DETERMINATION OF ANNUAL MASS VARIATIONS IN THE MEDITERRANEAN SEA THROUGH ALTIMETRY MISSIONS AND GRACE

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INTRODUCTION

Sea Level Variations can be viewed as the sum of two contributions: Mass and Volume [Eq. 1]

SLVtotal = SLVvolume + SLVmass [Eq.1]

SLVvolume results from expansion or contraction induced by variations of water temperature and salinity (T, S),which are monitored from in situ observations. They change volume without change of mass (gravity). The SLVmass is the result of adding (precipitation, river run-off, melted ice) or removing (evaporation, dams in rivers) water mass. It can be determined through measurements of the GRACE mission, a mission sponsored by NASA and DLR (German Space Agency) that started in March 2002. It infers gravity variations from variations in the distance between two spacecrafts that move in the same orbit separated 220 Km. SLVtotal started to be monitorized by satellite in 1973, but it was in 1992 when it reached an unprecedented accuracy of 2-3 cm after the launch of the NASA/CNES TOPEX/Poseidon altimeters. At present, the T/P successor, Jason, is expected to reach 1 cm accuracy.

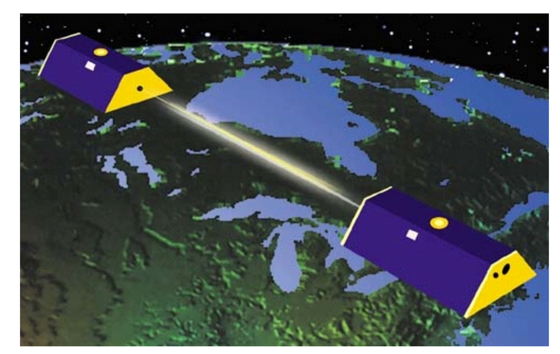
Each term of Eq. 1 can be obtained from independent data sets. The aim of this work is to determine the importance of each term (SLVvolume and SLVmass) in the annual SLVtotal signal in the Mediterranean Sea using direct and indirect measurements. The Mediterranean Sea is suitable for this purpose because it is a semi-enclosed basin connected to the open ocean by a single point at the Strait of Gibraltar.

2. ORIGINAL AND PROCESSED DATA

Several sources of data have been used, spanning the period from April 2002 to July 2004 when possible:

ORIGINAL

Dataset 1: GRACE



This mission sponsored by NASA and DLR (German Space Agency) started in March 2002, infers gravity variations from variations in distance between two spacecrafts which orbiting in the same orbit at 500 km altitude and separated 220 Km. They can measure the distance to each other with a very accuracy grace to a K-Band microwave ranging system. Changes in time of the gravity field can be inferred from changes in the distance between the spacecraft.

- Format: Fully Normalized (or 4-Normalized) Spherical Harmonics (SH) up to degree 120, although we only use up to degree 10. SH calculated by Center of Space Research (CSR)
  - Resolution: 2000 Km approximately
  - Span of time: 22 monthly SH for the period 04/2002 - 07/2004.
  - Observation: J2 coefficient has not been used in this work.

Dataset 2: Altimetry

- Format: Monthly Sea Level Anomalies (SLA) maps from Topex/Poseidon (T/P) and Jason altimetry missions. Data has been provided by Brian Beckley from the Goddard Space Flight Center GSFC/NASA)).
  - Resolution: 1 degree by 1 degree
  - Span of time: 10/1992 - 07/2002 for T/P and 02/2002 - 07/2004 for Jason.
  - Corrections: recommended corrections applied, except the Inverted Barometer (IB) correction, which is known not suitable for semi enclosed basins as the Mediterranean (Le Traon and Gauzelin, 1997).

Dataset 3: Hydrographic data

- Format: Salinity (S) and Temperature (T) profiles from the CORIOLIS projects collected using XBT, CTD, buoys and moorings.
  - Resolution: different for each month depending on the availability
  - Span of time: the same as GRACE data

Dataset 4.: Sea Surface Temperature (SST)

- Format: Reynolds Optimally Interpolated (OI) Version 2 Sea Surface Temperature (SST) maps provided by NOAA/NCEP. Satellite and in situ data are combined.
  - Resolution: 1 degree by 1 degree
  - Span of time: 01/1993 - 01/2004.

Dataset 5.- Precipitation (P) and Evaporation (E) data from NCEP atmospheric GCM products.

DATA PROCESSING

1.- Monthly spherical harmonics can be used to estimate mass variations as indicated in equation 2 (Chao, 2004).

$$(\;,\;) \quad \frac{a_E}{3} \sum_{l=0}^{}\sum_{m=0}^{l} \frac{(2l \quad 1)}{(1 \quad k_l)} \tilde{P}_{lm}(\cos \quad) \quad C_{lm}\cos m \qquad S_{lm}\sin m \qquad \text{[Eq.2]}$$

Equivalent Sea Surface Height (ESSH) of the mass anomaly assumes water density equal to 1000 Kg/m^3 (each kg is equivalent to 1 mm water for square meter)

Due to inaccuracy in high degree spherical harmonics estimated from GRACE, only harmonics up to degree 10 are used, providing a spatial resolution of 2000 Km

2.- S and T profiles were averaged over three-month periods to improve spatial coverage and objectively interpolated on a regular grid of 0.5x0.5 degrees. As the availability of these data relies on the speed with which "in situ" observations are submitted to the CORIOLIS webpage, the spatial coverage near the end of the selected period is poor. A monthly sampling was then obtained using splines. These interpolated data were used to determine monthly SLVvolume through the computation of the anomaly of dynamic height. This computation was carried out from the sea surface down to 500 m depth, where the seasonal signal is negligible. A quality check procedure was applied to SLVvolume to eliminate spureous peaks and extreme values.

Mean was removed from all datasets and then detrended.

The different datasets cover the Mediterranean basin, although the spatial resolution is different for each source. Several gaps appears in dataset 3 due to the lack of measurements in certain areas of the basin.

RESULTS

The difference between SLVtotal and SLVvolume accounts for the mass variations. The annual signal was obtained fitting A and j in equation 4 (where A is the amplitude of the annual signal and j the phase of the maximum amplitude) to the real data. The same adjustment was applied to GRACE data and compared with the previous dataset.

$$signal = A\cos(\omega_a t - \varphi) \qquad \text{[Eq.3]}$$

Figure 1 shows the spatial maps of A and j, for SLVtotal (from T/P altimetry data), SLVmass ESSH (from GRACE), SLVmass indiretly derived from SLVtotal and SLVvolume and SST.

Amplitudes and phases of SLV$_{mass}$ derived from both datasets have a good agreement in the main features, taking into account the error intervals for all datasets. There is a well defined core of mass close to the Strait of Bosphore, which peaks between February and March with an amplitude of approximately 7 cm (this can be seen in the GRACE amplitude map). This accumulation of mass could be motivated by an increase in the river discharges due to melted snow which occurs often by the begining of Spring. From the Strait of Bosphore , the mass signal decreases towards the Strait of Gibraltar which approximately the same phase.

Comparing the maps of the gravity signal with the volume signal, amplitudes are approximately in the same range of values but distributed differently, higher volumes are placed near coastal regions where the differences between winter and summer are more important due to the heat exchange between land and sea. The volume signal exhibits a different temporal behavior than the mass, reaching the maximum in September. It can also be observed a propagation of the phase from East to West, since the maximum in the Western basin is reached in the first half of September, while the maximum in the Eastern Basin is reached in the second half of the same month.

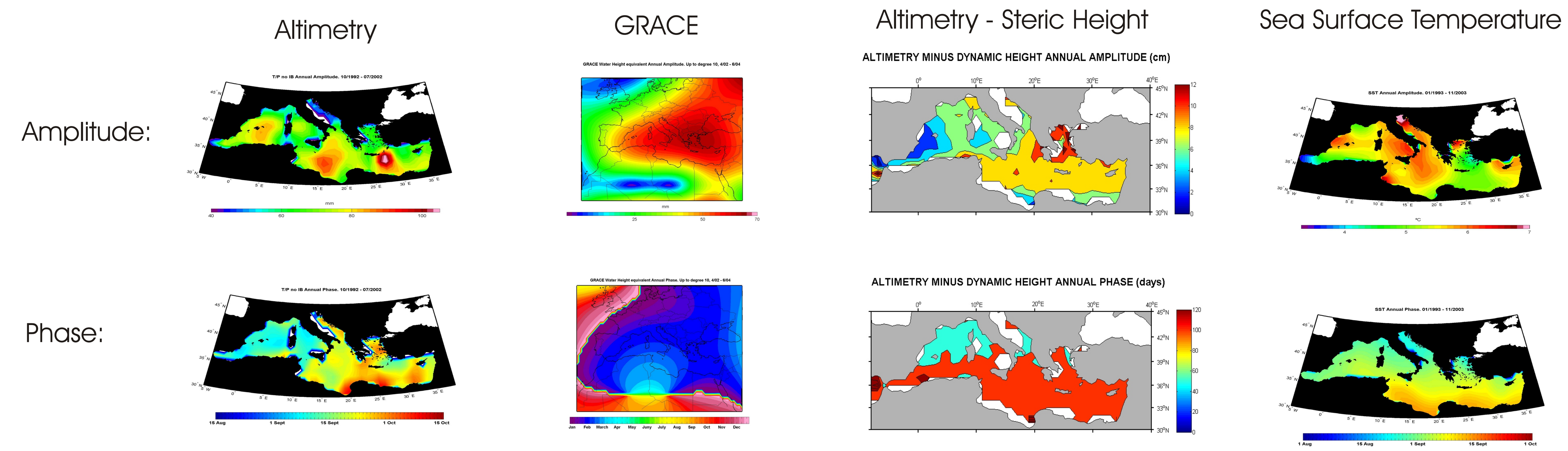


Figure 1. First row represents the amplitude of the annual signal for: A. SLVtotal from T/P altimetry data in mm; B. SLVmass from GRACE in mm (Equivalent Sea Surface Height); C. SLVmass inferred from altimetry minus dynamic height in cm; D. SST in Celsius degree. Second row represents the phase as in [eq. 4] for: E. SLVtotal from T/P altimetry data in days; B. SLVmass from GRACE in months; F. SLVmass inferred from altimetry minus dynamic height in days; D. SST in days.

A very good agreement is observed between SLA and SST phase. The latter reaches the maximum approximately 15 days before than SLA. Under the assumption that steric changes mainly drive the SLA variations, the previous 15-days out-of-phase agrees well with the fact that SST phase can be up to 1 month before than the steric height phase (Garcia-Lafuente et al., 2004).

A very surprising out-of-phase between ESSH, SLA (SLVtotal) and SST is clearly observed. The first one reach the maximum value in February and the second one in September. Therefore, the maximum concentration of mass in the Mediterranean is produced 5 months after that the maximum in volume is observed. That result is completely unexpected and to study it in more detail, we study the time evolution of the different kind of data in the Mediterranean sea.

Because of inaccuracy in high degree spherical harmonics estimated from GRACE, to study the gravity signal in the Mediterranean sea we apply a gaussian filter as described in Swenson and Wahr (2002) [Eq.4] to extract the mean SLVmass for the mediterranean Sea:

$$\tilde{\ }_{region} \quad \frac{1}{\ \ _{region}} \quad (\;,\;)\overline{W}(\;,\;)d \qquad \text{[Eq.4]}$$

Where W(q,f) takes value 1 over the Mediterranean Sea and 0 otherwise, changing smoothly (taking 200 km) in the boundary, and W is the solid angle of the Mediterranean sea. Therefore we obtain a mass anomaly value for the Mediterranean sea for each month of data.

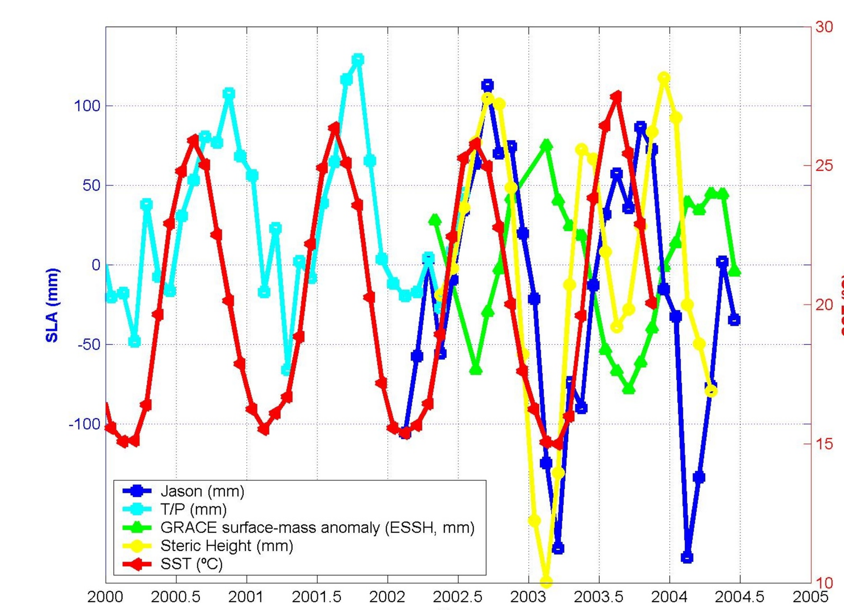


Figure 2. Monthly Mean values in the Mediterrean Sea of all dataset considered. SLVtotal (red) signal agrees in phase with the SLVvolume (green). SLVmass is almost opposite in phase with respect to SLVvolume, which implies that mass variations smooth steric changes in sea level. SST peak occurs between a month and 45 days before of SLVtotal peak, in that period heat is redistributed through the water column.

Once signals were averaged over the Mediterranean Sea (figure 2), the agreement between the volume measured using on-site salinity and temperature measurements and the volume estimated through GRACE and altimetry increases significantly (figure 3). The volume cycle in the Mediterranean Sea is extracted, the amplitude is approximately 10 cm and the phase peaks approximately in October which is consequent with previous results. Figure 2 shows that Mediterranean sea level is almost completely determined by volume variations which are smoothed by mass variations.

Volume measured using on-site salinity and temperature measurements and the volume estimated through GRACE and altimetry exhibit the same behavior in phase and in amplitude appears, although the disagreement after late 2003 is not understood yet although it can be motivated by less T and S data available in that period . The agreement would mean that the 3 datasets: GRACE, altimetry and S and T profiles are consistent.

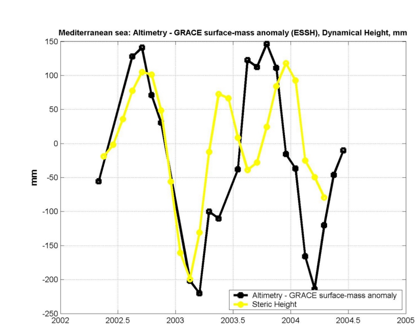


Figure 3. Montly Mean values in the Mediterranean Sea of SLVvolume derived from SLVtotal and SLVmass (black) and SLVvolume computed directly from T and S (yellow). The good agreement shows that inferring values of one magnitude (SLVtotal SLVvolume or SLVmass) knowing the other two is correct.

Phase of SLVtotal and SLVvolume are almost coincident and phase of SLVmass is delayed almost 180º respect the other two (Figure 2), implying a decrease of mass when sea level is rising. This fact suggests that SLVtotal is driven by volume changes which are smoothed by mass. Peaks of SST signal occurs between 30-45 days before of the SLVtotal peak (Garcia-Lafuente et al., 2004), in that period heat

CONCLUSIONS

This work shows the application of several remote sensing missions to understand the behavior of sea level variations in the Mediterranean Sea. Volume changes has been derived from T and S and mass changes from GRACE. To establish the relationship between datasets altimetry data has been also used.

Sea level has been decomposed in volume and mass terms, implementing a cross-validating procedure to derive the observed variable obtaining independent datasets which match largely, ensuring that the procedure and the results obtained are consistent. Mean Volume changes have a peak of approximately 10 cm and peak in October, while sea level variations due to mass changes has lower amplitudes (approximately 7 cm) and the peak appears in the late February or beginning of March. Previous studies (Chambers at al. 2004) of global mass variations in oceans shows that the annual amplitude is significantly lower than in the Mediterranean Sea , global 7-9 mm to 7-9 cm Mediterranean.

Results shows that SLVtotal in the Mediterranean Sea is driven by volume changes. There is a delay between SLVtotal peak and SST peak of 30-45 days depending on the area considered. This delay corresponds to a redistribution of heat through the water column

The combination of several remote-sensing missions allows us to decompose sea level variations and understand the relationship between mass variations, volume variations and the resulting observed sea level.

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