ENHANCED MEAN DYNAMIC TOPOGRAPHY AND OCEAN CIRCULATION ESTIMATION USING GOCE PRELIMINARY MODELS

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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, the new preliminary gravity models have been combined with the recent DNSC08MSS mean sea surface model to construct a global GOCE satellite-only mean dynamic topography model. At a first glance, the GOCE MDT display the well known features related to the major ocean current systems. A closer look, however, reveals that the improved gravity provided by the GOCE mission has enhanced the resolution and sharpened the boundary of those features. A computation of MDT slopes clearly displays the improvements in the description of the current systems. In the North Atlantic Ocean, the Gulf Stream is very well defined and the Labrador and the Greenland currents are clearly displayed. Furthermore, different branches of the North Atlantic Current are seen. In the North Pacific Ocean, the Kuroshio and its extension are well recovered, also with its branches. In the Southern hemisphere, both the Aghulas and the South Atlantic current systems are very clearly displayed. In the Antarctic Circumpolar Current system different flow paths are revealed. The results of this preliminary analysis using preliminary GOCE gravity models clearly demonstrate the potential of GOCE mission. Already at this stage the resolution and the estimation of the surface currents have been increased by at least a factor of two compared to similar pre-GOCE satellite-only studies. Future GOCE models are expected to further enhance studies of the ocean circulation.

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 are 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 new preliminary gravity models have been combined with the new DNSC08MSS 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 three preliminary releases of the GOCE gravity field models, i.e. the models derived using the so-called direct method (DIR), the space wise approach (SPW) and time wise approach (TIM) may all be used for this study. However, the direct method yielded the model with the highest resolution and it was found to be less noisy. Hence, the analysis was carried out using this model. 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

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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.

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

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

where $\bar{h}$ 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

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

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

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

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

Tabel 1. Standard deviations of quantities after filtering with a quasi-gaussian function with half-width at half-max values varying from 0.25° to 2.0° computed in a region covering $10<\varphi<50$ and $140<\lambda<220$ in the North Pacific.

Filter half-width (deg)	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
Geoid omission error (m)	0.165	0.040	0.009	0.005	0.004	0.003	0.002	0.002
GOCE-Maximenko MDT (m)	0.195	0.068	0.044	0.038	0.034	0.032	0.030	0.029
u component (m/s)	1.168	0.287	0.101	0.066	0.051	0.042	0.036	0.032
v component (m/s)	0.979	0.217	0.061	0.035	0.024	0.019	0.015	0.013

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

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.

The GOCE preliminary geoid

As mentioned above in the Introduction, the preliminary GOCE gravity field model derived using the so-called direct method (DIR) was used for this study. This model is represented in terms of spherical harmonic coefficients up to harmonic degree and order 240 and was found to have the highest resolution and to be less noisy. The direct method aims at optimally combining prior information (dominated by GRACE) with GOCE observations, resulting in a so-called combined model (Bruinsma, et al., 2004). GOCE data from the two months period from 1 November to 31 December 2009 was used.

The Mean Sea Surface

The DNSC08MSS mean Sea Surface (MSS) (Andersen and Knudsen, 2009) is the time-averaged physical height of the oceans surface derived from a combination of 12 years of satellite altimetry from a total of 8 different satellites covering the period 1993-2004. The MSS is truly global and has been derived without a polar gap by including all of the Arctic Ocean by including laser altimetry from the ICESat mission. DNSC08MSS is derived independently of any geoid model except for the region north of 86°N where no altimetry is available, and it has been derived using a 2-step procedure. In this procedure a coarse long wavelength MSS is initially mapped from the 12 years temporally averaged mean profiles of TOPEX and JASON-1 merged with the adjusted 8 year mean profiles from ERS-2 and ENVISAT. The adjusted mean refers to the fact that the ERS-2 and ENVISAT is initially fitted onto the 12 year mean of TOPEX+JASON-1 in order to ensure that no systematic differences between the two datasets remains. Subsequently retracked altimetry from the Geosat and ERS-1 Geodetic Mission (Andersen et al., 2010) is added using a remove-restore technique with respect to the coarse long wavelength MSS. This way, wavelengths with spatial scales down to roughly 15 km are being mapped in the final DNSC08MSS.

The GOCE preliminary Mean Dynamic Topography

Both the geoid and the MSS were referenced to the same reference ellipsoid and the same tidal system. Then the residual obtained by subtracting the geoid from the MSS were filtered in order to eliminate short wavelength geoid signals not recovered by the preliminary GOCE geoid model. Bases on experiences and tests using an isotropic truncated Gaussian filter with different filter widths were carried out for each filter width the effects of the filtering were evaluated using the standard deviations of filtered geoid residual associated with harmonic degrees above 240 as well as of filtered differences between the height residuals, eq.(3), and the Maximenko MDT (Maximenko et al. 2009). In addition to the height differences, standard deviations of the associated surface geostrophic current components derived using eq.(5), were computed.

The results of the analysis of the filtering (see Table 1) show that all quantities decrease rapidly with the half-widths increasing from 0.25 deg to 0.75 deg. With half-widths increasing from 1.25 deg to 2.0 deg, on the other hand, the standard deviation hardly decrease. For all quantities, the residual geoid signal associated with harmonic degrees above 240 is believed to cause this behaviour. Hence, the trade-off between minimising the effects the residual geoid signal and filtering as little as possible should be sought by selecting the filtering half-width between 0.75 deg and 1.25 deg. In this analysis the final filtering was carried out using the isotropic truncated Gaussian filter with a half-width at half-maximum of 1.0 spherical degree. With this filter width the standard deviations of the filtered differences between the GOCE MDT and the Maximenko MDT and the associated surface geostrophic current components u and v are 0.038 m, 0.066 m/s, and 0.035 m/s respectively. In addition, to smear out a North-south striping at low latitudes a zonal filtering was applied using a highly anisotropic filter with an East-west half-width at half-maximum of 1.5 degrees at the Equator and attenuating to 0 towards the poles as $\cos^4(\varphi)$. In the North-south direction the filter width was 0.25 degrees. Subsequently, the standard deviations of the differences between the filtered GOCE MDT and the unfiltered Maximenko MDT and the associated surface geostrophic current components u and v are 0.030 m, 0.070 m/s, and 0.050 m/s respectively. The resulting MDT is shown in Figure 1. The surface geostrophic current speed and direction are shown in Figure 2 and 3 respectively.

The GOCE preliminary 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 preliminary 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 and 3 display 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.

Evaluation

The evaluation of the GOCE preliminary MDT is carried out through comparisons with a GRACE based MDT and a MDT which has been enhanced by integrating oceanographic in-situ data (e.g. Rio and Hernandez, 2004, and Rio et al., 2005, Rio et al., 2009). In this evaluation the MDT constructed by Maximenko et al. (2009) was used. The comparisons are carried out using the associated surface geostrophic current components, mainly, since the MDTs appear very similar as pointed out above (See also Bingham and Haines, 2006).

The GRACE based MDT was derived using the EIGEN GL04S gravity field model up to harmonic degree and order 150 following the same procedure as described above for the derivation of the GOCE MDT. However, since the resolution of GRACE is poorer than GOCE the filtering was carried out using an isotropic truncated Gaussian filter with a half-width at half-maximum of 1.7 spherical degrees. In addition, a zonal filtering was applied to smear out the North-south striping at low latitudes. The GRACE derived surface geostrophic currents shown in Figure 4 while the surface currents based on Maximenko's MDT are shown in Figure 5.

Both the GRACE based surface geostrophic currents (Figure 4) and the surface currents based on Maximenko's MDT (Figure 5) display distinct and consistent expressions of the major current systems (Figure 3). However, by closer inspection it is evident that the GRACE based surface current fields clearly display less details than those based on the GOCE and Maximenko's MDT as expected from the coarser resolution of GRACE.

Both with respect to the surface geostrophic current speeds and the recovery of the many different flow paths the GOCE derived fields 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). Hence, the enhanced details in the preliminary released GOCE MDT and the corresponding surface geostrophic current are very promising and consistent with the oceanographic in-situ data that has been used to derive the Maximenko MDT. This is further quantified in the subsequent sections with focus on the Gulf Stream, the Kuroshio, the Agulhas, the Brazil-Malvinas confluence and the ACC.

Discussion

In this study of the performance of GOCE, the new preliminary gravity models have been used to construct a global GOCE satellite-only MDT. Naturally, it is important to have in mind that this preliminary first release GOCE model only use a subset of data processed using algorithms that may be improved as more experiences are obtained. Later releases of the GOCE gravity models will most probably be significantly improved. 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 associated with harmonic degrees higher than degree where the GOCE models has been truncated; in this case 240. Also the use of optimal filtering methods where the actual error covariances are taken into account may lead to substantial improvements and, in turn, provide error estimates of the filtered MDT (e.g. Knudsen et al., 2007).

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 preliminary analysis using preliminary GOCE gravity models clearly demonstrate the potential of GOCE mission. Already at this stage the resolution and the estimation of the surface currents have been increased significantly compared to similar pre-GOCE satellite-only studies. Future GOCE models are expected to further enhance studies of the ocean circulation.

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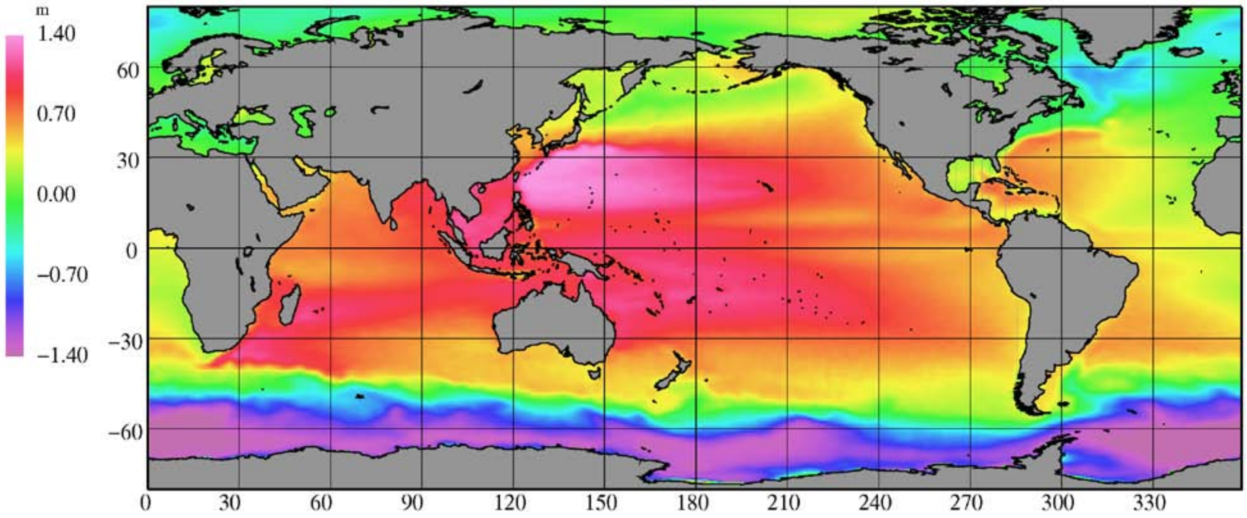

Figure 1. MDT based on GOCE.

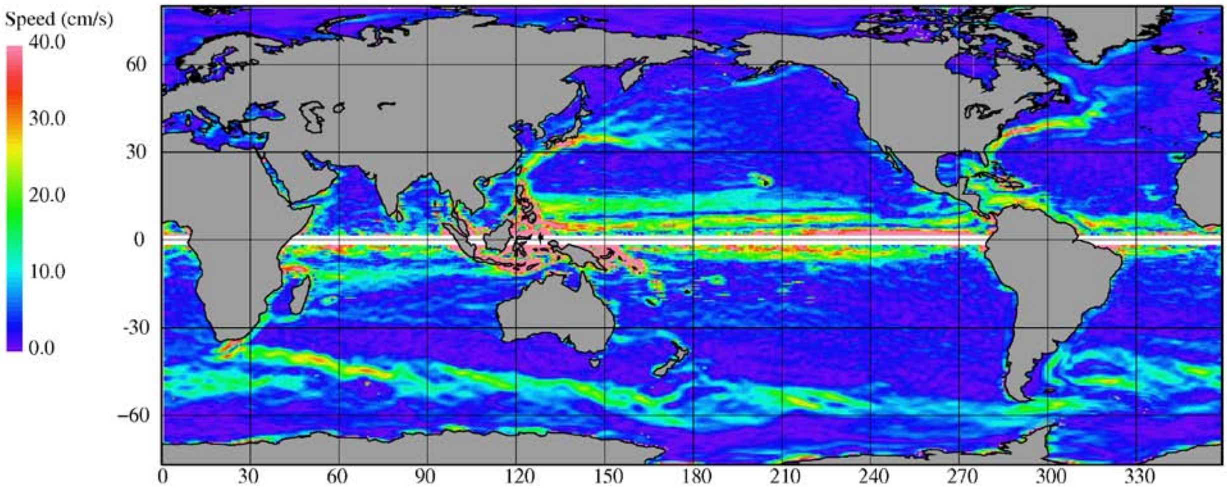

Figure 2. Surface geostrophic current speed from MDT based on GOCE.

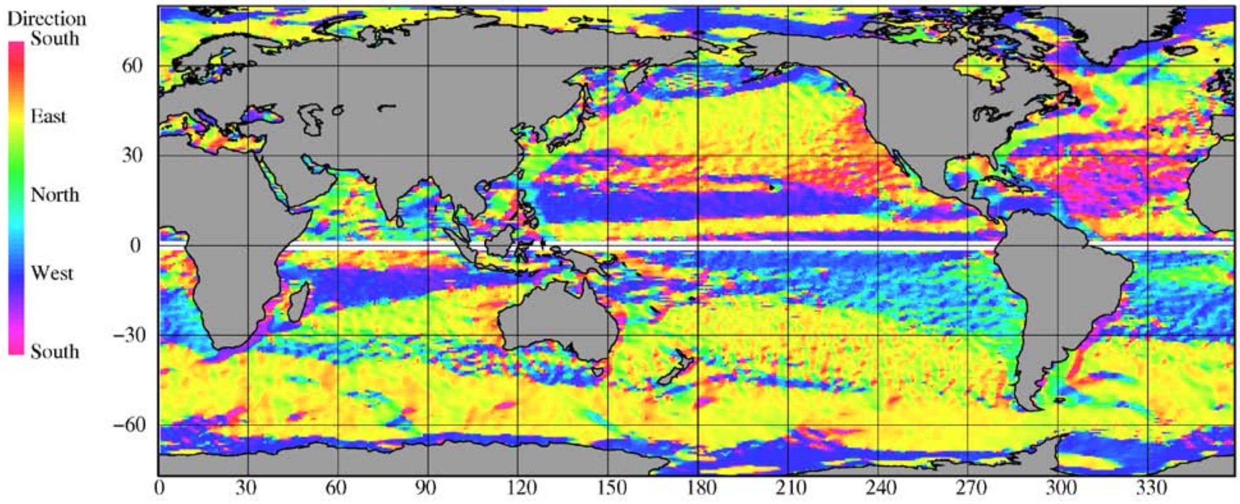

Figure 3. Surface geostrophic current direction from MDT based on GOCE.

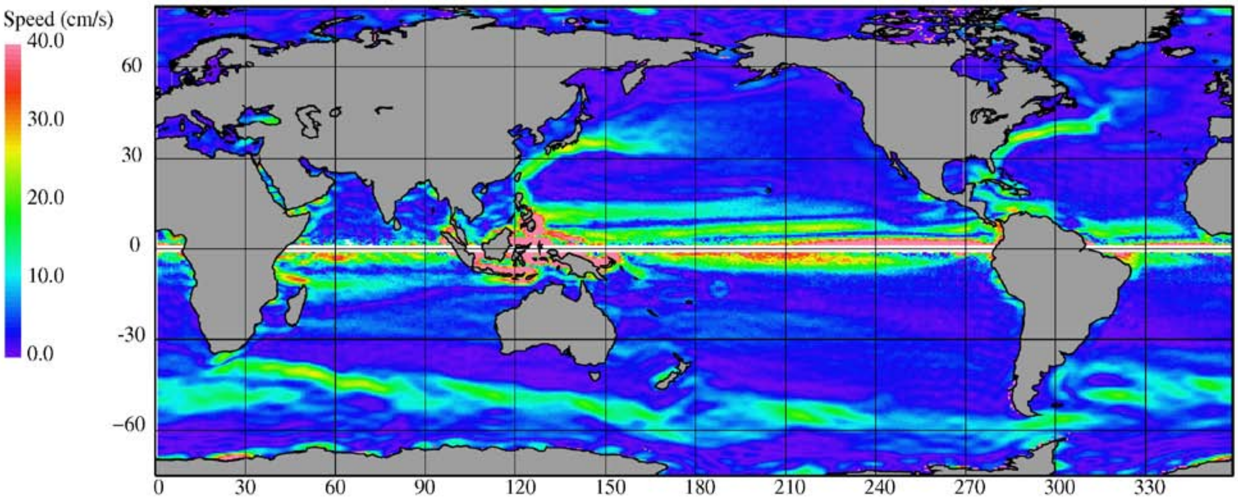

Figure 4. Surface geostrophic current speed from MDT based on EIGEN GL04S.

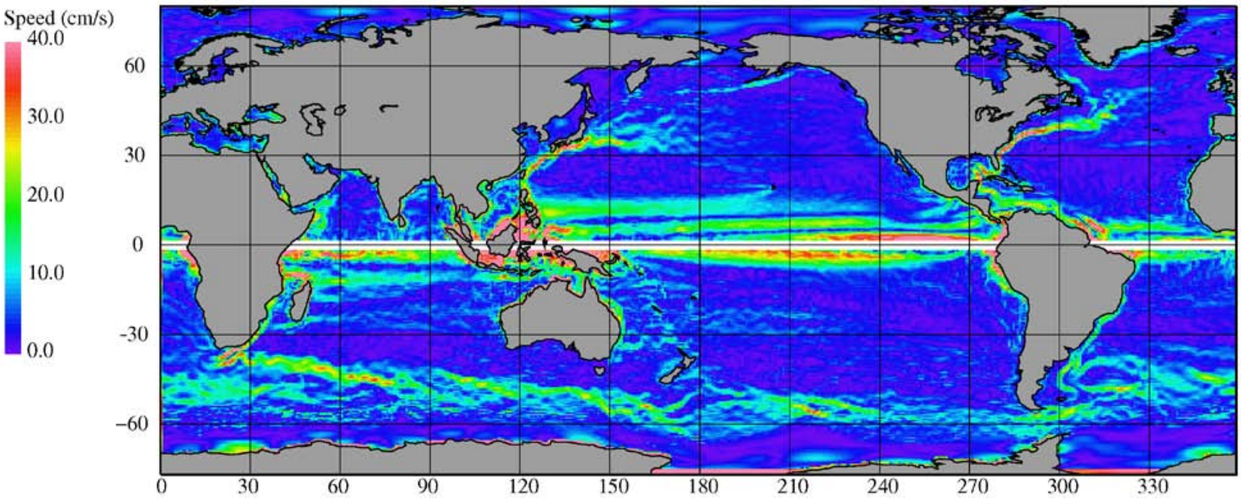

Figure 5. Surface geostrophic current speed from Maximenko's MDT.