The estimation of the ocean Mean Dynamic Topography through the combination of altimetric data, in-situ measurements and GRACE geoid: From global to regional studies

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Abstract. The contribution of a recent geoid model derived from GRACE data (EIGEN-GRACE03S) for estimating the ocean Mean Dynamic Topography is investigated for global and regional studies. The recent EIGEN-GRACE03S geoid model allows to greatly improved the estimate of the ocean Mean Dynamic Topography (hereafter GR3-400 MDT) at scales larger than 400 km. A global and full resolution estimate of the ocean MDT was calculated using a similar method than (Rio and Hernandez, 2004): synthetic estimates of the ocean MDT (dynamic heights and drifting buoy velocities minus concurrent altimetric height and velocity anomalies) are used to provide the short scales missing in the GR3-400 MDT and compute a Combined MDT on a ½° regular grid for the period 1993-1999 (CMDT RIO05). This new MDT compares globally better to independent observations than other existing solutions. A focus on the Mediterranean Sea is done to highlight the limits of GRACE geoids for oceanographic studies in areas where the MDT is characterized by scales shorter than 50-100 km. In such regions, the contribution of the future Gravity Field and Steady-State Ocean Circulation Experiment (GOCE) will be determinant, as shown by the confrontation between the GR3-400 MDT and a simulated “GOCE MDT”. However, in such areas, the GOCE data will not allow to resolve all spatial scales of the MDT and combination techniques will still need to be used to achieve the full resolution.

1. Introduction

This study lies within the framework of setting up, at national and international levels, operational ocean forecasting systems. A key issue is the computation of absolute altimetric signal for its assimilation into ocean general circulation models. For that purpose, the knowledge of either the marine geoid or the ocean Mean Dynamic Topography (MDT) is required with centimetric accuracy at spatial scales down to 50-100 km. In term of geoid, such a resolution is not achieved yet. Various estimates of the MDT are presently available, based on climatological datasets (Levitus et al., 2001), model outputs or drifter velocities (Niiler et al., 2003). Recently, a method was proposed by (Rio and Hernandez, 2004) – hereafter called RH04 – to compute a global MDT by combining in-situ measurements, altimetric data and a geoid model. A Combined MDT (CMDT RIO03) was computed on the 7 year (1993-1999) period used to reference the altimetric Sea Level Anomalies (SLA) distributed by AVISO. The geoid model used in the estimation was the EIGEN-2 solution computed from 6 months of CHAMP data (Reigber et al., 2003b). Significant improvements have been made
in estimating the marine geoid by the launch of GRACE (Gravity Recovery And Climate Experiment) satellites (Tapley et al., 2004). Tapley et al. (2003) highlighted the enhanced geostrophic currents evaluation permitted by the combined use of GGM01 model and an altimetric Mean Sea Surface (MSS) at scales longer than 500 km compared to the previous geoid model EGM96. The aim of this paper is to investigate the contribution of GRACE data to estimate the ocean Mean Dynamic Topography from global to regional scales. Globally, an improved Combined MDT was computed using the RH04 method integrating a geoid model based on GRACE data as well as an updated dataset of in-situ measurements. It is presented and validated in section II. In section III we focus on the Mediterranean Sea where the spatial scales of the mean circulation are known to be shorter than 100 km and where the resolution of GRACE geoid models is still too coarse to be used for oceanographic applications. A huge step forward will be done in the near future with the launch in 2006 of the Gravity Field and Steady-State Ocean Circulation Experiment (GOCE) satellite whose objective is to measure the geoid with centimetric accuracy at a 100 km resolution. A “GOCE MDT” is simulated to characterize the contribution and limits of future GOCE data in this area. Main conclusions and perspective are given in section III.

2. The Combined Mean Dynamic Topography RIO05

2.1 Estimation method

As stated in introduction, significant improvements have been made recently in our knowledge of the geoid down to 400 km by the exploitation of GRACE data. While the cumulated error at degree and order 50 (400 km spatial resolution) of the EIGEN2 geoid model was estimated to be at least 20 cm, it falls down theoretically to 7mm for the EIGEN-GRACE01S model (computed at GFZ from 39 days of GRACE data, see http://op.gfz-potsdam.de/grace ) and to 0.3 mm for the EIGEN-GRACE03S model (computed at GFZ from 376 days of GRACE data). Although the absolute value of the cumulated error may be uncertain, depending highly on calibration choices (Jean-Michel Lemoine, personal communication), the relative improvement between the various models is reliable and highly significant.

These results encouraged us to estimate an improved global MDT using the RH04 method. In RH04, the EIGEN-2 geoid was subtracted from the MSS CLS01 (Hernandez et al, 2001) at spherical harmonics degree 30 to provide a MDT at scales larger than 660 km. To provide scales shorter than 660 km, it was then merged with the MDT deduced from the Levitus climatology referenced to 1500m (Levitus et al., 2001) – hereafter Lev1500 MDT -. The merged field was used as a “first guess” for the computation of a global, full scale MDT. Again as described in RH04, T/P and ERS1, 2 measurements of the ocean variability were then subtracted to concurrent in-situ measurements of the full dynamical signal (buoy’s velocities from 1993 to 1999 and XBT, CTD casts from 1993 to 2001), providing “synthetic estimates” of the mean field - in terms of current or dynamic topography –that were used to improve the first guess using a multivariate inverse method.

In the present work, an updated first guess was constructed using EIGEN-GRACE03S instead of EIGEN-2. The geoid was first subtracted from the MSS CLS01 and a Gaussian filter was then applied to remove from the obtained MDT field the scales shorter than 400 km.
As described in RH04, the first guess is then completed at short scales using “synthetic estimates”. Here, an updated dataset of synthetic heights and velocities is obtained by collecting all in-situ measurements (buoy velocities and hydrological profiles) available from 1993 to 2002, ensuring a better coverage of the oceans. However, high latitudes remain poorly sampled. The synthetic estimates are averaged into $\frac{1}{4}^\circ$ boxes. The resulting box mean heights and velocities are finally used to improve the first guess using a multivariate objective analysis (for details, see RH04) and to map the ocean Combined MDT (hereafter CMDT RIO05) on a $\frac{1}{2}^\circ$ regular grid (Figure 1).

2.2 Evaluation of the RIO05 CMDT

To validate the estimated field, we compare the absolute height or velocity given by CMDT RIO05 plus SLA, to concurrent values given by drifter or hydrographic data. More than 680000 velocity measurements and 12500 hydrological profiles relative to 1500m, collected in 2003 and not used in the estimation procedure, are selected. Geostrophic velocities are derived from drifter trajectories. Because at high latitudes dynamic height relative to 1500m miss a significant part of the barotropic height measured by altimetry, we only consider hydrographic data equatorward of $40^\circ$ (7244 profiles).

To evaluate the improvements relative to previous work, global RMS differences of dynamic heights $H$ and geostrophic velocities $(U, V)$ computed using the RIO05 CMDT are compared to values obtained with the RIO03 CMDT, the Lev1500 MDT as well as two other MDTs computed recently: the first one (hereafter named NIILER MDT) was estimated on a $\frac{1}{2}^\circ$ grid by (Niiler et al., 2003) using drifting buoy velocities from 1993 to 2002 and corresponds to the ocean MDT over that same period. The second external MDT used was computed on a $1^\circ$ grid, as part of the ECCO (Estimating the Circulation and Climate of the Ocean) consortium for the period 1993-2002. In all two cases, for the purpose of our comparisons, the mean field was adjusted to
the period 1993-1999 by removing the SLA mean over 1993-2002. Comparisons are presented in Table 1. First, drifting buoy velocity comparisons show an improvement from RIO03 to the new RIO05 CMDT: RMS differences are reduced to 13.1 cm/s (resp. 12.3 cm/s) for zonal (resp. meridional) velocities. It is a significant improvement compared to the ECCO differences while values are rather close to NIILER’s differences. However, the NIILER MDT is not defined at high latitudes (where no drifting buoys were available) so that both fields can not be compared in these areas. The main benefit of using GRACE data appears here because the geoid model provides height information where no other in-situ dataset exist.

Over all oceans, the smallest RMS differences to dynamic heights are obtained using the CMDT RIO05 (Table 1). The difference reaches globally 10 cm RMS and is minimum in the Pacific Ocean (5.8 cm RMS). To properly compare absolute altimetric heights and in situ dynamic heights, both quantities have to be computed in the same reference frame. All tested MDT are adjusted to the mean value of the in-situ heights used in the comparison. Global RMS differences obtained with the NIILER and ECCO MDTs are high, what can be explained as follows: the sea level height relative to 1500m computed from hydrological profiles is, on average, higher in the Pacific and Indian oceans than in the Atlantic Ocean. For instance, the difference between the Pacific and Atlantic mean levels (equatorward of 40° latitude) in the Lev1500 MDT is 39 cm. A similar value is found for the RIO03 and RIO05 fields (38 cm) as well as in the GR3-400 MDT (42 cm). Conversely, higher values are found in the ECCO MDT (49 cm) and in the NIILER MDT (54 cm). The inconsistency in difference level computed between one ocean and the other compared to what is measured from in-situ data, results in a bias when adjusting globally the NIILER and ECCO mean fields to the in-situ dynamic heights. When focussing on single basins (Table 2), the bias vanishes and the RMS differences to observations are significantly reduced, though still higher than the values obtained with CMDT RIO05.

Table 1. Root Mean Square differences between in-situ heights and velocities for the year 2003 and absolute altimetric signal computed using different MDT.

<table>
<thead>
<tr>
<th></th>
<th>GLOBAL</th>
<th>PACIFIC</th>
<th>ATLANTIC</th>
<th>INDIAN</th>
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<tbody>
<tr>
<td></td>
<td>U cm/s</td>
<td>V cm/s</td>
<td>H cm</td>
<td>U cm/s</td>
</tr>
<tr>
<td>RIO05</td>
<td>13.0</td>
<td>12.3</td>
<td>10.1</td>
<td>13.0</td>
</tr>
<tr>
<td>RIO03</td>
<td>13.3</td>
<td>12.5</td>
<td>10.4</td>
<td>13.2</td>
</tr>
<tr>
<td>NIILER</td>
<td>13.3</td>
<td>12.4</td>
<td>15.5</td>
<td>13.3</td>
</tr>
<tr>
<td>ECCO</td>
<td>14.7</td>
<td>13.0</td>
<td>15.2</td>
<td>14.8</td>
</tr>
<tr>
<td>Lev1500</td>
<td>14.3</td>
<td>12.9</td>
<td>10.7</td>
<td>14.2</td>
</tr>
</tbody>
</table>

3 The Mediterranean Sea

The Mediterranean Sea is a very interesting area to focus on in order to highlight the limitation of the present state-of-the-art geoid models and investigate how oceanography will benefit from the future GOCE mission. In effect, the circulation of the Mediterranean Sea, similarly to other semi-enclosed basin or coastal areas, is characterized by very short scale structures (down to 10-20 km). The resolution of up-to-date GRACE geoids (400 km) is still far too coarse to be used to estimate the Mean Dynamic Topography, as clearly shown on Figure 2, and other methods have to be developed.
The RH04 method was used by Rio et al (2005) to compute a Synthetic MDT of the Mediterranean Sea on a 1/8th resolution grid. The mean, computed for the period 1993-1999, of dynamic topography outputs from the MFSTEP model was used as first guess. Synthetic estimates were computed using drifting buoy velocities available from 1993 to 1999 and concurrent altimetric anomalies. Independent in-situ data collected during sea campaigns were then compared to absolute altimetric heights or velocities computed using the SMDT. RMS differences are displayed in Table 2. Values clearly highlight the limits of GRACE data to estimate a MDT in this area.

In a near future, the exploitation of GOCE data will allow to compute the geoid height
with a 1 cm accuracy for spatial scales down to 100 km. This will be clearly a huge step forward for oceanographic studies in the open ocean. In order to better understand the contribution such data will have in more challenging areas as the Mediterranean Sea, we filtered from the obtained SMDT all scales shorter than 100 km. The obtained field simulates the resolution of future GOCE data. Compared to the GR3-400 MDT, the simulated “GOCE MDT” now contains the signature of the Mediterranean circulation major patterns. In particular, the signature of the northern part of both Alboran gyres is visible as well as the Algerian current, the signature of the Ionian Atlantic Stream crossing the Ionian basin, the overall anticyclonic circulation in the southern Ionian basin and the overall cyclonic circulation around the Levantine basin. The comparison to in-situ data is much improved in respect to the use of the GR3-400 MDT. In this area, the exploitation of GOCE data will have a strong impact in our knowledge of the MDT. However, the simulated “GOCE MDT” lacks many significant short scales information (the signature of the Ierapetra and Shikmona anticyclones for instance are not visible anymore, the 100km resolution is too coarse to fully describe the Alboran gyres) and the comparison results to observations are deteriorated in respect to values obtained using a higher resolution field as the SMDT.

Consequently, in challenging areas like the Mediterranean Sea, or other semi-enclosed seas, or coastal areas where the scales of the Mean Dynamic Topography are expected to be shorter than 100 km, the combined use of various datasets will still be necessary to resolve them, even after GOCE data become available.

Table 2. Root Mean Square differences between in-situ heights and velocities from various Sea Campaigns and absolute altimetric signal computed using different MDT of the Mediterranean Sea

<table>
<thead>
<tr>
<th></th>
<th>Adriatic/Ionian Sea</th>
<th>North Balaeres</th>
<th>Sicily channel</th>
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<tbody>
<tr>
<td></td>
<td>RMSU cm/s</td>
<td>RMSV cm/s</td>
<td>RMSH cm</td>
</tr>
<tr>
<td>SMDT</td>
<td>9.6 (11.9)</td>
<td>11.5 (13.2)</td>
<td>3.3 (3.3)</td>
</tr>
<tr>
<td>‘GOCE’</td>
<td>10.4 (12.1)</td>
<td>12.1 (13.2)</td>
<td>3.5 (3.5)</td>
</tr>
<tr>
<td>GRACE</td>
<td>(14.2) (14.2)</td>
<td>(3.7) (5.1)</td>
<td></td>
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</table>

4 Conclusion

An improved MDT, intended for computing absolute dynamic topographies from altimetry was estimated globally and validated using independent in-situ observations. Integrating the information brought by a very recent geoid model based on GRACE data allows to estimate with an unprecedented accuracy the ocean mean dynamic topography where no in-situ measurements of the ocean dynamics is available (mainly at high latitudes). At low and mid latitudes, the use of synthetic heights and velocities allows to improve the accuracy of the mean field at short scales. A focus is done in the Mediterranean Sea, where the mean circulation is characterized by scales shorter than 100 km. In this area, as in other semi-enclosed seas and in coastal areas, the resolution of GRACE data is still too coarse to be used for oceanographic studies. In the near future, the contribution of GOCE data will be high though not sufficient to fully resolve the shortest scales of the MDT in these areas. Other techniques will still be necessary to combine them with other sources of information (local geoids, in-situ or modelled MDT…). The technique described in RH04 and further used in this paper is one of them, since it enables to continuously enhance our knowledge of the ocean MDT (from the largest to the
shortest spatial scales) as more in-situ data and improved geoid models (with the further exploitation of GRACE and the launch in 2006 of GOCE) become available.

References


