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An initial estimate of the North Atlantic steady-state geostrophic circulation from GOCE

R. J. Bingham,[1] P. Knudsen,[2] O. Andersen,[2] and R. Pail[3]

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[1] The GOCE satellite mission was launched in 2009 and the first gravity models were released in July 2010. Here we present an initial assessment of the GOCE data in terms of the mean circulation of the North Atlantic. We show that with just two months of data, the estimated circulation from GOCE is already superior to a similar estimate based on 8 years of GRACE observations. This result primarily depends on the fact that the GOCE mean dynamic topography (MDT) is generally less noisy than that obtained from the GRACE data. It therefore requires less smoothing and so there is less attenuation of the oceanographic signal. Our results provide a strong validation of the GOCE mission concept, and we anticipate further substantial improvements as the mission progresses. **Citation:** Bingham, R. J., P. Knudsen, O. Andersen, and R. Pail (2011), An initial estimate of the North Atlantic steady-state geostrophic circulation from GOCE, *Geophys. Res. Lett.*, *38*, L01606, doi:10.1029/2010GL045633.

1. Introduction

[2] In October 2009 the GOCE (Gravity and steady-state Ocean Circulation Explorer) satellite mission was launched with the objective of measuring the Earth's gravity field to an unprecedented accuracy, with errors less than 1 cm for spatial scales down to 100 km [*Drinkwater et al.*, 2003]. As indicated by its name, a primary scientific goal of the GOCE mission is the global determination of the ocean's geostrophic current systems. Of particular interest are the current systems of the North Atlantic, which play an important role in the regulation of the Earth's climate. The Gulf Stream and its extension transport heat poleward from the equator, helping to maintain the relatively temperate climate of western Europe [*Rhines et al.*, 2008]. Meanwhile, the East Greenland Current carries freshwater from the Arctic into the Atlantic to maintain the freshwater balance between the Atlantic and the Pacific [*Woodgate et al.*, 1999].

[3] The first GOCE earth gravity models (EGMs), based on just two months of observations, were released in July 2010. This paper presents an initial analysis of an estimate of the North Atlantic's mean dynamic topography (MDT) and associated geostrophic currents derived from a GOCE EGM. The GOCE MDT is assessed against an MDT derived from an EGM based on 8 years of GRACE observations and an MDT based solely on in-situ drifter observations. It will be shown that the estimate of North Atlantic circulation from GOCE is already superior to that obtained from GRACE. This is an impressive result given that this estimate is based on just two months of GOCE data. In the next section the data used in the analysis are briefly described. The results are presented in section 3, and we conclude with a brief discussion of the results in section 4.

2. Data

2.1. GOCE

[4] The GOCE High-level Processing Facility (HPF) is responsible for delivering the level 2 global gravity model from which geoid heights can be determined [*Koop et al.*, 2007]. Within the HPF three processing strategies have been adopted. Here we use the GOCE EGM produced by the so-called timewise approach, which does not rely on an *a priori* external estimate of the gravity field. Therefore, it gives the clearest demonstration of the capabilities of GOCE. The methodology and the solution are described respectively by *Pail et al.* [2007, 2010]. The GOCE data were obtained from the GOCE Virtual Online Archive at http://eo-virtual-archive1.esa.int/Index.html.

2.2. Other Data

[5] We wish to assess the MDT derived from the GOCE EGM against an MDT based on a state-of-the-art, satellite only GRACE solution. Here we use ITG-Grace2010s, which can be downloaded from http://www.igg.uni-bonn.de/apmg/index.php?id=itg-grace2010.

[6] The geodetic MDTs are calculated by subtracting the derived geoid heights from a mean sea surface (MSS). Here we use a MSS provided by CLS (Collecte Localisation Satellites) covering the period 1993–1999 [*Hernandez and Schaeffer*, 2001].

[7] Finally, we wish to assess the geodetic MDTs and their associated geostrophic currents against an MDT based solely on in-situ data. For this we use an MDT based on drifter data produced by *Niiler et al.* [2003].

3. Results

3.1. Raw MDTs

[8] The MDT based on the GOCE EGM (henceforth, simply the GOCE MDT) is calculated on a 0.5 degree global grid using the spectral approach, as described by *Bingham et al.* [2008], with truncation at the maximum available degree and order (d/o) of 224 (Figure 1a). The MDT based on the GRACE EGM (the GRACE MDT) is computed in a similar fashion to d/o 180, the maximum of the GRACE EGM

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[1] School of Civil Engineering and Geosciences, Newcastle University, Newcastle Upon Tyne, UK.

[2] Department of Geodesy, Danish National Space Center, Copenhagen, Denmark.

[3] Institute of Astronomical and Physical Geodesy, Technical University of Munich, Munich, Germany.

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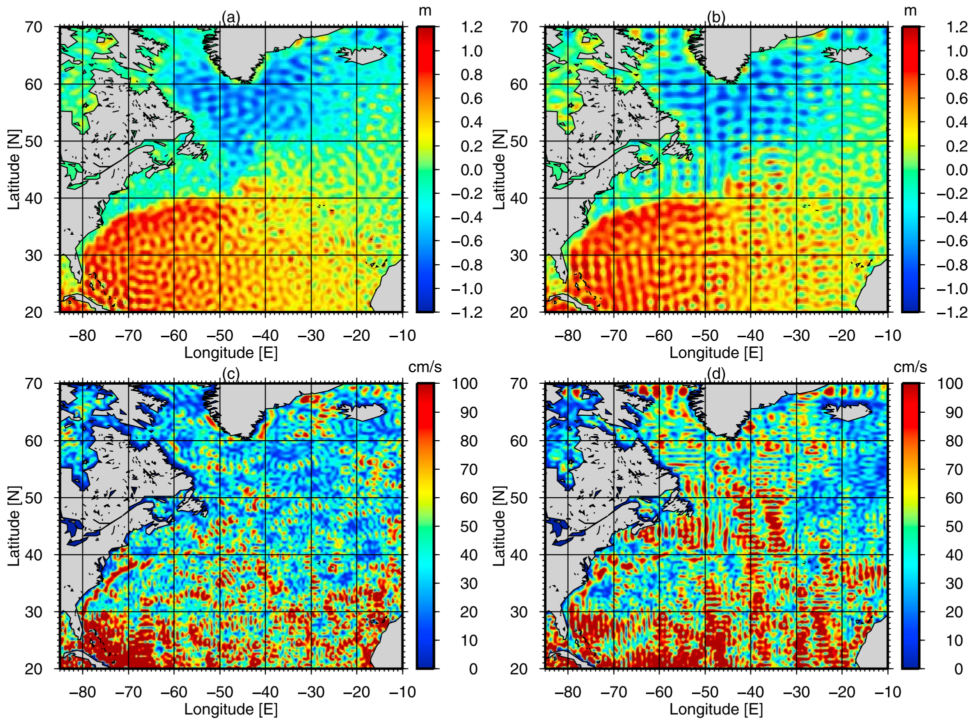

Figure 1. (a) The time-mean ocean dynamic topography (MDT) of the North Atlantic obtained from GOCE by the spectral approach with truncation at degree and order 224. (b) As in Figure 1a but using a GRACE EGM, with truncation at degree and order 180. (c) The mean geostrophic current speeds determined from the GOCE MDT shown in Figure 1a. (d) As in Figure 1c but for the GRACE MDT.

(Figure 1b). The minimum resolved spatial scales of the GOCE and GRACE MDTs are, therefore, roughly 89 km and 111 km, respectively. The two MDTs are broadly similar with regard to the gross features of the North Atlantic circulation. However, both MDTs are clearly contaminated with noise, which is amplified when we calculate the associated mean geostrophic surface currents (u, v) according to the geostrophic equations:

$$u = -\frac{g}{f}\frac{d\eta}{dy}, \quad v = \frac{g}{f}\frac{d\eta}{dx}, \qquad (1)$$

where η is the MDT height, f is the Coriolis parameter, and g is acceleration due to gravity (see Figures 1c and 1d).

[9] The simplest approach to determining a geodetic MDT is to calculate the geoid on the same geographical grid as the MSS and subtract one from the other. Essentially, the only extra step in the spectral approach is to express the MSS as a set of spherical harmonic coefficients and then recompute it with truncation at the same d/o as the geoid. As detailed by *Bingham et al.* [2008], the advantage of this extra step is that it reduces MDT noise due to geoid omission errors and numerical errors inherent in the projection from the spectral to geographical domains. This is confirmed for the present analysis in Figure S1 of the auxiliary material.[1] The remaining noise in the MDTs shown in Figure 1 is then due mainly to geoid commission error. This can be demonstrated by comparing spectral MDTs based on different EGMs but computed to the same d/o. This ensures that any residual geoid omission errors or numerical noise due to the transformation of the MSS to the spectral domain and back again will be identical in the two MDTs, and so differences in MDT noise must be due geoid commission error. This is demonstrated for the GOCE and GRACE MDTs in Figures S2 and S3.

3.2. Noise Levels and Filtering

[10] Clearly, whatever the noise source, the MDTs must be filtered to obtain more reasonable estimates of the ocean currents. Here we use a filtering method based on anisotropic diffusion, which significantly reduces the problem of signal attenuation by preferentially filtering along, rather than across, steep MDT gradients [*Bingham*, 2010]. Yet, if we are to assess whether the GOCE estimate of ocean currents improves upon what can be obtained from GRACE, the problem remains of how to choose the appropriate degree of smoothing, here controlled by the number of filter iterations, to ensure all the noise is removed, while preserving as much oceanographic detail as possible.

[11] To make a more robust and objective estimate of the appropriate level of filtering for the two geodetic MDTs, than a simple visual inspection, we compare their associated currents with those from the Niiler MDT. By comparing currents, rather than heights, we focus on the short wavelengths where the noise is concentrated and were we can be confident that the Niiler MDT is closer to the truth. The Niiler currents can be written as $C_n = C + \epsilon_n$, where C represents the true currents and ϵ_n is the error. Similarly, for the geodetically derived currents we have $C_g = C + \epsilon_g$. Then, signi-

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL045633.

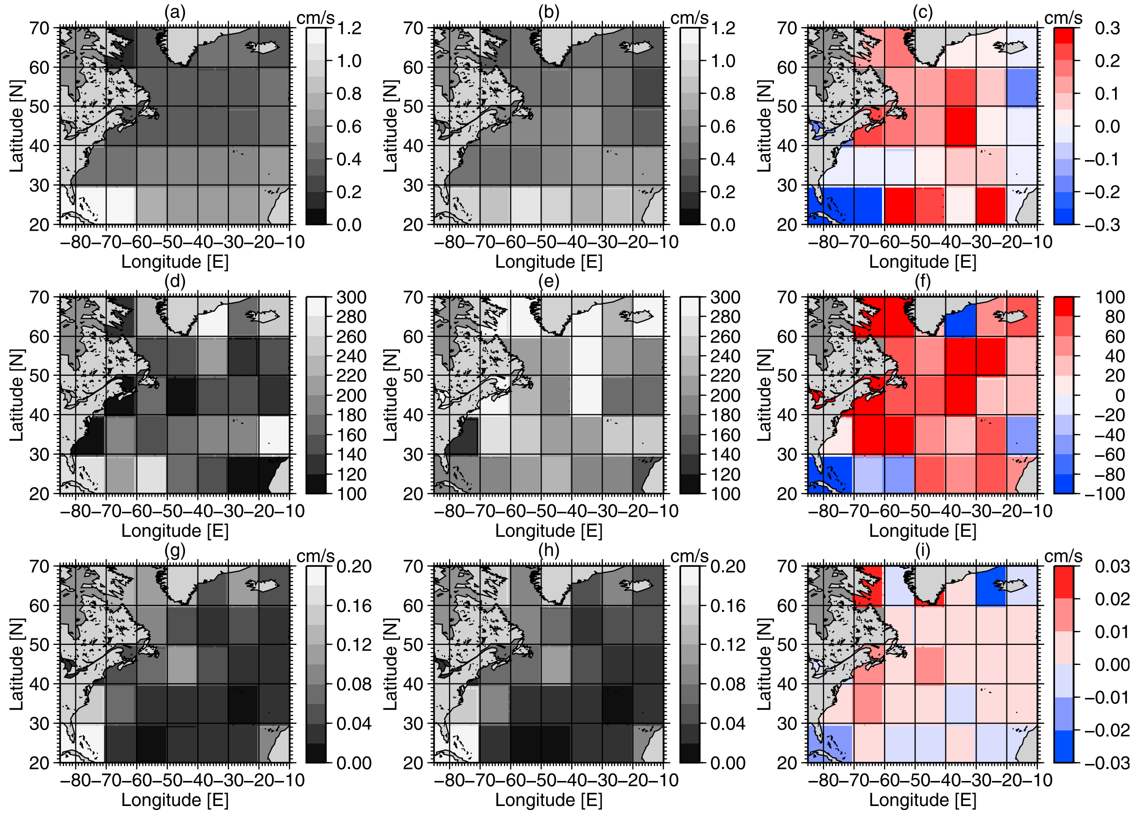

Figure 2. (a) The RMS difference in 10° tiles between the Niiler current speeds and the unfiltered GOCE current speeds (R_0^{GOCE}). (b) As in Figure 2a but for the GRACE current speeds (R_0^{GRACE}). (c) The difference $R_0^{GRACE} - R_0^{GOCE}$. (d) The number of filter iterations that minimise the RMS difference between the Niiler current speeds and the GOCE current speeds (N^{GOCE}). (e) As in Figure 2d but for the GRACE current speeds (N^{GRACE}). (f) The difference $N^{GRACE} - N^{GOCE}$. (g) The minimum RMS difference between the Niiler current speeds and the GOCE current speeds ($R_{\min}^{GOCE}$). (h) As in Figure 2g but for GRACE current speeds ($R_{\min}^{GRACE}$). (i) The difference $R_{\min}^{GRACE} - R_{\min}^{GOCE}$.

fying filtering with an overbar, for the currents derived from the filtered geodetic MDTs we have:

$$\overline{C_g} = \overline{C} + \overline{\epsilon_g} = C + \left(\overline{C} - C\right) + \overline{\epsilon_g} \qquad (2)$$

Here, the middle term on the right-hand side of (2) represents the error introduced by the filtering due to signal attenuation.

[12] To determine the optimum number of iterations N over which we should run the filter, we consider the residual

$$R = \left\langle C_n - \overline{C_g} \right\rangle = \left\langle \left(C - \overline{C}\right) + \overline{\epsilon_g} + \epsilon_n \right\rangle, \qquad (3)$$

where $\langle * \rangle$ represents the RMS of quantity * over some geographical area. Initially, R is dominated by ϵ_g. As the degree of filtering (the number of iterations) is increased, R decreases due to the decrease in $\overline{\epsilon_g}$. At some point, when most of the noise has been removed, the growing error due to filter attenuation begins to dominate, and R begins to increase again. We define N to be the number of iterations for which R is at a minimum. We can reasonably assume that ϵ_n is small in comparison with the other two terms, since geodetically derived ocean currents are still not as accurate as those derived from in-situ observations (as will be confirmed below). In any case, since ϵ_n is a constant, it does not impact on this analysis.

[13] To assess the required filtering we divided the domain into 10° × 10° or 15° × 10° tiles (as shown in Figure 2) and calculated R for each tile. For most tiles, the initial value R_0 for the GOCE MDT is less than that for the GRACE MDT (Figures 2a–2c). The southwest corner of the domain between 20–30°N and 85–60°W is a notable exception to this. This confirms the visual impression from Figure 1 of the relative levels of noise in the two MDTs. GOCE is also somewhat more noisy at all latitudes for the most easterly tiles. This indicates that the GOCE geoid commission errors are greater for these tiles, a situation that should improve with a longer record of observations. Note that both the GOCE and GRACE MDTs are noisier at lower latitudes. This is to be expected due to the near polar orbits of both the GOCE and GRACE satellites, which mean observations increase in density towards the poles.

[14] The greater noise levels in the GRACE MDT are also reflected in the number of iterations N required to reach the minimum residual value $R = R_{\min}$ (Figures 2d–2f). For nearly all tiles, with the exception of those where the GOCE MDT is considerably noisier than the GRACE MDT, many fewer iterations are required to minimise the difference between the GOCE MDT currents and the Niiler currents. Because of this, we can expect less attenuation of GOCE ocean currents (the $(C - \overline{C})$ term in equation (2)). This is confirmed in Figures 2g and 2h, which show $R_{\min}$ for the

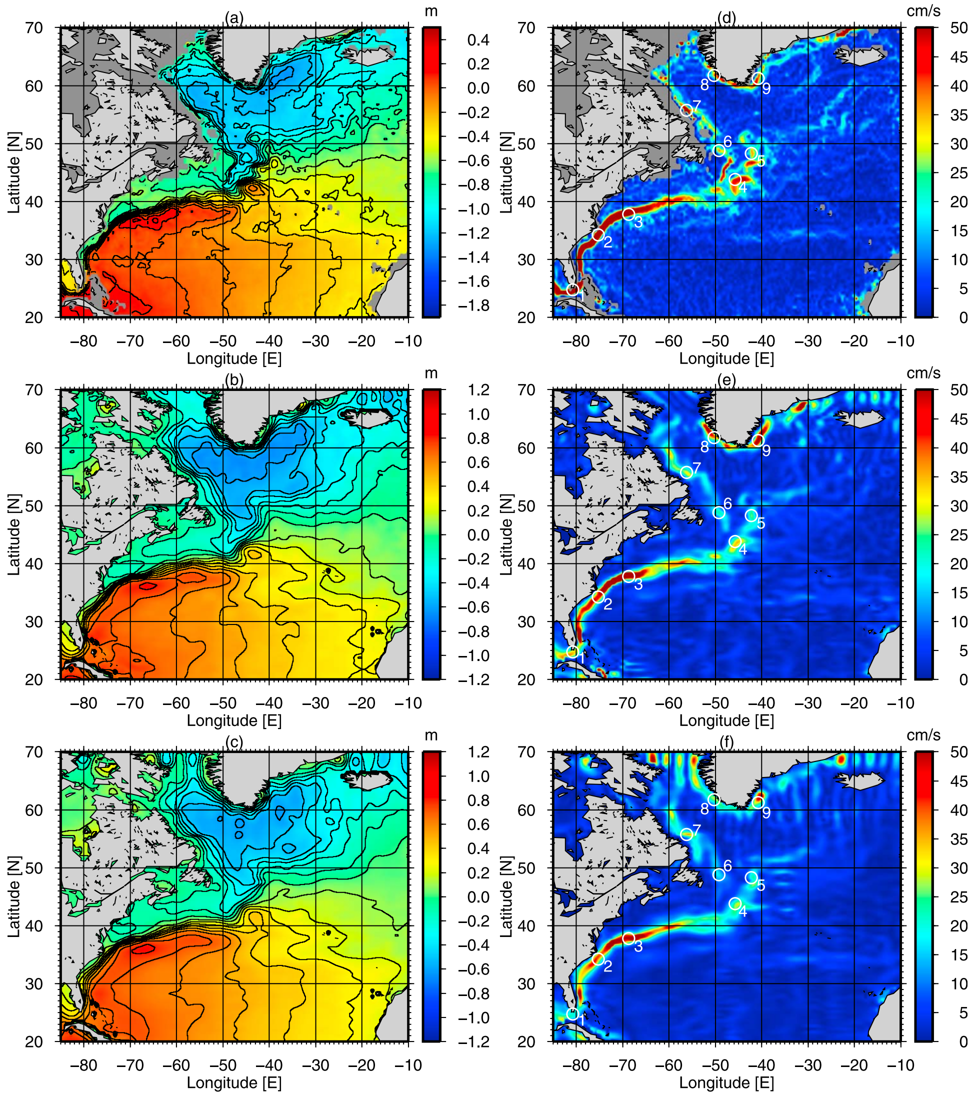

Figure 3. (a) The Niiler MDT. (b) The filtered GOCE MDT. (c) The filtered GRACE MDT. (d–f) The associated mean geostrophic surface currents.

GOCE and GRACE MDTs and Figure 2i which shows the GRACE-GOCE difference between $R_{\min}$ for the two MDTs. For most tiles, $R_{\min}$ for GOCE is less than it is for GRACE. This demonstrates that the filtered currents from GOCE are closer to those from Niiler. The $R_{\min}$ difference shown in Figure 2i is small in comparison to R_0 for either MDT, which suggests that the GOCE MDT is only marginally better than the GRACE MDT. However, the $R_{\min}$ difference primarily reflects differences in the localised attenuation of currents, which will have a small RMS value in comparison to R_0 which reflects the much more evenly distributed noise.

[15] Having found the optimum number of filter iterations for each tile, we could now proceed to filter each tile individually. Here, however, we wish to present a consistent picture of the circulation for the North Atlantic. To determine the optimum number of iterations for the entire domain, for each case, we calculate the area weighted mean of *N*. Because some tiles, were the currents are strongest, are more important than others, we apply a further weighting, based on RMS of the Niiler current speed, over the tile to reflect this. By this approach we find that the optimum number of iterations for the entire domain is 156 for GOCE and 229 for GRACE. This difference in the required number of filter iterations is the key reason why the GOCE MDT represents an improvement over GRACE as we now demonstrate.

3.3. Comparison of Filtered MDTs

[16] In Figure 3 the MDTs filtered with the optimum number of iterations as found above and the associated currents are compared with the (unfiltered) Niiler MDT (Figure 3a). The filtered GOCE (Figure 3b) and GRACE (Figure 3c) MDTs are overall somewhat smoother than the Niiler MDT. This is to be expected, because the Niiler MDT will contain some detail whose scales are comparable to or smaller than the noise in the geodetic MDTs. Hence, even if that detail were present in the initial geodetic MDT, it would be lost in the filtering. The GRACE MDT does still seem to retain some noise at higher latitudes suggesting that further filtering is required. Turning to the mean geostrophic currents (Figures 3d–3f), it is immediately clear that the GOCE currents are somewhat stronger than those from GRACE, and therefore closer to the Niiler currents.

Table 1. Current Speeds (cm/s) at Nine Locations Marked in Figure 3d

MDT	1	2	3	4	5	6	7	8	9
Niiler	96	93	65	48	34	38	79	41	38
GOCE	34	47	60	31	26	24	31	39	59
GRACE	20	37	51	27	21	17	35	28	30

[17] For a more quantitative assessment, in Table 1 we give current speeds at 9 locations, marked by circles in Figure 3. For most locations the Niiler current speeds are greater than those from the geodetic MDTs. This is due, partly, to the fact that the geodetic MDTs have been filtered, whereas the Niiler MDT has not, and, in part, due to the geodetic MDT omission errors, imposed by the maximum degree and order of the EGMs. In all but two cases, however, the currents from GOCE are closer to the in-situ estimates, confirming that the GOCE estimate of the North Atlantic circulation does indeed represent an improvement upon GRACE. Increased current strength is seen at the three locations along the length of the Gulf Stream (positions 1–3). The best agreement between the geodetic and in-situ estimates is found where the Gulf Stream leaves the boundary and begins to flow east (position 3). Here the GOCE estimate is only 5 cm/s (8%) less than the in-situ estimate. The GOCE MDT also better resolves the finer scale features where the Gulf Stream feeds into the North Atlantic Current (positions 4 and 5) and the southerly tip of the Labrador Current (position 6). Further north along the Labrador Current (position 7) is the only location where the current from GRACE is stronger than that from GOCE. This seems to be due to residual noise in the filtered MDT boosting the GRACE current speed here. For the West Greenland Current (position 8) the GOCE and Niiler estimates are both close to 40 cm/s, while for the East Greenland Current (position 9), the GOCE estimate is about 20 cm/s stronger than the in-situ estimate. This may be because the in-situ estimate is poor here due to a paucity of observations, indicating a possible advantage of the geodetic approach at high latitudes. However, because complications in the geodetic MDT calculation can arise close to land/sea boundaries, more work is required to establish this.

4. Concluding Remarks

[18] A primary goal of the GOCE mission is the improved determination of the ocean's circulation. Our objective with this letter has been to provide an initial assessment of the performance of GOCE, in terms of the ocean's MDT and associated geostrophic currents. It should be borne in mind that the GOCE results presented here are based on just two months of observation. Nonetheless, we find that the estimate of the North Atlantic's mean circulation from GOCE is already superior to an estimate using a state-of-the-art, satellite only GRACE solution, which is based on 8 years of data. This is a remarkable validation of the GOCE mission concept.

[19] The improvement from GOCE is due partly to an increase in the number of spherical harmonic terms available for the MDT calculation, but, mainly, it is because the GOCE commission errors are smaller for the higher degree terms. This means the raw GOCE MDT is less noisy and so less filtering is required. As a result, there is less attenuation of the MDT gradients associated with strong ocean currents. Presently, the improvements are quite small and careful filtering is required to reveal them. Also, there are certain regions such as the western Atlantic between 20–30°N and the Eastern North Atlantic between 20–10°W where the errors from GOCE are greater than those from GRACE. These issues, however, will most likely be addressed as the number of observations from GOCE grows and the commission errors are reduced.

[20] Finally, here we have chosen to focus on pure GOCE and GRACE solutions for the sake of demonstrating unambiguously the relative merits of each system. However, due to way each system measures the Earth's gravity, GRACE is more accurate at long wavelengths. Therefore, the best gravity models, and so the best geodetic MDTs will, ultimately, come from combining the data from the two systems.

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O. Andersen and P. Knudsen, Department of Geodesy, Danish National Space Center, Juliane Maries vej 30, DK-2100 Copenhagen, Denmark.

R. J. Bingham, School of Civil Engineering and Geosciences, Newcastle University, Newcastle Upon Tyne NEU 7RU, UK. (r.j.bingham@ncl.ac.uk)

R. Pail, Institute of Astronomical and Physical Geodesy, Technical University of Munich, Arcisstrasse 21, D-80333 Munich, Germany.