THE DTU12MDT GLOBAL MEAN DYNAMIC TOPOGRAPHY AND OCEAN CIRCULATION MODEL

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Abstract.

The Gravity and Ocean Circulation Experiment - GOCE satellite mission measure the Earth gravity field with unprecedented accuracy leading to substantial improvements in the modelling of the ocean circulation and transport. In this study of the performance of GOCE, a newer gravity model has been combined with the DTU10MSS mean sea surface model to construct a global mean dynamic topography model named DTU10MDT. The results of analyses clearly demonstrated the value of the GOCE mission. Both the resolution and the estimation of the surface currents have been improved significantly compared to results obtained using pre-GOCE gravity field models. The results of this study show that geostrophic surface currents associated with the mean circulation have been further improved and that currents having speeds down to 5 cm/s have been recovered.

Introduction.

During the late eighties as satellite altimeter data became available globally over longer periods of time, huge efforts were made in the geodetic community to process global data sets to give joint analyses of geoid and ocean dynamic topography, along with a reduction in satellite orbit errors (Wagner, 1986, Engelis & Knudsen, 1989, Denker & Rapp, 1990, Marsh *et al.*, 1990, Nerem *et al.*, 1990). The quality of the available data were not sufficient to recover the details of the general ocean circulation, however the very large scales (>5000 km) of the dynamic topography could be recovered and compared with the early oceanographic results obtained from hydrographic data, e.g. Levitus and Boyer (1994). Already at this time the importance of consistency between the reference ellipsoids, as well as the role of the permanent tidal correction were identified as major issues. Meanwhile in local regions marine gravity data obtained from ships could increase knowledge of the gravity field, and thereby the geoid. Hence, such local data in combination with altimeter data did yield more accurate estimates and details of the dynamic topography (Wunsch & Zlotnicki, 1984, and Knudsen, 1991, 1992, 1993). More recently the release of satellite gravity data from the GRACE mission and the launch of the ESA Gravity and steady-state Ocean Circulation Explorer (GOCE) satellite on 17th March 2009 are providing more accurate and higher resolution global picture of the Earth's gravity field and its geoid. In turn, new details of the ocean dynamic topography is expected to be detected (Johannessen et al., 2003) (see also Hughes and Bingham, 2008).

The GOCE satellite mission is a new type of Earth observation satellite that measures the Earth gravity field with unprecedented accuracy. Combining GOCE geoid models with satellite altimetric observations of the sea surface height substantial improvements in the modelling of the ocean circulation and transport are foreseen. In this study of the performance of GOCE, the newer gravity models have been combined with the DTU10MSS mean sea surface model (MSS) to construct global GOCE satellite-only mean dynamic topography models (MDT). The computation of the MDTs follows the recommendations from the GOCE User Toolbox (GUT) tutorials and is carried out using GUT tools (Benveniste et al., 2007).

The GOCE gravity field models are released in three varieties, i.e. the models derived using the so-called direct method (DIR), the space wise approach (SPW) and time wise approach (TIM). They may all be used for this purpose. Bingham et al. (2010) already demonstrated the potential of GOCE using the TIM model in the Gulf Stream area. The evaluation of the GOCE based MDT was based on comparisons with a GRACE based MDT and a MDT based on oceanographic in-situ data constructed by Maximenko et al. (2009). The comparisons are carried out using MDT heights as well as the associated surface geostrophic current components. In Knudsen et al. (2011) the potential of GOCE was confirmed in a global analysis. In this analysis, the MDT is computed using the EIGEN-6C which combines information from GOCE with information from GRACE and terrestrial data into a high degree harmonic expansion gravity field model (Förste, et al., 2011).

Computation of the Mean Dynamic Topography

The practical task of computing a Mean Dynamic Topography (MDT) from a mean sea surface (MSS) and a geoid is conceptually very simple; however there are some issues that must be considered in order to obtain a good MDT product. Both the MSS and the geoid must be represented relative to the same reference ellipsoid and in the same tidal system. Then the MDT is expressed by

$$\zeta = \bar{h} - N \tag{1}$$

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where $\overline{h}$ is the height of the mean sea surface above the reference ellipsoid and N is the geoid height relative to the same reference ellipsoid. The mean sea surface is associated with a specific time period. When using the MDT together with satellite altimetry, it is important that the altimetry used for the MSS in the MDT calculation has the same corrections applied as the altimetry that is used for the computation of the sea level anomalies. Also, it is important that the reference time periods match.

Global gravity field models such as the GOCE models are normally represented in terms of spherical harmonic coefficient up to a certain harmonic degree and order L. Hence, when subtracting a geoid model based on such a set of coefficients from the MSS, then the residual heights

$$\Delta h = \overline{h} - N_L = \zeta + N - N_L = \zeta + \Delta N_L \tag{2}$$

consist of the MDT plus the unmodelled parts of the geoid associated with harmonic degrees above L. Naturally errors in both the MSS and in the gravity field model will play a role, but they are ignored at this stage. Subsequently, a proper filtering of the differences is required to eliminate the short scale geoid signals to obtain a useful estimate of the MDT. That is

$$\hat{\zeta} = F \circ (\zeta + \Delta N_L) \tag{3}$$

where MDT estimate is obtained by applying a filter F on the height residuals in eq.(2). The best estimate in a least squares sense

$$\begin{aligned} &\left\|\zeta - F \circ (\zeta + \Delta N_L)\right\| = \left\|\zeta - F \circ \zeta - F \circ \Delta N_L\right\| \\ &\leq \left\|\zeta - F \circ \zeta\right\| + \left\|F \circ \Delta N_L\right\| \end{aligned} \tag{4}$$

is obtained when the filtering does little harm to the MDT and minimizes the short scale geoid signals.

This filtering may be carried out in either the space domain, where the MSS is usually represented, or in the spectral domain where global geoid models are usually represented. Both methods have their advantages and their disadvantages. In both cases, it may be recommended to augment the GOCE spherical harmonic series using other higher degree harmonic expansions of the gravity field to reduce the magnitude of the short scale geoid signal in the MSS. The developments of methodologies for computing MDT models begun during the EU FP-5 GOCINA project (Knudsen et al., 2005, 2007 and 2007a). Research within the ESA GOCE User Toolbox study (GUTS) (Benveniste et al, 2007) looked at several procedures for determining the MDT, applying both space domain and spectral domain methodologies. Bingham et al. (2008) found that the spectral method is most efficient in removing the short scale geoid signals. However, the expansion of the residual heights into spherical harmonic coefficients may be tricky due to data gaps over land and at the poles. Also Losch et al. (2007) studied how different filtering methods perform and found that the spectral method is advantageous for filtering of global dynamic topography fields, but only in conjunction with remove-restore techniques that are designed to reduce the land-ocean discontinuity. For regional dynamic topography applications, the space domain methods are likely to be more efficient and accurate than spectral methods. For space domain methods filters with a Gaussian-like roll-off give more accurate results than those with sharp cut-offs space.

Surface geostrophic currents are associated with the slope of the MDT. If accelerations and friction terms are neglected and horizontal pressure gradients in the atmosphere are absent, then the components of the surface geostrophic currents (u,v) are obtained from the MDT by

$$u = \frac{-\gamma}{f\ R}\frac{\partial\zeta}{\partial\phi},\ v = \frac{\gamma}{f\ R\cos\phi}\frac{\partial\zeta}{\partial\lambda} \tag{5}$$

where f=2$\omega_e$sinφ is the Coriolis force coefficient, ω_e is the angular velocity of the Earth, R is the mean radius of the Earth, φ is the latitude, λ is the longitude, and γ is the normal gravity.

As mean sea surface the DTU10MSS is used. The geoid is computed using EIGEN-6C gravity model (Förste et al, 2011).

Subsequently, a proper filtering of the differences is required to eliminate the short scale geoid signals that are not recovered by the gravity model, to obtain a useful estimate of the MDT. Usually, the filtering is carried out using the isotropic truncated Gaussian filter with a half-width at half-maximum around 1.0 spherical degree. An example is shown in Figure 1.

In this study where the EIGEN-6C model is used, the unmodelled parts of the geoid is much smaller because EIGEN-6C is a combination model where, e.g., GOCE, GRACE and surface gravity based on satellite altimetry have been used. In addition, the shorter wavelength part of the geoid were removed using the EGM2008 geopotential model (Pavlis et al, 2008). Naturally, the use of altimetric gravity over the oceans will not improve the estimation of the MDT but less filtering is required. In this computation an isotropic truncated Gaussian filter with a half-width at half-maximum of 0.75 spherical degrees was used. Approaching the Equator an an-isotropic filter was used to overcome problems with stripes. Furthermore, the computation of geostrophic current components, especially the North-south velocity, was regularised at the Equator. The resullting geostrophic surface flows are shown in Figure 2.

Evaluation

The GOCE MDT (Figure 1) display the well-known features associated with the major current systems (e.g. Knauss, 1996) such as the Gulf Stream, the Kuroshio, the Agulhas, and the Antarctic Circumpolar Current (ACC) systems. In the Western Pacific Ocean the distinct high MDT values at the centres of the gyres associated with especially the Kuroshio are very clearly seen. Furthermore, high MDT values are also found at the gyre associated with the Agulhas current in the Southern Indian Ocean. In the Southern Ocean the MDT decrease by about 1.5-2.0 m across the ACC in accordance with its easterly flow direction.

The GOCE surface geostrophic current speeds and directions shown in Figure 2 and 3 respectively, display much more details about the mean ocean circulation. In Figure 2 the geostrophic flows of the Gulf Stream, the Kuroshio, the Agulhas, and the ACC systems are clearly depicted with their flows in the right directions. In addition, Figure 2 displays the Equatorial currents remarkably well. Especially in the Equatorial Pacific the Westward flow of the Equatorial current and the Eastern flow of the North Equatorial Pacific current are clearly seen. In the next section these findings are addressed in more details.

The evaluation of the GOCE preliminary MDT is carried out through comparisons with an MDT based on oceanographic in-situ data constructed by Maximenko et al. (2009). The comparisons are carried out using the associated geostrophic surface current components, mainly, since the MDTs appear very similar.

Both the GOCE based geostrophic surface currents (Figure 2) and the currents based on Maximenko's MDT (Figure 3) display the flows of the major current systems very clearly and consistently.

Going into a more detailed comparison of the recovered sub-current systems and their different flow paths, the GOCE flows agree very well with the Maximenko flows; e.g. in the Equatorial Pacific where the Westward flow of the Equatorial current and the Eastern flow of the North Equatorial Pacific current displayed by the GOCE flows are found in the Maximenko flows as well. Hence, the enhanced details in the GOCE MDT are consistent with the oceanographic in-situ data that was used in the derivation of the Maximenko MDT.

Discussion

The GOCE MDT display the well known features related to the major ocean current systems. In addition, the GOCE gravity model has enhanced the resolution and sharpened the geometry of those features. A computation of the geotrophic surface current speeds clearly display the improvements in the description of the current systems. Sub-current systems and their different branches and flow paths are revealed. The results of this analysis using a newer GOCE gravity model clearly demonstrate the success of GOCE mission. Future GOCE models are expected to further enhance studies of the ocean circulation.

The computation of the MDTs followed the recommendations from the GOCE User Toolbox (GUT) tutorials applying the so-called space domain method. With no doubt the filtering may be improved by incorporating elements of the spectral method especially for eliminating the influence of the short scale geoid. Also the use of optimal filtering methods where the actual error covariances are taken into account may lead to improvements and, in turn, provide error estimates of the filtered MDT.

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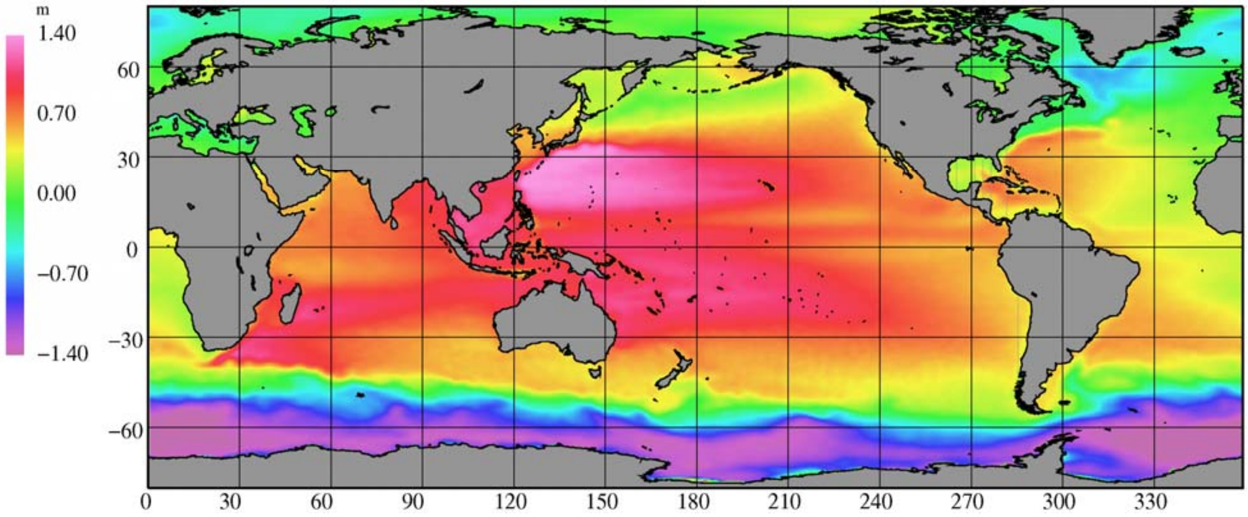

Figure 1. MDT based on GOCE.

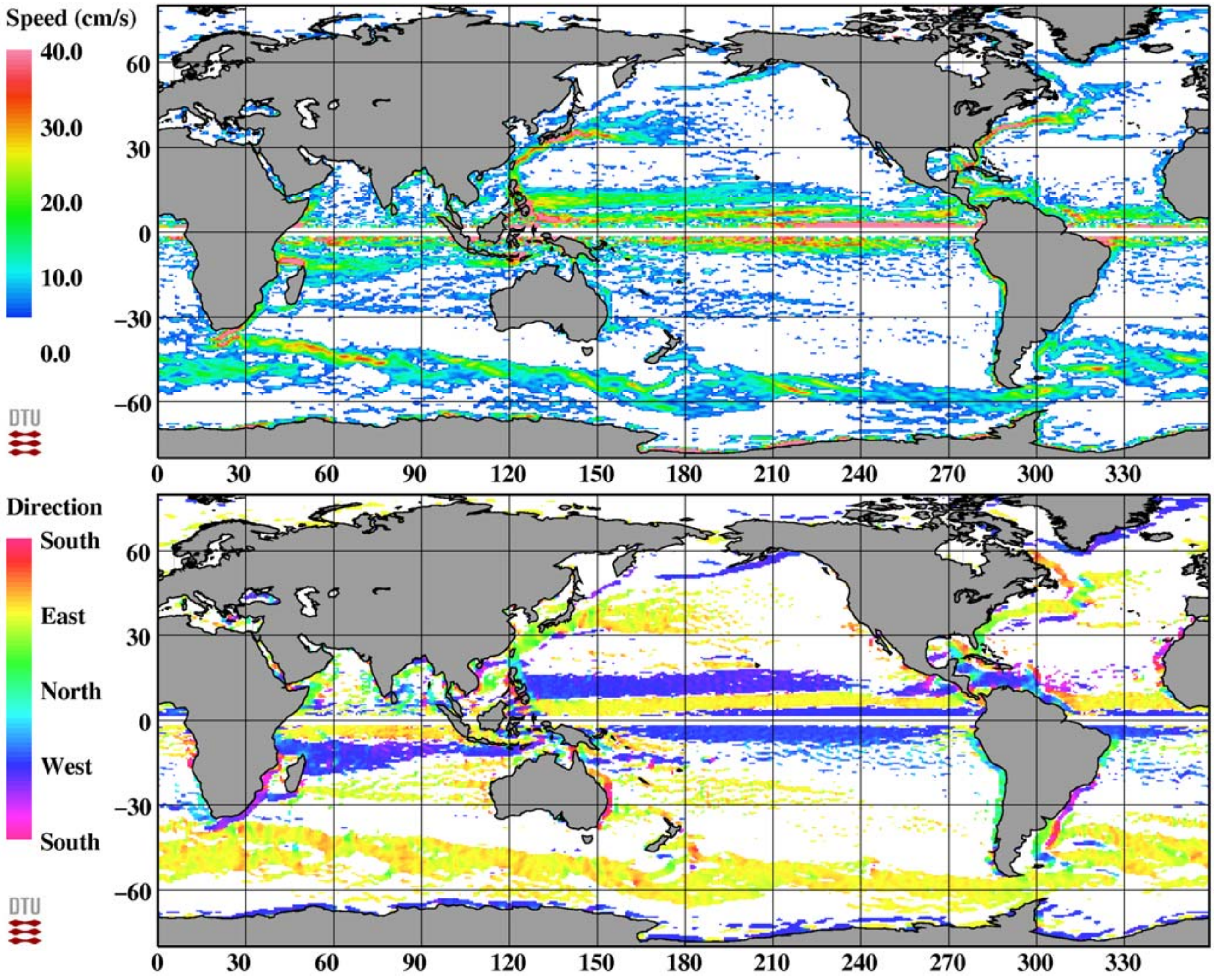

Figure 2. Surface geostrophic current speed and directions from MDT based on the DTU10MSS and EIGEN-6C.

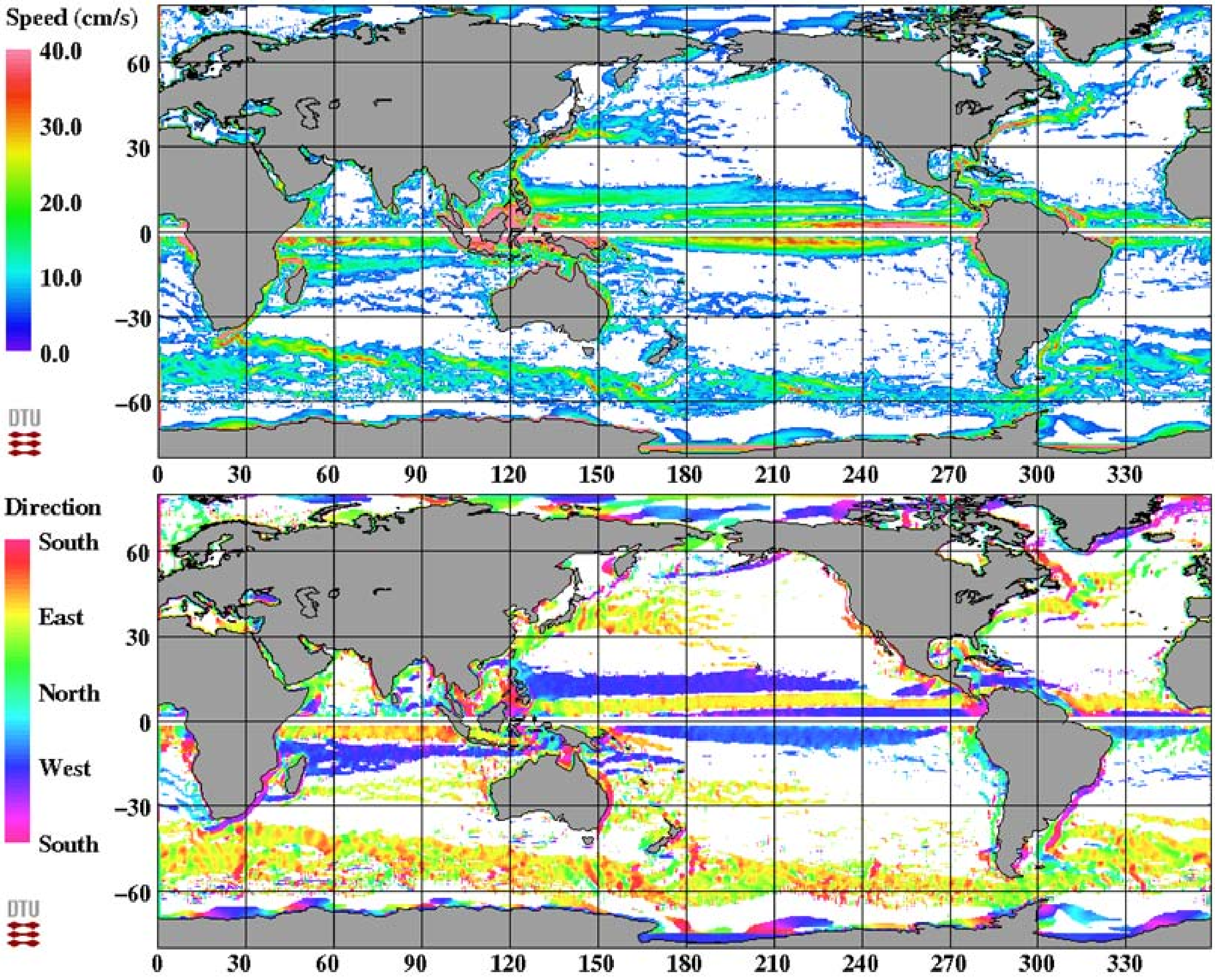

Figure 3. Surface geostrophic current speed and direction from Maximenko's MDT.