GOCE MISSION: IMPACT ON OCEANOGRAPHY

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INTRODUCTION

The shape of the geoid surface defines the local horizontal. On land it provides the reference surface for 'topography', and over the ocean it would correspond to sea-level if no currents were flowing. Present knowledge of the Earth's gravity field and its geoid, as derived from various observing techniques and sources, is incomplete. However, within a reasonable time, substantial new understanding will be derived by exploiting satellite based gravity observations from the GRACE mission scheduled for launch in late 2001 and the GOCE mission approved for launch in 2005. GOCE is specifically designed for the determination of the stationary gravity field and its geoid to high accuracy (1 mGal and 1 cm) and spatial resolution (100 km) [1]. In this paper we will address the impact of the GOCE mission for oceanography.

ABSOLUTE OCEAN CIRCULATION

The typical elevation scales of the dynamic ocean surface topography range from 0.1 m to 1 m. In comparison, the accuracy of present geoid models is also multi-decimetric on the scale of many ocean circulation features, in particular at wavelengths shorter than 400 to 500 km. Hence the mean ocean circulation cannot be properly estimated from satellite altimetry at these wavelengths. The use of imprecise geoid models for the determination of the absolute dynamic topography at shorter spatial-scales consequently result in computation of false multi-decimetric topographic signals which, in turn, will lead to false transport calculations of several 10's of Sv (1 Sv = 10^6 m^3/s and is typically corresponding to a heat transport of 5 x 10^{13} W in the North Atlantic basin). In contrast, the accurate and high-resolution marine geoid, as derived from GOCE, will in combination with satellite altimetry enable new precise estimates to be made of the absolute ocean topography as schematically illustrated in Figure 1.

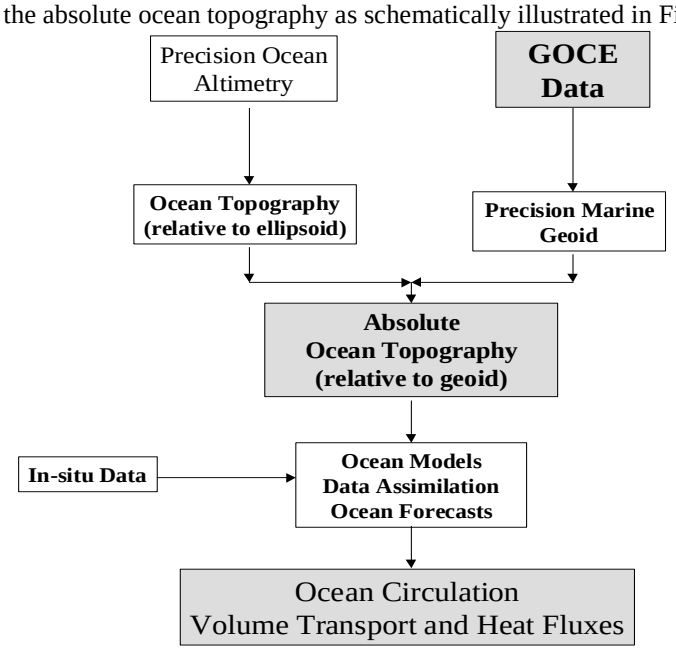

Fig.1. Absolute ocean circulation studies from combination of GOCE geoid with precision altimetry.

As suggested in Figure 1 the altimetric signal will be directly related to the marine geoid provided by GOCE, thus allowing the complete height measurements to be utilised. Complemented with in-situ data and numerical ocean models, the new knowledge of the absolute ocean topography will, in turn, act as an important constraint in assimilation and subsequent calculations of ocean circulation and its volume transport and heat fluxes.

In the next sections we will briefly summarise some of the achievements and results already confirmed in a series of simulation studies, as well as point to a few additional candidate studies to further explore the impact of GOCE data for oceanography.

Results

Short Spatial Scales

In studying non-linear, transient processes in the ocean it is essential to start from the best possible initial description. It is through mean flows, as well as variabilities (e.g. eddies) arising from instabilities in the mean flows, that the ocean transports its heat, fresh water and dissolved species. However, it is possible to generate different degrees of variability in different numerical models depending on the mean flows programmed into them and on the way in which the factors controlling the means are parameterised (e.g. interactions with bathymetry). In particular, the variability can act as a brake on or stimulant to the mean flows by means of internal stresses.

In a resent simulation study by [2] the ocean surface topography obtained using the 1/12˚ resolution MICOM ocean model of the North Atlantic were partitioned into: a) 1000 km wavelength corresponding to the present situation in which the spatial separation of the dynamic topography from the geoid height is performed adequately; b) 250 km wavelength corresponding to that part of the topography which can be well resolved with GOCE; and c) 100 km being that part of the dynamic ocean topography at the shortest scales which will remain unresolved to satisfactory precision after GOCE. The key findings suggest that many interesting features, such as mesoscale fronts and eddies associated with the Azores Current and western boundary currents can be resolved with GOCE. The only exception is the fairly intense decimetric signals associated with the intense and short-scale Florida Current and Gulf Stream front. In Figure 2 the schematic of 10% of the dynamic topography signals of selected ocean circulation features is shown as a function of spatial scales obtainable from present models and after GOCE (marked with arrows and solid lines).

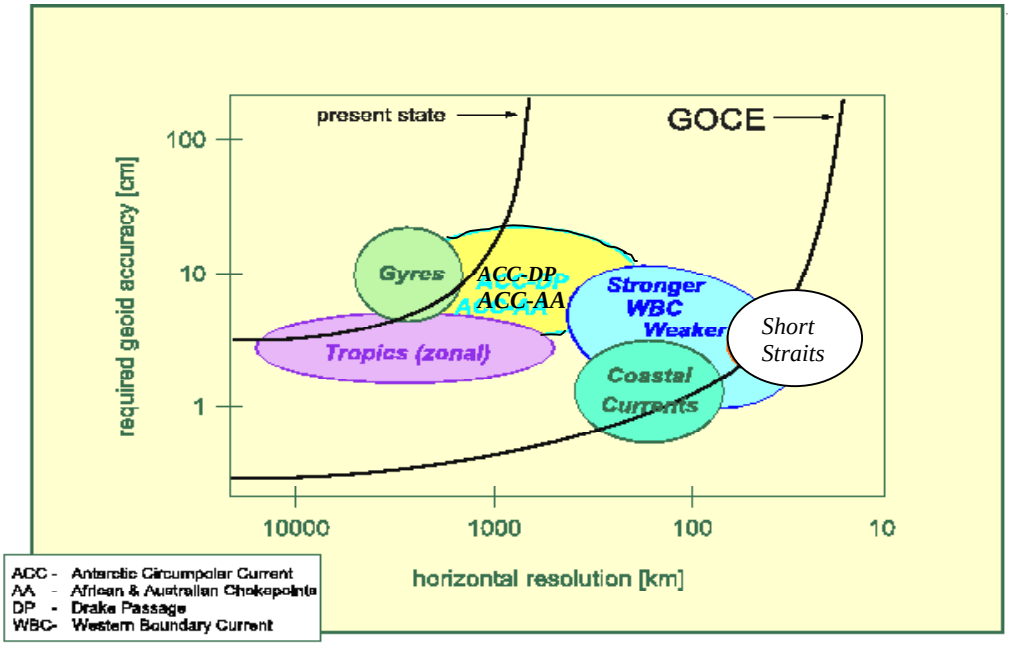

Figure 2. Schematic of 10% of the dynamic topography signals of selected ocean circulation features and geoid accuracy (solid curved lines) as a function of spatial scales obtainable from present models and after GOCE. Note that the 10% level represents order of magnitude knowledge of the mean flows associated with these circulation features.

At the short-spatial-scales of order several 100 km, the mean sea surface topography minus geoid signals will be decimetric, requiring a geoid determination of order 1-2 cm if these shorter scale signals are to be measured to within 10 % or better. Information of order 5 cm accuracy may, on the other hand, be of potential application to short-spatial-scale (30-50 km) coastal studies.

The expected advanced knowledge of the eddy statistics of the real ocean from altimetry, together with knowledge of the precise positions of the ocean jets from altimetry plus gravity (rather than from the assumption of frontal positions by means of sea-surface temperature or hydrographic information at present), will enable much better determination of the role played by the eddies in maintaining the jet components of the circulation. This was demonstrated by [3] using satellite derived sea surface temperature fields of the sharp frontal areas within the ACC, most of which will have decimetric signals in the absolute ocean topography, and which it is intended to localise precisely and measure by means of GOCE in combination with altimetry.

Improvement in Transport Estimates

Knowledge of the short-spatial-scale geoid will be essential to computations of fluxes through basin-size oceanic sections as demonstrated by the potential improvements in volume flux estimates in the South Atlantic using a 1˚ by 1˚ inverse ocean model [4, 2]. In this study an altimeter-derived sea surface topography (with uncertainty set to 2 cm as an estimate of the precision of altimetric measurements at the time of GOCE), together with hydrographic data and either the current EGM-96 or potential GOCE geoid model fields (GOCE error fields up to degree and order 180) were assimilated.

Sections at different lengths across selected parts of the South Atlantic were chosen to represent flows through: - the Drake Passage, - the widest part of the sub-tropical gyre, - a sharp front in the ACC, - the South African ACC 'choke point', - the Brazil Current, the Benguela Current, - and a zonal section at 32˚ S between Africa and South America. The overall reductions in volume transports are very significant, being over 50% for the top 100 m of the short ACC section and up to 40% for the top kilometre. In the deep-ocean, the relative impact of GOCE is also significant, with a 30% transport uncertainty reduction in the Circumpolar Current. Such reductions follow from the major improvements in geoid model accuracy to be expected for remote areas of the ocean and will be of major importance to climate modelling. The impact on surface-to-bottom transports is also large for the three sections located in the Circumpolar Current, reflecting its barotropic character.

Similarly the largest absolute impact on the ocean circulation (about 10 Sv) is obtained for the short ACC section whereas the largest relative impact is found for the sections across intense oceanic jets like the Brazil Current and the Benguela Current. This is consistent with the idea that the GOCE mission will have a larger impact on narrow and intense currents because of its high-resolution.

Benefits to Ocean Forecasting

The potential benefits of a precise, high-spatial-resolution geoid to ocean data assimilation and 'ocean forecasting' has been demonstrated for an area of eastern North Atlantic. In this feasibility study [5], fields from the high-resolution 1/10˚ ocean model were employed as 'sea truth' and to provide simulated altimeter mean dynamic topography (MDT) and residuals (with respect to the MDT) for assimilation into a similar resolution quasi-geostrophic (QG) model. The MDT, or the absolute ocean circulation, in the model acts as a constraint on the regional eddy field arising through the instabilities in the circulation. In the case of real data assimilation, of course, the dynamic topography parameterisation used in the model contains errors from the altimetric MDT and geoid models employed. The latter were simulated in the present study by using the ideal MDT derived from the high resolution ocean model, but excluding scales respectively below 100 km half wavelength (MDT-1) and 250 km (MDT-2).

The conclusion of this study highlights the potential benefit of GOCE. The range of the average departure of the one-week forecast of the total circulation (mean and eddy field) from a perfect prediction (using the full ocean model MDT) is a factor of 2 smaller using MDT-1 rather than MDT-2 (1.8 Sv rather than 4 Sv standard deviation in the upper 200 metres). Also, the predictive skill of the QG model was shown to make two-week forecasts feasible with MDT-1 to the same level of precision as one-week forecasts with MDT-2. This improvement is in addition to that in the knowledge of the mean circulation itself, i.e. in the spatial resolution of the absolute value of the velocity field. In this

case, the dynamic topography obtained from mean sea surface topography minus geoid, acts as a powerful model constraint on the assimilation of (inevitably) noisy altimeter variability information, providing a window on ocean processes at depth.

Candidate Future Simulation Studies

Open ocean

The advanced data assimilation methods, for instance as used in DIADEM-TOPAZ are based on dynamically consistent estimates of error statistics [6,7]. These methods ensure multivariate and physically consistent analyses with statistical covariance functions varying in space and time. This allows the extraction of maximum amount of information from satellite surface observations, since vertical projection of information is controlled by the dynamically evolving error covariances in the system.

Using simulated GOCE error covariance estimates these assimilation system should be further explored to estimate the eddy momentum flux associated with the smaller scales of the mean flow and eventually in combination with altimetry determine the energetics of eddy-mean flow interaction. (Some preliminary DIADEM-TOPAZ results from the North-East Atlantic – Nordic Seas will be shown.) Moreover, these system can be used to investigate how GOCE may improve modelling of float paths, and eventually how the floats provide additional information on smaller length scales.

Regional Oceans

Based on the end-to-end simulation results obtained by [8] (and briefly reported in [1]) it is suggested that the accurcay of the marine geoid height provided by GOCE will be about 2.5 mm at 100 km, rather than 1 cm. This means that a 1 cm accuracy can be expected at finer spatial resolution around 70 – 80 km. An important question in this context is the potential application of the GOCE geoid height data in combination with precision altimetry for ocean circulation studies along continental shelf breaks and subsequent shelf seas as well as in semi-enclosed seas such as the Mediterranean. The currents topographically steered along the shelf break acts as an open boundary between the coastal regions and the deep ocean and any exchanges of mass and energy between the two regions may therefore manifest itself along the shelf break.

How much of a constraint will GOCE place on the strength of the shelf slope current, and how small a scale can GOCE resolve in this region, given the covariance between gravity, bathymetry, and dynamic topography? A brief investigation has been initiated with model run to produce fields of mean and eddy-kinetic energy (EKE) for the ocean and shelf region southwest of the Fareo-Shetland Islands. These fields reveal how much of the time-varying altimetric signal (sea surface height anomalies and eddy kinetic energy) is found along the continental shelf break versus the deeper ocean basins. The remaining time-invariant mean signal derived from the ocean model is in turn reflecting the strength and importance of the mean flow which is largely controlled and steered by the relative steep shelf break topography with a typical cross-shelf width of 70-100 km.

The next question is then how the above indicative results may change with the range of different shelf breaks, and the addition of local gravity measurements. Can altimetric gravity help to regularise the problem when the distribution of gravity data is irregular? Can accurate bathymetry be used to fill in the short length scales of the gravity field?

Global Sea Level

The study of sea-level change spans research into changes in ocean circulation, steric changes and changes in ocean volume, vertical land movements, ice mass changes, height systems and satellite orbits. For instance, more accurate models of post-glacial rebound [9] and of local tectonics will result in more precise estimates of the rates of 'real' global- and regional-average sea-level change during the past century by reanalysis of the historical tide-gauge records. This will provide tighter constraints within which to assess the quality of hindcasted sea-level trends in climate models.

Moreover, the expected improved knowledge of the longer-wavelength components of the gravity field from GOCE and other missions will lead to a significant improvement in radial orbit accuracy for previous (GEOSAT, ERS) and future (Envisat, GEOSAT Follow Ons) altimeter satellites which are operated at altitudes lower than those of TOPEX/Poseidon and Jason-1. The result will be a reduction in geographically-correlated orbit errors in multi-decadal

time series of sea-level anomalies for studies of dynamic topography, low-frequency ocean circulation variability and subsequently long-term quasi-global sea-level change. An additional question is then if the advanced improvement in radial orbit accuracy in radar altimetry can be used to provide new information about tides.

A GOCE-derived marine geoid will in combination with radar altimetry and Argo floats also result in more reliable determinations of ocean heat and volume fluxes. This will in turn add better constraints for General Circulation Models employed to estimate sea-level change due to thermal expansion, which is expected to cause most of the change in the next century.

SUMMARY

Based on the fairly precise quantitative error estimates reported in [8,4], it is possible to reliably assess the degree of impact of GOCE in oceanographic research and applications. The results briefly presented above demonstrate promising impact of the GOCE mission for oceanography. Still we need to build on these and advance the impact simulation studies further in order to adequately promote the mission in the oceanographic community as suggested in Table 1.

Table 1. GOCE Impact Matrix for Oceanography

	Open Ocean	**Regional and semi-enclosed seas**	**Shelf breaks and coastal regions**
Mean Flow	Positive impact documented for North Atlantic	Relevant scales + strength and interaction with bathymetry needs to be examined	
Jets and Eddies	Positive impact documented at scales from 250 to 100 km Positive impact on interaction of mean flow with jets and eddies in the Azores current region	Interaction of mean flow with jets and eddies. Can shorter scales 50-100 km features be explored, and how do they interact with bathymetry? How important is addition of local gravity data?	
Heat and Volume Fluxes	Positive impact documented for the upper ocean (< 1000m) and across sharp fronts	The impact of GOCE for heat and volume fluxes needs to be further studied. Usually signals show strong variability on seasonal and interannual scales. Also strongly connected to fisheries in Nordic Seas	
Global Sea Level	Importance of steric effect on sea level needs to be explored combining GOCE, altimetry, Argo, SMOS, IR and GRACE	Combination of tide gauges and GOCE+ altimeter data should be investigated. How important is addition of local gravity data?	
Data Assimilation	Positive impact on predictive skills. Need to conduct multivariate assimilation using GOCE, altimetry, Argo, SMOS, IR, etc.	Assimilation experiments are needed to study the impact of the GOCE derived geoid The importance of local gravity data must also be examined.	

As revealed in the table, impact on the understanding of the role of the positions, strengths and dynamics of the short-spatial-scale fronts and jets in controlling the ocean circulation has been achieved for some ocean basins, notably in the North Atlantic and Southern Ocean. With the provision of GOCE data the opportunity to carry out real analyses of this kind for the entire global ocean, in combination with auxiliary data, will ensure greater confidence to the construction of the next generation of ocean and climate models. It is furthermore clear that studies should focus on regional and semi-enclosed seas as well as continental shelf break regions to explore the impact at finer spatial scales in the limit for the GOCE observation capabilities. In so doing, it will also be very relevant to consider additional use of local gravity data. Finally, in combination with in-situ data and ocean models, the new understanding gained from present and the future suggested studies, will in turn, act as an important constraint for calculations of oceanic mass and heat transport as well as its impact on global sea level.

The scientific results from GOCE will be perfectly complemented with observations from the US-German GRACE mission. The different technical concept of GRACE will recover the gravity field with very high precision for the long and medium spatial scales. This may allow to look for additional scientific applications like temporal variations

induced by ocean bottom-pressure variations. In addition, the results from GRACE, to be launched in late 2001, will support GOCE data processing for the recovery of the short scale gravity anomalies.

The new gravity field knowledge derived from these missions will be very timely in the context of the development of the integrated observing system for the ocean in which continuity of precision altimetry (Jason-1, Envisat RA-2, and possibly Jason-2) together with the Argo profiling float program play a fundamental role.

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