Mass variation in the Mediterranean Sea from GRACE and its validation by altimetry, steric and hydrologic fields

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The seasonal seawater mass variation in the Mediterranean Sea is estimated between April 2002 and July 2004 from GRACE and altimetry data and from hydrologic and oceanographic models. A smoothed spatial averaging kernel is applied to each field, in order to obtain comparable basin averages. The GRACE seawater mass corrected for the leakage of continental hydrology and the filtered steric-corrected altimeter sea level have similar annual amplitude and phase. To restore the magnitude of the GRACE-derived water mass signal we apply a scaling factor to the smoothed annual amplitude. The estimated scaled mass signal has an annual amplitude of 52 ± 17 mm peaking in November. We combine the seawater mass variation with the Mediterranean freshwater deficit and obtain a net flow at the Strait of Gibraltar with annual amplitude of 60 ± 25 mm/month (0.06 Sv) and maximum peaking in September. Citation: Fenoglio-Marc, L., J. Kusche, and M. Becker (2006), Mass variation in the Mediterranean Sea from GRACE and its validation by altimetry, steric and hydrologic fields, Geophys. Res. Lett., 33, L19606, doi:10.1029/2006GL026851.

1. Introduction

The ocean mass variation is addressed at global scale independently by using steric-corrected satellite altimetry or GRACE observations [Chambers et al., 2004]. Low-pass filters, in form of spatial averaging kernels, are typically applied to GRACE spherical harmonic (SH) coefficients to minimise both the effects of GRACE measurement errors and the contamination from surrounding signals [Wahr et al., 1998; Swenson and Wahr, 2002a].

The choice of an effective smoothing radius is critical and the smoothing significantly affects the magnitude of the signal [Chen et al., 2005; Velicogna and Wahr, 2006]. The region considered here is the Mediterranean Sea, a semi-closed basin of medium size (2.5 million m$^3$). The annual amplitude of the basin averaged sea level is 7–8 cm [Ayoub et al., 1998] and the steric part of sea level variability represents at seasonal scales about 50% of the sea level change [Bouzinac et al., 2003; Garcia-Lafuente et al., 2004; Vignudelli et al., 2003]. The mass change (loss) due to the Mediterranean freshwater deficit (MWD) is compensated by the net inflow from the Black Sea (B) and from the Atlantic Ocean (G) [Boukthir and Barnier, 2000; Mariotti et al., 2002]. This last quantity is difficult to measure, estimations based on water mass budget, steric-corrected sea level and direct measurements give annual amplitudes of 0.04–0.08 Sv peaking in September [Garcia-Lafuente et al., 2002; Bryden et al., 1994].

We assess the ability of GRACE to recover the ocean mass variation in the Mediterranean Sea from April 2002 to July 2004. We first discuss the computation of water mass basin average time-series in semi-closed seas and compare the two calculations (corrected GRACE and steric-corrected altimetry) when applying a smoothed spatial averaging kernel to each data field. The magnitude of the GRACE-derived water mass signal is then restored and used together with the Mediterranean water budget to estimate the net flow through the Strait of Gibraltar.

2. Data and Processing

2.1. GRACE Mass Variation

Twenty near-monthly level-2 CSR GRACE gravity field solutions between April 2002 and July 2004 are used. Tidal effects, including ocean tide, solid Earth and solid pole tide as well as non-tidal atmospheric and oceanic effects have been removed in the pre-processing [Bettadpur, 2003]. We expand the gravity solution to spherical degree and order 90 and smooth it using an isotropic Gaussian filter to construct spatial averages and down-weight the poorly known short-wavelength SH coefficients [Wahr et al., 1998]. The filtered basin average time-series of water thickness is computed as given by Swenson and Wahr [2002b, equation [13]]

$$
\Delta \sigma_m(t) = \frac{2 \pi \rho E}{3} \sum_{l=2}^{\max} \sum_{k=1}^{l-1} \frac{2l+1}{2l+1} W_l \times \sum_{m=0}^{l} \left\{ \Delta C_{lm}^{grace}(t) + \Delta S_{lm}^{grace}(t) \right\}
$$

with $\Delta C_{lm}^{grace}$ and $\Delta S_{lm}^{grace}$ being the SH coefficients corresponding to the basin function $\phi(\theta, \lambda)$ that describes the shape of the Mediterranean Sea (1 inside, 0 outside the basin), $W_l$ the Legendre coefficients of the Gaussian filter function, $\Delta C_{lm}^{grace}$ and $\Delta S_{lm}^{grace}$ the change in the GRACE Stokes coefficients with respect to the long-term solution, $a$ the radius of the Earth, $\rho_E$ the average density of the solid Earth, $k_l$ the load Love numbers representing the effects of the Earth's response to surface load. We select for the filter an averaging radius of 400 km based on formal error propagation from the CSR calibrated error statistics to ensure that the filtered basin average is not worse than 2 cm for year 2003. The truncation to degree 90 is not critical, as the filter of 400 km retains only 0.001% of the signal at degree 90. With a radius of 1000 km the formal error of...
Figure 1. Gaussian averaging kernel used for seawater mass variation estimation in the Mediterranean Sea.

GRACE is lower, but the aliasing mass signal from outside the basin is larger.

2.2. Sea Level Heights and Steric Contribution

We estimate sea level anomalies (a) using Jason-1 and Envisat altimeter from the Radar Altimeter Database System (RADS) [Naeije et al., 2002]. We apply the radiometric wet tropospheric correction, the ionospheric correction from the dual frequency altimeter, solid earth tide, ocean, pole and load tide corrections and the standard inverse-barometer (IB) correction. This last correction, that is not accurate in semi-closed basin, is not necessarily consistent with the de-aliasing corrections used in the GRACE pre-processing, that are based on the response of a barotropic ocean model. The Root-Mean-Square (RMS) of the differences between the filtered basin averages of the IB and of the GRACE ocean de-aliasing corrections is however small (6 mm). The Ocean Pole Tide (OPT) correction, which is not applied in the GRACE data pre-processing, is also not applied to the altimeter data.

The steric contribution to sea level variation (s) is estimated from the global ocean models ECCO/JPL (http://ecco.jpl.nasa.gov) and from the local model Mediterranean Forecasting System (MFS) [Fan and van den Dool, 2004] and from the Land Dynamics Model (LaD) (http://www.nodc.noaa.gov/OC5). Global and local climatologies, the World Ocean Atlas 2001 (WOA01) and Medar/Medatlas, are used for comparison.

2.3. Continental Hydrology and Hydrologic Cycle

Continental water storage is estimated from the Climate Prediction Center (CPC) model [Pan and van den Dool, 2004] and the Land Dynamics Model (LaD) (Euphrates) [Milly and Shmakin, 2002]. Grids and unfiltered basin averages of Evaporation (E) minus Precipitation (P) (E-P) are computed from the NCEP/NCAR reanalysis daily averages of precipitation rate and surface latent heat flux and from the ERA40 ECMWF re-analysis. Climatologies of P-E, river runoff and Black Sea net flow are considered [Boukthir and Barnier, 2000; Mariotti et al., 2002].

2.4. Times-Series for Water Change Comparison

We construct, in a rectangular region including the Mediterranean Sea, one degree monthly grids of steric-corrected sea level (a-s) (with zeros on land) and of continental water storage (h) (with zeros on sea). We compute the corresponding filtered basin average time-series \( a_s \) and \( h \) by convolution of the grids in the spatial domain with the averaging kernel \( W(\theta, \lambda) \) created by convolving the basin function \( \sigma(\theta, \lambda) \) with a Gaussian filter as given by Swenson and Wahr [2002a, equations (26) and (29)]:

\[
\Delta \sigma_m(t) = \frac{1}{\Omega} \int \sigma(\theta, \lambda, t) W(\theta, \lambda) d\Omega
\]  

Figure 1 shows the Gaussian averaging kernel applied. The smoothing in spatial domain is preferred for regional application with gridded data, to avoid the computation of SH coefficients. Equations (1) and (2) are numerically equivalent, as shown by the good agreement of the filtered basin averages of the LAD model (RMS difference 6 mm and correlation 0.98). The filtered basin averages of steric-corrected altimetry and of GRACE water thickness are comparable only after application of additional corrections. These are (1) the monthly averages of the non-tidal barotropic oceanic contribution, which were modeled in the data processing and (2) the land hydrology, that leaks into the GRACE estimate of water mass. The first signal needs to be restored, while the second needs to be removed. We add back the monthly average of the non-tidal oceanic contribution used by the project, after correction for the effect of the atmosphere on land that is evaluated in a grid on land and smoothed in the spatial domain. To eliminate the leakage of land hydrology in the seawater mass estimated by GRACE, we subtract the filtered continental hydrology time-series \( h \) from the GRAEC filtered basin average time-series. To be consistent with satellite altimetry measurements we include degree 1–2 of the geopotential in the estimation. As GRACE does not recover degree 1 and the degree 2 terms show anomalous large variability, we compute the filtered basin average mass variation from satellite laser ranging (SLR) degree 1 [Chen et al., 1999] and degree 2 [Cheng and Tapley, 2004]. The SLR coefficients include the effect of the atmosphere on land, that is removed as before using the NCEP SH coefficients.

As the smoothing reduces the amplitude of the signal, we derive a scaling factor by comparing the filtered and unfiltered steric-corrected anomalies and we use it to restore the magnitude of the GRACE-derived seawater mass variation. This derivation differs from the one used by Velicogna and Wahr [2006] in that it takes the actual signal from independent information into account. The Gibraltar net flow is finally estimated from:

\[
G = (E - P - R - B) + \frac{dM}{dt}
\]

with \( \frac{dM}{dt} \) the seawater mass change from GRACE (scaled and corrected for the leakage).

3. Results

Monthly error estimates \( \sigma \) are computed as average of the RMS differences of the basin averages corresponding to various data and models and from error propagation with uncorrelated components (Table S3 in the auxiliary material\(^1\)). We have fit an annual sinusoid to the basin

\(^1\)Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2006gl026851. Other auxiliary material files are in the HTML.
averages computing amplitude and phase, along with their errors, for seawater mass variation and Gibraltar net flow (Tables 1 and 2) and for the other fields (Tables S1 and S2). We consider an alternative error estimate for the monthly amplitude derived from error propagation ($\sigma/\sqrt{N}$, with $\sigma$ from Table S3 and $N$ equal to 20).

12 The unfiltered basin average of both Jason-1 and Envisat sea level has an annual amplitude of 83 mm peaking in October, the monthly error estimate is 8 mm. The basin average of the steric anomalies from the ECCO/JPL model has annual amplitude of 43 mm peaking in September, the monthly error estimate is 13 mm. The models gives the smallest amplitudes, differences in amplitudes and phase are $\leq 10$ mm and 20°. The basin average of the steric-corrected sea level anomalies evaluated from Jason-1 altimetry and steric ECCO/JPL contribution (Figure 2) has an annual amplitude of 45 ± 4 mm peaking in early November (Table 1), the monthly error estimate is 15 mm (Table S3).

13 We compute GRACE estimates of water thickness for four cases involving various treatment of low-degree harmonics: (c1) omission of degrees 1 – 2, (c2) omission of degree 1 and use of degree 2 annual coefficients from Cheng et al. [2002], (c3) degree 1 from SLR [Chen et al., 1999] and degree 2 SLR annual coefficients as before, (c4) degree 1 and C20 annual coefficients obtained performing an annual fit in 2002–2004 of the SLR time-series from Cheng and Tapley [2004] and the other degree-2 coefficients from GRACE. The two different C20 annual coefficients cause small departures in the resulting basin averages (RMS difference 0.6 mm and correlation 0.67). The RMS difference between the results is $\leq 20$ mm for c1-3. The smallest annual amplitude corresponds to c1 (40 mm) and is amplified by a factor 1.1 in c2, 1.4 in c3 and 1.7 in c4 (Table S1). The minimum phase delay relative to the steric-corrected altimetry corresponds to c2 (68 days).

14 The filtered basin average of the continental LAD hydrology has an annual amplitude of 29 mm peaking in November and monthly error estimate of 11 mm. The leakage error is corrected by subtracting the filtered basin average of continental hydrology $h$ from the filtered basin average of GRACE. The estimate given by c2 corrected using the LaD model (GRACEc2 – LAD) has the best agreement in RMS (18 mm) with the filtered steric-corrected altimetry (Figure S1). Its annual amplitude is 28 mm peaking in November and its phase delay relative to the steric-corrected altimetry is 26 days (Table 1).

15 The filtering reduces the amplitude of the steric-corrected altimetry by a factor 0.56, while the phase remains unchanged. We restore the original magnitude of the water mass signal by multiplying the filtered basin average by the scaling factor 1/0.56. An estimate of the error made in the filtering and scaling steps is the RMS difference (19 mm) between unfiltered and filtered-scaled steric-corrected altimetry. Monthly errors from error propagation are 39 mm for the scaled GRACE-derived seawater mass. The annual amplitude is 52 ± 11 mm and peaks in November (Table 1), its error from error propagation is 17 mm. The two seawater mass estimates, the hydrology-corrected GRACE and the steric-corrected altimetry, have correlation 0.74 and RMS difference 32 mm (Figure 3).

16 The mass change monthly error derived from error propagation ($\sqrt{2} \sigma$ with $\sigma$ the monthly error estimate of mass) is bigger (21 mm/month, Table S4) than the error computed as average of the RMS differences in Table S5 (11 mm/month). The Gibraltar net flow monthly error from error propagation is 56 mm/month and 24 mm/month respectively when computed from GRACE and from steric-corrected altimetry mass variation. The Gibraltar net flow from GRACE and NCEP data has an annual amplitude of 60 ± 16 mm/month peaking in September, error from error propagation is 25 mm/month.

Table 1. Annual Amplitude and Phase of Seawater Mass Variation From Monthly Steric-Corrected Altimetry (a–s) and From Hydrology-Corrected GRACE

<table>
<thead>
<tr>
<th>Field</th>
<th>Amplitude, mm</th>
<th>Phase, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>a – s (J1-ECCO/JPL)</td>
<td>45 ± 4</td>
<td>301 ± 5</td>
</tr>
<tr>
<td>a~s (J1-ECCO/JPL)</td>
<td>24 ± 3</td>
<td>301 ± 6</td>
</tr>
<tr>
<td>GRACEc2 – LAD</td>
<td>28 ± 6</td>
<td>327 ± 13</td>
</tr>
<tr>
<td>scaled (GRACEc2 – LAD)</td>
<td>52 ± 11</td>
<td>327 ± 12</td>
</tr>
</tbody>
</table>

Table 2. Annual Amplitude and Phase of the Gibraltar Net Flow

<table>
<thead>
<tr>
<th>Field</th>
<th>Amplitude, mm/month</th>
<th>Phase, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>G (J1-ECCO/JPL, NCEP)</td>
<td>39 ± 7</td>
<td>255 ± 9</td>
</tr>
<tr>
<td>G (J1-ECCO/JPL, ECMWF)</td>
<td>52 ± 7</td>
<td>247 ± 7</td>
</tr>
<tr>
<td>G (scaled (GRACEc2 – LAD), NCEP)</td>
<td>60 ± 16</td>
<td>269 ± 13</td>
</tr>
<tr>
<td>G (scaled (GRACEc2 – LAD), ECMWF)</td>
<td>71 ± 16</td>
<td>260 ± 13</td>
</tr>
</tbody>
</table>

Figure 2. Basin average seawater mass anomalies in the Mediterranean Sea from steric-corrected altimetry computed from the Jason-1 altimeter sea level corrected for the steric contribution given by the ECCO/JPL (solid circles) and by the MFSTEP (solid squares) ocean models, by the WOA01 (open circles) and by the Medar/Medatlas (open squares) climatologies. Results corresponding to Envisat altimeter sea level and ECCO/JPL ocean model are also shown (solid triangles).

Figure 3. Basin average seawater mass anomalies in the Mediterranean Sea from steric-corrected altimetry (Jason1-ECCO/JPL) (open circles) and from scaled hydrology-corrected GRACE and SLR annual degree 2 (solid circles) and their corresponding filtered curves (open and solid triangles).
The net flow derived from the steric-corrected altimetry has smaller values (39 ± 7 mm/month and error from error propagation of 11 mm/month) (Table 2 and Table S4, Figure 4). With ECMWF data the values are bigger, the differences in amplitudes and phase are ≤10 mm and 9°. The two estimations of the Gibraltar net flow, from hydrology-corrected GRACE and steric-corrected altimetry, have correlation 0.71 and RMS difference 39 mm/month.

4. Conclusions

[17] We have assessed the ability of GRACE to recover the seasonal seawater mass variation in semi-closed basins of the dimension of the Mediterranean Sea. We apply a smoothed spatial averaging kernel in order to obtain comparable basin averaged monthly time-series. The smoothing is done in the spectral domain for the GRACE SH fields and in the spatial domain for the regional gridded data to avoid their SH expansion.

[18] Additional corrections to GRACE data, that are not applied in the global analysis, are needed in basins: (1) the correction for the leakage of hydrology due to the smoothing and to the basin shape and (2) the scaling of the amplitude because of the higher smoothing radius. The best agreement between hydrology-corrected GRACE and filtered steric-corrected altimetry, is found when using SLR degree-2 annual coefficients and LaD hydrology, the largest departure when GRACE degree-2 terms are included. We scale the seawater mass variation by the ratio of the annual amplitudes of filtered and unfiltered steric-corrected altimetry. The agreement in amplitude and phase between the scaled hydrology-corrected GRACE and the steric-corrected altimetry mass variations is within 7 mm and 26°. We conclude that GRACE is able to detect water mass variations in the Mediterranean Sea with an error budget of 39 mm for the monthly values and an annual amplitude of 52 ± 17 mm peaking in November, while values from steric-corrected altimetry are slightly smaller (monthly error budget of 15 mm, annual amplitude of 45 ± 7 mm peaking in October). The Gibraltar net flow obtained from the GRACE-derived seawater mass change has an annual amplitude of 60 ± 25 mm/month peaking in September. Results agree with values derived from the steric-corrected altimetry (annual amplitude of 39 ± 11 mm/month) and with previous estimations.

[19] We have shown that GRACE alone cannot observe the seawater mass variation in the Mediterranean Sea without knowledge of other data. At present GRACE does not yet improve our knowledge of mass variation as the combined uncertainties of the corrections and of the GRACE fields are larger than the uncertainty of the steric-corrected altimetry. However, the improved ocean de-aliasing fields and low-degree coefficients from GRACE/SLR combinations and joint GRACE/GPS inversion [Kusche and Schrama, 2005] are expected to improve these estimates. In further investigations optimal methods for selecting the smoothing radius and for restoring the magnitude of the signal from the filtered results have to be carefully addressed. This will eventually allow to validate the steric correction applied to altimetry, that, based on cruise data, could be less accurate than expected.

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