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# Impact of the GOCE gravity mission on ocean circulation estimates

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**Abstract.** The impact of a geoid model derived from the GOCE gravity mission on estimates of large-scale oceanic transports is investigated using an inverse model of the North Atlantic. Because its precision would match the precision of satellite altimeters, GOCE would significantly improve estimates of ocean dynamic topography and would thus provide information on ocean surface velocities. The impact of this information in terms of uncertainties in volume transports would be limited in the deep ocean by the presence of noise in the density field, but it would be significant in the upper ocean, with for instance a 26 % reduction of the uncertainty in the top 100 m layer at 48° N. This impact is comparable in magnitude to the impact on top-to-bottom transport uncertainties found by Ganachaud and co-workers, but it is achieved here with realistic error bars in the density field. This result shows that the improvement in hydrographic data assumed by these authors is not a prerequisite to a significant impact of future gravity missions.

## 1. Introduction

The Gravity field and Steady-State Ocean Circulation Mission (GOCE) is a spaceborne gravity mission currently reviewed by the European Space Agency. Its aim is to provide a global model of the Earth's gravity field and of the geoid with high spatial resolution and accuracy [*European Space Agency,* 1996]. This model would have applications in a wide range of research domains, including global ocean circulation, physics of the interior of the Earth, and leveling systems based on a Global Positioning System (GPS). In oceanographic applications, in particular, such a model, combined with precise altimetric measurements, would yield an unprecedented, accurate, estimate of the difference between the sea surface height and the marine geoid height. This difference, usually referred to as dynamic topography, is related to the intensity of oceanic surface currents through geostrophic balance [*Gill,* 1982]. Hence improvements in estimates of the geoid height achieved by GOCE would indirectly impact estimates of ocean absolute circulation. The objective of this work is to quantify this impact in terms of large-scale, time-averaged volume transports in the North Atlantic. These transports are key elements in the problem of understanding the climate system because of their role in redistributing the radiative heat received by the ocean. Thus, the reduction in their uncertainties calculated in this study can be viewed as a quantitative estimate of the potential impact of GOCE for climate studies.

The impact of improved geoid models on estimates of oceanic fluxes across trans-oceanic sections has already been investigated by *Ganachaud et al.* [1997] (hereafter GWKT). Their study, however, is rather theoretical in the sense that it uses a geoid model based on hypothetical gravity mission characteristics, and it assumes that *in situ* observations have very low noise levels in order to estimate the best possible outcome of future gravity missions. In contrast, the present study is based on the characteristics of an existing gravity mission project, and on the noise level of existing *in situ* observations. In particular, uncertainties introduced by time variability in the density field are explicitly accounted for.

The present study, like that of GWKT, uses a satellite estimate of dynamic topography and its uncertainty to constrain an inverse model of the ocean circulation. Because the dynamic topography associated with the GOCE mission is not known ahead of time, this study focuses on the impact of topography uncertainties. These uncertainties are derived from the autocorrelation function of the uncertainty in the geoid height. The GOCE function yields a variance, less than $(0.1 \text{ cm})^2$ for a spherical harmonic expansion up to degree and order 40 (Figure 1), which is comparable in magnitude to the Bettadpur analysis produced in GWKT. Because of its gradiometry-based design, GOCE would greatly outperform the accuracy of other types of mission at spatial scales of 1° or less [*Balmino et al.,* 1998]. Unfortunately, the consequences of the high precision levels achieved by GOCE at these scales cannot be investigated with the present inverse model because of its low resolution.

The next section describes the model used in this work (referred to as the Laboratoire de Physique des Oceans (LPO) model), with an emphasis on how this model differs from the model used by GWKT. In particular, the section explains why the LPO model can estimate uncertainties in transports in any layer of the ocean whereas the model used by GWKT can estimate uncertainties in transports integrated from the surface to the bottom of the ocean only. The third section quantifies the reduction of uncertainties in surface-to-bottom volume transports achieved by replacing the error covariance of current geoid models by the error covariance expected for GOCE, and compares it to the reduction obtained by GWKT in the North Atlantic. It then examines whether the error reduction expected from GOCE would have a larger impact on uncertainties in surface transports than on uncertainties in deep transports. The fourth



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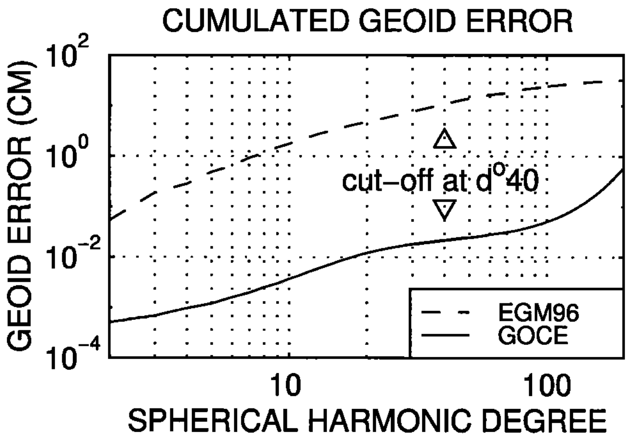


**Figure 1.** GOCE (full line) and EGM96 (dashed line) uncertainty as a function of spherical harmonic degree. A cut-off at degree 40 is used in the inverse model runs.

section discusses the assumptions made in this study and concludes.

## 2. The LPO inverse model

The LPO inverse model has been extensively described in previous papers [*Mercier et al.*, 1993; *LeGrand et al.*, 1998]; thus only its main features are presented here. The basic idea behind this model is to find an ocean circulation that best fits, in a least-squares sense, observational constraints and dynamical constraints. This best-fit is achieved by minimizing a cost function which is the sum of a data misfit term, weighted by the covariance of the observational uncertainties, and a dynamical imbalance term (mass imbalance in each elementary volume of the finite difference grid, for instance), weighted by the covariance of the model errors [*Mercier et al.*, 1993].

The observational constraints consist of a climatology of the density field and a satellite estimate of the mean dynamic topography based on the JGM-2 geoid height model [*Nerem et al.*, 1994] and the first two years of Topex/Poseidon sea surface height observations [*LeGrand et al.*, 1998]. The use of a more recent dynamic topography would not change the results of this study because of its focus on the impact of the topography uncertainties rather than the impact of the topography itself. To filter out small scale geoid errors, the topography constraint is discretized onto a 5° longitude x 4° latitude grid instead of the 2.5° longitude x 2° latitude grid used for the other constraints [*LeGrand et al.*, 1998]. Uncertainties in the density field are given by the climatology's standard deviations and uncertainties in the dynamic topography field are given by the sum of the covariance of the uncertainty in the geoid height expanded to spherical harmonic 40 and a diagonal matrix representing the uncertainty in the mean sea surface height [*LeGrand et al.*, 1998]. This later uncertainty, which corresponds to the temporal variability of the sea surface height on the 5° x 4° grid, is roughly spatially uniform and of amplitude $(1.5 \text{ cm})^2$.

The inverse model dynamical constraints are those relevant to the steady large-scale ocean circulation: mass conservation, heat conservation, the geostrophic balance that links surface currents to the slope of the mean dynamic topography, and the thermal wind relation [*Gill*, 1982]. Errors in the dynamical constraints, due to neglected physics and numerical approximations, are accounted for by appropriate weights in the cost function. The thermal wind relation, which is derived from leading order terms in the Navier-Stokes equations in the presence of rotation, links the velocity field to the density field

$$v(z) = v_{ref} - \frac{g}{\rho_o f} \int_{z_{ref}}^{z} \frac{\partial \rho}{\partial x} dz \qquad (1)$$

where $v(z)$ is the velocity at depth $z$, $v_{ref}$ is the velocity field at a prescribed reference level (the surface of the ocean for instance), $z_{ref}$ is the depth of this level, $g$ is the gravitational acceleration, $f$ the Coriolis parameter, $\rho_o$ a constant reference density, $x$ the coordinate along the longitude axis, and $\rho$ the *in situ* density. Most inverse models, like the one used by GWKT, use $v_{ref}$ as the only variable, and thus do not account for the depth-dependent character of uncertainties in the velocity field and associated transports. In constrast, the LPO inverse model treats density as an explicit variable, and thus provides estimates of uncertainties in the velocity field at any depth. This model can therefore estimate the impact of gravity missions on transport uncertainties in any layers of the ocean, including upper layers which are the most likely to be affected by a surface constraint like the dynamic topography constraint.

## 3. Results

Two calculations are performed with the same satellite constraint on dynamic topography and the same sea surface height uncertainties but with different geoid error covariances: the present-day EGM96 [*Lemoine et al.*, 1996] error in the first run (run 1) and the GOCE error in the second run (run 2). The error variance of the two geoid height models is shown in Figure 1 as a function of the number of spherical harmonics used, but only the expansion to degree 40 is used here. The dynamic topography constraint has little impact on the solution of run 1 because the EGM96 dynamic topography is less precise than an equivalent estimate from *in situ* data only [*LeGrand et al.*, 1998]. In contrast, this satellite constraint has a significant impact on the solution of run 2 because the GOCE error bars are small.

Figure 2 summarizes in a stick plot the impact of GOCE on uncertainties in zonally integrated transports across 24° N, 36° N, and 48° N, in four different layers. The reduction of surface-to-bottom transport uncertainties in run 2 relative to run 1 is not significant in the North Atlantic (less than 1% everywhere, Figure 2). This result is partly explained by the condition of mass conservation, which imposes that the net meridional volume flux is equal to the inflow from the Arctic Ocean, i.e. the inflow through the Bering Strait, within a small error bar of 1 sverdrup (1 Sv = $10^6$ $m^3/s$). It is also explained by the fact that the information on surface velocities provided by the satellite estimate of dynamic topography does not significantly constrain volume transports in the deep ocean. Indeed, at depths, velocity uncertainties are not determined by the precision of surface velocities, but by the uncertainties in the density term of equation (1). This point is confirmed by the small reduction of transport uncertainties in the 3000 m to 4000 m layer (Figure 2). The impact on surface-to-bottom volume transport uncertainties found here is smaller than the impact on surface-to-bottom heat flux uncertainties found by GWKT in the North Atlantic because these authors use small uncertainties in the density field in order to estimate the best possible outcome of gravity missions.

In contrast to the deep ocean, transport uncertainties in the upper kilometer of the ocean are significantly reduced in run 2 relative to run 1 because the contribution of density uncertainties to velocity uncertainties is relatively small there. In the upper 100 m of the water column, the maximum reduction is 26% at 48° N (Figure 2), which corresponds to a volume flux uncertainty reduction of about 0.2 Sv, or a heat flux uncertainty reduction of about $1.5\times10^{13}$W (assuming a 15° C temperature difference between the surface and the deep layers at this latitude). Such a heat flux uncertainty reduction, albeit small, represents about 10% of the total heat flux estimated by the model across 48° N. Note that the temperature field is not a variable in the model so that a full calculation of the heat flux uncertainty, although feasible in principle, would not be rigorous (the same problem is present in the calculations of GWKT). Transport uncertainties in the upper km of the water column are also reduced in run 2 compared to run 1, for instance at 48° N by about 0.4 Sv in absolute terms, or 15% in relative terms (Figure 2).

As a complement to the error analysis, it is interesting to examine the impact of GOCE on the transports themselves. As in the error analysis, only the impact of the geoid uncertainty can be estimated here. Moreover, unlike transport uncertainty estimates, transport estimates can be very affected by the choice of an existing dynamic topography to replace the actual GOCE topography, and may thus be unreliable. Therefore, the discussion of the impact of GOCE on transports is limited here to the main feature of the ocean

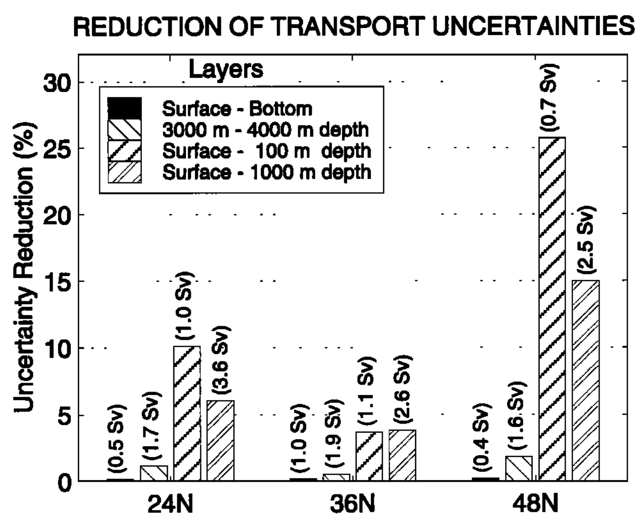


**Figure 2.** Percentage reduction of uncertainties in zonally integrated transports in run 2 (GOCE) relative to run 1 (EGM96). Each layer is associated to a shade of grey, as indicated in the legend. Reduction of 24° N, 36° N, and 48° N transport uncertainties are indicated from left to right. Numbers in parenthesis indicate transport uncertainties (in Sv) estimated in run 1 for each layer, and for each zonal section.

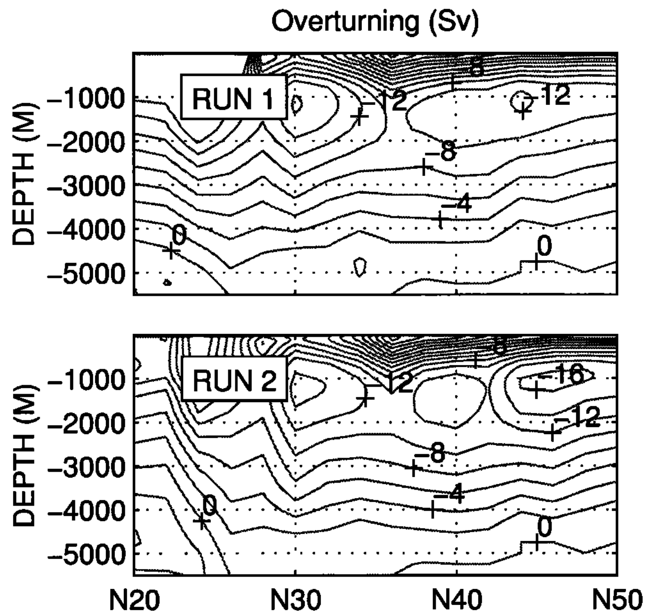


**Figure 3.** Meridional overturning (Sv) estimated in run 1 (top) and in run 2 (bottom). Isolines represent integrated meridional transports calculated from the bottom of the ocean, negative values corresponding to southward transports.

circulation in the North Atlantic, i.e. the meridional overturning cell of warm water flowing North in the upper-ocean and cold water returning South in the deep-ocean. In run 1, this meridional overturning has an amplitude of about 12 Sv at 45° N (Figure 3), which is smaller than usual estimates ranging from 16 Sv to 20 Sv, but acceptable in view of the low resolution of the inverse model and the use of a smooth climatology of the density field. In run 2, the meridional overturning is significantly larger than in run 1, by about 4 Sv at 45° N (Figure 3), which suggests that the impact of GOCE on estimates of the overturning rate in the North Atlantic should be of the order of the uncertainties in current transport estimates, i.e. several Sv (Figure 2).

Finally, replacing the GOCE autocorrelation function associated with a cut-off at spherical harmonic 40 by a function associated with a cut-off at harmonic degree 180 and a subsequent smoothing over a 4.5° spatial scale (Sneeuw and Rummel, personal communication) does not produce significantly different results. This indicates that it is the magnitude of the uncertainty in the geoid height that matters, not the details of the autocorrelation function, and suggests that the present results are robust with respect to changes in estimates of GOCE performances.

## 4. Discussion

The present impact estimate, which is based on available data and error budgets, is quite conservative for several reasons:

- GWKT show that, at least in terms of surface-to-bottom transports, the North Atlantic is the region where gravity missions will have the smallest impact.

- The model calculations use a satellite estimate of the mean dynamic topography which is low-pass filtered at spherical harmonic 40. The present study therefore underestimates the impact of GOCE on transport estimates along sharp oceanic fronts like the Gulf Stream.

- Because the present study is a steady state one, it treats the natural variability of the density field as noise. In the future, data assimilation techniques capable of producing error calculations will model this variability, thereby reducing levels of density uncertainties and allowing the altimetric-geoid information to better reach the deep ocean.

Despite its conservative character, this study demonstrates that the improved geoid height model that would result from GOCE would significantly affect circulation estimates in the North Atlantic, in terms of both oceanic transports and their uncertainties. The impact on transport uncertainties mostly concerns the upper ocean, because in the deep ocean the information provided by the dynamic topography constraint on surface velocities is swamped by uncertainties in the density field. More precise estimates of upper-ocean transports are valuable because these transports have a strong contribution to the meridional overturning in the Atlantic, one of the key components of the transport of heat by the ocean. The reduction of uncertainties found by GWKT for the Bettadpur geoid analysis is similar in magnitude to the reduction found here, but it concerns surface-to-bottom transports and it assumes very small uncertainties in the density field. This similarity may be explained by the fact that the uncertainties assumed by GWKT are qualitatively consistent with the limited role these uncertainties play in the upper ocean in the present study. It indicates that the improvements in hydrographic data assumed by GWKT are not a prerequisite to a significant impact of future gravity missions.

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## References

Balmino, G., F. Perosanz, R. Rummel, N. Sneeuw, and H. Suenkel, Some views on dedicated gravity field missions: GRACE and GOCE, *ESA report ESA-MAG-REP-CON-001*, ESA Publication Division, c/o ESTEC, Noordwijk, The Netherlands, 1998.

European Space Agency, The nine candidate Earth Explorer Missions - Gravity-field and steady-state ocean circulation mission, *ESA report SP-1196*, ESA Publication Division, c/o ESTEC, Noordwijk, The Netherlands, 1996.

Ganachaud, A., C. Wunsch, M.-C. Kim, and B. Tapley, Combination of TOPEX/POSEIDON data with a hydrographic inversion for determination of the oceanic general circulation and its relation to geoid accuracy, *Geophys. J. Int., 128*, 708-722, 1997.

Gill, A.E., *Atmosphere-Ocean dynamics*, 662 pp, Academic Press, 1982.

LeGrand, P., H. Mercier, and T. Reynaud, Combining T/P altimetric data with hydrographic data to estimate the mean dynamic topography of the North Atlantic and improve the geoid, *Ann. Geophysicae, 16*, 638-650, 1998.

Lemoine, F.G., D.E. Smith, L. Kunz, R. Smith, E.C. Pavlis, N.K. Pavlis, S.M. Klosko, D.S. Chinn, M.H. Torrence, R.G. Williamson, C.M. Cox, K.E. Rachlin, Y.M. Wang, S.C. Kenyon, R. Salman, R. Trimmer, R.H. Rapp, and R.S. Nerem, 1996: Proceedings paper for the international Symposium on gravity, geoid, and marine geodesy, (GRAGEOMAR, 1996), The University of Tokyo, Tokyo, Japan, 1996.

Mercier, H., M. Ollitrault, and P.-Y. Le Traon, An inverse model of the North Atlantic general circulation using lagrangian float data, *J. Phys. Ocean., 23*, 689-715, 1993.

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