Combination of multi-satellite altimetry data with CHAMP and GRACE EGMs for geoid and sea surface topography determination

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Abstract. Since the launch of the first altimetric missions a wealth of data for the sea surface has become available and utilized for geoid and sea surface topography modeling. The data from the gravity field dedicated satellite missions of CHAMP and GRACE provide a unique opportunity for combination studies with satellite altimetric observations. This study focuses on the combination of data from GEOSAT, ERS1/2, Topex/Poseidon, JASON-1 and ENVISAT with Earth Gravity Models (EGMs) generated from CHAMP and GRACE data to study the mean sea surface (MSS)/marine geoid in the Mediterranean Sea. Various combination methods, i.e., weighted least squares and least squares collocation are investigated and conclusions on the most appropriate combination strategy are drawn. Then, a remove-compute-restore scheme is followed to estimate the MSS model. Comparisons with other MSS models referenced to EGM96 and CHAMP/GRACE EGMs are performed in terms of the geoid height values at various control points. Finally, a sea surface topography model for the eastern part of the Mediterranean Sea is determined by a combination of the altimetric geoid and the CHAMP/GRACE EGM. The latter is validated against a sea surface topography model derived from altimetric data, in-situ oceanographic observations and an ocean general circulation model.

Keywords. CHAMP/GRACE EGMs, ENVISAT and JASON-1 validation, mean sea surface, sea surface topography.

1 Introduction

During the last twenty five years altimeters on-board satellites have offered a tremendous amount of high-accuracy measurements of the instantaneous height of the sea surface above a reference ellipsoid known as sea surface heights (SSHs). With the advent of technology new missions emerged offering always a more accurate picture of the ocean surface and continuing the missions of previous satellites. The latter, i.e., the continuity of one satellite mission from another is of very high-importance, since it offers a long time series of exactly repeating measurements of the sea surface. Such satellites are ERS1, ERS2 and ENVISAT and TOPEX/Poseidon (T/P) with JASON-1. JASON-1 and ENVISAT are the latest on orbit satellites (December 2001 and March 2002, respectively) and are both set on exact repeat missions (ERM).

This long series of altimetric observations has been widely used for studies on the determination of MSS models (Andersen and Knudsen 1998; Cazenave et al. 1996), global and regional geoid models (Andritsanos et al. 2001; Lemoine et al. 1998; Vergos et al. 2005) as well as on the recovery of gravity anomalies from altimetric measurements (Andersen and Knudsen 1998; Hwang et al. 1998; Tziavos et al. 1998). The main advantage of altimetric SSHs over shipborne gravity data can be viewed in terms of their high precision and resolution, homogeneity and global coverage.

One of the main aims of the present study was the validation of the data acquired so far from JASON-1 and ENVISAT with respect to their accuracy compared to the latest Mean Sea Surface (MSS) models. Both satellites are supposed to continue the missions of their predecessors. Therefore, their accuracy should be at least comparable to that acquired from ERS1/2 and T/P.

Another goal was the combination of multi-satellite altimetry data for the determination of a high-accuracy and high-resolution MSS model for the eastern part of the Mediterranean Sea. Both ERM and Geodetic Mission (GM) data have been used to achieve maximum resolution in the computed field. The MSS model was based on data from GEOSAT (ERM and GM), ERS1 (ERM and GM), ERS2, and T/P, while it was decided that the new mission’s data would be used only if they provided accurate results during their validation. The estimated MSS models were validated against the two latest KMS MSS models and a local one derived during an earlier study.

The altimetric MSS model to be computed in the frame of the present study actually coincides with the marine geoid, since they only deviate by the quasi-stationary sea surface topography (QSST) term, which is unknown for the Mediterranean Sea due to the absence of local models and the fact that global ones are inappropriate for closed sea areas. Therefore, the terms MSS and marine geoid models are considered the same for the present study, of course under the aforementioned condition, i.e., the absence of a sea surface topography model. The QSST in the area under study was estimated from a combination of the computed MSS/marine geoid model and a gravimetric geoid model computed during an earlier study. The resulting QSST was validated against a recent oceanographic QSST model for the Mediterranean Sea, which was based on altimetric data, in-situ oceanographic observations and a parallel ocean circulation model.

2 ENVISAT and JASON-1 data validation

For the validation of the ENVISAT and JASON-1 SSHs the available Geophysical Data Records (GDRs) from their launch until May 2005 have been collected. The data became available by ESA/CNES (ESA 2004) and CNES/AVISO (AVISO 2003), respectively. The ENVISAT SSHs span from September 4, 2003 to March 16, 2005, corresponding to cycles 15-34; JASON-1 SSHs span from January 15, 2002 to January 15, 2005. It should be mentioned that due to some problems detected in the ENVISAT CDs distributed by the responsible agency (lack of satellite cycle and track numbers) it was not possible to process cycles 1-14 of the satellite since the new records became available only in early August 2005 when the MSS and QSST models have already been developed. The area under study is bounded between $33° \leq \varphi \leq 38°$ and $20° \leq \lambda \leq 30°$ and the total number of SSH records was 26072 and 31109 from ENVISAT and JASON-1, respectively (see Figure 1).

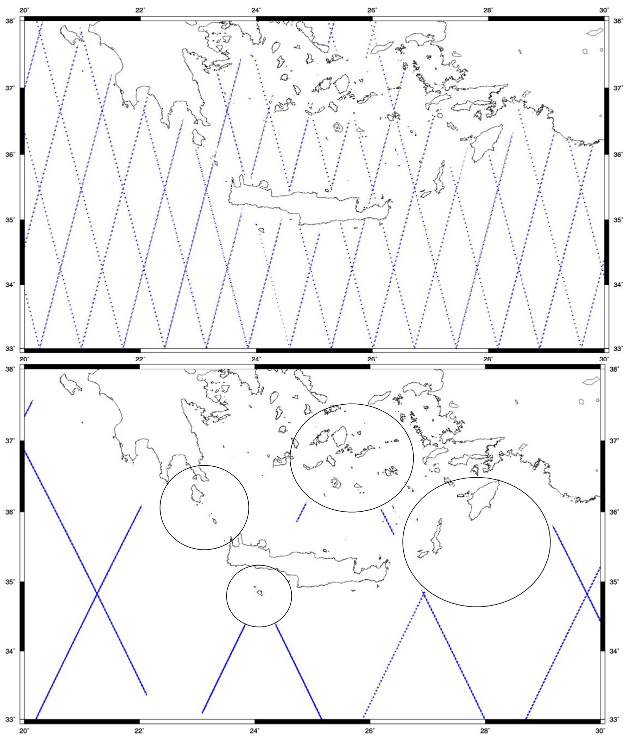

Fig. 1: Distribution of ENVISAT (top) and JASON-1 (bottom) data. Black circles denote areas where JASON-1 data are missing compared to T/P.

The validation was based on comparisons between the available SSHs from each satellite with high-accuracy (±4-6 cm) and high-resolution (1′×1′) altimetric and gravimetric geoid models for the area under study (Vergos et al. 2005). Additionally, a cycle-by-cycle analysis of the satellite records has been performed to conclude on their precision. Finally, stacked JASON-1 and stacked and crossover adjusted ENVISAT datasets have been constructed and compared with the available geoid models. This would allow the removal of (a) sea surface variability effects and (b) orbital errors from the GDRs and would make the comparisons more representative. It was not necessary to crossover adjust the JASON-1 data since this has already been done by AVISO. In all cases the comparisons were performed as $SSH\text{-}N^i$, where N^i is the predicted geoid height at the sub-satellite point using least squares collocation for the interpolation. The computed differences were minimized using a 3rd order polynomial model for bias and tilt fit according to the formula

$$\begin{aligned} SSH^y - N^i = {} & x_1 + x_2\left(\phi_i - \bar{\phi}\right) + x_3\left(\lambda_i - \bar{\lambda}\right) + x_4\left(\phi_i - \bar{\phi}\right)^2 + \\ & + x_5\left(\lambda_i - \bar{\lambda}\right)^2 + x_6\left(\phi_i - \bar{\phi}\right)\left(\lambda_i - \bar{\lambda}\right) + x_7\left(\phi_i - \bar{\phi}\right)^3 + x_8\left(\lambda_i - \bar{\lambda}\right)^3 \\ & + x_9\left(\phi_i - \bar{\phi}\right)^2\left(\lambda_i - \bar{\lambda}\right) + x_9\left(\phi_i - \bar{\phi}\right)\left(\lambda_i - \bar{\lambda}\right)^2 + v \end{aligned} \quad (1)$$

where SSH^y denotes either the ENVISAT or JASON-1 SSH, N^i the gravimetric or altimetric geoid height, x_1 to x_9 the unknown polynomial coefficients determined by least squares, and $\bar{\varphi}$ and $\bar{\lambda}$ the mean latitude and longitude of the sub-satellite points respectively. The selection of a 3rd order polynomial model for the minimization of the differences between altimetric SSHs and geoid heights was based on a validation performed by testing various parametric models. In this test, 1st, 2nd, and 3rd order polynomial models as well as the well-known four- and five-parameter similarity transformation models have been employed. From the results acquired, it was concluded that the 3rd order polynomial model provided the best fit, i.e., managed to give the smallest standard deviation (std) for the differences between the heights compared.

Table 1 presents the statistics of the differences between JASON-1 and the gravimetric geoid model for some of its cycles as well as for the entire dataset. The last two rows of the table give the differences of the stacked data before and after (italics) the bias and tilt fit. From that table it is evident that even after stacking the JASON-1 data and minimizing its differences with the geoid model, we end up to a σ of ±20 cm. This is far worse than the ±14 cm that T/P provided when compared in the same area and with the same geoid model (Vergos et al. 2005). Even when the stacked JASON-1 data was compared to the altimetric geoid model, the (std) of the differences after the bias and tilt fit reached the ±15.5 cm level compared to ±8 cm for T/P. The aforementioned results combined with the fact that JASON-1 data are interrupted far away from the coastline

Table 1. Statistics of differences between JASON-1 and the gravimetric geoid model. Unit: [m].

cycles	max	min	mean	std
1	0.530	-0.452	-0.009	±0.167
2	0.615	-0.542	-0.012	±0.281
4	0.426	-1.380	-0.057	±0.248
5	0.317	-0.633	-0.084	±0.254
45	0.449	-0.850	-0.222	±0.245
90	0.773	-0.346	0.165	±0.324
1 – 111	1.184	-3.536	0.041	±0.316
stacked 1 – 111	0.175	-1.049	-0.339	±0.254
stacked 1 – 111	0.578	-0.519	0.000	±0.202

(see Fig. 2 for the T/P case), forced us to decide not to use them in the MSS/geoid model determination. The latter may be correlated with the problems encountered with the radiometer on-board the satellite.

On the other hand, when the ENVISAT SSHs were compared with the gravimetric and altimetric geoid models, the results acquired were very encouraging (see Table 2), since the differences with the former after stacking and crossover adjustment (second last row) were at the ±22 cm and dropped to less than ±13 cm after the minimization procedure (last row). When compared to the altimetric geoid model, the ENVISAT SSHs presented a difference of only ±12.5 (±9 cm after the fit); therefore they were considered as very satisfactory and were used for the subsequent MSS model determination.

Table 2. Statistics of differences between ENVISAT and the gravimetric geoid model. Unit: [m].

cycles	max	min	mean	std
15	0.912	-1.026	-0.358	±0.323
16	1.388	-1.071	-0.243	±0.374
20	0.705	-1.126	-0.339	±0.267
25	0.639	-1.104	-0.430	±0.263
26	1.292	-1.052	-0.236	±0.321
15 – 34	1.555	-1.326	-0.312	±0.348
stacked & cross. adj. 15-34	0.694	-1.016	-0.426	±0.226
stacked & cross. adj.15-34	0.712	-0.697	0.000	±0.129

3 Mean Sea Surface Model Estimation

After the validation of the ENVISAT and JASON-1 data and the conclusion that the latter will not be used, a database of all available altimetric observations for the area under study was created to determine the MSS/geoid model. The altimetric SSHs came from: (i) the GEOSAT-GM mission (25402 SSHs), (ii) the ERS1-ERM mission phases c and g (34323 SSHs), (iii) the ERS1-GM mission (14901 SSHs), (iv) the ERS2-ERM mission (30991 SSHs), (v) nine years of the T/P mission (136864 SSHs), and (vi) the already used ENVISAT mission (26072 SSHs). Therefore, a total number of 299662 observations of the sea surface were available for the determination of the MSS model (see Fig. 2). In Fig. 2 the geodetic mission data from ERS1 and GEOSAT are denoted by the very dense dots covering the entire area. All data were provided by AVISO (1997) except from the GEOSAT SSHs which were provided by NOAA (1997). In all cases the geophysical and instrumental corrections proposed by the respective agency were implemented to construct corrected SSHs.

For the determination of the MSS/geoid model all data had to be consistent, i.e., no biases between them should exist. The ERS1 and ERS2 data have been reference to T/P by AVISO, since their orbits were recomputed based on that of T/P. The GEOSAT-GM data were processed during an earlier study (Andritsanos et al. 2001) by estimating and removing their bias and tilt w.r.t. T/P. Therefore, only the ENVISAT SSHs had to be referenced to T/P, so their bias (~14 cm) and tilt w.r.t. the latter were estimated and removed. In this way a homogeneous dataset has been constructed for use in MSS/marine geoid determination.

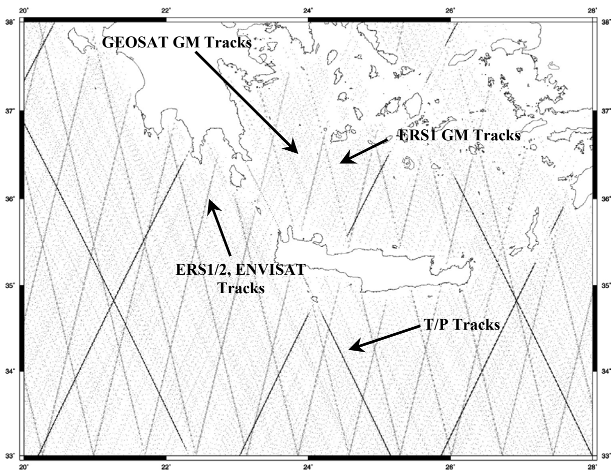

Fig. 2: Distribution of ERS1-ERM, ERS2, ENVISAT, ERS1-GM, GEOSAT-GM and T/P data.

Consequently, a remove-compute-restore method has been followed to determine the final MSS model, i.e., the altimetric SSHs were referenced to an earth geopotential model, gridded and then the GM contribution was restored to construct the final MSS. During the remove step and in order to assess the improvement that the latest CHAMP and GRACE EGMs offer, two models have been employed, namely the traditional EGM96 (Lemoine et al. 1998) and EIGEN-CG03C (Förste et al. 2005). The latter is the latest combination model by GFZ using CHAMP and GRACE data and is complete to degree and order 360. Table 3 summarizes the statistics of the SSHs before and after the reduction to the EGMs. From that table it is clear that EGM96 provides a (marginally) better reduction of the data by about 2 cm in terms of the std and 6 cm in terms of the range compared to EIGEN-CD03c. On the other hand the latter reduces the mean by 9 cm more than EGM96. Therefore, no clear conclusion can be drawn for their performance other than that the models are comparable.

Table 3. Statistics SSHs before and after the reduction to EGM96 and EIGEN-CG03c. Unit: [m].

	max	min	mean	std
SSHs	40.401	-0.358	14.541	±8.665
$SSHs^{red\ EGM96}$	1.461	-2.367	-0.266	±0.340
$SSHs^{red\ EIGEN\text{-}CG03c}$	1.627	-2.264	-0.175	±0.358

To grid the data and generate the reduced MSS/marine geoid mesh at 1′×1′ resolution three methods have been identified, i.e., conventional least squares, splines in tension and least squares collocation. From the analysis performed and the comparisons with global MSS models it was concluded that the LSC solution provided superior results by about ±7-11 cm (in terms of the std of the differences) compared to the other methods, something in line with an earlier study (Tziavos et al. 2004), where these algorithms were also tested. Due to the limited space available, only the results from LSC will be reported herein. Table 4 presents the gridded reduced MSS heights as well as the final MSS models referenced to EGM96 and EIGEN-CG03c. The EGM96 MSS model is also depicted in Fig. 3.

Table 4. Statistics of the reduced MSS heights and the final MSS models referenced to EGM96 and EIGEN-CG03c. Unit: [m].

	max	min	mean	std
$MSS^{red\ EGM96}$	0.940	-1.720	-0.370	±0.350
$MSS^{red\ EIGEN\text{-}CG03c}$	1.060	-1.660	-0.280	±0.360
MSS^{EGM96}	40.139	0.596	19.828	±10.839
$MSS^{EIGEN\text{-}CG03c}$	39.851	0.714	19.828	±10.839

The validation of the estimated MSS models was performed through comparisons with the latest KMS (Danish Survey and Cadastre) MSSs, namely KMS01 (Andersen and Knudsen 1998) and KMS04 (Andersen et al. 2003). Table 5 summarizes the results of the comparisons for both MSS models developed, while Fig. 4 depicts the differences between KMS04 and the referenced to EGM96 MSS model. From that table it becomes once again evident that the two EGMs give almost the same results, but EGM96 outperforms EIGEN-CG03c by ±1 cm in terms of the std and 50 cm in terms of the range, even though KMS04 is referenced to GGM01C (CHAMP-GRACE combination EGM). This is an indication that EGM96 can be regarded as a dominant geopotential model and is still not outperformed by the new EGMs. Of course this is true for the present study (relative accuracy), the data used, the area under study and may not repeat in other regions. Furthermore, EIGEN-CG03c gives a much smaller cumulative geoid error (30 cm compared to 42 cm for EGM96), which is of high-importance in terms of the absolute MSS/marine geoid error. In a next step, the computed differences were minimized using Eq. 1 to remove any bias and tilts between the KMS and the compute MSS models. This resulted in smaller std values at the level of ±14.2, ±15.3, ±10.7, and ±11.4 cm for the differences between KMS01, KMS04 and the EGM96 and EIGEN-CG03c MSS models, respectively. Therefore, even after the minimization of the differences the MSS referenced to EGM96 outperformed the EIGEN-CG03c model even by a slight margin. In Tziavos et al. (2004) MSS models for the same area were developed and also compared to the KMS models giving an overall best std at the ±17 cm (after bias and tilt fit). So, it can be concluded that the MSS models developed in this study are about 5 cm more accurate than the previous ones. Finally, the estimated MSS models agree better by almost ±9 cm with KMS04 compared to KMS01, which gives evidence that the latest KMS MSS model is indeed an improved version of its predecessor. The differences between KMS04 and the referenced to EGM96 MSS model (see Fig. 4) are almost zero in marine areas, while they reach their minimum and maximum values close to the coastline, where both models suffer due to the inherent problems of satellite altimetry in such areas.

Table 5. Statistics of the differences between the KMS and estimated MSS models. Unit: [m].

	max	min	mean	std
$KMS01\text{-}MSS^{EGM96}$	1.194	-0.959	0.207	±0.194
$KMS01\text{-}MSS^{EIGENCG03c}$	1.363	-1.109	0.208	±0.201
$KMS04 – MSS^{EGM96}$	1.199	-0.339	0.127	±0.117
$KMS04\text{-}MSS^{EIGENCG03c}$	1.179	-0.919	0.126	±0.122

4 Sea Surface Topography Estimation

For the determination of the quasi-stationary (QSST) model the estimated MSS model referenced to EGM96 was combined with the gravimetric geoid available for the area under study. The latter was estimated from airborne (Olesen et al. 2003), shipborne and land gravity data (Vergos et al. 2005). To derive a first QSST model, the differences between the MSS and the gravimetric geoid were formed as

$$QSST = MSS^{alt} - N^{grav} \quad (2)$$

where the gravity anomalies used to determine the gravimetric geoid are free-air reduced, i.e., reduced from the sea surface to the geoid, and the MSS heights refer to the sea surface. The statistical characteristics of this preliminary QSST are given in Table 6, from which it is evident that the QSST estimated presents some unreasonably large variations in the area (3.5 m) and reaches a maximum of almost 2 m. Therefore it is clear that blunders are present in the estimated field. Finally, noisy features are evident, thus low-pass filtering (LPF) was needed in order to reduce these effects.

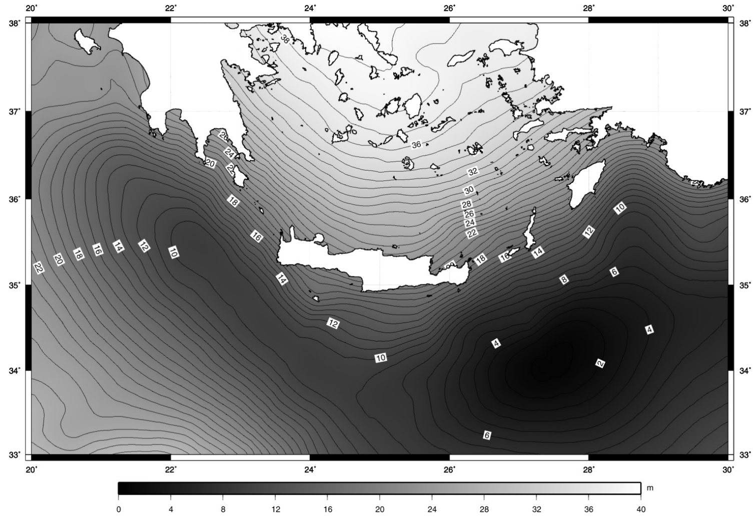

Fig. 3: The final referenced to EGM96 MSS model.

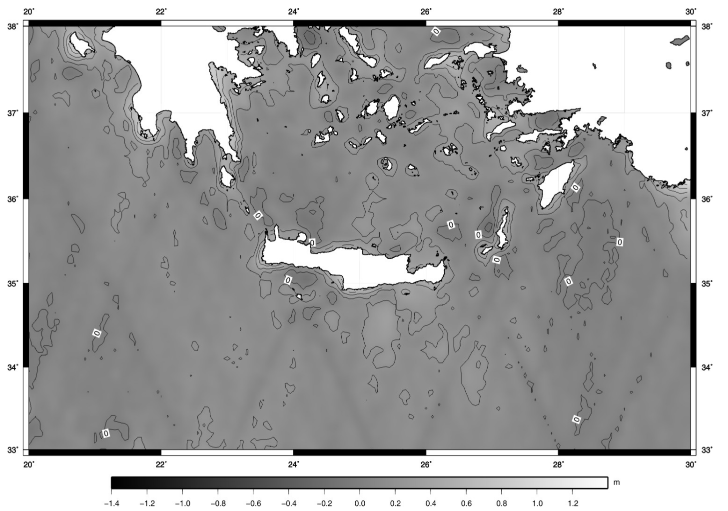

Fig. 4: Differences between KMS04 and the final referenced to EGM96 MSS model.

Table 6. Statistics of the preliminary, before and after the 3σ test, and final QSST model and its differences with MDT04. Unit: [m].

	max	min	mean	std
QSST	1.678	-1.448	-0.125	±0.318
QSST (after 3σ)	0.950	-0.953	-0.131	±0.287
QSST (after 3σ and LPF)	0.657	-0.510	0.014	±0.238
MDT04 – QSST	0.386	-0.265	0.000	±0.072

For the detection and removal of blunders, a simple 3σ test was performed, i.e., points with a QSST value larger than 3 times the σ of the preliminary field were removed. The statistics of the QSST model after this test are given in Table 6 as well. To low-pass filter the preliminary QSST model, a collocation-type of filter (Wiener filtering) was used, assuming the presence of white noise in the QSST field. Furthermore, it was assumed that Kaula's rule for the decay of the geoid power spectrum holds, i.e., that the geoid height power spectral density decays like k^{-4} where k is the radial wavenumber. These resulted in the flowing filtering function

$$F(\omega) = \frac{\omega_c^4}{\omega^4 + \omega_c^4} \quad (3)$$

where ω is the radial frequency, $\omega=\sqrt{u^2+v^2}$, and ω_c the cut-off frequency.

To filter the wanted field, the desired cut-off frequency needs to be selected. The latter relates to the final resolution of the filtered field and the reduction of the noise in the data. Thus, a trade-off is necessary, since higher resolution means more noise will pass the filter, while higher noise reduction means lower resolution of the final model. A high resolution is vital in the determination of regional to local QSST models, since if a high value cannot be achieved then a so-derived local model has little to offer compared to a global solution. It can be clearly seen, that the disadvantage of Wiener filtering is that the selection of the cut-off frequency is based on the spectral characteristics of the field only, while its spatial characteristics are not taken into account. Furthermore, the selection of the cut-off frequency is based on solely objective criteria. Thus, a trial and error process, based on maximum noise reduction with minimum signal loss, is needed to determine the desired cut-off frequency.

Various cut-off frequencies have been tested corresponding to wavelengths of 5, 10, 20, 40, 60, 100, 110 and 120 km and finally a wavelength of 100 km (about 1^o or harmonic degree 180) was selected since it offered the minimum signal loss with maximum noise reduction. Wavelengths shorter than 100 km left too much noise in the field, while those larger than 100 km were reducing not only the noise but some spatial characteristics of the QSST as well. If a longer wavelength was selected, then, and if the area was significantly larger (e.g. the entire Mediterranean Sea) it would have been possible to identify larger-scale QSST features and distinguish them from smaller ones. The problem in this case is that for the rest of the Mediterranean Sea only few ship tracks with gravimetric observations are available, therefore, a gravimetric geoid model cannot be determined at least at such high resolution (1′). The answer in such cases for geoid modeling is the combination of shipborne gravity data with satellite altimetry, but such a combination model cannot be used for QSST modeling (at least in the present context) due to the high correlation with the MSS model.

The final QSST field after filtering is shown in Fig. 5 (top), while the statistics are given in Table 6 (last row). From the aforementioned figure it can be seen that the noise present in the preliminary model is reduced significantly, while blunders cannot be identified. For validation purposes the estimated QSST model was compared with a Mean Dynamic Topography (MDT04) model estimated for the entire Mediterranean Sea from an analysis of satellite altimetry and oceanographic data (Rio 2004). The latter was given as a grid of mean QSST values of 3.75′×3.75′ resolution in both latitude and longitude. The statistics of the differences between the MDT and the estimated QSST models are given in Table 6 (last row). From the comparison it can be concluded that the two models agree very well to each other (std at the ±7 cm level only). The maximum and minimum values of the differences are found close to land areas only, where both models are inadequate. This comparison gives evidence that the estimated QSST model is in good agreement with existing regional oceanographic MDT models. Furthermore, it is a welcoming fact, which supports the appropriateness of the proposed methodology for the determination of a geodetic QSST model.

5 Conclusions

A first validation of the ENVISAT and JASON-1 data in the eastern Mediterranean Sea has been performed, from which it was found that the former provide accurate results comparable to the other altimetric missions, while the latter are of lower accuracy compared to T/P and present extensive gaps. The latter can be attributed to the radiometric correction problems in the JASON-1 data.

The MSS models developed present very good agreement with the corresponding KMS01 and KMS04 ones, with their smallest difference being at the ±11 cm level. Compared to earlier results achieved by the authors, the newly developed MSS is of higher resolution (1′ comparing to 5′) and accuracy (±11 cm comparing to ±17 cm) and presents an improved version. Furthermore, it can be concluded that at least in the present stage EGM96 is still comparable to the EIGEN/GRACE type of EGMS, but of course not in terms of the cumulative geoid error.

Finally, the estimated QSST model provided very encouraging when compared to an oceanographic MDT model, with its differences only at the ±7 cm. This is a tremendous improvement, since it can be used for local/regional geoid and gravity field modeling in the area, due to the inappropriateness of global MDT models in closed sea areas.

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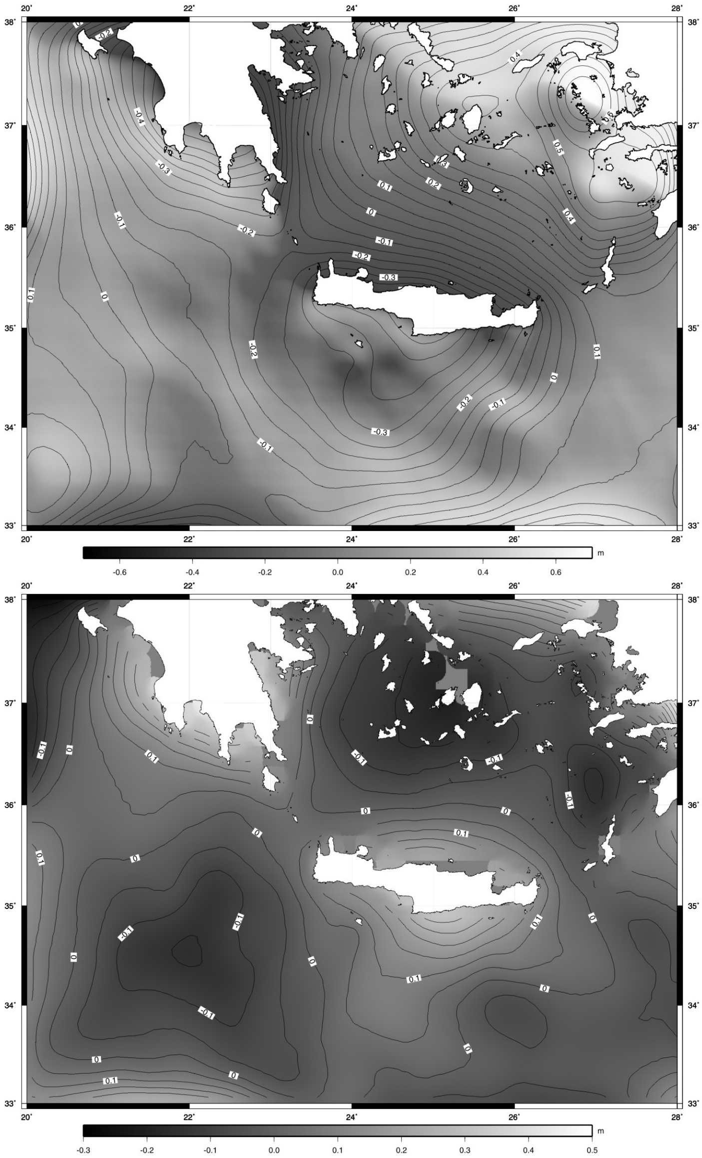

Fig. 5: The final (top) QSST model and its comparison with the oceanographic model.

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