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Geoid and Ocean Circulation in the North Atlantic

Final Report

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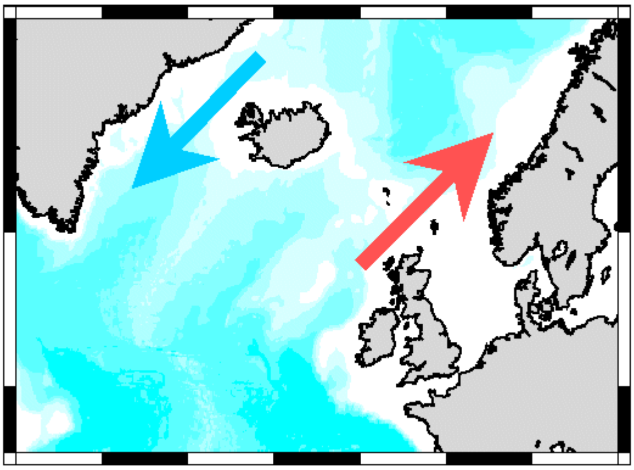

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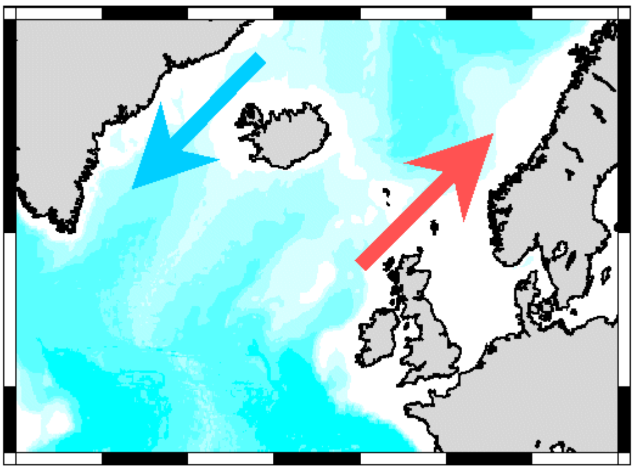

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Abstract

Objectives

The multi–disciplinary project GOCINA – **G**eoid and **O**cean **C**irculation **i**n the **N**orth **A**tlantic – has developed generic tools for ocean analysis from a simultaneous analysis of sea surface height and geoid related observations. Hereby, the project aims at enhancing the European capacity in Earth observation using data from the approved European Space Agency missions ENVISAT and GOCE.

GOCINA has been a shared cost project (contract EVG1–CT–2002–00077) co–funded by the Reseach DG of the European Commission within the RTD activities of a generic nature of the Environment and Sustainable Development sub–programme of the 5th Framework Programme and lasted over a three years period.

The main objectives were first to improve the separate techniques for the determination of the geoid, the determination of the mean sea surface (MSS), and the determination of the mean dynamic topography (MDT). Data sets associated with the three quantities have been compiled and new gravity data have been collected. The qualities of existing models have been assessed. New geoid, MSS, and MDT models have been computed and assessment and validation of these performed. For an optimal computation of those quantities integrated techniques have been tested.

The role of the improved MDT models on the mass and heat exchange across the Greenland–Scotland Ridge have been examined. The analysis has give invaluable information on the ocean role in climate. The project has in particular support the GOCE mission with a set of specific recommendation for integrating GOCE in ocean circulation studies and an accurate geoid model for validation purposes.

Scientific achievements

There has been an improvement in the basic data sets that are needed for the determination of geoid, MSS, and MDT. New gravity data were collected in an airborne survey to complete the existing ship data that were compiled for the improved geoid determination. Based on recompiled altimetry a new MSS for the period 1993–2001 was computed. In reviewing the MDT models the best currently available products were identified. The inter–comparisons of those models and MSS and geoid were tested to assess the models.

In the next step the individual models were improved. For the geoid modelling the ship and airborne gravity data have been merged and compiled with gravity information from the GRACE satellite mission. The MSS has been developed using

ENVISAT altimetry. For the MDT a composite model was derived using seven individual models. The assessment and validation of the models were carried out in several steps, e.g. by comparing with other solutions and with in–situ data. Comparisons along profiles through the region showed that the new GOCINA models picks up more important details, e.g. the southward current through the Faeroe–Shetlands Channel.

The models were further improved by integration and optimising of the three independent technologies – gravimetry, satellite altimetry, and oceanographic ocean circulation models from the previous work packages. An integrated MDT model that reached a level of precision similar to the MSS was produced. New techniques were developed to estimate the errors in the MDT. The MDT model was used for assimilation studies where transports through the Greenland–Scotland ridge were estimated and forecasting of the ocean circulation improved. The advantages in the project have been assessed in the context of the GOCE mission with special focus on issues related to calibration and validation.

Conclusions

In the context of ocean monitoring a major task for the GOCINA project has been to determine an accurate geoid in the North Atlantic and thereby create a validation platform for future GOCE Level 2 data. Analyses of the new optimised geoid have determined the extent to which GOCE data will improve the measuring and monitoring of ocean transport in the vital North Atlantic region. The new and optimised geoid was used together with the new and accurate mean sea surface to determine the mean dynamic topography (MDT). The MDT provides the absolute reference surface for the ocean circulation and the determination of the mean circulation will advance the understanding of the role of the ocean mass and heat transport in climate change.

The GOCINA ICM MDT product can now be used in ocean circulation models assimilating altimetry. It will help to better monitor and forecast transport through the Greenland–Scotland ridge and to carry out long–term climatic studies. Such studies are of vital importance to understand if, as some coupled circulation models have already indicated, the North Atlantic Thermohaline circulation is weakening. Through the new and highly important findings and results achieved, the GOCINA project has contributed to valuable promotion of the GOCE mission. The derived geoid, MSS, and MDT fields are important data sets for regional validation and calibration of GOCE data.

Keywords: Earth Observation, Mean Sea Surface, Mean Dynamic Toporaphy, Geoid determination, Satellite Altimetry, Ocean Circulation, Climate

Contents

1 Background

It is very possible that as global warming takes hold, the climate of Northern Europe will buck the trend and become cooler. The mechanism for this would involve the weakening or collapse of the Northward heat transport between Europe and Greenland by the mean ocean circulation. Furthermore, changes in the mean flows and transports in deep waters may change ocean upwelling and transports of larvae, both relevant for fish populations.

The European investment in Earth observing satellites has been significant. It is therefore of great importance that the value and utilization of this extensive provision of space borne data can be properly demonstrated in the field of ocean monitoring.

1.1 The scientific background and problems to be solved

In the context of ocean monitoring a major task is to determine an accurate geoid and, thereby, create a platform for validation of future GOCE Level 2 data and higher order scientific products. This will be done in the GOCINA project in the region between Greenland and the UK. A new and accurate geoid is used together with an accurate mean sea surface (MSS) to determine the mean dynamic topography (MDT). The central quantity bridging the geoid and the ocean circulation is the MDT, which is the difference between the MSS and the geoid. The MDT provides the absolute reference surface for the ocean circulation and is, in particular, expected to improve the determination of the mean ocean circulation. The determination of the mean circulation will advance the understanding of the role of the ocean mass and heat transport in climate change.

Satellite altimetry has proven its value in analyses of the ocean circulation. Sea surface height observations from multiple repeat altimetry missions have been used for determination of MSS and sea level anomalies. The sea level anomalies have improved the analyses of ocean tides and meso–scale variability. Also in determination of seasonal and longer term sea level changes satellite altimetry has demonstrated its potential.

Also global analyses of the MDT using sea surface heights from altimetry advanced through the eighties. Those analyses had limited success because the geoid was not determined accurately enough to recover important details in the MDT. Even though the MSS may be determined with a high accuracy and high resolution the insufficient accuracy of the geoid models prevented the breakthrough of satellite altimetry in determination of the MDT and the mean ocean circulation.

Global as well as local gravity field modelling in marine areas is hampered by lack of sufficiently accurate gravity observations. Either the coverage is too sparse or the existing gravity observations are affected by biases and poor navigation. Hence, it is often advantageous to utilise gravity anomalies that have been derived from satellite altimetry. However, such anomalies are contaminated by oceanic signals that make the geoid useless for determination of the MDT, although it can be used for other purposes. New airborne technology for cost efficient gravity surveying was developed in the MAST3–EU projects AGMASCO. Recent developments have improved this technique further, so that gravity data collected in limited regions make accurate geoid determination possible.

Methods for advanced integration of marine gravimetry and satellite altimetry have been tested and show promising results. The advantage of such methods is that optimal estimations of the geoid and the MDT as well as rigorous error estimates are provided. However, further developments in the modelling of the MDT are still needed. MDTs have traditionally been computed from in–situ hydrographic data. Such calculations require several assumptions. A level of no motion must be used to determine the barotropic component, which cannot be defined adequately in regions of both shallow and deep water depth. Furthermore, data from several decades are needed to obtain a sufficient coverage of data, which result in a solution that cannot be used in comparisons with satellite altimetry.

High–resolution ocean circulation modelling and data assimilation have advanced significantly in the past 10 years. Within 2005 the Global Ocean Data Assimilation Experiment will be nearing the end of the demonstration phase. Several European regional system covering the central North Atlantic, the Mediterranean, the North–East Atlantic, Nordic Seas, and European Shelf region, will be involved in this demonstration, in which assimilation of radar altimeter data is essential. These experiments would benefit greatly from provision of a geoid, which is accurate to the level of the ocean circulation, as this would allow use of the full altimetric signal for limited areas of the North Atlantic. These operational systems will then be capable of delivering the best possible products.

2 Objectives

The overall aim of the GOCINA project is to enhance European capacity in Earth observation technologies by promoting and developing methods for the joint exploitation of the approved European Space Agency ENVISAT (Radar Altimeter) and GOCE missions for ocean circulation studies and associated climate modelling and operational data assimilation.

Up to the expected launch of GOCE in early 2007 the gravimetric geoid is in general not known with sufficient accuracy to allow full use of the massive sea surface height information which several satellite altimetry missions have regularly provided since the early 90´ies, in global analysis of the ocean circulation. However, in a few marine regions in the world sufficient in–situ information about the Earths gravity field exists to compute a more accurate geoid. The region covering the Northern North Atlantic and the Nordic seas between Greenland, Iceland, Norway, and the UK is one of those regions. A major goal is therefore to determine an accurate geoid in this region and, thereby, create a platform for validation of future GOCE Level 2 data and higher order scientific products.

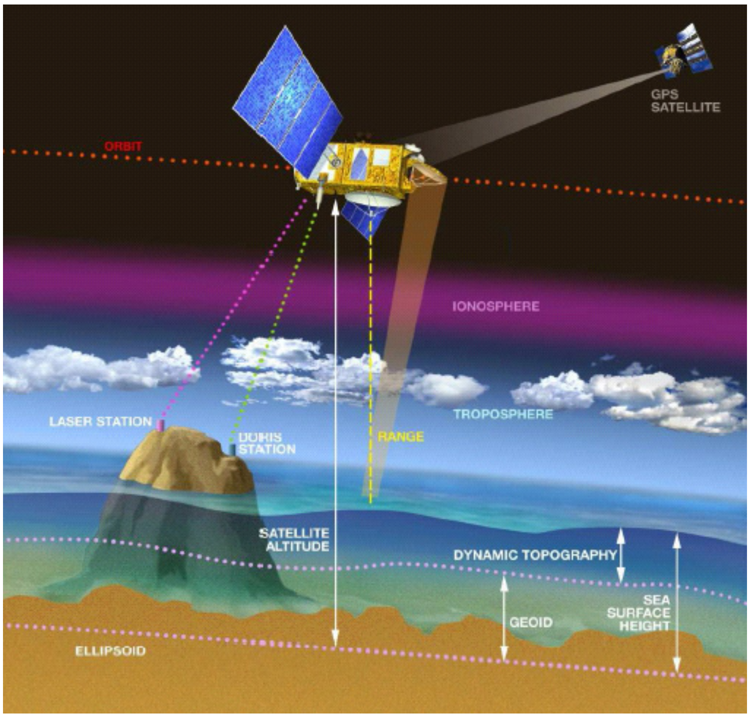

Figure 1: *The relationship between the geoid, the mean dynamic topography (MDT), and the mean sea surface (MSS). The geoid can be derived by gravity measurements or from GOCE observations and the MSS can be derived from satellite altimetry such as ENVISAT.*

2.1 Scientific/technological Objectives

A major goal of GOCINA is to use the new and accurate geoid for improved analysis of the ocean circulation. The ocean transport through the straits between Greenland and the UK is known to play an important role in the global circulation. Gulf Stream water flows into the Nordic Seas and feeds the formation of heavy bottom water that returns back into the Atlantic Ocean. Recent results have shown that changes in this bottom water transport may cause the inflow of Gulf Stream water to slow down or change into another stable circulation mode over a few decades. Such a change of the Gulf Stream with even a possible shut down of the heat transport towards high latitudes would have a huge impact on the North European climate. By analysing the best possible geoid in this region using currently available data we will be able to determine the extent to which GOCE data will improve the measuring and monitoring of ocean transports in this vital region.

GOCINA will advance the European capabilities in exploitation of Earth observation data from forthcoming satellite missions for ocean analysis of mass and heat transport, through the following seven scientific specific objectives, which all is divided into separate work packages:

Objective 1: To determine a regional high accuracy gravimetric geoid. An air–borne gravity survey will be made in the straits between Greenland, Iceland, the Faeroe Islands, and the UK to complete the coverage of existing gravity data and to establish an additional control of the ship–borne gravity data. Biases in the individual surveys will be detected in the cross–over analysis merging the data from the different sources. The gravimetric geoid and its error characteristics will be computed using state of the art methodology taking both marine and land gravity data into account as well as topographic data. Available data from the new satellite mission GRACE will be included enhancing the long wavelength parts of the geoid.

Objective 2: To determine a regional high accuracy mean sea surface. Satellite altimetry from ERS and TOPEX/POSEIDON for the period 1993–2001 will be collected and merged for this task. Furthermore, existing high–resolution global MSS for the study region will be compared. The quality of the MSS in the study region will also be evaluated through comparison with the altimeter data. Furthermore, the role of the inverted barometer correction will be evaluated. Based on the results of this analysis an optimal high–resolution MSS and its error characteristics will be computed. An updated MSS will be computed using data from ENVISAT and JASON–1 covering the period 1993–2003.

Objective 3: To determine a regional best possible mean dynamic topography using in–situ hydrographic data and ocean modelling. In–situ climatology, e.g., the Levitus data, will be used in the determination of the MDT. In addition recent hydrographic data will be used for computing a MDT, both in combination with altimetry and involving the use of ocean general circulation models (OGCM). Different OGCMs and different strategies for assimilation of hydrographical data will be used for determining several MDT models.

Objective 4: To provide detailed assessment of the geoid, the MSS, and the MDT. To assess the initial models, residuals between them are analysed. Furthermore, the MDT models will be compared with other in–situ data from tide gauges and current meter measurement. Residuals between the computed MSS and the sum of the computed geoid and MDT form the valuable basis for assessment and validation of the derived models. By comparing the residuals with the respective error characteristics, the accuracies of the products will be assessed. The validation will be carried out in different local areas as well as in the spectral domain. The analyses will result in modified error characteristics, which will provide the needed information for the further improvements by iterating on the methods used.

Objective 5: To integrate the three techniques for improved (optimal) estimation of the geoid and the MDT. Integrated techniques that consider all three quantities concurrently, and take their respective error characteristics into account will give optimal estimates of the geoid and the MDT. Especially, in regions with sparse data coverage the integrated techniques will show their strength. The optimal estimation technique is based on generalised inversion that allows a full integration of data of different kinds taking the full signal and error covariance relations into account. The technique that is based on iterative transformation and weighted combination of component data streams will be used. Also new techniques of data assimilation and geoid inversion will be evaluated for calculating the best possible local solution. The resulting best MDT will be used in the further analysis of the ocean circulation. The optimised geoid will be used to compute gravity field components and their errors at the height of the GOCE satellite.

Objective 6: To investigate the impact of the improved MDT on the ocean circulation estimation. The assimilation methods used in the OGCMs will be modified to allow the assimilation of the best MDT. Sensitivity studies will be performed to assess the impact of assimilation of MDT data on ocean circulation and mass and heat transports. A further exploration of the new and more precise estimates of the MDT will be carried out to examine if they can be used to improve the predictability of seasonal to inter–annual variability of the Northeast Atlantic and Nordic Seas and in particular the variability related to the North Atlantic Oscillation (NAO) Index. The impact on forecasting is investigated by examining the sensitivity of the forecasting anomalies to the new and more accurate MDT. The experiments will examine the mass and heat exchange across the Greenland–Scotland ridge, considering the Atlantic inflow, the surface outflow in the East Greenland Current, and the overflows. This analysis will give invaluable information on the ocean role in climate.

Objective 7: To provide specific recommendations for quality assessment of GOCE data and for integrating geoid and MDT computations with GOCE. Many conditions for the success of GOCE lies at the level of the processing of its data, which for a large part is going to be new to everyone. This implies that special and dedicated care of the data processing will be taken, to ensure that the best gravity field model can be delivered to the scientific users. The GOCINA project will in particular support the mission in two distinct cases, namely (1) to educate and prepare the community in using GOCE data for oceanography including sea level and climate research as well as operational prediction; and (2) to develop methods for generating regional gravity fields and to use them to generate a best possible regional gravity field and geoid model for the North Atlantic that can be used in validation of the GOCE products.

GOCINA is bringing together expertise in geodesy, geophysics, oceanography, and space engineering. The partners of GOCINA each have a high international reputation for expertise relevant to their specific roles. The Danish National Spacecenter (DRC – formerly the KMS), The Norwegian Mapping Authority (NMA), and The University of Edinburgh (UEDIN) have expertise in geodetic disciplines associated with geoid determination. The University of Reading (UREADERS), The Nansen Environmental and Remote Sensing Center (NERSC), and Collecte Localisation Satellites (CLS) have expertise in oceanographic disciplines associated with ocean circulation and data assimilation. DRC and CLS have expertise in processing satellite altimetry for both geodetic and oceanographic purposes. Several of the partners are associated with ESA missions ERS, ENVISAT, GOCE, and CRYOSAT, and NASA–CNES missions TOPEX/POSEIDON and JASON–1. DRC contributes to the GRACE science team. Hence, the outcome of the GOCINA project will benefit in the above–mentioned fields, and applications will have a wide–range of interests.

2.2 Socio–economic Objectives

GOCINA collect, calibrate, and validate a large amount of marine gravimetric data from very different sources. These data will be used to produce a geoid and a MDT with accuracies much better than it has been before. The geoid and MDT will be directly usable to derive absolute topography measurements from past, present, and future satellite altimetry missions. This will be crucial for a better exploitation of altimeter data (e.g. for the ERS/ENVISAT and TOPEX/ POSEIDON/Jason–1 missions) both for scientific and operational oceanography applications (CLIVAR, GODAE). It should benefit, in particular, to climate and seasonal prediction applications (much better description of the North Atlantic mean circulation and associated heat transport) but also to the offshore, marine safety, navies and fisheries applications real time monitoring of absolute currents at high space and time resolution.

GOCINA will directly benefit from the unprecedented amount of oceanographic in–situ measurements provided, in particular, by the ARGO international program that starts to deploy deep–floats in the North Atlantic Ocean. GOCINA will elaborate new techniques to determine climatology and MDT. The resulting techniques will supplement the available tool collection that could be applied to other regions of the world ocean. GOCINA is thus directly strengthening the European effort in the ARGO program.

Methodologies that is defined, developed and tested in GOCINA will also be directly applicable for the ESA GOCE mission. They will allow the preparation of an optimal MDT product from GOCE, altimeter and possibly in–situ data when GOCE is launched. This is a level 3 product (ESA terminology) and its production is not part of ESA responsibility. Still, this product is the one needed by the oceanographers. The work carried out in GOCINA will help to achieve the scientific and technical objectives of GOCE and should allow a better exploitation of the GOCE mission. To ensure an effective impact on GOCE, the GOCINA consortium will develop strong links with the ESA GOCE project and GOCE user's groups.

Providing a new geoid and MDT fields to the marine community, in particular the oil–industry, will tighten the links between the GOCINA consortium and this active community. It will be an opportunity to increase the cooperation with the marine communities and create synergies for future projects. A better knowledge of the geoid will assist geophysics studies in analysing potential areas for oil and gas drilling. The economic impact for European oil industries is thus significant since exploration studies are progressively moving from the coastal areas to the continental shelves.

In the context of a new era of space gravimetry, started with the CHAMP mission, GOCINA offers a unique chance to build up and share the necessary expertise for GOCE among the EU research and engineering communities. The outcome afforded by the GOCINA partners will stimulate and sustain the research initiative among the space agencies and other EU dedicated institutions. In particular GOCINA integrates future improvements provided by GOCE into the oceanographic problematic, at a stage where operational forecast systems are designed and can directly take the potential progresses into account.

For the past few years, impacts of climatic events like El Niño have been acknowledged by numerous sectors of the economy, in particular in the US insurance and financial risk assessment business. This growing awareness for climate prediction is also noticed and claimed by the European economy. GOCINA results and expertise will facilitate the climate prediction initiative over the European countries, and allow the development of a market for seasonal forecast products. While the European climate can be considered as mild, it is proved now that atmosphere–ocean coupled climatic mechanisms like the North Atlantic Oscillation can enhance extreme winter event like the recent storms and flood surges that paralysed the United Kingdom, Belgium, and French economy for several days during the past decade. A better forecast of such catastrophic events, will considerably reduce the impacts over the life and economy of entire Western Europe regions.

Many of the expected benefits are compliant with the Baveno Initiative and the international initiatives on climate and environment, which address topics of great political, social and scientific relevance to Europe. In addition it is compliant with the political recognition of the need to observe and monitor the environment as highlighted by the Environmental Obligations. Moreover, it will significantly contribute to improved usefulness of Earth Observation data information including ENVISAT and GOCE products.

3 Geoid determination

In the beginning of the project existing geoid models in the GOCINA region were collected. This included several regional geoid models computed by the partners and several global models (EGM96, Eigen–Champ). The geoid models have been reformatted into a common standard, and used for preliminary evaluation of solutions (WP4).

A significant effort has been undertaken to locate additional data, i.e. commercial surveys that could provide better coverage in key areas. Data obtained include data from the Norwegian Petroleum Directorate and the US National Imagery and Mapping Agency (NIMA).
Although the volume and intensity of work needed to compile and adjust gravity data was not anticipated in the initial project plan, the resulting improvements in coverage are central to the success of the project. A key question for the impact of climate change on ocean circulation is the route by which the North Atlantic Drift approaches and crosses the Shetland–Faroes–Iceland ridge. The Rockall data in particular provide a quantum improvement in data quality in an oceanographically vital region.

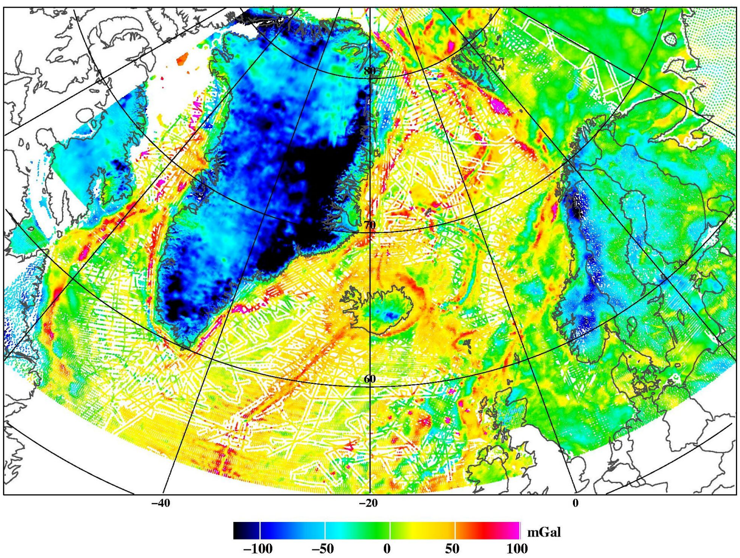

Figure 2: *Gravity data coverage in the North Atlantic region (excluding most recent Rockall and airborne data). Coverage of a much larger region than the GOCINA area is needed for most accurate geoid results, as the gravimetric geoid prediction methods are sensitive to far–zone effects.*

Work to perform a cross–over adjustment of all marine data, including the identification of some sources into along–track sequencing was done. Preliminary analyses show that corrections of many 10's of mGal are needed for some survey lines, reflecting errors in navigation or base ties of older surveys. Encouragingly, the analysis showed that the subset of the data making up a connected network included a large majority of the stations and covered the whole region systematically. This means that a formal network adjustment can address the problem of improving long wavelength trends as well as removing local inconsistencies.

A major airborne survey activity was carried out in the days June 26–July 18 and Aug 7–9 2003. An Air Greenland Twin–Otter was chartered and equipped with GPS instruments, a laser altimeter, an INS, and a modified marine Lacoste and Romberg marine gravimeter (S–99). The measurements were done in a band from Greenland over Iceland and the Faeroe Islands to Norway and Scotland. The survey operations were fully integrated with Norwegian gravity survey activities in the area to the north of the GOCINA region (OCTAS project).

The aerogravity computations for the GOCINA part of the project was completed Nov 2003, and results transferred to partners for evaluation. Internal checks of data included cross–over error evaluations, comparisons to existing marine data, and long–wavelength bias comparisons to satellite–only GRACE geopotential models. The cross–over statistics indicate that a very high–quality survey have been obtained. Comparisons to existing marine data showed no bias problems, expressing likely more the errors in the existing marine data than the airborne data.

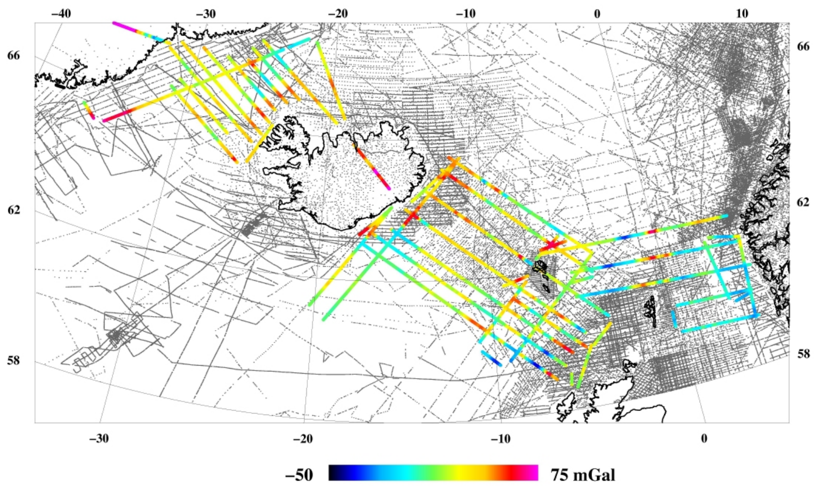

Figure 3: *Processed airborne gravity anomalies of the GOCINA airborne gravity. Reference GPS stations are also shown.*

Two different approaches to bias adjust the marine gravity data has been tested. The first approach is a linear survey–track bias adjustment scheme based on cross–

overs. The second approach is based on the fact that the KMS gravity database are structured so separate surveys can be identified. Surveys considered to be of superior quality were held fixed in the adjustment; these surveys include airborne surveys performed by KMS and recent marine surveys processed at KMS together with a few other sources acknowledged for their reliability. The identification of reliable sources, which should be held fixed in the adjustment, has been a key point in our approach. This is to make sure that we don't do more harm than good in the adjustment step.

The different approaches (on slightly different data sets) agreed in general very well in the determination of major survey biases. Differences are though seen mainly in two areas, one along the Southeast coast of Greenland and one near the Norwegian coast around latitude 65°N. Both areas are identified as problematic in the adjustment.

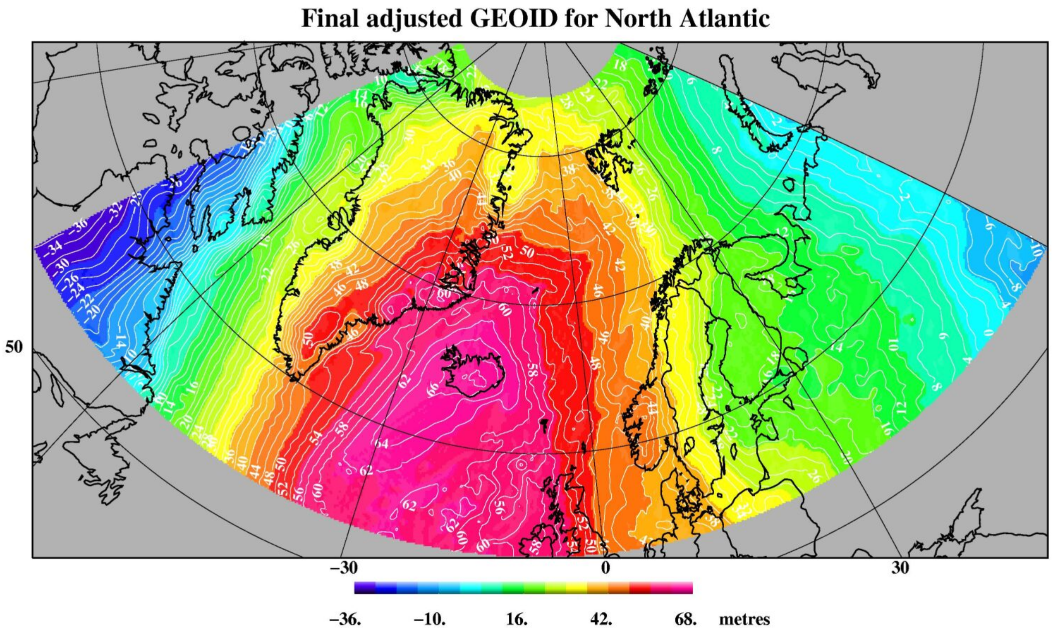

Figure 4: *Final FFT–GRACE geoid of the North Atlantic region. Unit: meter.*

The final adjusted gravity database was established in a joint adjustment of the University of Edinburgh (UEDIN) and the KMS databases, where the central and most reliable part of the adjusted UEDIN database was treated as one survey and held fixed at is initial value in the final adjustment of the KMS database. The final gravity database consists of the KMS data adjusted this way combined with data from the UEDIN database in regions where no KMS data exists. In this way an optimal solution is obtained for the complete region, utilizing all data, and utilizing the combined survey bias adjustment of both KMS and UEDIN.

The geoid modelling is based on the adjusted gravity database. Some altimetric gravity data from the altimetric gravity model KMS02 were patched in areas with larger data voids, i.e. more than 20 km to the nearest marine/airborne data point. A, at that time, newly released GRACE geopotential model from JPL was used for the longer wavelengths of the gravity/geoid field in the geoid modelling. This model was used up to degree and order 120. The residual geoid was determined with the spherical FFT approach used on gravity data reduced for reference field, restoring gridded terrain–corrected RTM anomalies into Faye anomalies prior to FFT. The reference geoid then subsequently restored. This final geoid is called nat04jpl.geoid.adj.final in the sequel.

Unit: metres	Mean	Std.dev	Min	Max
FFT residual geoid	-0.01	0.44	-1.53	2.58
GRACE geoid to $n = 120$	59.83	3.70	49.17	65.65
nat04jpl.geoid.ver2	59.82	3.72	49.04	66.17
KMS03_MSS minus nat04jpl.geoid90.adj.final	-0.47	0.19	-0.97	0.23
KMS03_MSS minus nat04jpl.geoid90.adj.final minus OCCAM	0.15	0.08	-0.25	0.64
do, but with geoid based on unadjusted gravity data	0.15	0.09	-0.25	0.69

Table 1: *Statistics of nat04jpl.geoid90.adj.final geoid for the area 54–63 N and 40–10 W.*

The table below shows the statistics of the computed geoids, as well as comparisons to the KMS03 mean sea surface, and the KMS03 MSS minus gravimetric geoid (in the sequel called gravimetric MDT) compared to the OCCAM mean dynamic topography. The latter comparison shows an 8 cm agreement with the OCCAM model, and it is worth noting that the gravimetric MDT based on the adjusted gravity database compares better to the OCCAM model than the MDT based on the unadjusted data set, 8 cm versus 9 cm for the standard deviation and 64 cm versus 69 cm for maximal difference. This is taken as indication that the adjustment improved the geoid.

The agreement to estimates of the geoid from MSS–MDT shows that the geoid accuracy should be better than 10 cm, which is probably the first time such results are obtained on oceanic scales.

For the error assessment a standard deviation was assigned to the gravity data based on the nature (terrestrial, marine, airborne) and the history (collector and processor) of the data. The surface, marine, and airborne gravity data was used for a rigorous least–squares collocation error estimate of the GOCINA region. Least–squares collocation uses an analytical signal covariance function, fitted to empirical covariance function estimates from data, to estimate the geoid errors. Because least–squares collocation requires the solution of as many linear equations as the number of data, data need to be thinned prior to applying the method. This also means that collocation error estimates by nature tend be pessimistic, since they are based on subsets of data.
Final results of the error estimation are shown in the figure 5 below. It is seen that the estimated errors are at the 8 cm level in areas with nearby airborne gravity data, increasing to 10 to 15 cm in areas with reasonable marine coverage. Higher error estimates are seen in areas with data voids.

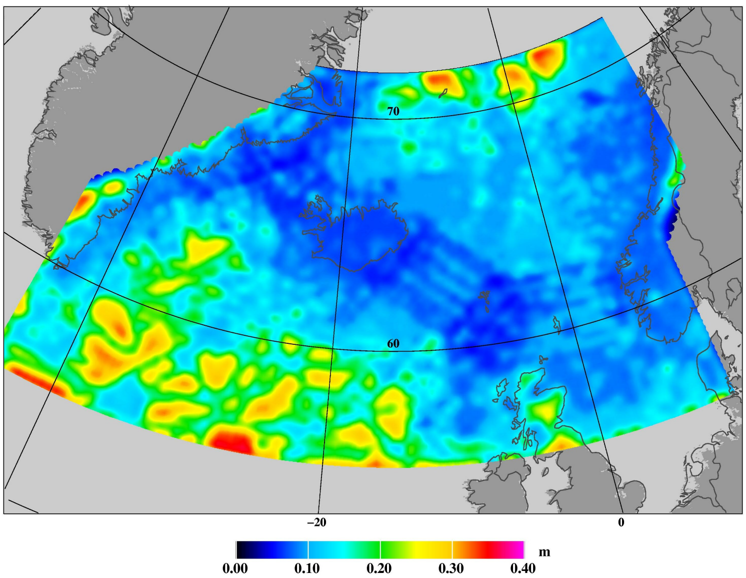

Figure 5: *Collocation geoid error estimates for the GOCINA area.*

4 Mean Sea Surface Determination

The initial comparison between existing mean sea surfaces showed, that three existing global mean sea surface are superior to all other mean sea surfaces available today. These three surfaces are called CLS01MSS, KMS01MSS, and GSFC00MSS and they have been derived by partner CLS and KMS/DRC and NASA Goddard Space Flight Center, respectively.

The partners generally use the same altimeter data, but the methodology and applied correction varies between the partners. The data processing stream was maintained at both KMS/DRC and CLS as independent approaches to improve the altimetric data processing at the two institutions and to provide a way of carrying out independent control on the derived mean sea surfaces. The advantage of this approach should also be the ability to derive two independent mean sea surfaces in order to perform a better estimate the quality of the products.
The major contribution by CLS has been on the quality controlling and updating of altimetric datasets and modification and improvement of the MSS computation technique.
The major contribution by KMS/DRC has been on the derivation of a MSS using the best available dataset for the GOCINA region.

In deriving the high resolution MSS grid file for the period 1993–2001 with associated quality indication grid on 2 km or 1/30° by 1/60° resolution the following scientific achievements were obtained.

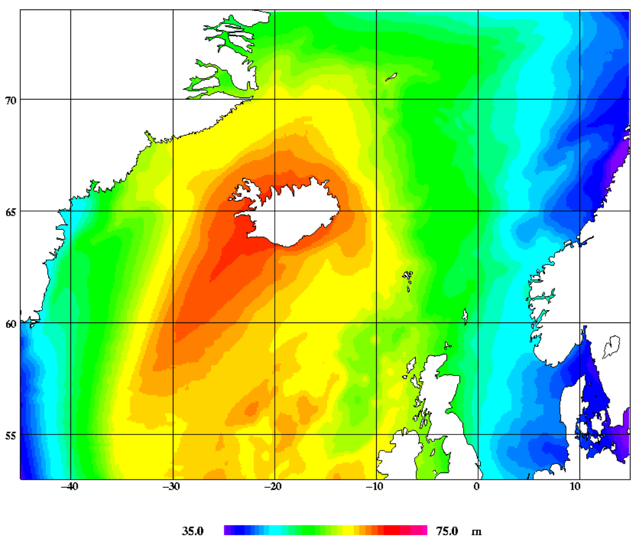

Figure 6: *The KMS03 mean sea surface from satellite altimetry (ranges between 35 and 70 meters).*

- The MSS model is based on 9 years of data (1993–2001) from multiple mission satellite altimetry (ENVISAT, ERS1, ERS2, TOPEX/POSEIDON, JASON–1, GEOSAT, and GFO) using T/P as reference.
- All data have been interpolated using least squares collocation taking into account the varying quality and coverage of the data.
- Global sea level change over the 1993–2001 was taken into account in the computation.
- A new method has been derived to account for the inter–annual ocean variability (like the major El–Niño event in 1997–98), as well as sea surface trends and pressure effects on the ocean surface.
- The MSS is available both with and without correction for the atmospheric pressure correction applied to the altimeter range (inverse barometer correction).
- All computations have been performed relative to a new global geoid model called GGM01EGM derived as a combination between the new GRACE satellite data and the EGM96 model.

The computations resulted in the development of a new high–resolution MSS grid file for the period 1993–2001 in the GOCINA study region with associated quality indication. The model is called KMS03MSS.

The quality estimate on the mean sea surface height ranges from 2 to 10 cm over the GOCINA study region with a value of 5 cm recommended to screen of bad regions in the MSS. This quality estimates is output from the interpolation of the data using least squares collocation. Consequently there might be unknown errors in the dataset not accounted by the a–priori quality estimate.

The accuracy of the MSS seems comparably to the accuracy of the derived geoid model in WP1. This means that the synthetic derived mean dynamic topography (MSS minus geoid) is more accurate than seen before.

A second task focused on updating the MSS computations for the period 1993–2003 using sea surface observations from the first years of the ENVISAT 35 day repeat mission and the JASON–1 9.9 day repeat radar altimetry missions. Again an associated quality indication grid was also produced. Other new altimetric data was also used in this update such as T/P Tandem Mission (tracks in between original tracks) and updated Geosat Follow On (GFO). The new MSS are called KMS04G.

The MSS model is consequently based on 11 years of data (1993–2003) using T/P and JASON–1 as reference. The resolution of the MSS is 1 minute in latitude and 2 minutes in latitude corresponding to 1/60 degree and 1/30 degree respectively,

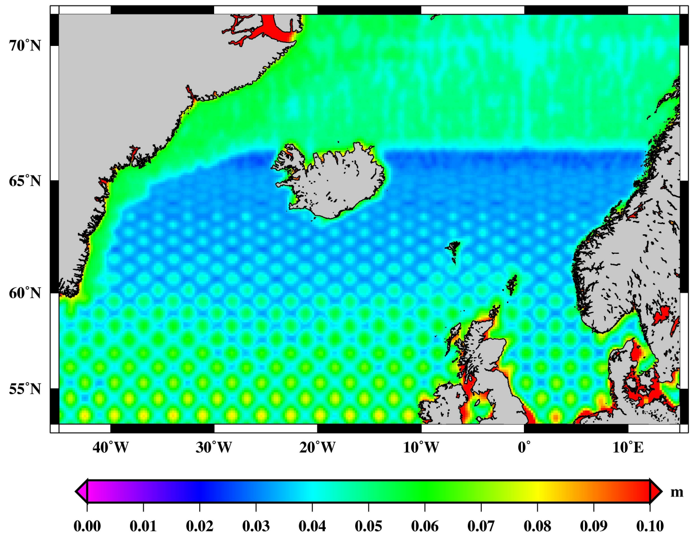

Figure 7: *The associated error file indicating the quality of the derived MSS from satellite altimetry.*

which is roughly equivalent to 2 by 2 km for the GOCINA region.

All editing computations have been performed relative to a new global geoid model called GGM01EGM. This is the presently most accurate geoid model available. The geoid model is a hybrid between the GRACE GGM01S geoid model (up to degree and order 65) and the EGM96 model to degree and order 360. For spherical harmonic coefficients of degree 65–95 a linear transition between the GRACE GGM01S and EGM96 coefficients have been used.

	0–20m	20–200m	200–1000m	1000m	All depth
KMS04G	0.26	0.15	0.15	0.13	0.14
CLS01	0.23	0.15	0.15	0.13	0.14
GSFC00	0.24	0.15	0.16	0.13	0.16

Table 2: *The table shows a global validation with Jason–1 data at different oceanic depths: Standard deviations are shown in meters.*

Both comparisons indicate, that it is presently very difficult to improve the currently best mean sea surfaces KMS03 and CLS01 with additional years of data. This clearly stems from the fact that in 2002 the TOPEX/POSEIDON satellite was replaced with its follower JASON–1. The two satellites should give slightly different sea surface height signal, because of the differences in the Sea State Bias model applied. The

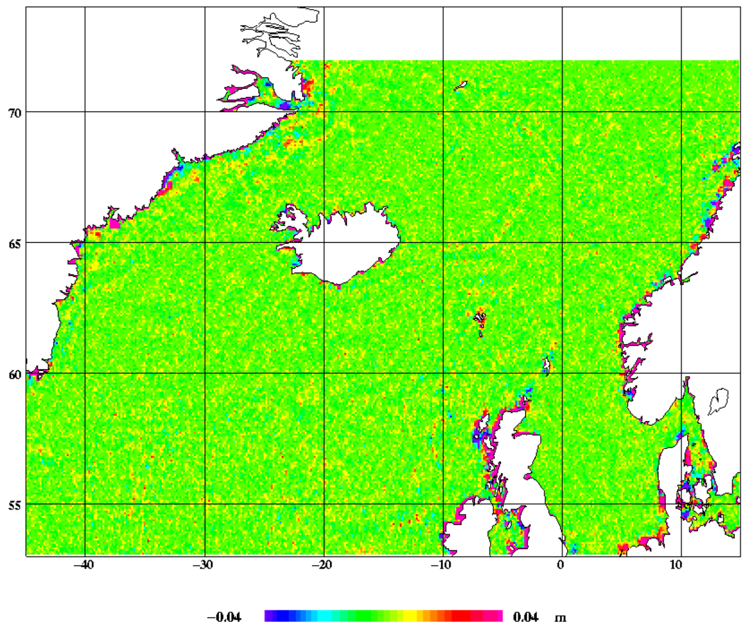

Figure 8: *The difference between the KMS03 MSS and the KMS04G MSS. The maximum difference is 25 cm.*

partners actively follow the development of SSB models and their impact on MSS determination.

5 Mean Dynamic Topography Determination

The MDT products of this work package are based on ocean hydrographic data, mostly available from scientific databases, but also obtained by project partners through special collaboration. These data are processed either by objective combination with themselves and other data sets, or by assimilation into a computational ocean circulation models to provide a dynamically evolving product.

The unique Russian hydrographical database consists of 127000 profiles of temperature, salinity, potential density, and oxygen interpolated to 30 standard Levitus depths. All measurements, predominantly from 1950 to 1990, are gridded into longitude–latitude boxes, ranging from approximately 55×55 km in the south to 15×55 km in the north. Using a Gaussian 8 points weight function on the nearest neighbors grid boxes containing no data has been filled. This may lead to artificial smoothing of the fields in areas with sparse data coverage, and in particular along the marginal ice zone and south of Iceland. For the central and eastern parts of the Nordic Seas, mainly in the Atlantic Water domain, the data coverage is generally very good, and errors due to the interpolation will for this study be negligible.

From these temperature and salinity fields we have calculated the dynamic surface topography, or dynamic heights using the level–of–no–motion assumption versus reference depths of 2000m, 1000m and 500m. As the data availability decrease with increasing depth the total area coverage of the dynamic height plot is accordingly larger when the reference depth of 500m is chosen. (The additional surface topography arising from the barotropic signal is calculated from the HYCOM model.) A mean dynamic surface topography over the entire data period as well as topographies from every decade between 1950 and 1990 is computed. In addition seasonal dynamic heights from summers and winters are computed.

Several MDT products were studied. All are based on ocean hydrographic data, and most were based on ocean model assimilation. Details of the models used to derive the MDTs are given in the table.
Two of these MDT products were produced by the partners themselves using leading expertise in methods for calculating dynamic topography from hydrographic data. The other products where obtained from external sources, including the leading ocean assimilation agencies and international project groups.
As can be seen from the table the MDTs differ in their resolution, their time period, and length of time to which they refer. To facilitate subsequent analysis and inter–comparisons, a bi–cubic spline interpolation procedure was first used to standardize the spatial format of each MDT to the finest resolution grid (1/9th degree). Using a zero land mask when interpolating introduces errors in the form of 'fringes' around the coastlines. This problem was overcome by filling in the land values by linearly interpolating zonally using values on either side of the data gap. Finally, the MDTs were centred by removing any mean offset over the region of interest.

MDT	Time period	Resolution	Comments
CLS v1	1993–1999	$1^\circ \times 1^\circ$	Model independent: Locally combine hydrography with altimetry and OI against Background (Rio and Hernandez 2002)
CLS v2	1993–1999	$1^\circ \times 1^\circ$	As above but additionally including surface drifter data
ECCO	1992–2001	$1^\circ \times 1^\circ$	4DVar, MIT model, hydrography/altimetry assim. (Koehl et al. 2002)
ECMWF	1993–1995	$1.4^\circ \times 1.4^\circ$	OI, HOPE Sys2, hydrography assim. for ENSO (Balmaseda 2003)
FOAM	May02–May03	$1/9^\circ \times 1/9^\circ$	OI, MOM Unified model, GODAE forecasting (Bell et al. 2000)
OCCAM v1	1993–1995	$1/4^\circ \times 1/4^\circ$	OI, MOMA free surface, pressure forcing, hydrography assim. (Fox and Haines 2003)
OCCAM v2	1993–1995	$1/4^\circ \times 1/4^\circ$	As above but using improved heat flux forcing

Table 3: *The important features of the MDTs used in this study.*

Since the sea–surface height varies on all timescales, the fact that the available MDTs cover differing time periods, influences the resulting MDT in two ways. Firstly, because small–scale features of the dynamic topography are generally short–lived energetic phenomena, such as eddies or advected density anomalies, we expect the smoothness of an MDT to increase in proportion to the time–span over which it is calculated. Secondly, due to integrated wind and heat forcing, there are long term trends in sea level, which result in large scale changes in the MDT. Within the GOCINA project it was decided to standardise the time period of study to 1993 to 2001 and this is the period to which we want all of the MDTs to refer.

Having adjusted each MDT to the reference time period of 1993–2001, and isolated the L component of each MDT by applying a 1 degree filter, a composite MDT (CMDT) was formed by taking the mean of the 7 MDTs in the table. For each of the filtered MDTs the implied geostrophic surface currents, were also calculated. Since the MDTs were smoothed with a 1 degree filter the derived currents correspond to average currents over 1 degree. A composite of these mean currents was also calculated and are represented by the vectors superimposed on. These currents agree well with mean geostrophic velocities for 1992–1996 calculated using d rifter data. The large currents in the South West corner of the region correspond to the North Atlantic Current (NAC) within the subpolar gyre. Part of this current feeds the Shelf–Edge Current along the west coast of the British Isles, which in turn supplies the Norwegian current via the Faroe–Shetland channel. These currents are important since they form the route by which relatively warm water travels northward into the Nordic Seas. The cold return flow in the East Greenland Current is also well represented, with the current speeds of up to 50 cm/s.

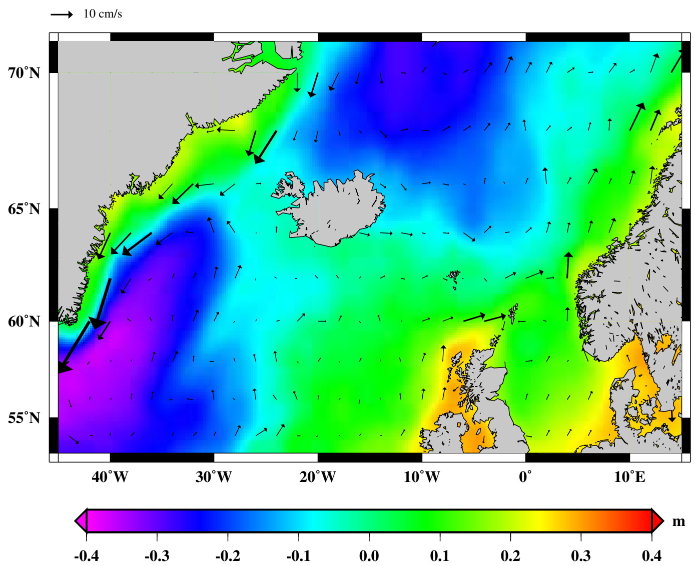

Figure 9: *The GOCINA composite MDT mode (CMDT).*

Taylor diagrams (Taylor; 2000) provide a convenient way of summarising the information in a single figure by exploiting a parallel between the cosine rule for triangles and a relationship between these four statistical quantities. For the Taylor diagram inter–comparisons (see the figure 10) the composite MDT is taken as the reference field against which the individual MDTs are compared. Thus, it appears on the diagram with a correlation of one. The standard deviations of the MDTs and current speeds are represented by the radial distance from the origin, and their correlation with the composite is represented by the clockwise angle from the x–axis. For comparison the Taylor diagrams also include the climatological MDTs from Levitus (1994) and Legrand et al (1998), and the CSR MDT, although these MDTs are not used in forming the composite.

In terms of their standard deviation the MDTs are clustered according to the methods used to produce them. The CLS MDTs are less well correlated with the composite MDT and have a greater standard deviation than the ocean model MDTs, some of which may be due to large scale differences. However, the high current speed standard deviations associated with the CLS MDTs suggest that they have greater spatial variability at small scales. The low standard deviations for the climatological MDTs, and their associated current speeds, reflects the greater smoothing involved in mapping the climatological data. The model derived MDTs all have similar variability and correlations with the composite MDT, however there is a clear increase in current variability with model resolution, with OCCAM and FOAM having the highest current variations, apart from the CLS products. The statistics for the CSR MDT should be treated with caution since they have been computed over a smaller area, and therefore the correlations are less significant. Nevertheless, the results indicate the level of agreement with the composite MDT.

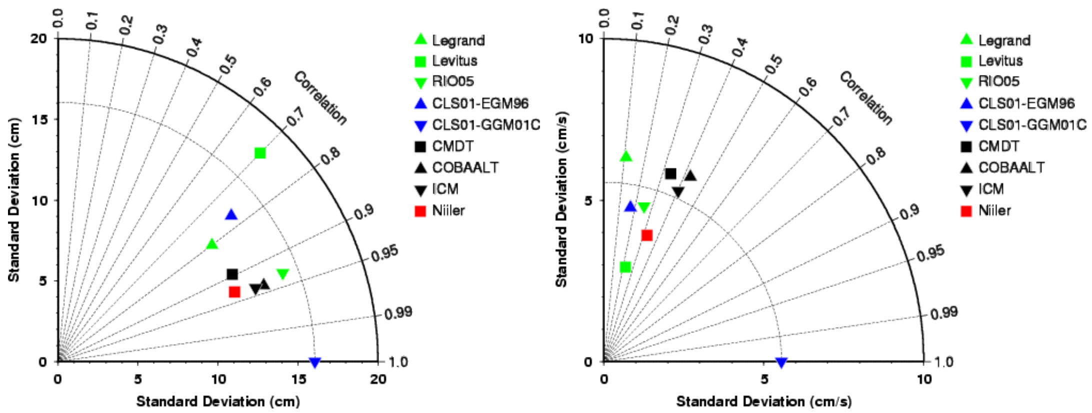

Figure 10: *A Taylor diagram inter–comparison of: (a) various MDTs; (b) associated geostrophic current speed.*

Also an MDT based on the MICOM isopycnic model was performed. The final product is an assimilation product based on hydrographic data assimilation into the isopycnal model. In result, the transport of Atlantic water into the Nordic Seas has qualitatively improved in free run experiments. Two different MDTs have been examined: A model–based (HYCOM) MDT and the CLS Rio03 MDT. Using these MDTs two assimilation experiments have been performed with the TOPAZ system to determine the optimum offset that minimize the impact on the deep–water stratification. The corresponding offset values were +11.0 cm for the HYCOM MDT and -130.0 cm for the Rio03 MDT. Currently these different MDT results are used to assess the impact on the transport calculations in TOPAZ with assimilation.

6 Assessment and Validation

The main purpose of this work package was to provide detailed assessment of the geoid, the mean sea surface (MSS), and the mean dynamic topography (MDT). For the validation the geoid, MSS, and MDT models have been inter–compared and best combinations formed. To perform the assessment and validation, the residuals r were determined by the simple formula r = MSS - geoid - MDT. This was done for all combinations of models. The results were analysed identifying best combination of models. These best combinations were formed in such a way that a combination of two of the model types gives an estimate of the third model.

Preliminary results from intercomparison of existing models indicate a correlation with the gravity coverage. Already early in the working phase a new MDT was calculated from the KMS–01 MSS and the GRACE geoid. The computations showed an improvement from the EGM96 (and KMS–01) MDT. An identification of problematic regions was performed. Also a set of best combination of models was prepared for the validations and intercomparisons.

Based on 11 different MDTs collected from various sources, including those produced in WP3, some new techniques have been developed to estimate the errors in the MDTs. This method offers a new way of making MDT errors more objective so that MDTs can be used appropriately in combination with MSS and geoid data. The new methods were borrowed from the climate change modelling community for estimating errors in climate change scenarios. Some of the updated MDTs obtained strong improvements in coastal areas, and in the description of the East Greenland Current.

Transport variability across sections in the OCCAM MDT model have been studied and compared with the sea level differences at the end of sections from Greenland–Iceland-Faroes–Shetland/Scotland (based on tide–gauge locations). Tide gauge data has been obtained for later comparisons with the MDT models. Also the drifter data set, that provide a set of geostrophic velocities at the surface, was updated. Geostrophic velocities are used in combination to altimetric SLA derived velocities to infer the MDT realism.

A vast model intercomparisons was performed, in addition to the following activities: A refined method, "The optimal smoothing method", was developed for computing synthetic MDTs from geoid and MSS models taking into consideration their error fields and the variance of the MDT and its slopes. Also a new method to derive error estimates on MDTs from assimilated ocean circulation models has been developed and refined over the three years of the GOCINA study period.

The assessment and validation of the models were carried out in several steps. Those steps are:

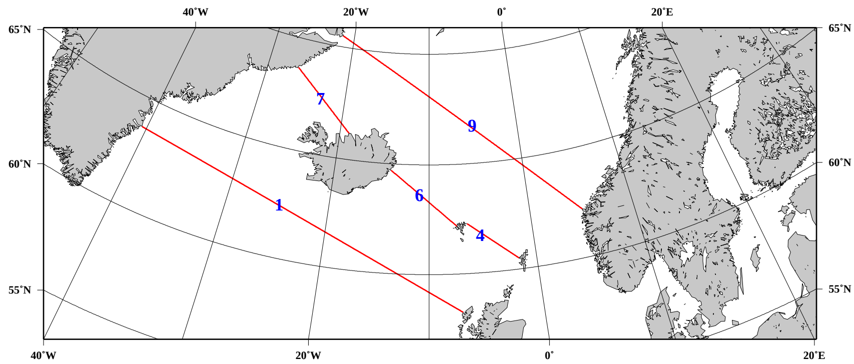

Figure 11: *The GOCINA study area and the five cross–sections used in the inter–comparisons.*

- First a detailed assessment of the best geoid, MSS, and MDT and its error field by comparing with other solutions was provided.
- Then the MDT models were compared with in–situ data from tide gauges and current meter measurement – this was mainly done in the ocean circulation and transport work package (WP6).
- Inter–comparison of the best geoid model, the best MSS model, and the composite MDT (CMDT) model along profiles was then done by comparing power spectra of the quantities.
- Finally the residuals (MSS-geoid-MDT) were investigated.

Five cross sections were used for the evaluation of the various MDTs. Two of these cross sections are extending all the way across the North Atlantic. The other three are covering the straits between Greenland, Iceland, Faroe Islands, and Shetland Islands. These areas are crucial for the North Atlantic circulation.

In the figure 12 below the evaluation of various MDTs are shown. The MDT models KMS04–GGM01S/EGM96, KMS04–NAT04, and CMDT are seen to follow the bathymetry more or less. These three models are also showing almost the same patterns along the cross sections. The MDT produced with KMS04 and EGM96 is smoother than the other models. This is particularly seen in cross section 1 where the water level in this model is different from the three other models and the structure of the MDT is not recovered by this model. For cross section 1 the direction of the geostrophic currents are more or less the same in the four models, but the speed of the currents are not the same except for the model derived using EGM96 (green). They differ by up to 10 m/s in the same point. In cross section 4 and 6 neither direction or speed is alike for the four models. In this vital region the model derived using the new GOCINA geoid and MSS models that is KMS04 - NAT04, picks up important details, e.g. the southward current through the Faeroe–Shetlands Channel.

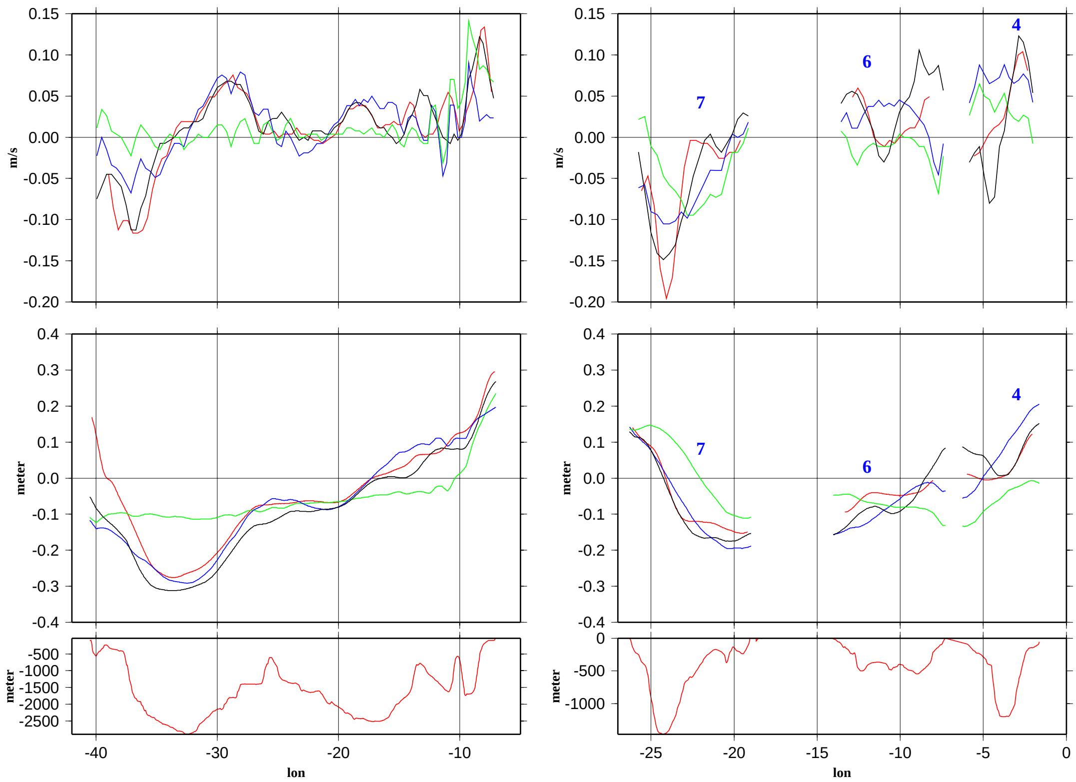

FIGURE LEGEND: Red:Composite MDT; Green: KMS04 - EGM96; Blue: KMS04 - GGM01S/EGM96; Black: KMS04 - NAT04.

Figure 12: *Left figure: Cross section 1;* ***Bottom:*** *Bathymetry.* ***Middle:*** *MDT models.* ***Top:*** *Geostrophic currents calculated from the MDT models. Same for the right figure, but for cross section 7, 6, and 4.*

In the residuals investigations of the inter–comparisons of the models, almost all residuals are zero – within the corresponding error field – over most of the GOCINA study domain. If the residuals are normalised by the combined errors, as shown in the figure 14, then they differ from zero by less than 3 standard deviations nearly everywhere. This also gives some indication of the locations, which might still bare some improvement to make the fields more consistent.

The final integrated models from WP5 of the geoid and MDT has also been investigated. These models have been computed by using least square collocation techniques (LSC) and an iterative combination method (ICM) – see section technique integration of WP5. To be able to solve the large system of equations a slightly larger grid spacing was utilized as compared to earlier geoid computations done by FFT.

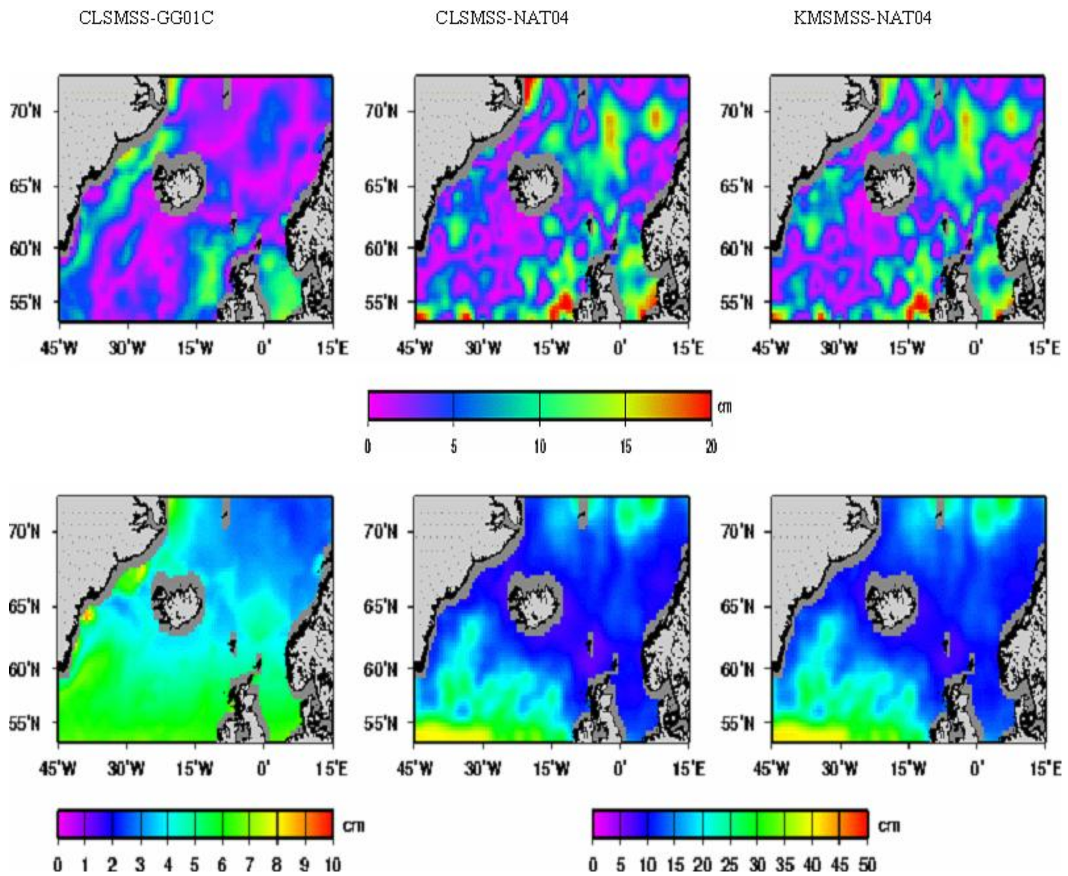

Figure 13: *The top row show the residuals R = MSS - Geoid - CMDT; where the top left corresponds to CLSMSS01-GG01C, the middle panel corresponds to CLSMSS01 - NAT04, and the right panel corresponds to KMSMSS - NAT04. Below them on the second row are the corresponding residual errors sR.*

Using the cleaned up GOCINA gravity data set and the GOCINA composite MDT (CMDT) several different models have been computed for different combinations of input data. The MSS used was the KMS04 model. The three different combinations of input data were: 1) gravity–only data, 2) gravity and MSS data, and 3) gravity, MSS, and CMDT data. The corresponding error fields of the new models were computed by the LSC method. The sparse gravity coverage in the southwestern part of the GOCINA study region was visualized in the gravity only error field and the effect of including MSS and also MDT in the data reduces the magnitude of the error clearly.

A new MDT, called the COBAALT MDT, was developed using the WP5 ICM MDT

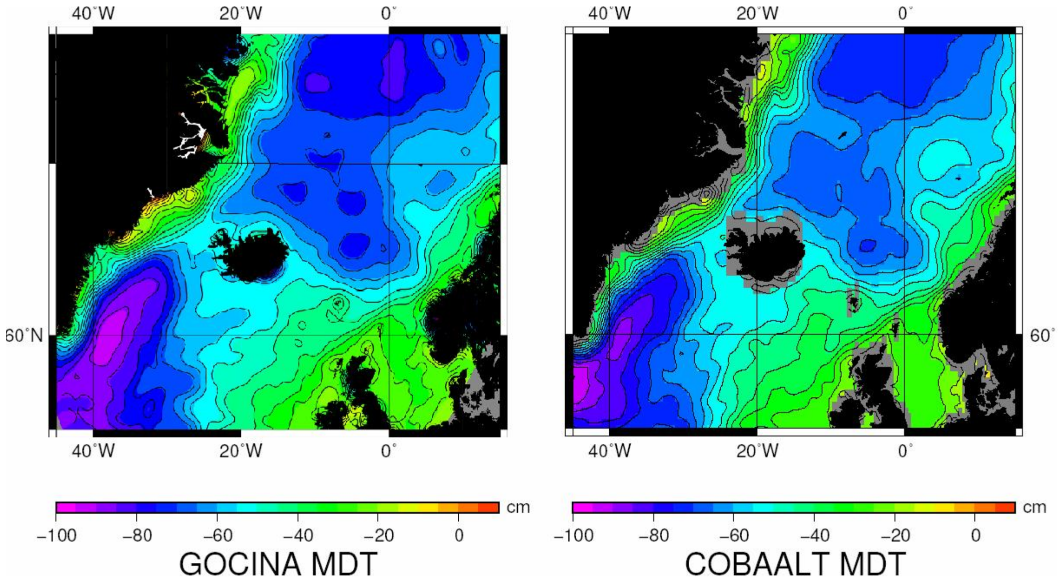

Figure 14: *The original ICM MDT to the left and the new COBAALT MDT to the right.*

averaged at 1/3 degree and limited to the region 45W–15E and 53N–75N and adding corrections to this model. The corrections have been computed using an altimeter data assimilation system that corrects potential systematic errors (bias) in the reference MDT. The resulting bias has been constrained by the GOCINA MDT error provided by the collocation method using gravity and MSS data. The model used is the FOAM 1/3 degree North Atlantic ocean model.

Using this new COBAALT MDT, new correlations studies was performed. The computations have been performed between the supplied models and the GOCINA CMDT for three different regions. The correlations are now more in accordance with what was observed and discussed previously. Compared to the earlier results the correlation with the GOCINA CMDT has generally increased.

7 Technique Integration

The purpose of this work package is to integrate the three independent technologies – WP1 gravimetric geoid computation, WP2 mean sea surface height determination from satellite altimetry, and WP3 mean dynamic topography from oceanographic modelling – into one single process that delivers an optimal geoid, mean sea surface, and mean dynamic topography. Three different approaches to this integration are being explored. The relationship between the data streams is MDT $=$ MSS $-$ geoid.

Early results of the work package made it clear that the relationship above is not the best way to combine the information used in work packages 1, 2, and 3. The MSS is the only quantity that comes from its own independent data stream and is observed directly and with essentially complete data coverage. The other two, geoid and MDT, are output products separated from a range of different types of primary observations by a long chain of modelling and analysis. In both cases, there are significant gaps in data coverage, so one key aspect of the analysis involves interpolating or extrapolating dimensionally different quantities from the points where they are observed in order to complete the coverage.

One of the explicit outcomes was the demonstration that no adequate geoid could be generated unless data gaps in surface coverage were filled in with 'pseudo–gravity' (derived from satellite altimetry by differentiating the MSS). Thus, stream one is redefined as gravity rather than geoid and we are now looking for optimal combination of gravimetry, satellite altimetry (both MSS and its derivative pseudo–gravity), and oceanographic MDT.

Earlier work packages showed that a range of MSS models derived from satellite altimetry had an rms mismatch of 2.7 cm or less. The previous best MDT models, based on gravimetric geoids produced for WP1, had an rms mismatch of 8 – 9 cm with a reference MDT model. MDT products from some global ocean circulation models had regional differences of 20 cm compared with the average. Work Package 5 sought to produce an integrated MDT model that reached a level of precision similar to the MSS.

The second phase of WP5 involves the interaction of GOCINA with GOCE: By producing a gravity field covering the GOCINA area at satellite height for validation purposes; and secondly by making proposals for how to integrate GOCE data with other forms of information into a product directly useful to the oceanographic and marine geodetic communities.

A direct estimation of geoid and MDT in a single stage process, using least square collocation (LSC) a stochastically optimal solution from the three streams of input were performed as the first task was done. For LSC, the solution depends on being able to determine and then model the covariance function of the input data and their associated errors. To characterise the covariance function, an analytical model with typically two parameters – variance and correlation–length – was fitted to an empirical data covariance for each form of data.

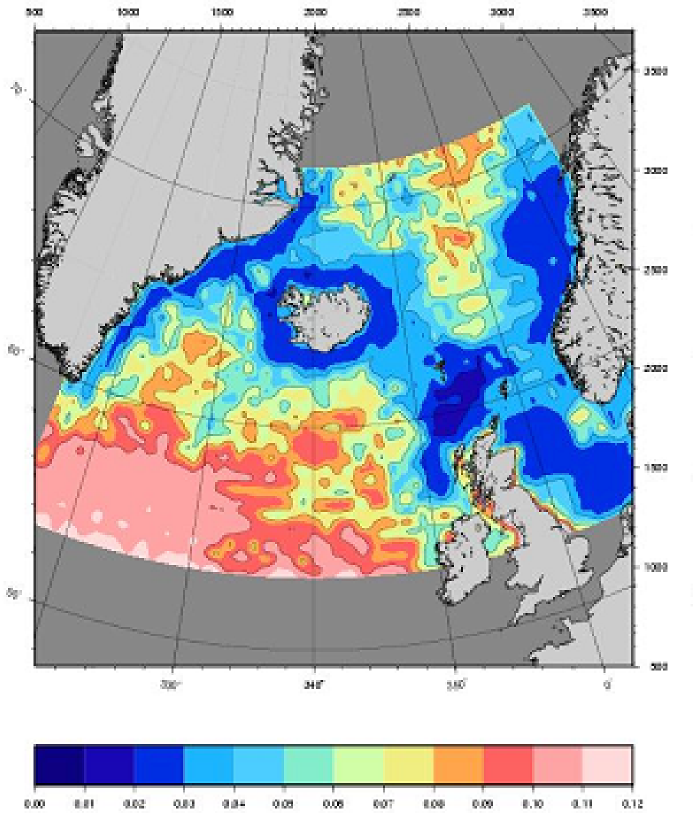

Figure 15: *The LSC predicted error from combining surface and airborne gravity and an altimetric MSS (scale bar 0 – 12 cm).*

The error variance parameter reflected the different origins of the data – smaller standard deviations being assigned to airborne gravity and larger ones for marine data, the latter becoming larger with increasing survey age.

LSC is computationally demanding, so all the data for the whole area could not be included in a single solution. Consequently, the GOCINA area was divided into nine sub–regions, each with an overlap of about 1° to avoid edge effects when the separate solutions were merged.

A strength of the LSC approach is that a prediction can be made using only some of the available informations – observables may be selected from ship–based gravity, airborne gravity, altimetric MSS and oceanographic MDT. In addition, other parameters such as a gravity bias for each ship survey may be included. These partial solutions provide a valuable tool for exploring what the impact of each data stream is, on the final prediction and on the errors associated with it.

The figure 15 shows the MDT error predicted by LSC when three input data streams are included – surface and airborne gravity anomalies and the altimetric MSS. Here, the predicted errors drop to about 2 cm near airborne gravity flight lines and are about 4 cm elsewhere where the surface gravity coverage is good. They rise well above 10 cm over regions of much poorer coverage.

In the second task an estimation of mutually consistent geoid and instantaneous sea surface topography using Fourier methods for iterative transformation and weighted combination of component data streams were done.

The work concentrated on a physical and geometrical model for combining the input data streams rather than a statistical one. Weights were designed in the space–domain to represent geographic variation in data reliability rather than give them an absolute statistical significance. This approach is able to tailor the algorithm more closely to problems of data gaps and the different forms of input. It is also able to generate a higher resolution product and use all available data. However, its major disadvantage is that it includes aspects that are 'skill–based' (intuitive) and gives no internal estimate of errors in the output.

A solution was sought treating two sources of data as 'reliable' – surface gravity (but only on land and along ship tracks or aircraft flight lines) and MSS everywhere at sea.

In this case, the tasks of interpolating gravity into the gaps and of finding MDT are one and the same. It involves two alternative versions of 'gravity' – a real one and a synthetic one derived from altimetry and the MDT model. The complete 'composite' gravity field is a weighted average of real and synthetic gravity, with the weights chosen to make the composite field match the real data in its immediate vicinity but providing a self–consistent interpolation based on synthetic gravity elsewhere. The method of solution involves a starting model for MDT, integrates a complete gravity field, and predicts a 'better' version of MDT. This is now used for the first MDT and the procedure iterated until the inserted MDT is consistent with the predicted MDT. The algorithm is called the Interative Combination Method (ICM).

While both LSC and ICM aim to produce their own concept of the 'best' model, the final judgement on its quality must come from comparison with independent, external observations.

The ICM produced a slightly better MDT model than LSC. The rms difference between the ICM and LSC models was 4.97 cm and between ICM and a FOAM GOCM assimilation was 3.93 cm.
Nevertheless, LSC is the only way to get a formal error estimate. Using the ICM MDT with the LSC error is self–consistent in the sense that both internal and external error estimates are similar in size.

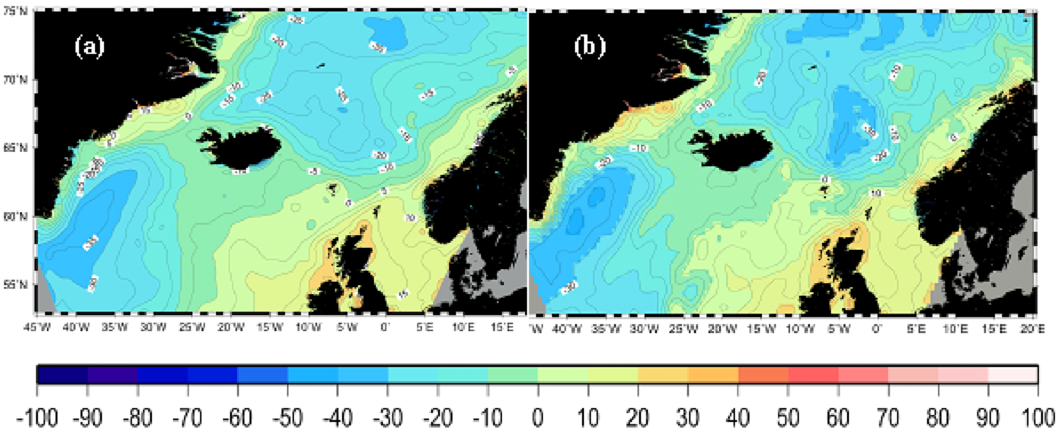

Figure 16: *The effect of including ICM MDT on the integrated MDT model. (a) before; (b) after. MDT in cm.*

An early result called ICM_MDT_150 (hereafter ICM MDT) were produced that not only looked very plausible oceanographically but also had at the time the smallest mismatch of any of the pilot products with respect to a reference MDT. Largely because the next task could not begin until it had a geodetic MDT as input, ICM MDT was chosen as MDT. Later, this choice was vindicated because it remained the product with the smallest mismatch with the reference MDT although the final product of LSC was only slightly worse and generally had a very similar form. Although neither of the other products of the work package fitted quite as well as the ICM MDT, all of the models tested were a substantial improvement over those without technique integration.

Therefore the key deliverable has been the ICM MDT. This has been the model used for assimilation studies, none of which have produced a result closer to the GRACE–corrected composite MDT, which has been a standard reference. The convergence of the GOCM assimilation models is impressive – the closest with an rms difference of 3.9 cm – and it is probable that future work would improve the result further.

The two other co–located deliverables are the heights of the geoid and the mean sea surface. The analysis used to produce this model for MDT used the CLS01 MSS model, and assumed that errors in the MSS would be negligible in comparison. This would mean that only one novel result was needed and the deliverables would be a new MDT model, a previously available MSS model and the geoid as the difference between the two.

The third and last approach did an estimation of an integrated solution based on assimilating techniques for analyses of the geoid and MDT and has a fundamental difference in the first two approaches. It incorporates a time–averaged MDT into a global circulation model that predicts the instantaneous (i.e. time–variable) ocean circulation. The output could then be averaged over the chosen standard period of 1993 – 2001 for comparison with MDT products, or compared with other forms of time–varying data such as water velocity measurements. Apart from their potential to improve the MDT model, the assimilating gravity field information into a GOCM also helps to assess what impact a GOCE–derived MDT would have on GOCMs, thereby providing continuity with Work Package 6 in investigating the impact of improved MDT on ocean circulation estimation.

For technique integration a given model of MDT to combine with point observations of height and water velocity in a multivariate objective analysis designed to predict an improved MDT were used.

	RMS east velocity V_{E} cm s^{-1}	RMS north velocity V_{N} cm s^{-1}	Vector correlation coefficient R_{C}
GOCINA composite MDT	11.2	10.5	0.49
ICMMDT	11.3	10.7	0.47
Niiler	11.1	10.4	0.50
ECCO	11.5	11.2	0.41

Table 4: *Validation results for different models of the mean flow*

The figure 16 above compares the original ICM MDT with the result of assimilating it. Compared with the input ICM MDT. The output shows amongst other features the Irminger Sea gyre broadened and slightly deepened. It has an intensification of northwards flow along its eastern edge.

Another approach assumes that the given ICM MDT model has systematic errors. A GOCM assimilation scheme embedded in the $1/2°$ FOAM model implemented at the UK Meteorological Office explicitly takes account of systematic errors in the data, rather than in the model. The algorithm predicts state variables at the location of subsequent observations and model adjustment is in response to the forecasting error. It dissociates the rms error into one objective function that relates to the bias and another that relates to the dynamical behaviour.

One of the partners adapted the Hybrid Coordinate Ocean Model with a detailed grid for the North Atlantic. This has allowed a response to more detailed bathymetry to some aspects of the resulting assimilated MDT and shows interesting bathymetric correlations compared with other products. Of all the models, the TOPAZ assimilation shows the strongest influence of the mid–ocean ridge and has more detailed flow patterns west of the British Isles.

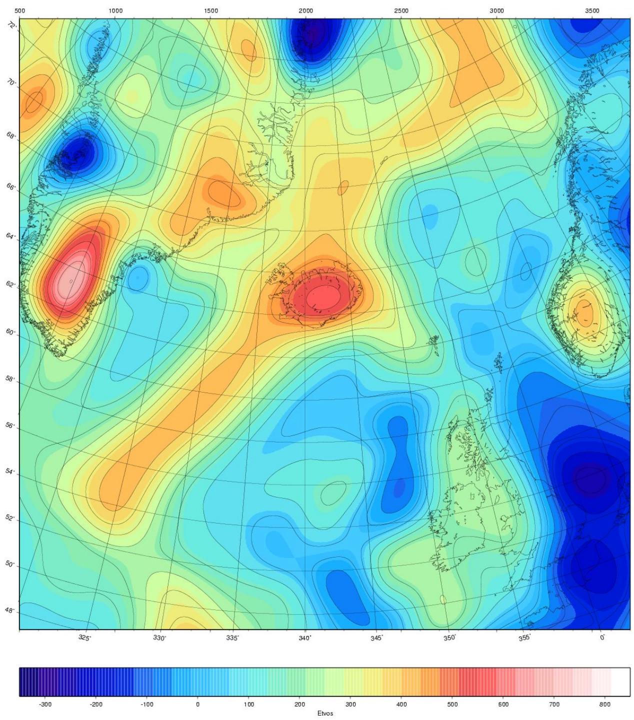

Figure 17: *Diagonal components of the gravity gradient tensor for the total field (radial component* Γ_{zz}*).*

Furthermore the ability of the ICM MDT to predict the velocity of drifting buoys was tested. The experiment compared 172920 observations of buoy velocities for the period 1993 to 2003 with predicted instantaneous velocities. The experiment was repeated with four MDT models: ECCO, Niiler, the GOCINA composite MDT, and the ICM MDT. It determined the root–mean–square deviation of the east–west and north–south components of velocity difference and a vectorial correlation coefficient (table below).

Not surprisingly, the best model is the Niiler MDT, which was itself deduced from the drifter data. However, both GOCINA products do better than the independent MDT derived from the ECCO GOCM. The largely gravimetric product ICM MDT has a slightly worse agreement than the GOCINA composite MDT, which is purely oceanographic product.

A set of gravity gradient tensor values for comparison with future GOCE measurements has been computed. They are evaluated at satellite altitude over the northern Atlantic Ocean between Europe and Greenland from about 53°N to 72°N. Real ship–borne and air–borne gravimetry was compared with synthetic but theoretically rigorous gravity anomalies derived from satellite altimetry and oceanography. This combination of different disciplines has resulted in gravity coverage over the GOCINA region of the Atlantic that is complete and has an accuracy of locally representative free–air anomalies that has hitherto not been matched on adjacent land. The ESA GOCE mission aims to provide satellite–only models of the Earth's gravity field and its equipotential surface on a global scale with a high spatial representation. It exploits gradiometry, not only externally by tracking a satellite–to–satellite baseline but also internally with a centimetric instrumental baseline.

8 Ocean Circulation and Transport

The purposes of this work package were to analyse the impact of the MDT model (issued from WP5) on the estimate of the North Atlantic Ocean circulation given by ocean forecasting systems. The water masses, the heat transport, and the seasonal variability of the circulation are key elements for these analyses. The analyses have been carried out in three distinct operational systems. The first model is the FOAM model (Forecast Ocean Assimilation Model) operated by the UK Met Office. The second model is the TOPAZ (Towards an Operational Prediction system for the north Atlantic and european coastal Zones) model from the Nansen Environmental Remote Sensing Center (NERSC). The third system is the French operational forecasting system MERCATOR.

There are three main tasks in this work package:

- From simulations of numerical models assimilating altimetric and sea floor pressure data (and using the new ICM MDT), two ocean processes have been examined. 1) The water exchanges (mass and heat) across the Greenland–Scotland Ridge. 2) The topographic steering and the subsequent heat transport at the continental shelf breaks. From a one year simulation (assimilating all available data), the climate capabilities of current ocean forecasting system using new MDT have been investigated.

- Analysing ensemble integration of the ocean model forced with atmospheric fields and comparing to existing coupled atmosphere–ocean model results, the impact of more precise MDTs have been determined in terms of seasonal to decadal climate prediction, and in particular, how the North Atlantic thermohaline circulation is depicted, and how temperature and salinity anomalies are distributed, and correlated with NAO indices.

- Using two ocean operational forecasting systems, the impact of the new MDT on their respective ocean forecast capabilities have been analysed. After one year simulation, data misfits and forecasting skills have been regionally analysed in the first system. A twin experiment has been performed with the second system, testing error levels expected for GOCE, MDT improvements, and enhancement of the high–energetic mesoscale circulation (strength and position of fronts and jets) that might modify the thermohaline circulation.

8.1 Impact on Transport and Topographic Effects

Volume, heat and salt transport estimates through key sections of the Greenland–Scotland ridge (GSR) were computed using three distinct systems, FOAM, TOPAZ, and MERCATOR, that assimilate altimetry data referenced to the GOCINA ICM MDT. A strong attention must be paid to the fact that all three systems were run for different periods, so that direct comparison of the obtained transports must be done with caution. However, values obtained for the three systems are rather consistent one with the other.

Section		Obs	Simulated					
			FOAM	FOAM-C	TOPAZ	TOPAZ-C	MERCATOR	MERCATOR-C
Iceland-Greenland	N	0.8	1	0.7	2.5	2.2	4.23	4.45
	S	4.3	7.5	10.4	4.8	5.3	6.64	7.68
Faroe-Iceland	N	3.8	5	5.8	5.0	5.2	-	-
	S	1.0	1.3	1.2	2.3	2.2	-	-
Faroe-Shetland	N	3.8	4.3	5.9	3.2	3.5	-	-
	S	2.6	2.4	1.8	2.3	2.2	-	-
Iceland-Shetland	N	7.6	9.3	11.7	8.2	8.7	4.49	4.36
	S	3.6	3.7	3	4.6	4.4	3.02	3.24
All sections	N	8.4	10.3	12.4	10.7	10.9	8.72	8.81
	S	7.9	11.2	13.4	9.4	9.7	9.66	10.92
Net flow through the GS ridge		0.5N	0.9 S	1 S	1.3 N	1.2 N	0.94 S	2.09 S

Figure 18: *Observed and simulated north (N) and southward (S) volume transport over the GSR in Sv (106 m^3/s). Yellow shaded boxes stand for sections where the GOCINA run leads to transport values closer to observations than the reference run.*

The sensitivity of the volume transport has been investigated through a twin experiment: Comparisons are done between the transports from a reference (control) run and the GOCINA run. In the control run the operational systems ”ow” MDTs are used. The GOCINA run uses the ICM MDT. In the FOAM system the new bias aware data assimilation scheme (COBAALT) that allows the chosen MDT to vary slightly from this according to the error covariance matrix is furthermore used.

Northward and southward volume transport through the GSR was found to be overestimated in all three systems compared with observations. Using the ICM MDT to assimilate altimetry had a significant positive impact in all systems. Estimated volume transport values got closer to observations in all systems, while the northward heat transport was significantly improved in the FOAM system, meaning that the assimilation of altimetric data, referenced to an accurate MDT, allows to better reproduce the Atlantic Thermohaline Circulation (THC).

8.2 Impact on Seasonal to Inter–Annual Variability

The impacts of new MDTs on the seasonal to interannual variability of the volume, heat, and salt transports through three key sections between Scotland and Greenland have been investigated. Three key sections were considered for the trans-

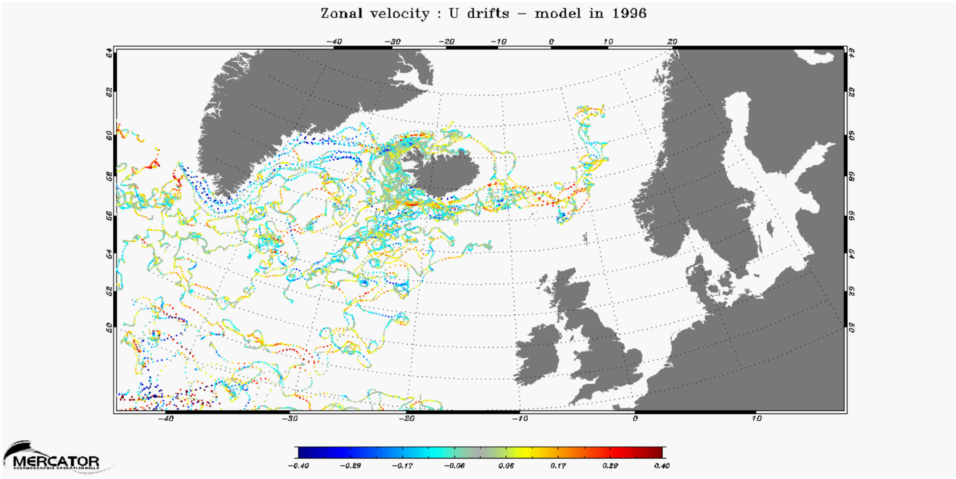

Figure 19: *The annual zonal velocity in the GOCINA run compared with drifters.*

port computation. They are the Iceland–Greenland (IG) section, the Faroe Islands–Iceland (FI) section, and the Shetland Islands–Faroe Islands (SF) section. The sum of the transport through these three sections defines the largest fraction of the exchange of water and heat between the North Atlantic and the Arctic.

To study the impact of integrating a new MDT for assimilating altimetry in a general circulation model, twin experiments have been run using three different operational systems. The first system is based on the FOAM model (Forecast Ocean Assimilation Model) operated by the UK Met Office. The second model is the TOPAZ (Towards an Operational Prediction system for the north Atlantic and European coastal Zones) system, and the third system is the French MERCATOR system.
The first runs in the twin experiments are the control runs, using the operational systems own MDT with altimeter data assimilation in order to produce forecasts of ocean currents for the North Atlantic and Arctic. The second run is similar to the first except that the MDT is replaced with the GOCINA MDT. In the FOAM system the new bias aware data assimilation method is used to allow for errors in the MDT is used in addition. This run is labelled as COBAALT (COnstrained Bias Aware ALTimeter) data assimilation system developed by UREADES for GOCINA (Drecourt and Haines, 2005).

In the FOAM system, the impact of using the GOCINA ICM MDT to assimilate altimetry instead of the FOAM MDT was studied. The twin experiment was run for one year (June 2002 – June 2003) so that no inter–annual variability could be studied. The use of the ICM MDT led to a reduction of the amplitude of the seasonal variation as well as a reduction of the overall flow, for each subsection taken separately and also for the entire Greenland–Scotland section.

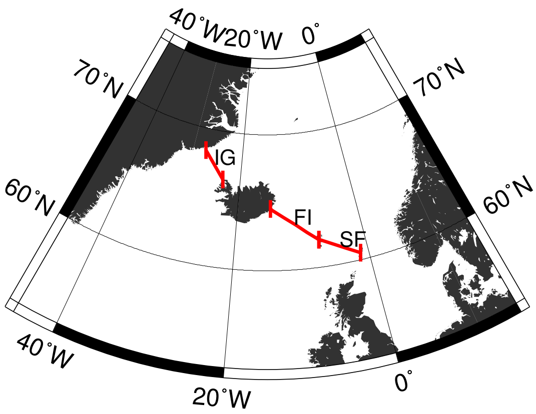

Figure 20: *Sections used in the FOAM system: the Iceland–Greenland (IG) section, the Faroe Islands–Iceland (FI) section, and the Shetland Islands–Faroe Islands (SF) section.*

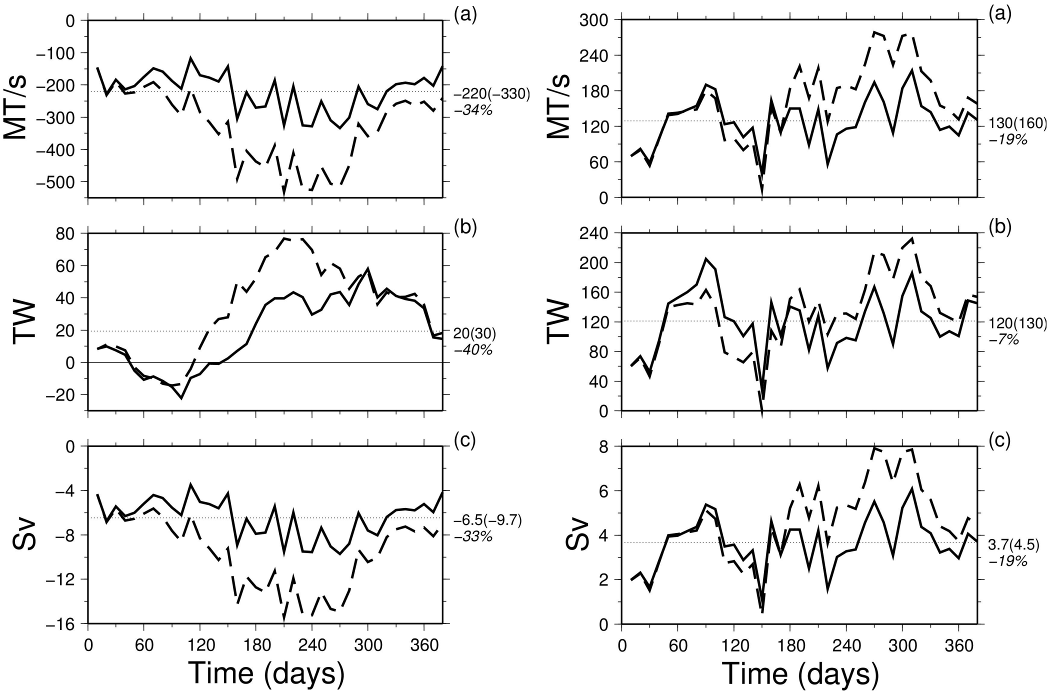

Figure 21: *Left figure: This shows the total transports in the FOAM system through the section Greenland–Iceland with the top figure showing the salt transport, the middle figure shows the heat transport, where the reference of 0°C has been used; and the bottom figure shows the volume transport. The GOCINA (COBAALT) run is represented as the full line and the control run as the dashed line. The dotted line indicates the mean value for the GOCINA (COBAALT) run. Right figure: Transport time series for the Faroe–Iceland section. The conventions are the same as in the figure to the left.*

In the TOPAZ system, a run assimilating altimetry (using the ICM MDT as reference) and in–situ data was compared with a run without assimilation (control run). All transports over the GSR show a distinct variability on the inter–annual time scale. Results from the control run are highly correlated with that from TOPAZ based on the weekly snapshots but disagree considerably on longer time scales. While the frequency spectra of the transport time series drawn from the two models agree considerably well the variance based on the weekly snapshots is generally somewhat higher in TOPAZ.

From nine years integration of TOPAZ–C trends were calculated for each of the transports. It comes out that the inflows towards the Nordic Seas decrease for each of the sub–sections over the GSR and in addition the outflow through Denmark Strait also reveals a negative trend. Those decreases exceed the inter–annual variability. For TOPAZ no trends are drawn due to the shortage of the integration and the high variability found on inter–annual time scales, but it is expected that transports in TOPAZ will behave different on long time–scales and lower or no strong trends will be found.

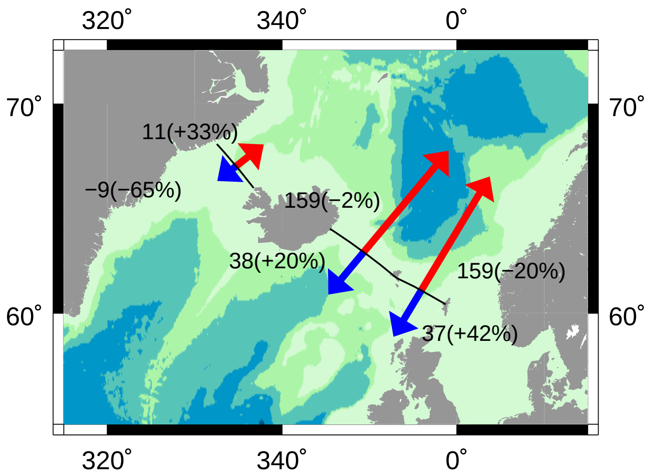

Figure 22: *Total annual average heat tranports (in TWatt) both northward (red) and southward (blue) through the straits between Greenland and Scotland. Percentages changes by indroducing the COBAALT MDT are shown in brackets.*

In the MERCATOR system, as in FOAM, the simulation period (one year) prevented from studying inter–annual variability of the transport. On seasonal scales, the transports show very little variability for both sections studied as well as for the whole Greenland–Shetland section. Impact of using the ICM MDT is small. In the Iceland–Greenland section as well as for the whole Greenland–Shetland ridge, a slight decrease of the southward flow is observed in the GOCINA run in respect with the control run.

8.3 Impact on Ocean Forecasting

The aim of this study was to investigate the impact, in term of prediction capability, of using the ICM MDT for assimilating altimetry data in operational ocean forecasting system. This was done in two distinct existing operational systems (FOAM and MERCATOR). In each system, a twin experiment was realized, and a comparison with in–situ data was performed.

In FOAM, the two experiments differed by the change in MDT but also by the use of an assimilating system allowing for errors in the MDT. It was found that the use of the ICM MDT in combination with the new assimilation system (COBAALT) does improve the ability of the model to forecast temporal variability.

In MERCATOR, the twin experiments differed only by the change in MDT. However, the ICM MDT is very close, though a little smoother, to the MDT used in the control run, computed from a combination of altimetric, in–situ and GRACE data. Consequently, no systematic behaviour could be found. Slight improvements were found in some areas, balanced by slight degradations in others.

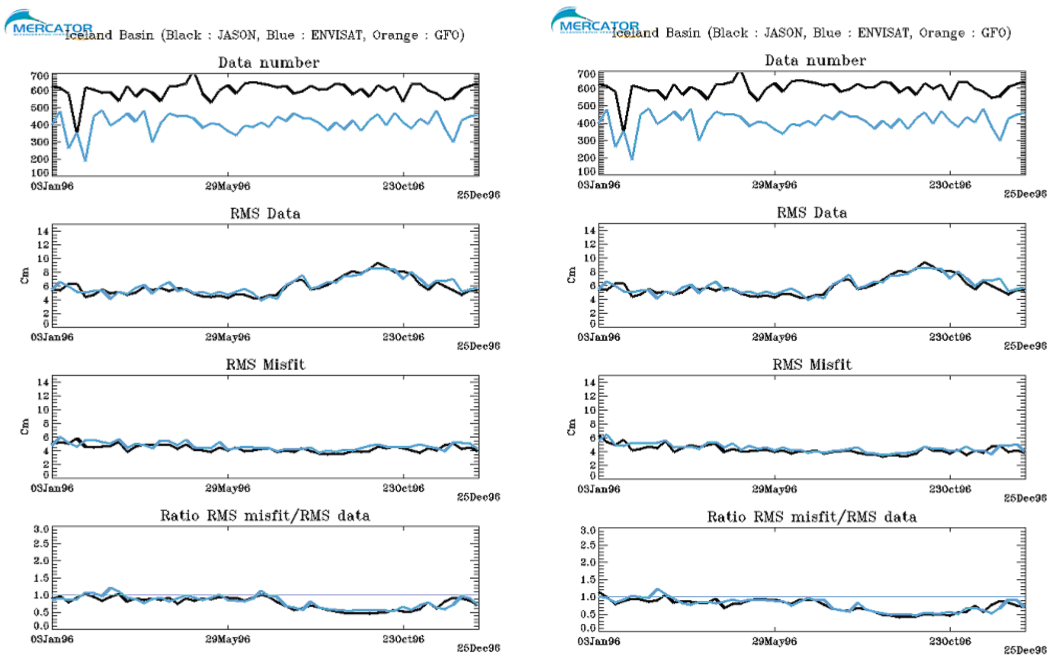

Figure 23: *7 days forecast scores of SLA in the Iceland Basin in the control run (left) and the GOCINA run (right) in the MERCATOR system.*

9 Recommendation for Integrating GOCE

GOCE is a very ambitious mission, and many conditions for its success lie at the level of the processing of its data, which for a large part is going to be new to everyone. This implies that special and dedicated care of the data processing should be taken, to ensure that the best Earth's gravity field model can be delivered to the scientific users. For this reason a European GOCE Gravity Consortium, EGG–C is established. Its main purpose is to determine the best possible global model of the Earth's gravity field from the pre–processed data of the GOCE mission of ESA, with derived grids of geoid heights, free–air gravity anomalies, geoid slope, together with their uncertainties mapped from the covariance information on the model parameters, all this after thorough evaluation of the model quality.

The GOCINA project in particular supports the EGG–C tasks in two distinct cases, namely (1) by educating and preparing the community in using GOCE data for oceanography including sea level and climate research as well as operational prediction; and (2) by generating a best possible regional gravity field and geoid model for the North Atlantic that can be used in validation of the GOCE products.

The task of educating and preparing the scientific community in using GOCE data for oceanography and a test of the performances of the schematic approach, was done in providing two proceeding from the GOCE ESA–ESRIN and GOCINA Luxembourg workshops. A resume of the proceedings is as follows:

The accurate and high–resolution marine geoid, will in combination with precise satellite altimetry enable new estimates to be made of the absolute ocean topography. In combination with in–situ data and ocean models, this will, in turn, provide a high–resolution "window" on the ocean circulation at depth. Developments for merging the gravity information, which will be obtained by GOCE and other gravity missions, into ocean models have been addressed. Three application areas are, in particular, considered:

- *First*, it is through mean flows and mesoscale eddy variability that the ocean transports its heat, fresh water and dissolved species. It is important to identify the locations and measure the magnitudes of such features and to understand their relationships to bathymetry and other controlling factors.

- *Secondly*, in dealing with non–linear eddies and in studying transient perturbations of the current systems, it is essential to understand both the mean and variability of the ocean circulations and their transport of heat and mass.

- *Thirdly*, the dynamic topography, obtained from mean sea surface height minus geoid, will provide a constraint on the mean surface circulation and will therefore be beneficial to the assimilation of altimeter variability information.

The GOCINA project, in particular, examined the latter issue confined to the Northeast Atlantic and southern region of the Nordic Seas. The Arctic Ocean to the north, the deep North Atlantic Ocean to the southwest, and the shallow North Sea to the southeast bound the region. The exchange of water masses across the Scotland–Greenland gap has a profound influence on the thermohaline circulation leading to a horizontal and vertical density structure unlike any other ocean regions. The question is then how the mean dynamic topography (MDT) reveal this characteristics structure. To examine this the GOCINA project has produced three surface fields for the ocean area under investigation, including the mean sea surface (MSS), the geoid, and the MDT.

The GOCINA MSS, KMS04 is based on 9 years (1993–2001) of different altimeter data. The geoid was estimated by solving the integral of the gravity field over the Earths surface using data from a new e stablished database, consisting of new and earlier airborne surveys and ship data. The partners of WP3 obtained several MDTs from existing ocean circulation models. Although they display similar large scale patterns, clear differences are observed at local scale such as confined to the Irminger Sea, the Scotland–Greenland gap, and the Norwegian Sea. However, there are several possible sources for the disagreement: the ocean models are different; the MDTs represent the model means over different integration period; the spatial resolutions of the models vary; the forcing fields are different.

Hence, we decided not to make any conclusive ranking of them. Moreover, existing in–situ hydrographic data were too sparse to allow proper validation although comparison of the observed steric height. A composite MDT (CMDT) was thus computed to yield the best estimate from these independent model MDTs. Because of geoid errors due to unavoidable data gaps, an Iterative Combination Method (ICM) MDT was developed. It combines gravity observations and synthetic gravity data derived from altimetry and the MDT model. The complete 'composite' gravity field is then a weighted average of the real and synthetic gravity.

Despite some small local defects the MDT pattern reveals an expected structure. For currents following the western European shelf edge, the ICM solution has a very coherent flow. In the South–eastern Norwegian Sea, the ICM model resolution is good enough to identify the two branches of the North Atlantic water that enters the Norwegian Sea, i.e. the one directed through the Faeroe–Shetland channel and the one flowing along the north side of the Iceland–Faeroe ridge. In the Irminger Sea a low of -17 cm implies some local cyclonic circulation and does not form a continuous boomerang–shaped feature deepening continuously into the Labrador Sea, as shown by the GOCINA composite model and some other GOCM's.

The variability found in the transports in and out of the Nordic Seas has been investigated regarding the contributions of wind forcing and steric height. In so doing the sensitivity of the transports to errors in the MDT can also be investigated.

Variability both in the seasonal and interannual to decadal scales was considered. Moreover, the overall pattern agreement in the regression reveals more dominance of the wind forcing for the inflow, whereas the outflow is more controlled by the steric effect. In the context of the thermohaline circulation these results quantify the combined importance of wind stress and local convective processes for the meridional overturning in the northeast Atlantic–Nordic Seas. The MDT adjust to these forces and processes, suggesting that interannual–to–decadal changes in MDT are likely to occur in the presence of global warming and climate change.

The input from providing a regional gravity field and geoid model of the GOCINA study region relevant for validation of GOCE was mainly from the technique integration part of the project. Existing ship and airborne marine gravity data (from Russia and Scandinavia, the Arctic Ocean, and NIMA data) was assembled for the study area and error–screened. In addition a dedicated airborne gravity survey from Greenland over Iceland and Scotland to Norway was done, to improve the existing marine data and augment data coverage. The final marine gravity database contains approximately 1 million individual gravity points. The marine gravity data has been cross–over adjusted for survey biases following the UEDIN and the KMS/DRC approaches where the survey was held fixed in the adjustment. The two agreed in general very well and the final adjuste d gravity database was established in a joint adjustment.

The geoid modelling was based on this gravity database and further extended with altimetric gravity data patched in areas with large data gaps, i.e. more than 20 km to the nearest data point. A new GRACE geopotential model from JPL was used for the longer wavelengths up to degree and order 120 of the gravity/geoid field in the geoid modelling. The residual geoid was determined with the spherical FFT a pproach and to estimate the geoid errors least–squares collocation was used. The estimated errors are at the 8 cm level in areas with nearby airborne gravity data, increasing to 10 to 15 cm in areas with reasonable marine coverage. Higher error estimates are seen in areas with data gaps.

The task on the data assimilation relevant for GOCE had mainly input from WP6 and WP5. The impact of the new ICM MDT on ocean circulation and transport estimations was examined in a series of assimilation experiments using the FOAM, TOPAZ, and MERCATOR systems. This focused, in particular, on the hydrography in selected sections and the volume transport across the Scotland–Greenland gap using all three assimilation systems. The sensitivity study for the TOPAZ system on the temperature and salinity structure comprises two experiments; the first uses the full forecast and analysis scheme and assimilates salinity and temperature profiles as well as sea level anomalies (SLA) from altimetry referenced to the ICM MDT, hereafter named TOPAZ; the second simulation is done as control integration without assimilation, hereafter named TOPAZ_C.

A conclusion is that the assimilation of SLA referenced to the ICM MDT together with salinity and temperature profiles improves substantially the forecasts from the hydrodynamic HYCOM model. It is furthermore expected that the simulation of the Nordic Seas circulation will improve by changes in the model configuration, e.g. opening of the Bering Strait for through flow and increasing the spatial resolution. An improvement in the initial salinity field for the North Atlantic would probably have large impact on the results for the interior Nordic Seas, since these areas lie downstream from the inflow over the Greenland–Scotland Ridge and are affected over the time span the water needs to reach the area.

Impact on transport estimates: The volume transports (given in units of Sv; 1 Sv = 10^6 m^3/s) over the Greenland–Scotland ridge as simulated with TOPAZ and the control integration show distinct results for the different sub–sections represented by the Faeroe–Shetland Section (FSC), Iceland–Faeroe Ridge (IFR) and the Denmark Strait (DS). In the FSC the simulated transports are close to the observed values; In the IFR both in– and outflow are slightly too high. For both sections TOPAZ and TOPAZ_C give basically the same results and are generally somewhat closer to observations than transports from a global version of MICOM; In the DS MICOM is in close agreement to observations, while both, the TOPAZ and TOPAZ_C integrations reveal too high inflow to the Nordic Seas. The outflow is more comparable to observations, roughly 10% (20%) too much in TOPAZ (TOPAZ_C).

In the FOAM system, the new ICM MDT decreases the net northward flow of waters across the IFR and FSC and also decreases the net southward flow of waters in the DS. In total the annual net average southward transport (from the three sections combined) is decreased by 10% from 1.0 Sv to 0.9 Sv by the application of the GOCINA ICM MDT. All in all the use of the ICM MDT run lead to improved transport estimates compared to observations. One of the key questions regarding the assimilation is the impact of the errors in the assimilated fields of the gravity gradients and the geoid via the MDT on the final retrieved oceanographic products such as surface current and transports. Some preliminary examination of this was carried out at the end of the project.

GOCE error covariance modelling: The simulations of GOCE impact on the gravity field recovery were done using the full spectra of the signals and the errors. Hence, both commission and omission errors are taken into account when, e.g., a spherical harmonic expansion truncated at a certain harmonic degree and order is considered. The standard Level 2 product coming from GOCE is a spherical harmonic expansion to degree and order 200 that can fulfil the aim of the satellite mission, which is to model the geoid at a resolution of 100 km with an accuracy of 1–2 cm. Based on mission parameters and extensive simulations it has been demonstrated that GOCE will meet those requirements. An important outcome of the simulations is thus a set of error degree variances that may be included as commission errors in other simulations of the GOCE performance.

10 Project Management

The general objectives of this work package are to oversee the progress of the project, to facilitate interactions between the partners, and to report to the European Commission. Furthermore, the objectives are to monitor progress, to update work plans, and to organise project team meetings to facilitate interactions between the partners.
The project co–ordinator has acted as the overall project manager and the main point of contact between the European Commission and the project partners. A Steering Committee composed of the responsible scientists of each partner including the Project coordinator undertook the administrative steering of the project. This steering involved the work package managers who are leading the activities of each work package and are responsible for deliverables.
An Advisory Committee was composed of three external experts. These were Prof. C. C. Tscherning from University of Copenhagen, Prof. C. K. Shum from Ohio State University, and Dr. Roger Haagmanns from ESA. The external experts are persons associated with the ESA GOCE project, the ESA ENVISAT RA project, the US GRACE science team, and other relevant geodetic and oceanographic disciplines.

The co–ordinator has during the project collected and compiled input from the partners and the work package leaders for the quarterly status reports and the annual reports. The co–ordinator has also set up, maintained, and completed the Technology Implementation Plan (eTIP).

11 Conclusions including socio-economic relevance, strategic aspects, and policy implications

In section 2 seven scientific objectives for advancing the European capacities in exploitation of Earth observation data were listed. The GOCINA project has accomplish all of these and thereby preparing the exploitation of data from forthcoming satellite missions for ocean analysis of mass and heat transport.

Objective 1: To determine a regional high accuracy gravimetric geoid. New gravity data were collected in an airborne survey, which provided a link across the majority of older gravity data sets in the GOCINA area. All data were reprocessed and a cross–over adjustment that detected biases in the individual surveys were performed. The statistics indicated that a very high–quality survey has been obtained.

A new gravimetric geoid and its error characteristics was computed taking both marine and land gravity data into account as well as topographic data. Data from the new satellite mission GRACE was included enhancing the long wavelength parts of the geoid. The model shows an excellent agreement to estimates of the geoid from MSS–MDT, showing that the geoid accuracy should be better than 10 cm, which is probably the first time such results are obtained on oceanic scales.

Objective 2: To determine a regional high accuracy mean sea surface. Based on recompiled altimetry from ERS and TOPEX/POSEIDON for the period 1993–2001 a new highly accurate high–resolution mean sea surface (MSS) was computed. The model is called KMS04MSS. The model showed very high quality evaluated against altimeter data and existing high–resolution global mean sea surfaces.

Based on the results of the analyses an updated MSS was computed using data from ENVISAT and JASON–1 covering the period 1993–2003. The statistics of the two mean sea surfaces shows that it is presently very difficult to improve the currently best MSS KMS04MSS with additional years of data.

Objective 3: To determine a regional best possible mean dynamic topography using in–situ hydrographic data and ocean modelling. Different existing MDT products based on ocean hydrographic data were studied, two of them produced by the partners themselves. The scientific achievements included the production of new MDT versions by project partners using models and data analysis algorithms, and in the inter–comparison of the various products from partners and external sources. This includes some assessment of the products quality. Several of the MDTs studied were identified as suitable for continued study and comparison with sea level data from satellites and gravitational geoid data. Having adjusted each MDT to the reference time period of 1993–2001, a composite MDT (CMDT) was formed by taking the mean of seven MDTs. For each of the filtered MDTs the implied geostrophic surface currents, were also calculated. These currents agree well with mean geostrophic velocities for 1992–1996 calculated using drifter data.

Objective 4: To provide detailed assessment of the geoid, the MSS, and the MDT. To assess the initial models, residuals between them were analysed. Residuals between the computed MSS and the sum of the computed geoid and MDT form the valuable basis for assessment and validation of the derived models. By comparing the residuals with the respective error characteristics, the accuracies of the products were assessed. The validation was carried out in different local areas and the analyses resulted in modified error characteristics, which provided information for further improvements by iterating on the methods used. The final integrated models of the geoid and MDT has also been investigated.

Objective 5: To integrate the three techniques for improved (optimal) estimation of the geoid and the MDT. Integrated techniques that consider gravity, MSS, and MDT concurrently, and take their respective error characteristics into account, gave optimal estimates of the geoid and the MDT. The optimal estimation technique is based on generalised inversion that allows a full integration of data of different kinds taking the full signal and error covariance relations into account. The key outcome has been the ICM MDT that has been used for assimilation studies to further analyse of the ocean circulation. The optimised geoid has been used to compute gravity field components and their errors at the heights of the GOCE satellite.

Objective 6: To investigate the impact of the improved MDT on the ocean circulation estimation. The ICM MDT has been assimilated using modified assimilation methods in three OGCMs. Through twin experiments sensitivity studies have been performed to assess the impact of assimilation of MDT data on ocean circulation and mass and heat transports.

Further explorations of the new and optimized MDT have been carried out to improve the predictability of seasonal to inter–annual variability. The positive impact of using an improved MDT in operational forecasting systems, in the perspective of the future GOCE mission, has been demonstrated. This analysis has given invaluable information on the ocean role in climate.

The state–of–the–art MDT product in the GOCINA area can now be used to better monitor and forecast the ocean circulation of the Northern Atlantic and to validate GOCE data in the area.

Objective 7: To provide specific recommendations for quality assessment of GOCE data and for integrating geoid and MDT computations with GOCE. The new and highly important findings and results achieved in the GOCINA project has been arranged and assessed in the context of the GOCE mission with special focus on issues related to calibration and validation.

Through the participation in the GOCE workshop and especially the GOCINA workshop, the GOCINA consortium has interacted with recommendations and developed strong links with the GOCE project, GOCE user's groups, and the climate and operational oceanography community. The key results have been made available for the ocean community at the GOCINA server (http://geodesy.spacecenter.dk/~gocina).

In the context of ocean monitoring a major task for the GOCINA project has been to determine an accurate geoid in the North Atlantic and thereby create a validation platform for future GOCE Level 2 data. Analyses of the new optimised geoid have determined the extent to which GOCE data will improve the measuring and monitoring of ocean transport in this vital region.
The new and optimised geoid was used together with the new and accurate MSS to determine the MDT. The MDT provides the absolute reference surface for the ocean circulation and the determination of the mean circulation will advance the understanding of the role of the ocean mass and heat transport in climate change.
The GOCINA ICM MDT product can now be used in ocean circulation models assimilating altimetry. It will help to better monitor and forecast transport through the Greenland–Scotland ridge and to carry out long–term climatic studies. Such studies are of vital importance to understand if, as some couple d circulation models have already indicated, the North Atlantic Thermohaline circulation is weakening.

11.1 Strategic aspects and potential to improve competitiveness

The new gravity data and improved gravity field models may contribute to hydrocarbon exploration activities. Providing the new geoid and MDT surfaces to the marine community, in particular the oil–industry, will tighten the links between the GOCINA consortium and this active community. It will be an opportunity to increase the cooperation with the marine communities and create synergies for future projects. A better knowledge of the geoid will assist geophysics studies in analysing potential areas for oil and gas drilling. The economic impact for European oil industries is thus significant since exploration studies are progressively moving from the coastal areas to the continental shelves.
The gravity data also provides independent background information to ongoing effects to delineate extended national continental shelf regions beyond 200 n.m., present highly relevant information for the nations of the region that all have initiated activities related to the UNCLOS §76. This will also directly benefit to the cable layer companies, and more generally to science and defence/military interests.

In the context of the new era of space gravimetry, started with the CHAMP mission, GOCINA have build up and shared the necessary expertise for GOCE among the EU research and engineering communities. The outcome afforded by the GOCINA partners stimulates and sustains the research initiative among the space agencies and other EU dedicated institutions. The methodologies that have been defined, developed, and tested in the GOCINA project will be directly applicable for the GOCE mission. This will allow the preparation of an optimal MDT product from GOCE that will lead to improvements in the heat and thermohaline transport estimates and hence lead to benefits from understanding climate and climate change.

Through the participation in the GOCE workshop and especially the GOCINA workshop, the GOCINA consortium has interacted with recommendations and developed strong links with the GOCE project, GOCE user's groups, and the climate and operational oceanography community. The GOCINA integration of future improvements by GOCE will significantly contribute to improved usefulness of Earth Observation data information including the marine environment and climate.

The oceanographic results and competence over the North Atlantic issued from GOCINA will further on improve the seasonal weather predictions, that have a significant strategic impact for end–users, either companies, governmental bodies, or Europe as a whole. For the past few years, impacts of climatic events like El Niño have been acknowledged by numerous sectors of the economy, in particular in the U.S. insurance and financial risk assessment business. This growing awareness for climate prediction is also noticed and claimed by the European economy. GOCINA results and expertise will facilitate the climate prediction initiative over the European countries, and allow the development of a market for seasonal forecast products. While the European climate can be considered as mild, it is proved now that atmosphere–ocean coupled climatic mechanisms like the North Atlantic Oscillation can enhance extreme winter event like the recent storms and flood surges that paralysed the United Kingdom, Belgium, and French economy for several days during the past decade. A better forecast of such catastrophic events, will considerably reduce the impacts over the life and economy of entire Western Europe regions.

11.2 Socio–economic relevance and policy implication

The overall aim of the GOCINA project has been to enhance European capacity in Earth observation technologies by promoting and developing methods for the joint exploitation of the ESA ENVISAT and GOCE missions for ocean circulation studies and associated climate modelling and operational data assimilation.

Tide gauges still have a very uneven distribution globally but altimetry provides uniform globally distributed sea level height data worldwide. The GOCINA geoid and MDT are directly usable to derive absolute topography measurements from past, present, and future satellite altimetry missions. This will be crucial for a better exploitation of altimeter data (e.g. for the ERS/ENVISAT and TOPEX/ POSEIDON/ Jason–1 missions) both for scientific and operational oceanography applications. The mean sea surface height is an important parameter on mean ocean mass and heat transports across the GOCINA section and is consequently crucial for the European climate. The new GOCINA MSS simultaneous estimates the sea level height change over the 1993–2001 period. The sea level trend parameter is of great important to studies of climate change. The mean sea level is also an increasing important parameter for navigation. With the increased use of positioning using GPS the MSS becomes a more and more important tool for referencing sea level observations across borders.

The GOCINA ICM MDT products can now be used to carry out long–term climatic studies to understand if the North Atlantic Thermohaline Circulation (THC) is weakening. Changes in the mean flows and transports in deep waters may change ocean up welling and transports of larvae, both relevant for fish populations.
The very diverse objectives of the GOCINA project have required the involvement of experts from many different scientific fields. The expertise necessary to make this project successful is not available on a national basis. In the project expertise in analysing satellite altimeter data is mainly available in France and Denmark. Geoid calculation techniques are contributed by Denmark and the UK. Ocean modelling expertise comes for the UK, Norway, and France.
The project has involved a lot of cooperation between the different teams and countries in order to develop the most accurate and consistent products for mean sea surface, geoid, and mean dynamic topography. The simultaneous analysis of all of these together in a self–consistent manner has never been attempted before and could only be done through a European consortium.

There are two aspects of the GOCINA project, which absolutely requires a pan–European initiative:

1. The historical gravity data sets of each country have been collected over many years at great expense, often for commercial purposes. Although the commercial value of these data is now sometimes questionable, it is not possible to get the best gravity data, which will be vital to calculate accurate geoids, released internationally, even for research purposes. Note that the calculated geoid from this project has been published freely, as the recovery of the raw data is not possible through this route. The involvement of Denmark, the UK, and Norway ensure that the main countries, which have important national and commercial data in the areas between the European continent and Greenland, are all involved.

2. The contribution of this project to the ESA GOCE mission guarantees a European dimension. The GOCINA region of the North Atlantic is large enough

and the existing gravity data is extensive and potentially accurate enough to offer excellent possibilities for Cal/Val of the small geoid scales for GOCE. In addition there are several other reasons why the results of this project should acquire a European dimension:

3. From a science perspective it can be argued that the mean ocean mass and heat transports across this section of the world's oceans, between the UK and Greenland, are crucial for determining European climate.

4. The computation of local geoids is a difficult task carried out by small groups of practitioners, often with a national focus. Up to now it has been very difficult to validate the methods for producing local geoids due to the lack of independent data. The GOCINA project have offered the opportunity to compare different methods for calculating a local geoid over the same area and using the same shared gravity data set as input.

5. The improved methods of geoid derivation developed in this project will be valuable to the national programs of each of the countries, for example in improving the quality of products for the ordnance surveys.

Two areas of EU policy may be identified into which the expected outcomes of this project have an influence. The first is climate change policy and particularly the climate change implications for Europe. It is very possible that as global warming takes hold, the climate of Northern Europe will buck the trend and become cooler. The mechanism for this would involve the weakening or collapse of the Northward heat transport between Europe and Greenland by the mean ocean circulation. The improved understanding reached of the mean ocean transports in this area based on an accurately known geoid, enable these transports to be more effectively monitored using altimeter data. Any sign of weakening ocean transports towards the arctic should have very important implications for European climate policies.

The project also has relevance to other European policies relating to the ocean, in particular for fisheries and for pollution policy. At present mean ocean circulation and transports are well known on the continental shelves because they are dominated by tidal circulation. The improved calculations of mean flows and transports in deep waters from this project provide a clearer picture of areas of ocean upwelling and transports of larvae, both relevant for understanding fish populations. The improved constraint of deep ocean currents through knowledge of an improved geoid contributes to pollution policies, by for example determining areas where sea floor debris from drilling could contaminate.

12 Dissemination and exploitation of the results

The aim of the GOCINA project has been to enhance European capacity in Earth observation technologies by promoting and developing methods for the joint exploitation of the approved European Space Agency ENVISAT (Radar Altimeter) and GOCE missions for ocean circulation studies and associated climate modelling and operational data assimilation.

A major task was to determine an accurate geoid in the region between Greenland and the UK and, thereby, create a platform for validation of future GOCE Level 2 data and higher order scientific products. The new and accurate geoid was used together with an accurate mean sea surface to determine the mean dynamic topography. The mean dynamic topography was used for improved analysis of the ocean circulation and transport through the straits between Greenland and the UK.

GOCINA has developed generic tools to enhance ocean analysis using Earth observation data from ENVISAT and GOCE. The project has examined the mass and heat exchange across the Greenland–Scotland Ridge. This analysis has given invaluable information on the ocean role in climate. The project has in particular supported the GOCE mission with a set of specific recommendations for integrating GOCE in ocean circulation studies and an accurate geoid model for validation purposes.

12.1 Identification of users

The GOCINA project brought together expertise in geodesy, geophysics, oceanography, and space engineering. The outcome benefits all these fields, and applications have a wide–range of interests in the respective science communities. Hence, the following user groups can be identified as users:

A The scientific community of Geodesy,

B The scientific community of Oceanography,

C The scientific community of Geophysics, and

D The scientific community of Space Engineering.

The precise geoid and the accurate absolute dynamic topography have a high degree of interest for a wide range of end users.

GOCINA has taken an active role in disseminating results to ESA, to GOCE involved people, to the oceanographic and geodesy scientific communities, to the operational community, and to the marine community, including oil and gas companies. Hence, additional user groups may be identified:

E ESA GOCE project, and

F The operational community of Oceanography.

12.2 Description of data products

Data sets have been important deliverables of the GOCINA project as well. Some of the data sets are restricted, but most of the data sets are public. In general, data sets have been made available on ftp and the GOCINA server. However, some restricted data sets have been made available to the project only by email or CD–rom.

Data sets have been made available in the well–defined ASCII format with coordinates in decimal degrees. Sets of discrete point data contain information about source identification, latitude, longitude, height, value, and an associated error. Discrete values arranged in a geographical grid are spaced equidistantly in latitude and longitude. Information about area and spacing are contained in the file. Normally, the area covers the GOCINA study region.

Data are published on the project web page http://geodesy.spacecenter.dk/∼gocina/ and on FTP: ftp://ftp.spacecenter.dk/pub/GOCINA/.

12.3 Interaction with users

Results of the project have been presented in the usual process of scientific publications, conferences, and workshop. Technical improvements and methods have been published in peer reviewed international scientific journals and thereby widely disseminated in the research community, i.e. the identified user groups A–D.

Results have been presented at international congresses, like the annual symposia of the EUG, the IAG, the EGS or the AGU.

Furthermore, the results of the project have been disseminated to the general public using the project web, the glossy brochures, and other project deliverables such as public reports, to reach the identified user groups E–F.

Methodologies defined, developed and tested in GOCINA are also directly applicable for the ESA GOCE mission. They allow the preparation of an optimal MDT product from GOCE, altimeter and possibly in–situ data when GOCE is flown. This is a level 3 product (ESA terminology) and its production is not part of ESA responsibility. Still, this product is the one needed by the oceanographers. The work carried out in GOCINA helps to achieve the scientific and technical objectives of GOCE and allows a better exploitation of the GOCE mission. To ensure an effective impact on GOCE, the GOCINA consortium have developed strong links with the ESA GOCE project and GOCE user's groups. The project in particular supports the EGG–C (European GOCE Gravity Consortium) in two distinct cases, namely (1) by educating and preparing the community in using GOCE data for oceanography including sea level and climate research as well as operational prediction; and (2) by generating a best possible regional gravity field and geoid model for the North Atlantic that can be used in validation of the GOCE products.

In order to increase public awareness of the role of the ocean in the global environment and global change, and more precisely on the role of the North Atlantic ocean in the western European climate, GOCINA oceanic results have been displayed in other forms of communication through the media and participation in science fairs. GOCINA have been an opportunity to elaborate new techniques to determine climatology and mean dynamic topography. The resulting techniques supplement the available tool collection and could be applied to other regions of the world ocean. GOCINA is thus directly strengthening the European effort in the ARGO program as well as operational oceanography applications (CLIVAR, GODAE). In particular GOCINA supports the European funded GYROSCOPE project.

Moreover, contact were established to the marine communities, like defence and navy institutions with military interests, fisheries, oil industry, and shipping companies with economic interests, and results have been presented at more dedicated workshops and international conferences.

12.4 Workshops and attended meetings

Expertise in geodesy, geophysics, oceanography, and space engineering are brought together in GOCINA. The outcome benefits all these fields, and applications have a wide–range of interests. Therefore results of the p roject have been presented in the process of scientific publications, conferences and workshops.

ECGS/Workshop on GOCINA held in Kirchberg, Luxembourg The dedicated GOCINA workshop focused on topics related to the determination of the mean circulation in the straits between Greenland and the UK, and the understanding of the role of the ocean mass and heat transport in climate change. The central quantity in this discussion is the mean dynamic topography, which is the difference between the mean sea surface and the geoid and bridging the geoid and the ocean circulation together.

Together with radar altimetry from satellite missions such as ENVISAT and JASON, gravity field missions such as GRACE and in particular GOCE will be important. The workshop promoted and raised the awareness of the GOCE mission to the oceanographic community. In particular the workshop focused on improving the modelling of ocean transport and climate prediction in the North Atlantic region using GRACE and in–situ gravimetry data. In addition, invited lecturers provided the status of in–situ observations of ocean transport and ocean modelling.

Participants from the ESA GOCE Mission Advisory Group and the ESA GOCE High–level Processing Facility as well as key persons in the relevant groups E–F mentioned in section 2 attended the workshop, so the workshop was very successful in all respects. Also, we managed to interact with the ocean modelling community and present the results of the GOCINA project.

A dedicated session was held to discuss the development of a toolbox for processing GOCE data for oceanographic application. The GOCINA Group and the GOCINA workshop participants strongly urged ESA to launch prior to GOCE Launch, the GOCE User Toolbox Specification Study (GUTS) and its follow–on development of the Toolbox.

Titles of GOCINA partner presentations:

- Airborne gravimetry in the North Atlantic region (P1, P2)
- Marine gravity network adjustment in the North Atlantic (P3)
- Marine gravity from satellite altimetry (P1)
- Geoid model of the North Atlantic region for the GOCINA project (P1, P2, P3)
- Integrating gravimetry and altimetry by collocation (P1)
- GOCINA products of relevance for GOCE validation and calibration (P5, P1, P2, P3)
- MSS improvements and errors (P1)
- MDTs in the GOCINA region (P4)
- Intercomparisons of geoid, MSS and MDT models (P2)
- Mean dynamic topography by the iterative combination technique (P3)
- Use of bias aware data assimilation to improve the GOCINA mean dynamic topography (MDT) (P4)
- Estimation of the global ocean Mean Dynamic Topography through the combination of altimetric data, in–situ measurements and GRACE geoid (P6)
- Steric height variability in the Nordic Seas (P5)
- Possible influence of climate change on the steric height and ocean circulation in the Northern North Atlantic region (P5)

Other workshops and meetings: All partners participated in the Second International GOCE User Workshop "GOCE, The Geoid and Oceanography", ESA–ESRIN, Frascati, Italy, 8–10 March 2004.
The workshop was open to all scientists with an interest in exploiting GOCE gravity data products. In particular, the workshop focused on the oceanographic applications, such as absolute dynamic topography, of the GOCE data in conjunction with other space–borne data, such as radar altimetry, and in–situ data and models.

Titles of GOCINA partner presentations:

- The GOCINA project – an overview and status (P1)
- Gravity field improvements in the North Atlantic region for the GOCINA project (P1)
- GOCINA developments of recommendations for using GOCE data in ocean analyses (P5)
- Transports and sea level slopes in high resolution ocean models (P4)
- Recent improvement in altimetry: how MSS and MDT can benefit from it in combination with a GOCE geoid? (P6)

The GOCINA partners have furthermore participated with presentations in various scientific meetings and conferences such as the EGU, AGU, and IUGG.

12.5 Dissemination for the general public

In order to present the GOCINA project to the general public and thereby increase their awareness of the role of the North Atlantic Ocean in the western European climate the following actions have taken place.

October 2003 and 2004: P1 presented the project for students at the Department of Geophysics at the University of Copenhagen.

February 2004: Article about GOCINA in the Danish magazine "Miljø Danmark"

November 2004: P1 presented the project at the "Day of Geophysics" at the University of Copenhagen, Denmark. The participants were bachelor, master, and Ph.D. students from the Nordic Countries.

February 2005: In connection with the Danish Ocean Science Meeting in Copenhagen, P1 presented the project for public authorities, fish industries, navy institutions, and other marine communities.

April 2005: P2 gave a presentation of the GOCINA and OCTAS project at the conference "Transforming Maritime and Environmental Security & Safety: Approaches from NATO, Norway and the U.S.", presented by The Royal Norwegian Embassy, Washington, D.C. in connection with Norfolk's International Azalea Festival. The focus of the conference was marine military subjects.

November 2005: P4 gave a presentation (title Improvement of ocean models using satellite altimeter and gravity field observations) at DHI Water & Environment (Horsholm, Denmark). DHI Water & Environment is an independent, international consulting and research organization. The consulting services are based on the development and application of know–how and advanced technologies within ecology and environmental chemistry, water resources, hydraulic structures and hydrodynamics and other areas related to water environment.

12.6 GOCINA web pages

A project website was set up with public and internal project sections. The public sections provide information about the project background, aims, progress, and results.
The internal project sections contain details of the project work plan, actions, and results accessible to project partners and the EC. These sections have facilitated corporation and provided a central point for information exchange through the project. Both website have been updated regularly throughout the project.

The public website is located at the following URL: http://www.gocina.dk
The project website is located at the URL: http://geodesy.spacecenter.dk/~gocina/

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A Appendix

A.1 Partners of the GOCINA project

Below is a list of the six partners and the respectively scientific staff and contact persons that joint the GOCINA project.

Partner	Person	E-mail
DNSC Danish National Space Center Department of Geodesy Juliane Maries Vej 30 2100 Copenhagen Ø Denmark	Per Knudsen *co–ordinator* René Forsberg Ole B. Andersen Anne L. Vest Arne V. Olesen Henning P. Föh	pk@spacecenter.dk rf@spacecenter.dk oa@spacecenter.dk alv@spacecenter.dk avo@spacecenter.dk hf@spacecenter.dk
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UEDIN The University of Edinburgh School of GeoSciences Grant Institute The King's Buildings West Mains Road EH9 3JW Edinburgh UK	Roger Hipkin *contact person* Addisu Hunegnaw	Roger.Hipkin@glg.ed.ac.uk ahunegna@staffmail.ed.ac.uk
UREADES University of Reading Environmental Systems Science Centre P.O.Box 238 Whiteknights RG6 6AL Reading UK	Keith Haines *contact person* Rory Bingham Jean-Philippe Drecourt	kh@mail.nerc-essc.ac.uk rjb@mail.nerc-essc.ac.uk jpd@mail.nerc-essc.ac.uk

(Table of GOCINA partners continued)

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Collecte Localisation Satellites	*contact person*	
Space Oceanography Division		
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Parc Technologique Du Canal		
31526 Ramonville St. Agne	Philippe Schaeffer	Philippe.Schaeffer@cls.fr
France		
	Fabrice Hernandez	Fabrice.Hernandez@cls.fr

A.2 Data and model access

All data of the produceded models of the GOCINA project can be found on the project webpages, at the URL: http://geodesy.spacecenter.dk/~gocina/. How to find the different data on the pages is described below:

The data of the models of first three work packages, WP1 Gravity and Geoid computation, WP2 Mean Sea Surface determination, and WP3 Mean Dynamic Topography modelling, can be found on the GOCINA project webapage in the left menu under **Project Management** → **Data/Models**. Most of the models contains an *Info* or *Readme* file, that explains the data format etc.

The data of the final models is the result of the integration of the three independent technologies of the above mentioned work packages. The final models can be found in the left menu under **Project Management** → **Final Models**. Also the tensor gravity for GOCE validation can be found here. All the models contains an *Info* file.

A.3 Main literature produced

Results, technical improvements, and methods of the GOCINA project have been published in order to be widely disseminated in the research community. Peer reviewed articles and non-refereed literature are shown in the list below.

Peer reviewed articles

Bingham, R. and Haines K., (June 2004). Mean dynamic topography: inter–comparisons and errors. In *Proceedings of The Second International GOCE User Workshop "GOCE, The Geoid and Oceanography". ESA Publications Division*.

Drange, H., Korablev, A., Johannessen, J., Gao, Y., and Johannessen, O., (June 2004). Intercomparison of dynamic height in the Nordic Seas from observations and climate model simulations for the period 1950 to 2000. In *Proceedings of The Second International GOCE User Workshop "GOCE, The Geoid and Oceanography". ESA Publications Division*.

Forsberg, R., Olesen, A., Vest, A. L., Solheim, D., Hipkin, R., Omang, O., and Knudsen, P., (June 2004). Gravity field improvements in the North Atlantic region for the GOCINA project. In *Proceedings of The Second International GOCE User Workshop "GOCE, The Geoid and Oceanography". ESA Publications Division*.

Hernandez, F., Andersen, O., Dorandeu, J., and Schaeffer P., (June 2004). Recent improvement in altimetry: how MSS and MDT can benefit from it in combination with a GOCE geoid? In *Proceedings of The Second International GOCE User Workshop "GOCE, The Geoid and Oceanography". ESA Publications Division*.

Knudsen, P., Andersen, O. B., Forsberg, R., Föh, H. P., Olesen, A. V., Vest, A. L., Solheim, D., Omang, O., Hipkin, R., Hunegnaw, A., Haines, K., Bingham, R., Drecourt, J-P., Johannessen, J. A., Drange, H., Siegismund, F., Hernandez, F., Larnicol, G., Rio, M-H., and Schaeffer, P., (in press). Combining altimetric/gravimetric and ocean model mean dynamic topography models in the GOCINA region. Accepted for publication in *Proceeding of the Dynamic Planet 2005, IAG Symposia Series, Springer Verlag*

Knudsen, P., Forsberg, R., Andersen, O. B., Solheim, D., Hipkin, R., Haines, K., Johannessen, J., and Hernandez, F., (June 2004). The GOCINA Project – An Overview and Status. In *Proceedings of The Second International GOCE User Workshop "GOCE, The Geoid and Oceanography". ESA Publications Division*.

Knudsen, P. and Tscherning, C. C., (in press). Error Characteristics of Dynamic Topography Models Derived from Altimetry and GOCE Gravimetry. Accepted for publication in *Proceeding of the Dynamic Planet 2005, IAG Symposia Series, Springer Verlag*.

Non-refereed literature

Andersen, O. B., Knudsen, P., Berry, P., and Kenyon, S., (in press). Marine gravity from satellite altimetry – ongoing improvements. In *Cahiers du Centre Européen de Géodynamique et de Séismologie volume 25. Proceedings of the Workshop: "GOCINA: Improving modelling of ocean transport and climate prediction in the North Atlantic region using GOCE gravimetry"*. Edited by P. Knudsen, J. Johannessen, T. Gruber, S. Stammer, and T. van Dam. Distributed by: ECGS.

Andersen, O. B., Vest, A. L., and Knudsen, P., (in press). The KMS04 Multi-Mission Mean Sea Surface. In *Cahiers du Centre Européen de Géodynamique et de Séismologie volume 25. Proceedings of the Workshop: "GOCINA: Improving modelling of ocean transport and climate prediction in the North Atlantic region using GOCE gravimetry"*. Edited by P. Knudsen, J. Johannessen, T. Gruber, S. Stammer, and T. van Dam. Distributed by: ECGS.

Drecourt, J.-P., Haines, K., and Martin, M., (in press). Use of bias aware data assimilation to improve the GOCINA mean dynamic topography. In *Cahiers du Centre Européen de Géodynamique et de Séismologie volume 25. Proceedings of the Workshop: "GOCINA: Improving modelling of ocean transport and climate prediction in the North Atlantic region using GOCE gravimetry"*. Edited by P. Knudsen, J. Johannessen, T. Gruber, S. Stammer, and T. van Dam. Distributed by: ECGS.

Forsberg, R., Olesen, A. V., Omang, O., and Solheim, D., (in press). Geoid from surface and airborne gravity data and GRACE in the North Atlantic region. In *Cahiers du Centre Européen de Géodynamique et de Séismologie volume 25. Proceedings of the Workshop: "GOCINA: Improving modelling of ocean transport and climate prediction in the North Atlantic region using GOCE gravimetry"*. Edited by P. Knudsen, J. Johannessen, T. Gruber, S. Stammer, and T. van Dam. Distributed by: ECGS.

Haines, K. and Bingham, R., (in press). Mean Dynamic Topographies (MDTs) in the GOCINA region. In *Cahiers du Centre Européen de Géodynamique et de Séismologie volume 25. Proceedings of the Workshop: "GOCINA: Improving modelling of ocean transport and climate prediction in the North Atlantic region using GOCE gravimetry"*. Edited by P. Knudsen, J. Johannessen, T. Gruber, S. Stammer, and T. van Dam. Distributed by: ECGS.

Hipkin, R. and Hunegnaw, A., (in press). Mean dynamic topography by an iterative combination method. In *Cahiers du Centre Européen de Géodynamique et de Séismologie volume 25. Proceedings of the Workshop: "GOCINA: Improving modelling of ocean transport and climate prediction in the North Atlantic region using GOCE gravimetry"*. Edited by P. Knudsen, J. Johannessen, T. Gruber, S. Stammer, and T. van Dam. Distributed by: ECGS.

Hunegnaw, A. and Hipkin, R., (in press). Marine gravity network adjustment in the North Atlantic. In *Cahiers du Centre Européen de Géodynamique et de Séis-*

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