Mean Dynamic Ocean Topography in the Southern Ocean from GRACE and GOCE and Multi-mission Altimeter Data

Alberta Albertella, Roman Savcenko, Tijana Janjić, Reiner Rummel, Wolfgang Bosch, and Jens Schröter

Abstract

The ocean north of the Antarctic continent is one of the most dynamic ocean areas on our globe. It is also critical for the regulation of the global climate. We compute a high resolution mean dynamical ocean topography (MDT) using geodetic data and derive a detailed model of the global ocean circulation in this crucial area. The MDT is determined using multi-mission altimeter data and the GRACE/GOCE gravity model GOCO2s. The mean sea surface is observed from joint cross-over adjustment of 17 years of satellite altimetry. The two geodetic gravity missions GRACE and GOCE allow the computation of a global geoid with unprecedented accuracy and spatial resolution. While GRACE greatly improved the accuracy and global consistency of gravity models at long to medium wavelengths, GOCE is adding highly accurate geoid information in the medium wavelength range. The geoid and mean sea surface have been made consistent by a spectral filter. The MDT is represented as a spherical harmonic expansion. This allows us to analyze the oceanographic content in different wavelength bands. In order to assess properties of the MDT and of the derived geostrophic velocity field, velocities are compared with independent data from satellite tracked surface drifters in the area of the Antarctic Circumpolar Current (ACC). The RMS of the differences is less than 9 cm/s even if shortest scales (100 km) are considered. Our study shows that, with just 6 months of GOCE data, we are able to improve significantly the geodetic MDT.

Keywords

Gravity model • GOCE • Mean dynamic ocean topography • Geostrophic velocities

1 Introduction

The determination of the global mean dynamic ocean topography (MDT) is of fundamental importance for ocean and climate research (Wunsch 1993, 1996). A strong argument for the development of increasingly sophisticated satellite altimetry and refined geoid models was to derive the MDT from the combination of satellite altimetry and precise geoid models. This concept was one of the basic motivations which led to the development and realization of the present gravity field satellite missions CHAMP, GRACE and GOCE (Balmino et al. 1999). For the preparation of the GRACE (Gravity Recovery

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And Climate Experiment) and GOCE (Gravity field and steady-state Ocean Circulation Explorer) missions, a number of oceanographic simulation studies have been carried out, such as Le Grand (2001) and Schröter et al. (2002). The studies demonstrated that the new satellite geoid models will allow the determination of geostrophic surface velocities with an accuracy of a few cm/s. Recent studies (Bingham et al. 2011; Knudsen et al. 2011) show that the few months of data from GOCE provide already considerable improvements in the MDT determination and in the corresponding geostrophic velocities compared to a GRACE only solution. In this study a pure satellite gravity model GOCO2s derived from GOCE and GRACE data (Pail et al. 2010) and a new altimetric mean sea surface (MSS) are considered. The aim of this article is to show the improvement in the observations of global ocean due to the GOCE satellite with special attention to the Southern Ocean (south of 50°S latitude). We analyze the computed MDT as well as the derived geostrophic velocities, in various spectral ranges. Further, we compare the geostrophic velocities to the appropriately filtered geostrophic components of velocities measured by drifters in Southern Ocean.

2 Data

We have generated a new MSS, denoted DGFI10, averaging the measurements of altimeter missions with exact repeat periods (ERS-1/2, ENVISAT, TOPEX-Poseidon, Jason-1 and Jason-2), acquired within the time window from October 1992 to April 2010. The MSS heights are computed for the nodes of a regular $30' \times 30'$ geographical grid, far below the smallest filter length of the low pass filter, applied to generate the MDT. The DGFI10 MSS is constructed by a careful pre-processing of the altimeter measurements (Bosch and Savcenko 2012). The interpolation of the pre-processed altimeter data was performed with instantaneous sea surface heights reduced by a reference surface, here the CLS01 MSS (Hernandez and Schaeffer 2000). The along-track instantaneous heights were then averaged to fixed points along the nominal ground track and in a second step all mean instantaneous sea surface heights within the grid cells were averaged to a multi-mission mean anomaly. Finally, the CLS01 sea surface heights within the $30' \times 30'$ grid cells were averaged and added back to the multi-mission mean anomaly.

The geoid is the missing quantity needed for the computation of the MDT from MSS and it is calculated in our study from gravity field satellite data. There are two complementary gravity field satellite missions currently mapping the Earth's gravity field. GRACE is a joint US/German satellite mission. It uses low-low satellite-to-satellite tracking (SST) by a precise, dual-frequency microwave ranging system. The second mission is the satellite GOCE of the European Space Agency. It flies at an orbit altitude of only 255 km and uses gravity gradiometry (SGG) for the recovery of a high spatial resolution static gravity field (Rummel et al. 2011). In the low to middle part of the wavelength spectrum the low-low SST concept of GRACE determines the gravity field better than GOCE. Based on 6 months of data, GOCE measurements start to become superior at about harmonic degree and order 150 (≈133 km). In the range of spherical harmonic degrees between 120 and 150 the two missions have the same level of accuracy (Pail et al. 2010). In order to produce a geoid of high accuracy the gravity model GOCO2s combines the information from the mission GOCE with the normal equations of GRACE model ITG2010. More specifically GOCO2s model uses: 7 years of GRACE data, 12 months of GOCE's orbits data, 8 months of gradiometric GOCE data, 8 years of CHAMP and 5 years of Satellite Laser Ranging observations. The model is complete up to degree and order 250.

3 Mean Dynamic Topography (MDT)

The geodetic estimate of the MDT H is obtained by subtracting geoid heights N from the mean altimetric sea surface heights h:

$$H = h - N\,. \tag{1}$$

We want to represent both h and N in terms of spherical harmonic series. This simplifies the consistent filtering and allows a comparison of the spectrum of the MDT with results of the ocean circulation models (Janjić et al. 2011). In order to do this, the altimetric sea surface has to be extended over the land areas and over all the areas of missing ocean data. In this way the entire globe has been covered. This process requires much care in order to avoid boundary effects at the land/ocean transitions. Experience shows that it is essential to use an appropriate reference surface on land (Albertella and Rummel 2009; Bingham et al. 2008). In our computation, the land is filled with the geoid filtered to degree 180 from the GOCO2s model. Then, to smooth the transition along the coastline, a moving window operator is applied to each point of the land areas. The value $H(\vartheta_i, \lambda_j)$ in each land point is replaced by a moving 2D box car average of the values of the surrounding grid points:

$$\bar{H}(\vartheta_i, \lambda_j) = \frac{1}{(2k+1)^2} H(\vartheta_{i+p}, \lambda_{j+q}) \tag{2}$$

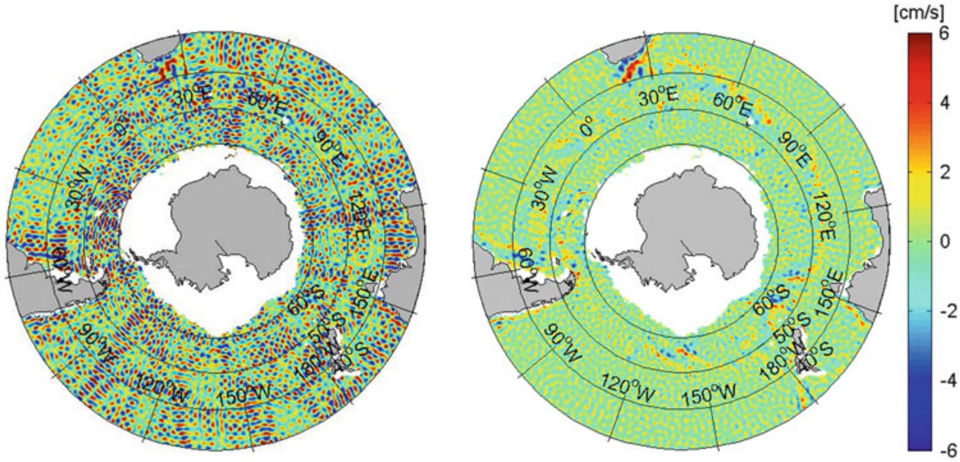

Fig. 1 Spectral bandwidths of the MDT from $L = 150$ to $L = 180$ (from ≈133 to ≈111 km) in the ACC area. In the *left panel* the MDT computed using ITG2010 is considered; in the *right panel* the MDT is computed using GOCO2s

where $p = -k, \ldots, k$ and $q = -k, \ldots, k$. Best results are obtained for $k = 4$. That procedure is applied during 30 iterations, maintaining in each step the original values on sea and considering the new mean values on land. The MDT is computed using Eq. (1) based on this extended MSS. The computed MDT can be expressed in terms of a spherical harmonic expansion as:

$$H(\vartheta, \lambda) = \sum_{\ell=0}^{L} \sum_{m=-\ell}^{\ell} T_{\ell m} Y_{\ell m}(\vartheta, \lambda) \qquad (3)$$

with $T_{\ell m}$ the spherical harmonic coefficients, $Y_{\ell m}$ the surface spherical harmonics of degree ℓ and order m, (ϑ, λ) the spherical latitude and longitude. In order to remove short wavelengths present in the MSS but not in the geoid, a Gaussian filter is applied spectrally acting on the spherical harmonic coefficients $T_{\ell m}$, as described in Zenner (2006). The advantage of the Gaussian filter is the elimination of side lobes in the spectral as well in the spatial domain. Unfortunately its spectral shape weighs down the high degrees and orders, just where the main improvement from GOCE is expected.

The MDT computed using the MSS DGFI10 and GOCO2s is compared with an independent MDT computed by Maximenko et al. (2009). In Maximenko et al. (2009) three MDTs are presented. We consider the MDT computed with a combination of satellite altimetry (data from 1992 to 2002), near-surface drifters, NCEP wind data and a GRACE gravity model. The RMS difference between our geodetic and the independent MDT, in the Southern Ocean, is equal to 8.57 cm when a filter up to $L = 180$ is applied to the geodetic MDT. This value is larger than what is reported in Knudsen et al. (2011) (7.73 cm), where a similar analysis is presented with a 140-km spatial Gaussian filter, corresponding to a maximum spherical harmonic degree of about 100, and with the earlier gravity model (GOCO1s). The higher RMS is due to the additional signal content of our MDT between degrees 100 and 180.

Equation (3) allows an analysis of the spectral content in different bandwidths. In this way it is possible to identify the parts of the oceanographic signal detectable on the shorter scales. Focusing on the ACC, in Fig. 1 the spectral bandwidth of the geodetic MDT from $L = 150$ to $L = 180$ is shown. When the MDT from GOCO2s gravity model is considered (right panel), a clear oceanographic signal is visible for example in the area of the Agulhas current ($20° < \lambda < 50°$) and in the Drake Passage area (around $\lambda = -60°$). For comparison an MDT model based on the GRACE model ITG2010 (Kurtenbach et al. 2009) is used. The expectation is that the strength of a pure GRACE model is confined to degrees up to 120 (or possibly 150) and that its accuracy rapidly decreases at higher degrees and orders. In the spectral bandwidth from $L = 150$ to $L = 180$ the noise dominates the signal, see left panel of Fig. 1. In the GOCO2s gravity model, the information coming from GOCE is affecting the spherical harmonic coefficients starting from $L = 150$. In Fig. 1 we can observe that, as to be expected, with only 6 months of data from GOCE we are able to better determine the short spatial scales of the MDT.

4 Geostrophic Velocities

The geostrophic flow is directly derived from the MDT. The formulas for the geostrophic surface velocities of the ocean circulation, in longitude (east) and in latitude (north) direction are:

$$v_e = -\frac{g}{f}\frac{1}{R}\frac{\partial H}{\partial \vartheta}\,, \quad v_n = \frac{g}{f}\frac{1}{R\sin\vartheta}\frac{\partial H}{\partial \lambda}. \qquad (4)$$

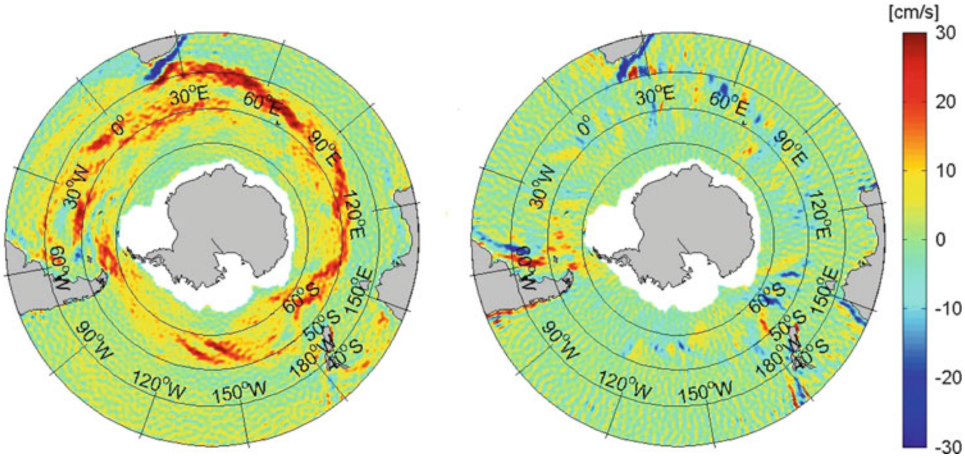

Fig. 2 Geostrophic velocities in the ACC area derived from the geodetic MDT. The Eastward component is shown in the *left panel*, the Northward component in the *right panel*. A Gaussian spectral filter to approximately degree $L = 180$ is applied

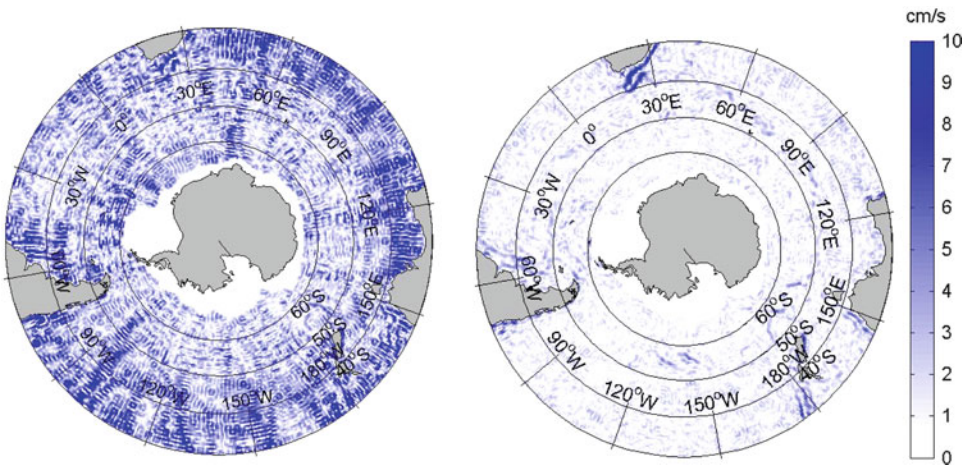

Fig. 3 Spectral bandwidth of the geodetic surface velocities (modulus) from $L = 150$ to $L = 180$ (from ≈133 to ≈111 km) in the ACC area. In the *left panel* the MDT computed using ITG2010 is considered; in the *right panel* the MDT is computed using GOCO2s

Here g is the gravitational acceleration, $f = 2\Omega \cos\vartheta$ the Coriolis term, Ω angular velocity of the earth, λ the longitude, ϑ the colatitude and R the earth radius. These equations express the surface geostrophic velocities of the ocean circulation and they give good insight into the main patterns of the ocean circulation. In Fig. 2 the surface velocities in the ACC area computed from the MDT and filtered up to $L = 180$ are shown. Although some noise is present, the currents in this area are clearly delineated.

Also for the surface velocities it is interesting to analyze the information content of the shortest scales, taking into account that the effect of the derivatives with respect to ϑ and λ is an amplification of the high degrees and orders of the spherical harmonic expansion that is proportional to $(L+1)$. In Fig. 3 the bandwidth range between $L = 150$ and $L = 180$ of the modulus of the geostrophic current speeds is shown. The information contained in this bandwidth from only GRACE is poor and noisy, left panel of Fig. 3. When the GOCO2s gravity model is considered (right panel Fig. 3), a significant contribution of the Agulhas current is visible.

To validate the computed geostrophic velocities, derived from our geodetic MDT, a comparison with in-situ measurements is done. The Global Drifter Program of NOAA and AOML collects data of the satellite-tracked drifting buoys ("drifter") measurements of upper ocean currents and sea surface temperatures around the world. These raw data are processed applying quality control procedures and interpolated via Kriging to regular 6-h intervals.

At http://www.aoml.noaa.gov/envids/gld/ a large set of data is available from February 1979 to December 2010, covering almost all of the sea surface (Lumpkin and Pazos 2007). The number of measurements from 1.1.1993 to 31.12.2010 is shown in Fig. 4; we can observe that this number is definitely small south of parallel $-50°$. The velocity extracted from the drifting buoy path includes the tide currents, Ekman currents, inertial currents and other high-frequency non-geostrophic

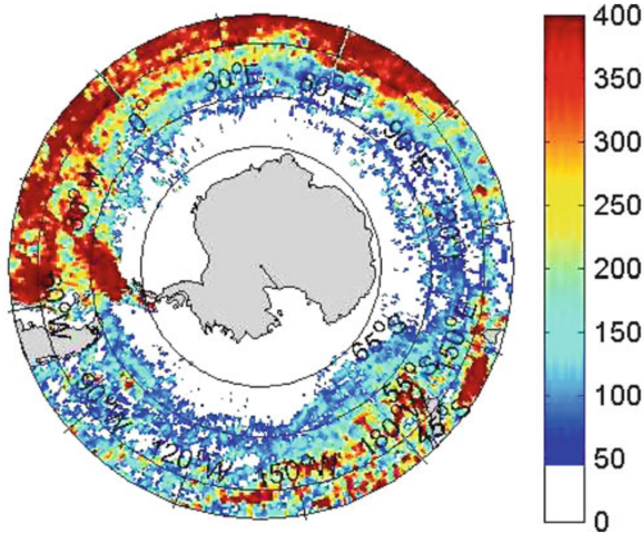

Fig. 4 Number of drifter measurements (per cell of 30′ × 30′ grid) in the ACC area, from 1.1.1993 to 31.12.2010. Data from http://www.aoml.noaa.gov/envids/gld

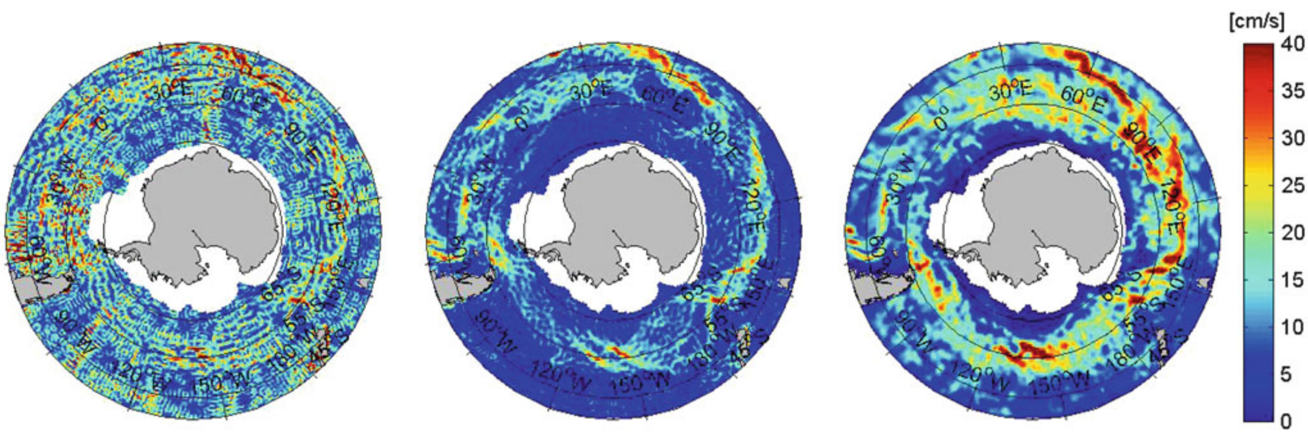

Fig. 5 The modulus of the surface current speed from geodetic MDT, using GRACE data (*left panel*) or GOCE data (*middle panel*), and from in situ measurements (*right panel*) in the ACC area. Gaussian filter up to $L = 180$ is applied on the three fields. Units are cm/s

contributions. To extract only the geostrophic component of the drifter data, an estimate of the Ekman component is considered (Albertella et al. 2012). Furthermore the surface velocities corresponding to the time series of Sea Level Anomalies are taken into account, as described in Albertella et al. (2012).

The drifter measurements in the area of the ACC from 1.1.1993 to 31.12.2010 are considered. After application of the above corrections, the measurements are averaged on a grid 30′ × 30′. In Fig. 5 the modulus of the surface current speed computed from the MDT relative to ITG2010 (left) and to GOCO2s (middle) is shown. They can be compared with the modulus of the geostrophic velocities from in-situ measurements (right panel). The geodetic surface velocities are generally smaller than those obtained from in situ measurements. In the Drake Passage area and around $\lambda = 60°$ there is good agreement, while in the area south of $\varphi = -50°$ the differences are high reaching up to 20 cm/s. The areas in which high discrepancies exist often have poor drifter coverage. In Table 1 mean and RMS of the differences between measured drifter velocities and geostrophic velocities computed from MDT are shown, after applying filters with various spatial resolutions. Also when the shorter scales are included (L filter = 180 and $L = 210$) the RMS of the differences is less than 8 cm/s for both components. When ITG2010 is considered, the RMS of the differences becomes worse. The RMS of the measured drifter eastward component v_e is 17.62 cm/s, for the northward component v_n it is 12.12 cm/s. Therefore the geostrophic velocities as computed from the MDT are acceptable, because the relative error is about 25 %. Further investigations will consider the assimilation of the geodetic MDT in numerical ocean models. In Janjić et al. (2012) it was shown that assimilation of geodetic MDT data improves significantly free model results for temperature

Table 1 Statistics of the differences between estimated geostrophic velocities from drifter measurements and geostrophic velocities from the geodetic MDT in the ACC area. Different filter resolutions L, corresponding to different spatial scales, are considered. The statistics in parenthesis refer to a land/ocean mask which excludes areas without altimetric data and (in bold) to a land/ocean mask which excludes also areas where less than 50 observations available. $\Delta v_e = v_e^{drifter} - v_e^{geo}$ are the differences between the Eastward components, $\Delta v_n = v_n^{drifter} - v_n^{geo}$ are the differences between the Northward components and ΔV is the vector difference between drifter-based and GOCE-based currents. The RMS are computed after removal of an offset (5.36 cm/s for the Eastward component and −5.00 cm/s for the Northward component). Units are cm/s

L	km	$m(\Delta v_e)$	$m(\Delta v_n)$	$m(\Delta V)$
120	≈ 167	**−0.01** (−0.19)	−0.01 (0.81)	**4.43** (5.24)
150	≈ 133	**0.00** (−0.11)	−0.04 (0.80)	**5.04** (5.85)
180	≈ 111	**0.00** (−0.16)	−0.06 (0.79)	**6.61** (7.26)
210	≈ 95	**0.00** (−0.14)	−0.08 (0.78)	**9.55** (9.91)
L	km	$RMS(\Delta v_e)$	$RMS(\Delta v_n)$	$RMS(\Delta V)$
120	≈ 167	**4.38** (5.06)	**2.78** (3.40)	**5.20** (6.10)
150	≈ 133	**4.84** (5.57)	**3.39** (3.94)	**5.91** (6.82)
180	≈ 111	**5.86** (6.53)	**4.88** (5.25)	**7.63** (8.38)
210	≈ 95	**7.91** (8.38)	**7.48** (7.61)	**10.89** (11.32)

also in areas that are without altimetric coverage. This study suggests that the geodetic MDT in Southern Ocean could provide additional information to hydrographic data that are naturally sparse in space and time and often limited to summer months. Southern Ocean presents a challenge not only due to sparsity of data but also for ocean modeling due to poor knowledge of surface forcing and prevailing strong winds, inadequate parametrization of subgrid processes and missing details of the complex bottom topography used in the model (Gille 2003).

5 Conclusions

The computation of the MDT from the new altimetric model DGFI10 of the mean sea surface and the geoid model GOCO2s data shows good agreement with the independent MDT of Maximenko et al. (2009). GOCE is adding short wavelength geoid information, in particular between spherical harmonic degrees 150 and 200, corresponding to spatial scales of between 130 and 100 km. With GOCE collecting more and more data the accuracy of this spectral range will further increase. This strength of GOCE at shorter scales is even more pronounced when looking into geostrophic velocities as derived from the geodetic MDT. In terms of spherical harmonics, this derivation implies an amplification by a factor $(\ell + 1)$ per spherical harmonic degree ℓ. Filtering is necessary in order to get the altimetric surface spectrally consistent with the geoid model. Gaussian filtering, as applied here, has nice symmetrical properties in the space and spectral domain. However, it has the severe disadvantage of significantly reducing the signal power at higher degrees (and shorter spatial scales). Some alternative must be investigated. The filtering procedure can also not fully eliminate some Gibbs oscillations along coastal lines and short scale altimetric (e.g. tectonic) features, compare Bingham et al. (2011). The agreement of the geostrophic velocities as derived from the geodetic MDT with those based on drifter data is acceptable, but there seems room for improvement. This concerns both a better procedure for the isolation of the geostrophic part from the drifter velocities (including realistic error estimates) and improved filter procedures for the geodetic part. With GOCE—in combination with many years of high precision radar altimetry—it is now possible to derive MDT and the geostrophic velocity field, globally consistent, with rather high spatial resolution and independent of oceanographic data and modeling. It will turn out to be an increasingly valuable new data source for ocean studies and, in particular, for assimilation into ocean circulation models.

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