimilate altimeter data is combined with the Rio05 MDT.

Recently the observation bias method has been introduced and results are shown below. The full bias code, including model biases, has not yet been implemented operationally, however. This is because applying the model bias involves changing the model and this was seen as requiring more testing than the observation bias correction. Figure 3 shows example bias fields from the operational system (from August 2009) for the global model and the various regional models. If we use a new combined MDT or a direct MDT it will be important to use the altimeter bias correction method to correct for or specify the small scale components of the MDT only.

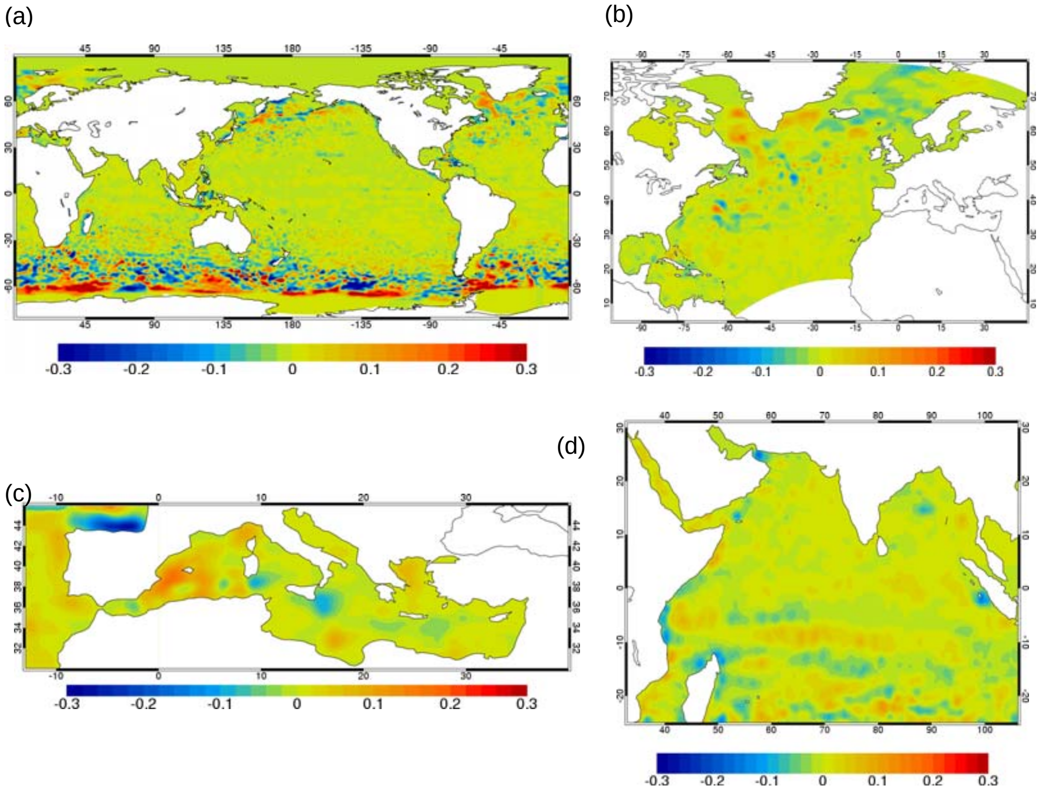


Figure 3: Observation bias, in cm for the NEMO operational models (19 August 2009). a) ¼ degree global, b) 1/12 North Atlantic, c) 1/12 degree Mediterranean d) 1/12 degree Indian Ocean.

With respect to implementation of a GOCE MDT the work has started at the Met Office on testing the 3D-Var NEMOVAR assimilation scheme within the FOAM system. In this case we would directly solve a cost function similar to that in equation (1). Within the timescales for producing GOCE based MDT it is likely that we will be testing NEMOVAR for operational implementation so we may transition both to using a GOCE MDT and NEMOVAR at the same time. Any new scale selective bias correction scheme will be implemented and tested directly in NEMOVAR.

The bias field currently takes about three months to spin-up therefore we will need to perform at least one hindcast assimilation experiment of at least that length of time for the each model domain (global and regional) run in FOAM. In addition we will want to show that the GOCE MDT improves the overall assimilation results by comparing it to a hindcast with the Rio05 MDT. We will also want to compare the scale selective and existing bias correction scheme. Additionally we may also wish to compare a direct GOCE MDT and a potential new Rio-type combined MDT. The different MDTs and bias correction schemes will be assessed by the hindcast innovation statistics as shown in section 4. We will also want to compare the hindcast results with drifter data for an independent verification of the MDT. We expect to show that by correcting the model MSS on the large scale using a GOCE based MDT and the MDT on the small scale using bias correction we should obtain maximum benefit from altimeter data assimilation.

The MERCATOR model system

In the MERCATOR system, the observed Mean Dynamic Topography used to assimilate altimetric Sea Level Anomalies is built from two main steps. The first step consists in estimating a large scale ocean Mean Dynamic Topography from the subtraction and further filtering of an altimetric Mean Sea Surface and a geoid model. This is the so-called ‘direct’ method. This large scale MDT solution can be compared to ‘synthetic’ estimates of the mean computed combining ocean in-situ measurements and altimetric Sea Level Anomalies, which provide an insight onto the shortest scales of the mean field. The consistency between these two types of MDT estimates is such that they can be combined to obtain a high resolution MDT field.

The previous study demonstrated the strong positive impact of using a realistic Mean Dynamic Topography to assimilate altimetric Sea Level Anomalies into operational ocean forecasting systems. As a consequence, the RIO05 MDT is nowadays routinely assimilated into the MERCATOR operational system. On the other hand, assimilation systems as MERCATOR, do the synthesis, in an optimal and dynamically consistent way, of different kind of observations (altimetric data, temperature and salinity in-situ profiles). Any inconsistency between the different data entering into the assimilation scheme may therefore be highlighted by the analysis of the model outputs. Figure 4 shows the mean in-situ innovation of dynamic heights for the 2005-2008 period. A large scale bias of 5cm amplitude is revealed between the Pacific ocean (mainly western part) and the Atlantic ocean at mid latitudes. Very interestingly, a bias of similar amplitude is found (**Error! Reference source not found.**) doing the difference between the RIO05 MDT and the latest large scale MDT based on GRACE data.

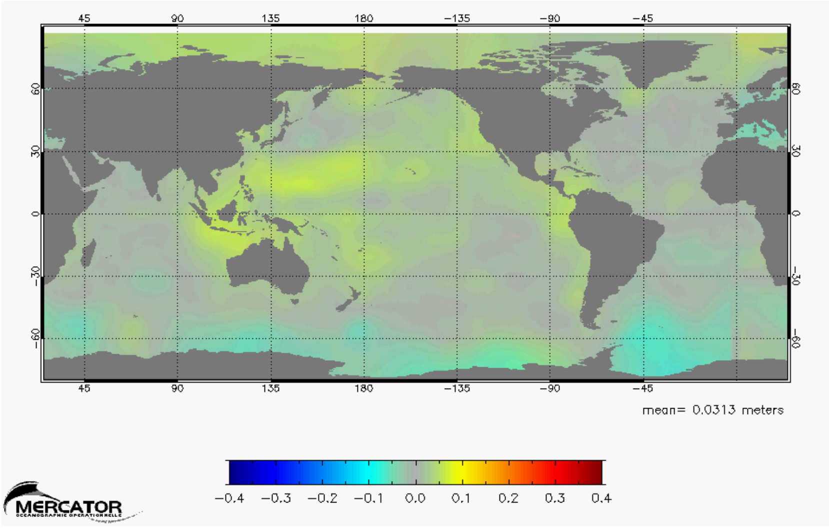


Figure 4: Top: Mean in-situ hdyn innovation 2005-2008 ***– units in metres.***

The strategy developed at MERCATOR for assimilating the future GOCE data is fully in line with a number of studies that have been realized in the past for the optimal use of GRACE data. It consists in combining spatial and in-situ data so as to estimate the ocean Mean Dynamic Topography at the highest resolution for further assimilation into the operational forecasting system. Data from the GOCE mission will allow resolving the geoid at spatial scales down to 100km with centimetric accuracy. The methodology presented and applied in different region of the global ocean will help identify areas where the 100km resolution permitted by GOCE won't be sufficient to fully resolve the mean circulation (mainly in coastal areas, or in strong western boundary currents) so that further combination with synthetic heights will be needed. In this combination step, the covariance error information from the GOCE data will be very useful. On the other hand, the assimilation scheme from the MERCATOR system does not need at the moment the MDT covariance error information.

The MFS model system

A 3D-VAR assimilation scheme has been recently developed to be integrated into the MFS forecasting system. The assimilation is based on the minimization a cost function J. When GOCE data will be available, this variational scheme may be used to further correct the MDT by taking into account the GOCE errors in that cost function.

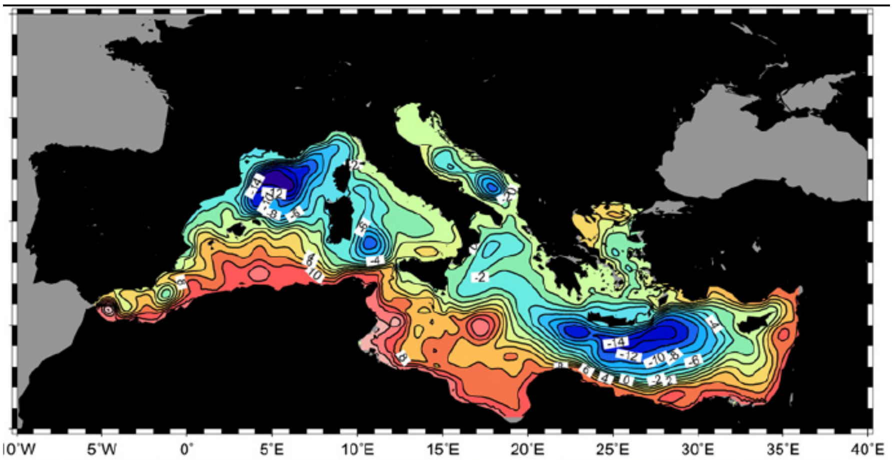


Figure 5: Mean Dynamic Topography obtained by averaging outputs from the MFS model over the 1993-1999 period.

The estimation of the Mean Dynamic Topography is particularly difficult in the Mediterranean Sea due to the short characteristic spatial scales of the Mediterranean circulation. However, the use of an accurate MDT when assimilating altimetric Sea Level Anomalies into the Mediterranean Forecasting System (MFS) is a crucial issue. A strategy has been developed to take benefit of and improve the existing Mean Dynamic Topography of the Mediterranean Sea, as well as to prepare for the future use of GOCE data into the MFS forecasting system.
The strategy is based on the assumption that the error in the MDT field appears in the assimilation system as a temporally constant and spatially variable observational bias. By assimilating jointly the MDT with other in-situ observations (gliders, surface drifters, ARGO floats…) and provided these observations are unbiased, a correction term can be computed for the MDT.

When assimilating altimetric data, no error is put on the MDT, but the Sea Level Anomaly error is slightly increased from 2cm to account for the error in the observational operator (interpolation and the signal difference). At the present time, no covariance information is used. When available (together with the GOCE geoid information), it will be used for constructing the MDT. In the future, GOCE observations may be used in a variational scheme to further improve the MDT of the Mediterranean Sea.

1.2.4. Website

The GOCINO web site was set up for dissemination of information, knowledge and experiences from the GOCINA project, and the developments within the ***GOCINO*** project. The structure and layout of the website was improved throughout the project in order to ensure simpler access to technical and scientific information etc as these became available.

The structure of the GOCINO web is as follows:

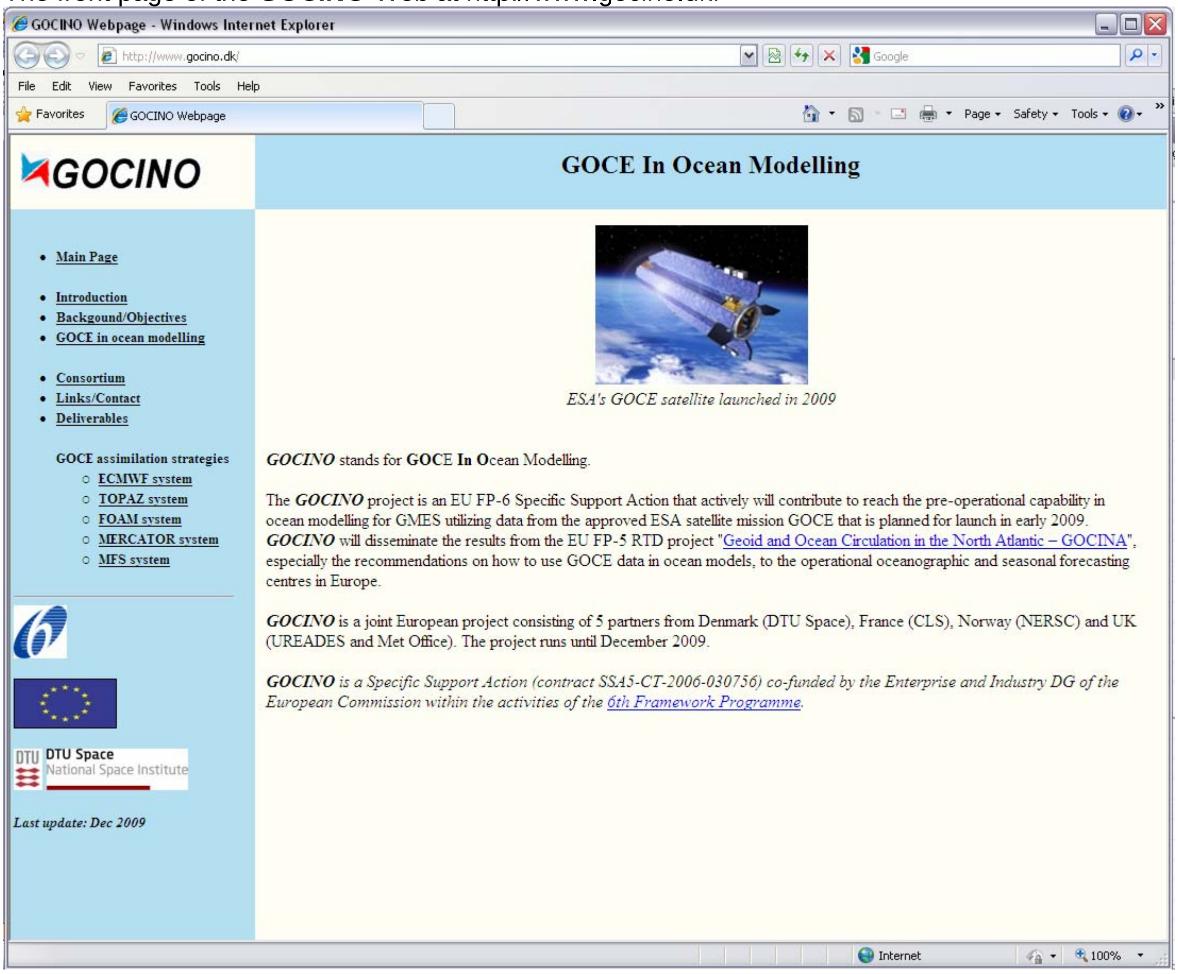
Main Page

- Introduction
- Backgound/Objectives
- GOCE in ocean modelling
- Consortium
- Links/Contact
- Deliverables

GOCE assimilation strategies

- ECMWF system
- TOPAZ system
- FOAM system
- MERCATOR system
- MFS system

The front page of the ***GOCINO*** Web at http://www.gocino.dk:



1.3. Conclusions

GOCINO was successful in preparing a series of reports describing the scientific results from the EU FP-5 RTD project “Geoid and Ocean Circulation in the North Atlantic – GOCINA”. A workshop was held with participation of the invites ocean centres. The outcome of the workshop formed the basis for the development of the strategies for implementation of GOCE products in operational ocean models of the ECMWF, TOPAZ, FOAM, MERCATOR, and MFS operational centres.

Furthermore, ***GOCINO*** was successful in preparing a series of reports describing the strategies for implementation of GOCE products in operational ocean models together with the ECMWF, TOPAZ, FOAM, MERCATOR, and MFS operational centres. A second workshop was held with participation of the relevant ocean centres to discuss for finalisation of the strategies. Subsequently, the ***GOCINO*** conference was held to disseminate and transfer the implementation strategies to support the further implementation of GOCE data into the marine component of GMES. Finally, ***GOCINO*** was successful in setting up a website for dissemination of information, knowledge, and experiences.

The success of the project to meet its objectives, however, was affected by the delays in the launch of the GOCE satellite. Finally, GOCE was launched in March 2009. The satellite data was not delivered to the scientific community before the project ended. The absence of GOCE data had the effect that the motivation and interest in the operational community for working on GOCE related issues was reduced.

GOCE data products are expected to become available in the near future. At this time it is extremely important that the ***GOCINO*** results are available to the ocean modelling community.

GOCINO results have already stimulated research that will be important for the future improvements in the performances at the operational centres. Hence, it is important to maintain the collaboration between the GOCE community, oceanographic research and the operational centres and to stimulate research in those fields.

2. DISSEMINATION AND USE

2.1. Publishable results

N/A (No exploitable results with commercial value are expected)

Deliverables List

Deliverable number	Report Name	Deliverable Title
D4.1	D1	Set up website for the ***GOCINO*** action and prepare and publish a Project Presentation
D1.1	D2	Report on GOCE data and recommendations on how to use GOCE data in ocean modelling
D1.2	D3	Report on initial results and experiences from the initial tests on assimilating GOCINA models into the MERCATOR system
D1.3	D4	Report on initial results and experiences from the initial tests on assimilating GOCINA models into the FOAM system
D1.4	D5	Report on initial results and experiences from the initial tests on assimilating GOCINA models into the TOPAZ system
D5.1	D6	Documentation of progress to the end of year 1, update of workplan
D3.1	D7	Report describing strategy for assimilation of GOCE products in the ECMWF system
D3.2	D8	Report describing strategy for assimilation of GOCE products in the TOPAZ system
D3.3	D9	Report describing strategy for assimilation of GOCE products in the FOAM system
D3.4	D10	Report describing strategy for assimilation of GOCE products in the MERCATOR system
D3.5	D11	Report describing strategy for assimilation of GOCE products in the MFS system
D5.2	D12	Final plan for using and disseminating knowledge
D5.4	D14	Final Report