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Bingham, Rory J.; Knudsen, Per; Andersen, Ole Baltazar

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ESTIMATING THE NORTH ATLANTIC MEAN DYNAMIC TOPOGRAPHY AND GEOSTROPHIC CURRENTS WITH GOCE

Rory J. Bingham[1], **Per Knudsen**[2], **and Ole Andersen**[2]

[1]*Newcastle University, United Kingdom*
[2]*Danish National Space Center, Denmark*

ABSTRACT

Three GOCE gravity models were released in July 2010 based on two months of observations. Subsequently, two second generation models, based on 8 months of observations, were released in March 2011. This paper compares these five models in terms of the mean North Atlantic circulation that can be derived from them. Because the high degree commission errors of all of the GOCE models are lower than those from the best satellite only GRACE solution, all of the derived GOCE MDTs are much less noisy than the GRACE MDT. They therefore require less severe filtering and, as a consequence, the strength of the currents calculated from them are in better agreement with those from an in-situ drifter based estimate. Where the comparison is possible, the reduction in MDT noise from the first to second releases is also clear. However, given that some filtering is still required, this translates into only a small improvement in ocean currents. This is, primarily, a reflection of the limitation of the filtering method employed, and indicates the need for more sophisticated MDT filtering strategies.

Key words: GOCE, mean dynamic topography, geostrophic currents.

1. INTRODUCTION

The current systems of the North Atlantic 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 relative to similar latitudes in North America and Eastern Europe (*Rhines et al.*, 2008). 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). Given their importance in these respects, the accurate determination of the North Atlantic currents is highly desirable. Since, taking the long-term mean sea surface (MSS) as the reference, the time variable component of the circulation is readily obtainable from satellite altimetry, accurate determination of the mean circulation is the outstanding challenge.

In March 2009 the GOCE 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 of 100 km (*Drinkwater et al.*, 2003). The first results based on two months of data, were released in July 2010, with a subsequent release based on 8 months released in March 2011. This paper presents an initial analysis of an MDT and associated currents derived from this GOCE data for the North Atlantic region. After briefly describing the data and methods in the next section, in Section 3 we considered the MDT signal up to degree and order (d/o) 180. In section 4 we ask if additional MDT signal can be recovered from the spherical harmonic terms beyond this d/o. Finally some brief conclusions are provided in section 5.

2. METHOD

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: the direct (DIR) approach (*Bruinsma et al.*, 2010), the timewise (TIM) approach (*Pail*, 2010), and the spacewise (SPW) approach (*Migliaccio et al.*, 2010). The GOCE data were obtained from the GOCE Virtual Online Archive at http://eo-virtual-archive1.esa.int/Index.html. The GOCE MDTs are calculated by subtracting the GOCE derived geoids 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). The MDTs are calculated using the spectral approach as described in *Bingham et al.* (2008).

Removal of MDT noise is commonly achieved by spatial smoothing with a Gaussian or similar filter (e.g. *Tapley et al.*, 2003; *Jayne et al.*, 2003). However, as illustrated by (*Bingham et al.*, 2008), such *isotropic* filters, by filtering across MDT gradients have the undesired side-effect of drastically attenuating ocean currents calculated from the smoothed MDT. As demonstrated by

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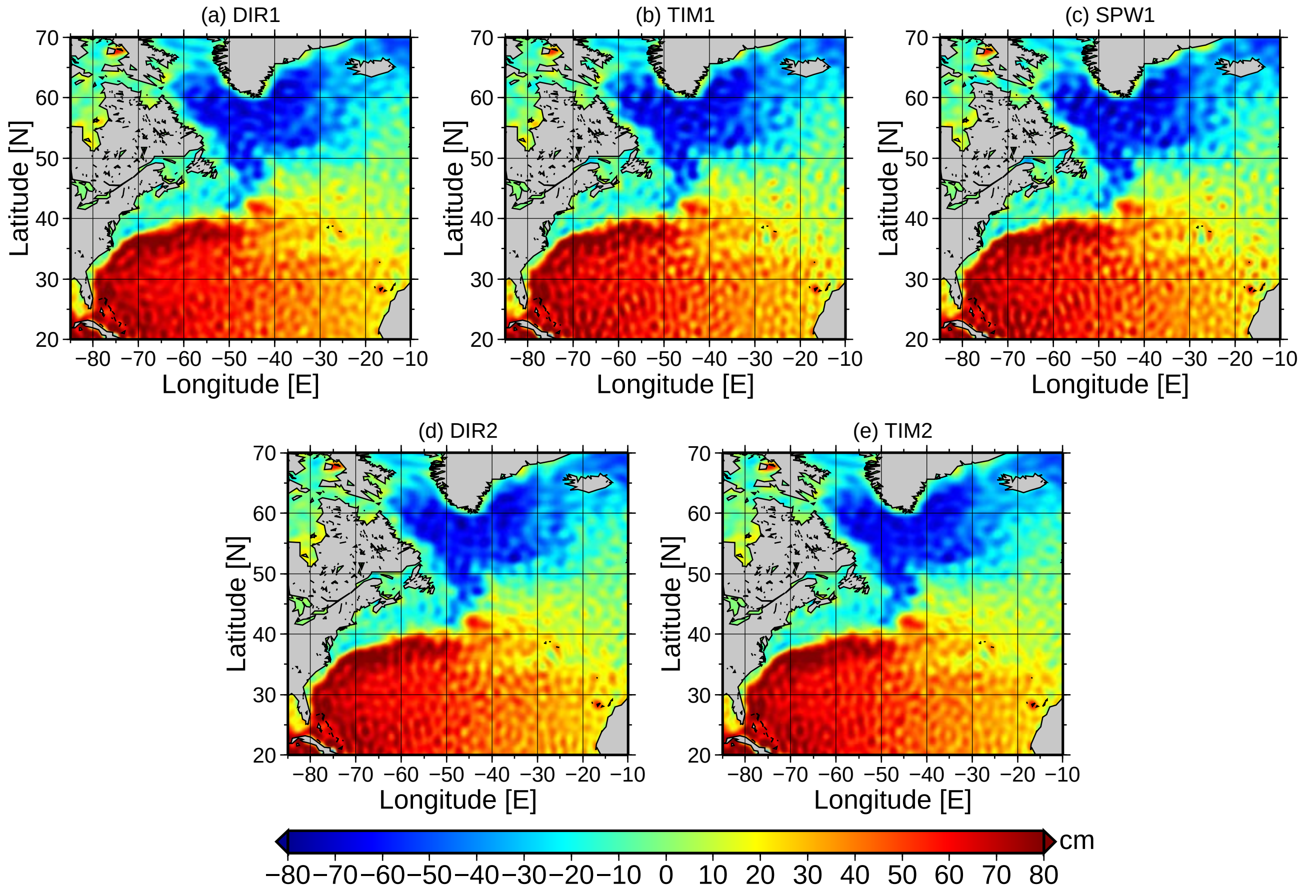

Figure 1. The North Atlantic mean dynamic topography (MDT) determined from the five GOCE gravity models released so far. The top row shows the first generation of models and the bottom row shows the second generation. MDTs are computed by the spectral method with truncation at degree and order 180. DIR, TIM, and SPW refer to the direct, timewise and spacewise approaches to obtaining the GOCE gravity models.

Bingham (2010), an alternative filtering method based on anisotropic diffusion significantly reduces the problem of gradient attenuation, and loss of current resolution, by preferentially filtering along, rather than across, steep MDT gradients. Therefore this *anisotropic* filtering method is the one employed here.

3. MDTS TO DEGREE AND ORDER 180

We begin by considering MDTs computed to d/o 180. This is the maximum d/o of ITG2010S gravity model, considered, at the time of writing, to be the best satellite-only GRACE solution. As such, it provides an important benchmark against which GOCE can be judged. Figure 1 shows the GOCE MDTs to d/o 180 for all of the available models. All of them capture the main features of the North Atlantic circulation. And all are, to some extent, contaminated with small scale noise, which, since we have used the spectral approach, comes mainly from geoid commission error. For this perspective there is little to distinguish the models.

The currents speeds derived from the five models are shown in Figure 2. In all, the path of the Gulf Stream is clear, but, because the process of taking the gradient of the MDT to determine currents also amplifies small scale noise, differences between the models are now clearer. For the first generation of models, it is clear that the direct solution is much smoother than either the timewise or spacewise approaches. This is because the GRACE EIGEN5C gravity model, which also includes surface data, was used as an a priori constraint on the DIR1 solution. The DIR2 model does not use this constraint and for this reason the noise in the DIR2 MDT is little greater, even though the second release is based on four times more GOCE observations. The true impact of the additional data on the MDT calculation is seen by comparing the current maps for TIM1 and TIM2, where the processing method as remained consistent between releases. It is clear that the noise in the TIM2 MDT has been much reduced, and this is due to the reduced geoid commission error.

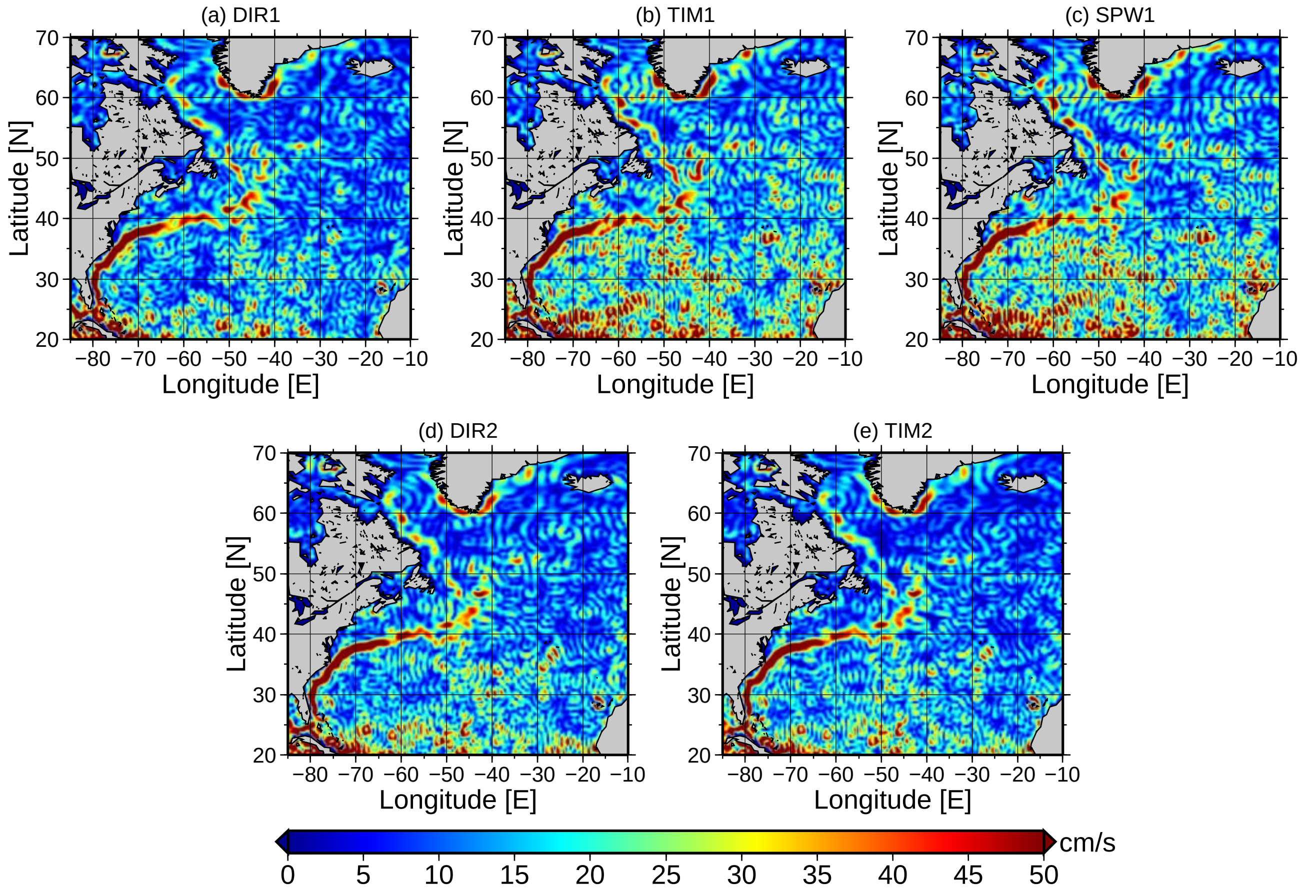

Figure 2. Geostrophic current speeds obtained from the GOCE MDTs shown in Figure 1.

If we quantify the noise in the geodetic MDTs by computing the RMS residual between the currents obtained from the geodetic MDTs with those from the Niiler MDT (*Niiler et al.*, 2003), which is based solely on drifter data, over 10x10 degree tiles, then it is possible to determine the percentage reduction in noise of the GOCE MDTs compared with the GRACE MDT. This is shown in Figure 3. The improvement between first and second generation timewise solutions is clear, and for the latter, the noise as been reduced by up to 85% compared to the GRACE solution. Similar improvements are seen in the DIR1 and DIR2 MDTs. One poor area lies in the southwest corner of the domain. Although, even here, noise has been reduced between the first and second releases of the timewise solution so that the TIM2 MDT is about 50% less noisy than the GRACE MDT under the metric specified. Incidentally, since the calculation method is the same in all cases, this shows that this is true geoid commission error rather than being merely numerical issues associated with the spectral calculation method.

Figure 4 shows the currents computed from the GOCE MDTs (to d/o 180) once the MDTs have been diffusively filtered. The number of iterations required in each case to minimise the RMS difference between the geodetic and Niiler MDTs, as defined above, are shown above the panels. This is the halting criterion for the filtering procedure, analogous to choosing the filter radius for a spatial averaging filter. As expected, the number of iterations is closely related to the noise in the unfiltered MDTs. Thus, the DIR1 MDT required less filtering than the other two first generation models and there is little difference in the number of iterations required for the DIR1 and DIR2 MDTs, while, of the second generation models, the TIM2 MDT requires less filtering than the TIM1 MDT.

From visual inspection alone there is little to distinguish the current maps in Figure 4. Therefore, in Figure 5, we compare the currents at nine locations, considered of oceanographic interest, as marked in Figure 4e. For comparison, also included are current speeds at the same location from Niiler and from the ITG2010S MDTs. Because the GRACE MDT is much more noise than any of the GOCE MDTs, it requires much more filtering (235 iterations). We should expect, therefore, that in general the GRACE currents will be more attenuated than those from GOCE. With the exception of location 8, were the current speeds are similar sue to residual noise in the GRACE MDT boosting the current estimated from GRACE here, this is just what we find; at all other locations the cur-

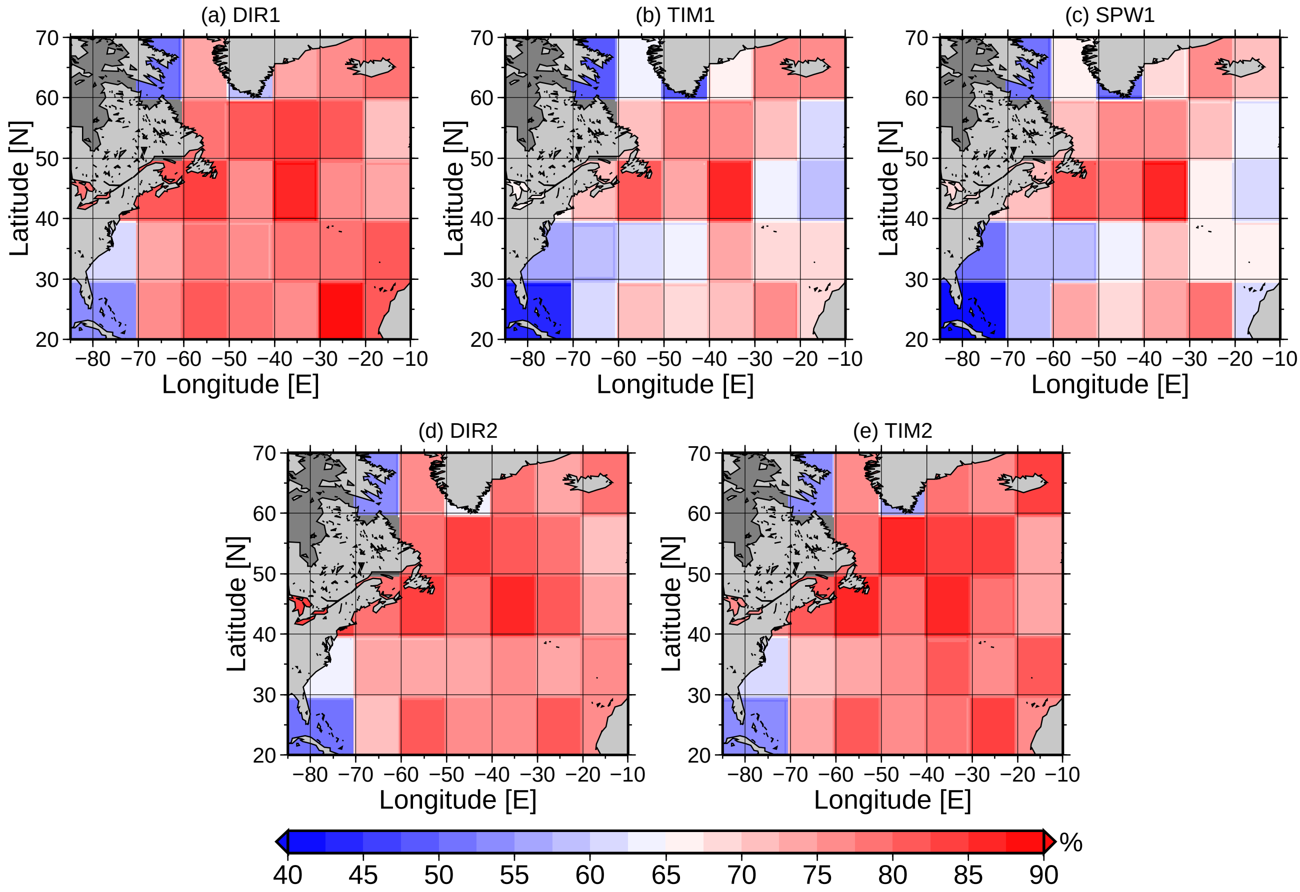

Figure 3. The reduction in the noise of the GOCE MDTs relative to the GRACE ITG2010S MDT, where noise is here defined as the RMS difference, computed over the 10x10 tiles shown, between the currents obtained from the geodetic MDTs and the currents from the Niiler drifter-only MDT.

rents speeds from the GOCE MDTs are, by varying degrees ,greater than those from GRACE. For locations 2 and 3 along the Gulf Stream the difference is greater than 20 cm/s. The most marked difference with the Niiler currents is at location 1. Because of the path taken by the current here through a narrow passage this is a challenging current for the filtering method to preserve. At the other locations the agreement between Niiler and the GOCE currents is remarkable good. Surprisingly, perhaps, at four locations the currents from GOCE exceed those based on the in-situ data. At location 7, which samples the West Greenland Current, where the difference is most marked, this seems to result from the Niiler estimate failing to properly capture the current along this coastline. This may be due to sparse sampling in this ice prone region. Location 5, corresponds to the North Atlantic Current, and the difference here seems to result from this current being better resolved in the GOCE estimates. Finally ,at location 3, the Niiler estimate seems too weak by about 10 cm/s.

The reader will note, however, there does not seems to be systematic differences between the GOCE estimates, in so far as there is not a clear relationship between the number of iterations required to filter each MDT and the relative strength of the currents derived from it. This would suggest that any differences in current speeds due to 20 iteration range among the GOCE MDTs cannot be resolved against the impact noise may have on the filter.

4. GOING BEYOND DEGREE AND ORDER 180

In the previous section we limited all of the MDTs to d/o 180, even though more spherical harmonic terms are available for each of the GOCE gravity models. This essentially showed that the reduced noise in all of the GOCE MDTs due to reduced geoid commission error in the GOCE gravity models, compared with the noise in the GRACE MDT, enabled a better estimate of ocean currents because less noise entailed less filtering, and therefore less attenuation of ocean currents. Yet, the noise differences between the GOCE MDTs themselves were not great enough to change how well the ocean currents could be resolved. We now consider whether the addi-

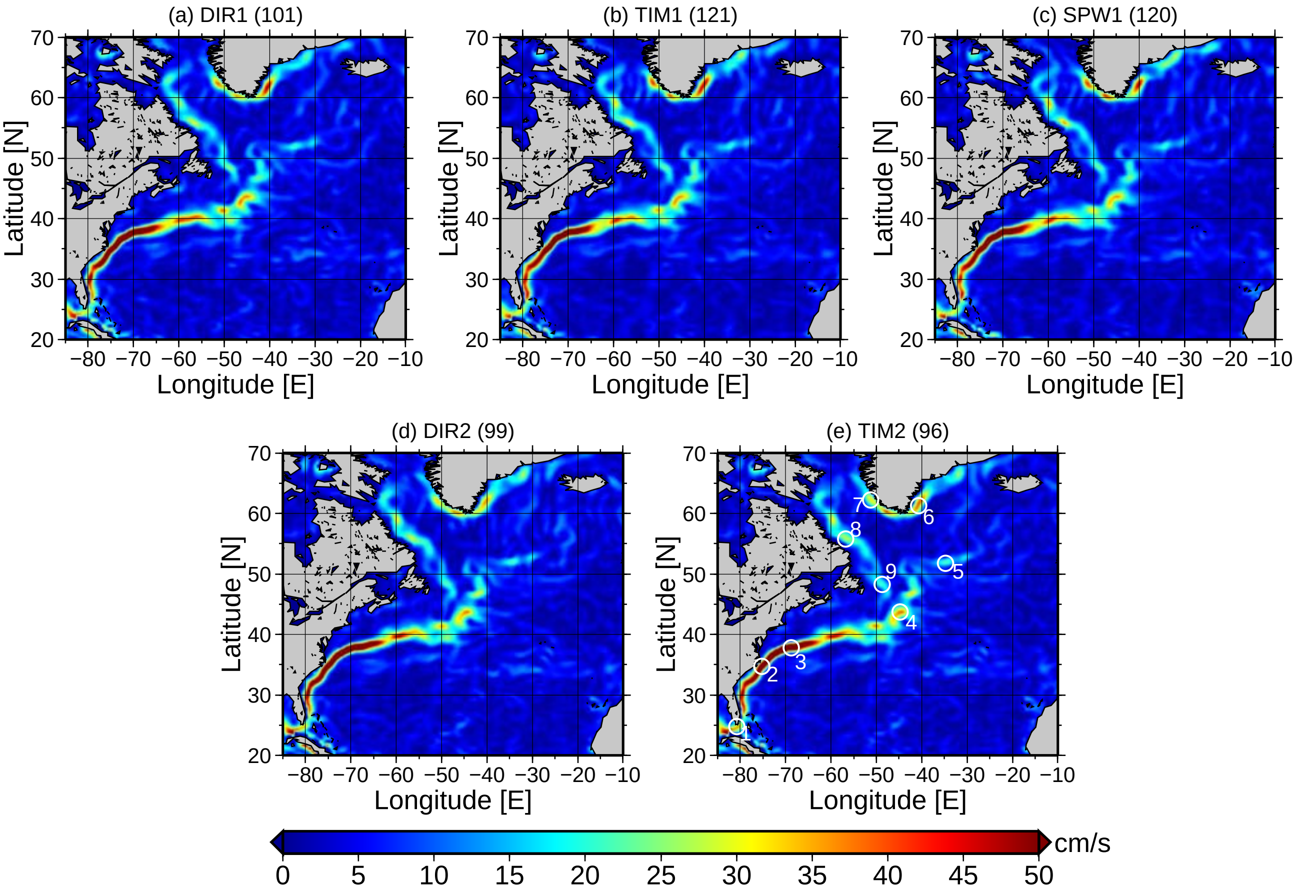

Figure 4. Geostrophic current speeds obtained from the GOCE MDTs shown in Figure 1 once the MDTs have been diffusively filtered as described in the text. The number of iterations required to minimise the RMS difference with the Niiler MDT are shown above each panel.

tional spherical harmonic terms that are available in the GOCE gravity models can be used to improve further the estimated currents.

Presently, the TIM2 MDT is given to the highest degree and order (250). Figure 6 shows ocean current speeds from TIM2 MDTs computed in 10 d/o intervals from d/o 180 to d/o 250. *Bingham et al.* (2011) (elsewhere in this volume) show how geoid commission errors grow with increasing d/o of truncation. Figure 6 clearly demonstrates how this geoid commission error leads to increasingly noisy current speeds as the truncation d/o is increased, such that at d/o 210 the noise, particularly at lower latitudes, has a similar magnitude to the currents we are trying to resolve. At d/o 250, even the Gulf Stream cannot be resolved against the noise. From the discussion above, it should be clear that as the d/o is increased, the number of filter iterations require to minimise the RMS difference with the independent Niiler estimate is going to grow. The question is, therefore, at what point does this requirement for ever more severe filtering, negate any advantage to be had, in terms of additional signal, from the extra spherical harmonic terms?

Reflecting the visual impression from figure 6, the average RMS residual prior to filtering for the currents determined for the TIM2 MDTs grew from 17 cm/s at d/o 180 to 64 cm/s at the maximum d/o of 250. In line with this, the number of iterations required to minimise the RMS difference between the geodetic currents and the Niiler currents rose from 96 to 191, with the finally obtained residual maintaining a relatively constant value of about 9 cm/s.

From a visual inspection alone of the current speed maps (not shown) derived from the filtered MDTs there is little to distinguish between them over the range of truncations shown in Figure 6. We, therefore turn again to a comparisons of current speeds at the nine locations described above. Again a systematic pattern, showing a clear and consistent d/o threshold that maximises the current speed is not obvious. If, however, we consider only those locations (1, 2 and 8) where the GOCE estimates are always lower than the in-situ estimate, then closet agreement, that is, the maximum current strength, is found at d/o 190 or d/o 200 (second or third bars). For the location where the GOCE estimates span the in-situ estimate

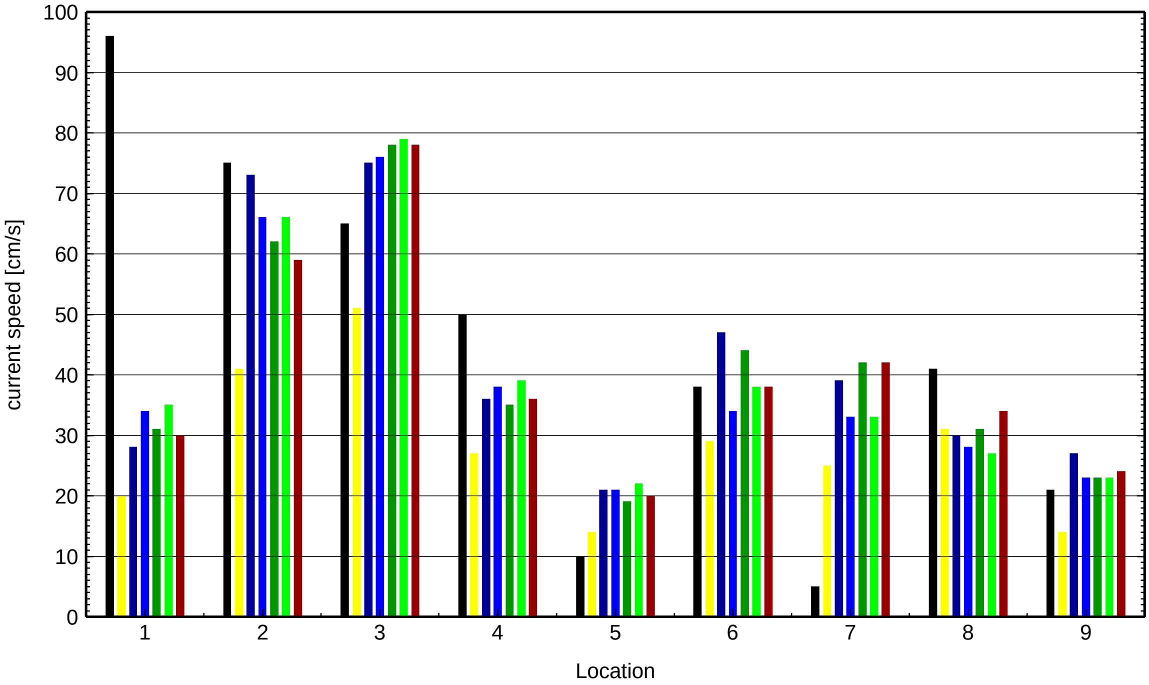

Figure 5. A comparison of current speeds obtained from the diffusively filtered MDTs shown in Figure 4 at the nine locations marked in Figure 4e. DIR1 (dark blue), DIR2 (blue), TIM1 (dark green), TIM2 (green), SPW1 (dark red). Currents at the same locations from the Niiler drifter only MDT are shown in black (no filtering), and the currents from the diffusively filtered GRACE ITG2010S MDT are shown in yellow.

(3, 4, 5, and 9), with the exception of location 9, the maximum current speed is found between d/o 200 and d/o 220. For the two locations where the GOCE estimate always exceeds the in-situ estimate (locations 5 and 7) and location 9, the maximum strength is attained for d/o 180. Taken together these suggest an optimum truncation of about d/o 200, and this is confirmed by visual inspection. Yet, it is clear from Figure 7, that for all of the locations considered, the difference between the currents obtained with truncation at d/o 180 and those obtained at the maximising d/o is quite small, the largest difference of about 15 cm/s being at location 4 - corresponding to the Mann Eddy.

5. CONCLUSIONS

In this paper we have compared the first five GOCE gravity models in terms of the mean North Atlantic circulation that can be derived from them. Because the high degree commission errors of all of the GOCE models are lower than those from the best satellite-only GRACE solution, all of the derived GOCE MDTs are much less noisy than the GRACE MDT. This is especially evident when currents rather than heights are considered, as in taking the height derivative we amplify the short scale noise. Quantifying the noise in the geodetic MDTs against the Niiler drifter-only MDT we find that for the second generation of GOCE models, based on 8 months of data, noise is reduced by between 40% and 80% compared with the best satellite only GRACE model. They therefore require less severe filtering and, as a consequence, the strength of the currents calculated from them are in better agreement with those from an in-situ drifter based estimate. Because the processing has remained consistent between the first and second generations of the timewise models, it is possible to demonstrate that the reduction in MDT noise from the additional data in the second release is substantial. However, given that some filtering is still required, this translates into only a small improvement in ocean currents.

That the improvement in terms of ocean currents between the first and second solutions is ultimately rather small, is partly a reflection of both the strength and limitations of the filtering method employed. Firstly, the diffusive filtering method employed is very successful at finding and preserving the gradients in the underlying MDT while removing the background noise, particularly for strongest currents such as the Gulf Stream. Therefore, if we restrict ourselves to a fixed degree and order such as 180, as we have done above in section 3, then despite the greater noise in the first generation models compared to the second generation, the filter can still effectively remove this noise without much additional effort, and the underlying gradients are preserved. Only when the noise is much greater, as it is for the GRACE estimate, does the addi-

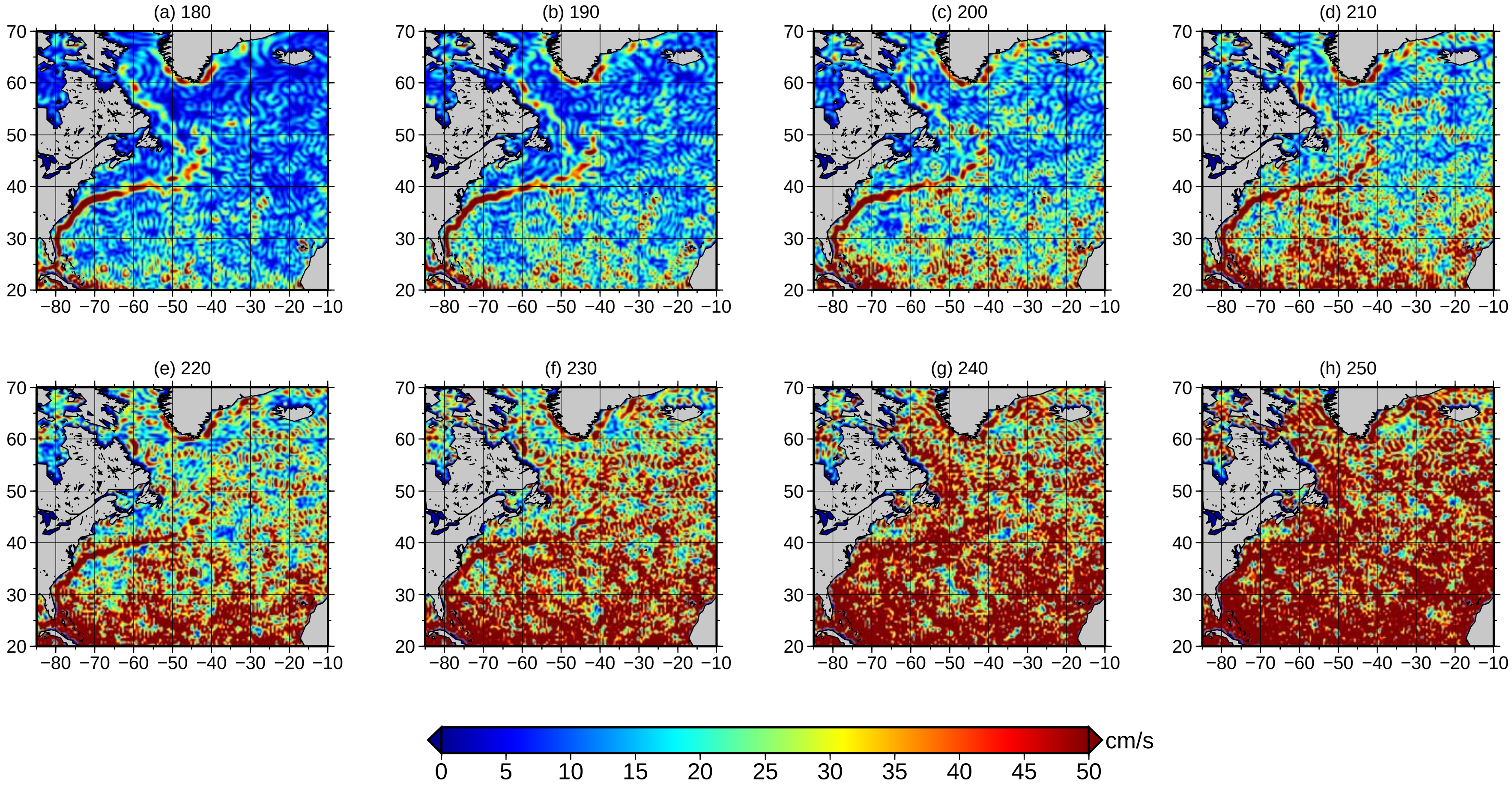

Figure 6. Geostrophic current speeds obtained from unfiltered TIM2 MDTs over a range of truncations as shown above the panels.

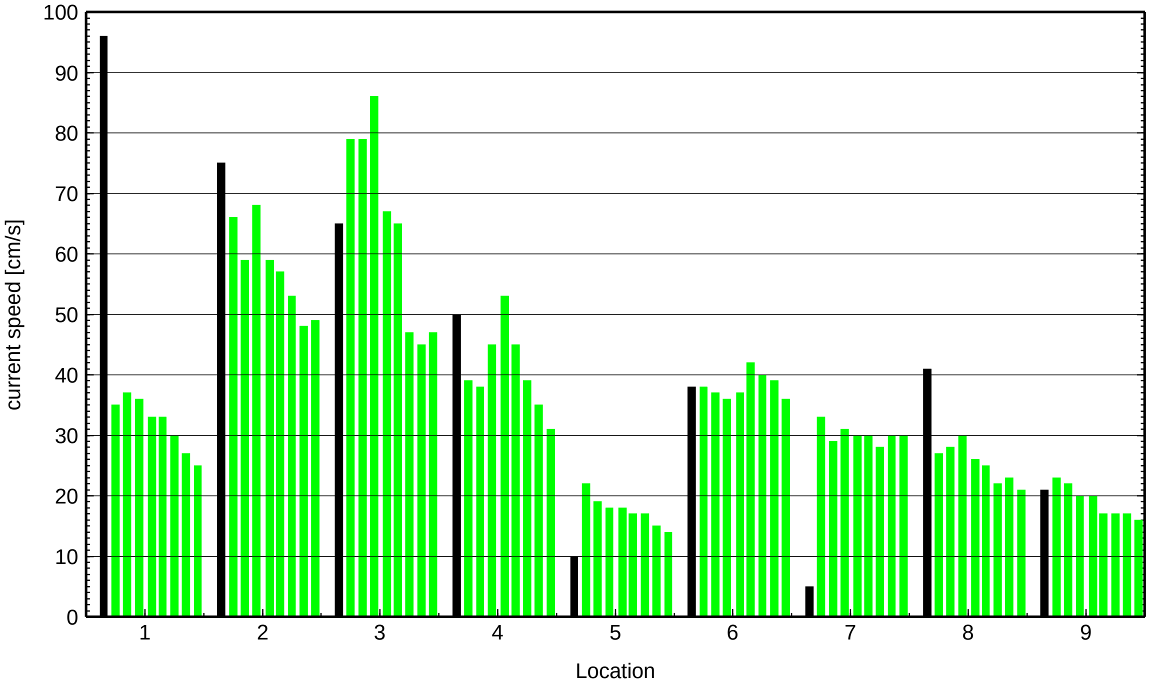

Figure 7. A comparison of current speeds, at the nine locations marked in Figure 4e, obtained from the TIM2 MDTs shown in Figure 6 once diffusive filtering has been applied. The leftmost bar at for each location represents the currents from the MDT truncated at d/o 180 while the rightmost represents the MDT truncated at d/o 250, with a 10 d/o increment between successive bars. Currents at the same locations from the Niiler drifter-only MDT are shown in black (no filtering).

tional effort by the filter result in substantial degradation of the signal.

The limitation of the filter reveals itself as we move beyond degree and order 180. At degree and order 250, for example, we expect the *MDT* omission error to have been reduced. Due the error characteristics of the gravity model, however, at d/o 250 the noise as grown substantially. A perfect filter would remove this noise while preserving the additional signal. With the filter employed here, we find a threshold at about d/o 210, beyond which the rise in noise, and the additional burden it places on the filter, means no additional signal can be extracted. So, although the diffusive filter is much more effective than simple Gaussian filtering, a more sophisticated filter, perhaps taking into account the error variance covariance information provided with the GOCE gravity models, may be required, as things stand, to extract the additional MDT signal present in the higher order terms. Of course, as the data record grows the noise may come down to a level at which any additional signal can be obtained without the need for advanced post-processing methods.

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