SEA LEVEL VARIABILITY IN THE AEGEAN SEA AS A TOOL FOR CLIMATE CHANGE MONITORING

Georgios S. Vergos, Ilias N. Tziavos
Department of Geodesy and Surveying, Aristotle University of Thessaloniki, Greece

Abstract

Climate change has become an undoubted reality and can be viewed in various forms in our everyday life. Sizzling hot weather has become more common in the Mediterranean combined with blasting storms in Central Europe. Moreover, polar ice melt, sea level trends and global temperature rise are blamed for the alteration of our natural marine ecosystems, while representing at the same time a threat to our society, cities and economy. During the last twenty years many remote sensing satellites carrying on board altimeters provide a long record of measurements of the instantaneous sea level thus allowing the study and monitoring of the sea level variations in periods ranging from ten days to ten years. This offers a powerful tool to understand seasonal variations in sea level, which can be regarded as normal and attributed to the epoch change, while at the same time it gives the opportunity to determine trends in sea level change, which cannot be regarded as normal and can therefore be attributed to long-term, constant changes or responses to global climate events. This work presents the results from a study contacted in the Aegean Sea aiming at the determination of the sea level variations and the identification of trends in sea level change. Seasonal, annual and inter-annual variations are identified while the response to ENSO events like El Niño and La Niña are determined. Finally, rates in the sea level change for the Aegean Sea are determined from a twelve year record of continuous sea surface measurements.

Keywords. sea level variability, geoid, sea level rise, climate change, least squares collocation

1. Introduction

During the last three decades altimeters on-board satellites have offered a tremendous amount of measurements of the ocean surface. This mapping of the oceans refers to the determination of the height separation between the sea surface and a reference ellipsoid. The measurements of sea surface, called sea surface heights (SSHs), are of main interest to both geodesy and oceanography. In geodesy, SSHs are commonly used to determine an altimetric marine geoid model and/or combined gravimetric and altimetric solutions. This is feasible, since the combination of multi-satellite SSHs leads to the determination of a Mean Sea Surface (MSS) model, which approximates the geoid very closely. It is then just a matter of reduction of the MSS heights, actually the removal of the quasi-stationary part of the sea surface topography, to determine a marine geoid model.

There have been many studies on the determination of MSS models (Andersen and Knudsen 1998; Cazenave et al. 1996; Yi 1995), global (Lemoine et al. 1998; Wenzel 1998) and regional geoid models (Arabelos and Tziavos 1996; 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). MSS models and altimetric observations in general offer a powerful tool for the determination and monitoring of mean sea level variations and the identification of trends with time (Fu and Le Traon 2006, Leuliette et al. 2004, Nerem et al. 2006). As an example, Figure 1 (left) shows the current (1993-2008) global trend in sea level change from TOPEX/Poseidon (T/P) and JASON-1 data. A positive rate of +3 mm/y is evident when fitting a first order linear trend to the altimetric observations. These records are in agreement with historical tide gauge (TG) records (see Figure 1 right), which however show a significant increase in the mean sea level during the last century. It is therefore evident that satellite altimetry data can assist greatly the determination of mean sea surface models as well as the investigation of mean sea level trends. The main advantage of altimetric SSHs over other marine data, like shipborne gravimetry, can be viewed in terms of their high precision, resolution, homogeneity and global coverage.

The main purpose of the present study is to a) determine a MSS model for the Black Sea and the Aegean, b) investigate sea level changes in the area, c) validate the estimated MSS models with respect to quasi-geoid heights at TG stations, d) estimate corrector surfaces between gravimetric and altimetric geoid models, and e) determine trends and variations in the sea level due to climate change events. In this context altimetric SSHs from the Exact Repeat Missions (ERMs) of various satellites are used in combination with MSS models to monitor sea level change and relate to historical and recent TG records. A very good review on the applications of satellite altimetry to geodesy and sea level changes is given by Tapley and Kim (2001) and Nerem and Mitchum (2001) respectively.

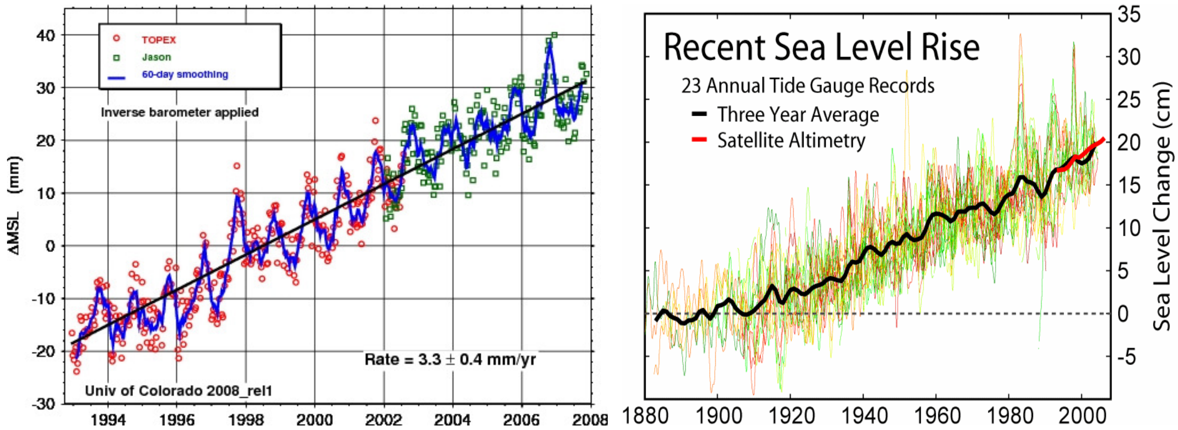

Figure 1: Recent sea level variations from satellite altimetry (left) (Image from http://sealevel.colorado.edu) and global average of sea level rise from tide gauge and altimetry observations (right) (Image from http://www.globalwarmingart.com).

2. Mean Sea Surface Determination

To achieve the goals outlined above, altimetric data from the ERM missions of ERS1/2 and T/P have been used (AVISO 1998). The ERS1 data (95576 point values) come from the 35-day ERM mission of the satellite from April 14, 1992 to December 13, 1993 and March 21, 1995 to May 16, 1995 phases *c* and *g* respectively. From ERS2 six years worth of data have been used (368617 point values) covering the period from April 21, 1995 to June 16, 2001. Finally, nine years of the T/P SSHs were employed (488634 point values) covering the period from October 2, 1992 to October 8, 2001. Figure 2 depicts the area under study and the distribution of the altimetric data.

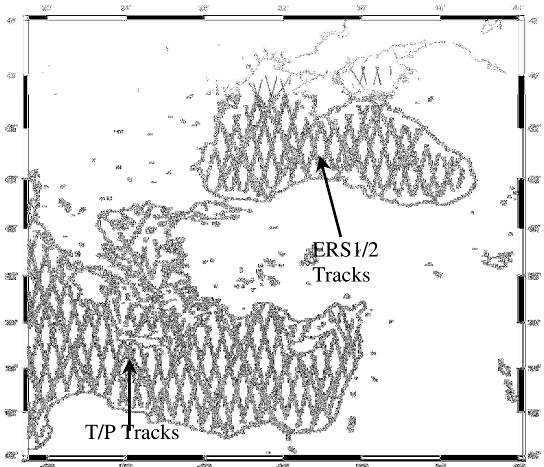

Figure 2: Area under study and distribution of ERS1, ERS2 (gray) and T/P (black) tracks.

For the estimation of the MSS model we have estimated single-satellite solutions, i.e., using T/P, ERS1 and ERS2 data only, while a combined model was determined as well employing all available SSHs. For each of these cases three algorithms for the prediction on a grid have been tested, i.e., conventional weighted means, with the inverse of the square of the distance of each point serving as its weight, splines in tension (Smith and Wessel 1990) and least squares collocation (LSC) (Moritz 1980; Knudsen 1993). Therefore twelve solutions have been estimated and validated in total to decide on a) whether single or combined models are preferable and b) the most appropriate algorithm. The prediction of the models using splines in tension was based on the algorithm incorporated in the Generic Mapping Tools software (Wessel and Smith 1998), while for the estimation of the LSC models a local covariance function for the area determined by Vergos et al. (2003) from shipborne and airborne gravity data has been used.

From the MSS models estimated it was concluded that the T/P only solutions (regardless of the algorithm) showed significant discontinuities within small areas, which are mainly attributed to the large cross-track spacing (~3^{o}) of the T/P tracks. The ERS1 and ERS2 models had better behavior compared to T/P (reduced discontinuities) but once again there were many artifacts in the estimated field.

Finally, all single-satellite MSS models did not manage to depict the short-wavelength features of the gravity field in the area due to the presence of, e.g., the Hellenic Trench. This was expected due to the large cross-track spacing of the data. On the other hand, the estimated combined models, regardless of the algorithm used, managed to give a more or less realistic picture of the gravity field of the area. From the comparisons between the algorithms it was concluded that the weighted means solutions, at least with the particular weight used, does not manage to predict the short-wavelength details of the field, while spline interpolation produced some artifacts. Nevertheless, the combined model using splines in tension managed to provide a very good picture of the MSS of the area, which was very close to the geoid signature of the underwater structures in the region. LSC is a method traditionally used in geodesy to predict gravity field related quantities or as a gridding algorithm. It is preferred due to its statistical rigorousness and the fact that it can take into account the local statistical characteristics of the area under study through the use of a local empirical covariance function. Therefore, it was expected that the LSC combined MSS model would give the best results. The estimated LSC combined model did not show any "trackiness" while no discontinuities were detected as well. Furthermore, it managed to depict very well all the structures of the gravity field of the area giving good detail.

Nevertheless, in order to be confident on the selection of the collocation solution as the MSS model for the area, a comparison of all available combined models was performed w.r.t. the KMS01 MSS (Andersen and Knudsen 1998). The combined solutions were overwhelmingly better than single-satellite ones, thus the comparisons with KMS01 discussed below refer only to the combined models to assess the performance of the gridding algorithms. As an indication of the improvement that combined models offer, it should be mentioned that the standard deviation (σ) of differences between the LSC single-satellite ERS1, ERS2 and T/P MSS with KMS01 reached the ±0.303, ±0.214 and ±0.332 m level respectively. Table 1 presents the statistics of the differences between KMS01 and the estimated MSS models before and after the minimization of the differences with a 3rd order polynomial model. In Table 1 SP denotes the spline, WM the weighted means and LSC the collocation MSS models respectively. It can be easily concluded that the LSC MSS model gives the best agreement w.r.t. KMS01 since the range is smaller by about 23% and the σ by 16% compared to the SP model. The worst results are obtained when the WM model is compared with KMS01, showing that this gridding algorithm is inadequate. The last row in Table 1 gives the statistics of the LSC combined MSS model for the area under study, which is also depicted in Figure 3. Thus, it was concluded that combined models are preferable to single-satellite ones, while least squares collocation was selected as the most rigorous algorithm to provide the final mean sea surface model for the area under study.

Table 1. *Statistics of differences between KMS01 and the estimated MSS models. Unit: [m].*

		max	min	mean	σ
SP	**before**	1.505	-1.990	-0.086	±0.20
	after	1.679	-1.854	0.000	±0.20
WM	**before**	1.622	-3.121	-0.094	±0.27
	after	1.790	-3.079	0.000	±0.26
LSC	**before**	1.452	-1.219	-0.083	±0.17
	after	1.627	-1.104	0.000	±0.16
LSC MSS		42.15	0.840	21.607	±9.30

3. Sea Level Variations

The next goal of this study, as outline in Section 1, was the investigation for trends in the sea level change of the Black and Aegean Seas for the period covered by the data (1992-2001). To assess that a two-fold procedure was followed. Firstly, a stacked dataset from all nine years of T/P data was constructed and differences between that and annually stacked T/P SSHs were formed. Stacking is a procedure of constructing means of repeated altimetric profiles, which successfully manages to remove effects influencing the data with period longer than the repeat period of the satellite (Knudsen 1992). Thus, for the 10-day repeat period of T/P, if an annual set of ERM data is stacked, then we manage to remove the ocean effects with period longer than 10 days and shorter than one year, influencing the ERM data. On the other hand, if a nine-year dataset is stacked, then we manage to remove effects with periods between 10 days and nine years. Thus, it can be assumed that the differences between an annual stacked dataset and a nine-year one will be free of a) short-time (but longer than 10 days) phenomena and b) phenomena with a period between one and nine years. It should be noted that the effect of the dynamic ocean topography is not periodic thus it remains in the data. Therefore, what remains is the sea level variation between each year and a nine-year mean. Plotting these differences for

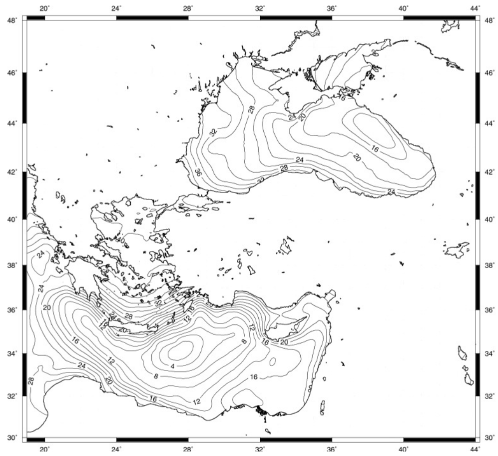

Figure 3: The final LSC combined MSS model.

all nine years and fitting a linear trendline will yield an annual rate of sea level change. The second approach was to generate monthly and annual datasets from the T/P SSHs for the period 1993-2001 and then compute their differences w.r.t. the final MSS model estimated for the area under study. In the latter approach, the differences presented are after the removal of a first order polynomial trend surface, so as to remove or at least reduce any mean trend between the datasets compared.

Figure 4 presents a plot of the mean of the differences between the stacked annual T/P SSHs and the nine-year stacked dataset as well as a first order trendline fitted to the data. From that figure a very small trend (-0.4 mm/y) in sea level change can be seen, which cannot be regarded as significant. Therefore, we can conclude that there is no significant sea level change in the Black sea and the Aegean for the period 1993-2001. On the other hand, if the observation record is extended to 2008 and the study covers the entire Mediterranean Sea (see Figure 5) a positive trend of +2.78 ±0.3 mm/y was determined. This is in close agreement with the current global trend in sea level rise. Nevertheless, even in the Mediterranean record, a very clear seasonal cycle is evident after computing a 60-day moving average (blue line).

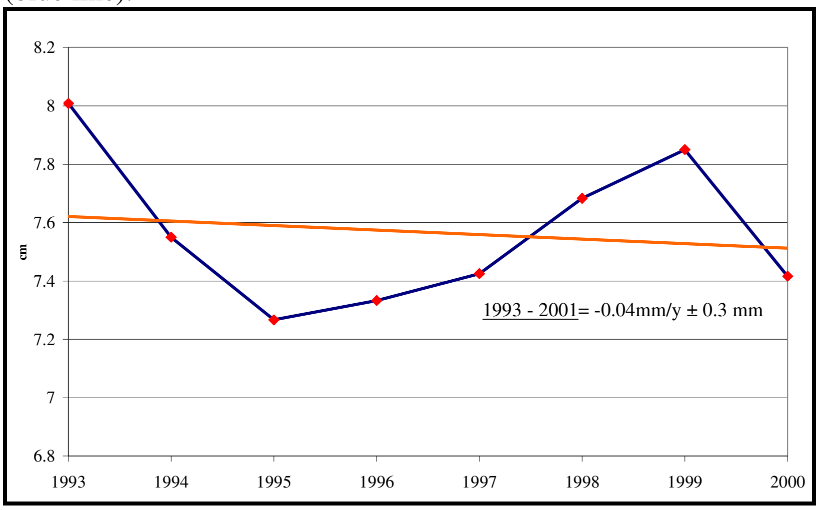

Figure 4: Annual sea level variations from T/P SSHs.

Figure 6 depicts the standard deviation of the differences between the monthly T/P datasets and the LSC combined MSS model for the period between January 1993 and January 2001. In all cases the differences are formed in terms of the differences ($h^{monthly}$-*MSS*). The black circles represent the highest peak of each year while the gray ones the lowest. It can be clearly seen that there is a very strong seasonal pattern in the sea level variation, with the highs and lows occurring in January and June to July of each year, respectively. Additionally, the highest peak in sea level in these nine years occurs in February 1998 and coincides with the El Niño event (~1 cm highest than the other yearly peaks), while La Niña in December 1998 does not seem to influence the sea level in the area significantly. This is probably expected since the Aegean and Black Seas are more or less closed, so they are less influenced by ENSO events, especially if the influence of the latter is not so strong (like in the case of La Niña). Finally, it is interesting to notice that even though the highs in each year occur in January, when El Niño occurs then the high appears in February. The aforementioned comments consist a clear indication that monitoring sea level variations and sea level change is a powerful and useful tool for climate change monitoring, since the ocean responds almost immediately to large scale changes due to ENSO events like temperature increase and decrease.

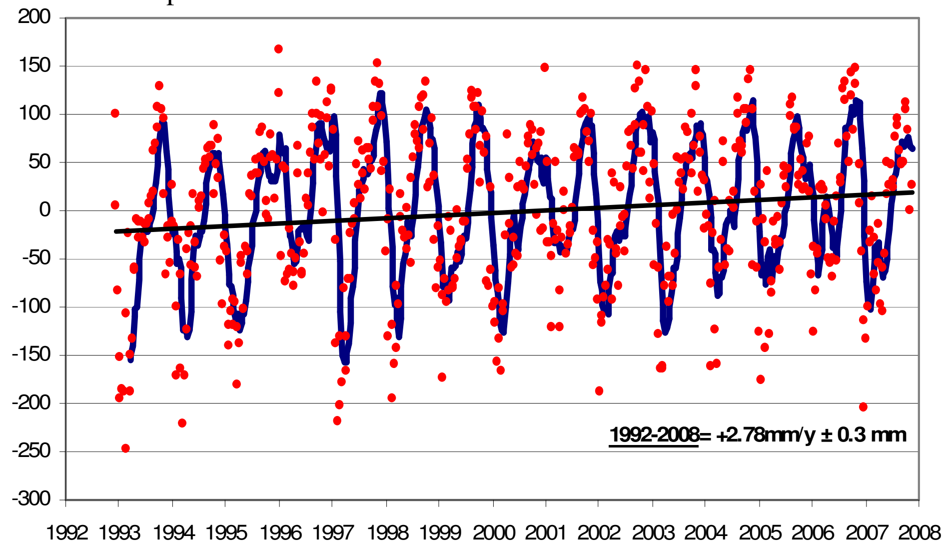

Figure 5: Sea level variability from T/P and Jason-1 SSHs (red dots), 60-day moving average variations (blue line) and 16-year trend (black line).

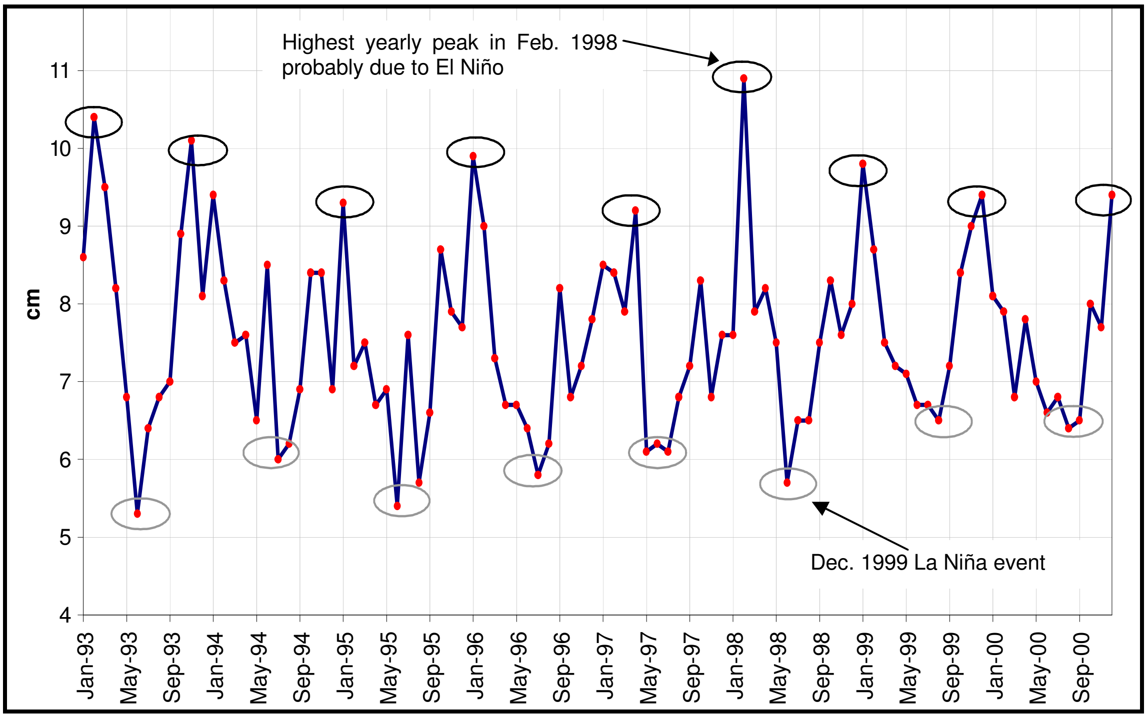

Figure 6: Sea level variations between 1993 and 2001

From the analysis of the differences between the annual T/P data sets and the estimated MSS, before the removal of the trend surface it was found that for the period 1993-1995 there was of rate of sea level change of -0.33 mm/y while between 1995 and 2000 it reversed its sign and was rising by about +1.5 mm/y. Additionally, when determining the rate of sea level change for the entire period (1993-2001), it was found to be at the sub-mm level, which agrees with what was found from the differences between the stacked T/P datasets. This is good evidence that the two approaches followed, i.e., a) comparisons between stacked T/P datasets and b) comparisons between a MSS model and monthly/annual T/P data can lead to reliable results. From the results obtained it is evident that there is a very strong seasonal pattern in the sea level variation in the area under study while no sea level change can be identified.

4. Comparisons at TG stations

The final objective of the present study is the validation of the estimated MSS model w.r.t. TG records available for the region. There is only a small amount of TG stations (seven) available all of them located in the

Table 2. Statistics of differences between the T/P yearly MSSs and stacked 9-year T/P data after trend removal. Unit: [m].

TREND	**year 1**	**year 2**	**year 3**	**year 4**	**year 5**	**year 6**	**year 7**	**year 8**	**year 9**
max	0.360	0.390	0.370	0.340	0.310	0.390	0.390	0.370	0.450
min	-0.270	-0.270	-0.300	-2.970	-1.510	-1.840	-1.820	-2.000	-1.800
mean	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
rms	0.094	0.093	0.094	0.156	0.112	0.121	0.120	0.125	0.115
std	0.094	0.093	0.094	0.156	0.112	0.121	0.120	0.125	0.115

western part of the Black Sea (see Fig. 7). For these stations gravimetric quasi-geoid heights were available (Becker et al. 2002; Ihde et al. 2000) so that a comparison with the estimated MSS model and KMS01 was feasible. We assume that the QSST in the Black Sea is small in magnitude, so that the MSS and the geoid coincide, therefore such a comparison is feasible. Furthermore, since the TG stations are close to the coastline, it can be assumed that the geoid and the quasi-geoid coincide. The differences are minimized using a 2nd order polynomial model as

$$N^{TG} - N^{i} = x_1 + x_2\left(\phi_i - \bar{\phi}\right) + x_3\left(\lambda_i - \bar{\lambda}\right) + x_4\left(\phi_i - \bar{\phi}\right)^2 + x_5\left(\lambda_i - \bar{\lambda}\right)^2 + x_6\left(\phi_i - \bar{\phi}\right)\left(\lambda_i - \bar{\lambda}\right) + v \quad (1)$$

where N^{TG} is the TG quasi-geoid height, N^{i} denotes the estimated MSS model or KMS01, and x_1, x_2, x_3, x_4, x_5, x_6 are parameters to be estimated using a least squares method. The results of these comparisons are summarized in Table 3 where the differences, both before (regular numbers) and after the fit (numbers in italics) of the polynomial model, are presented.

From Table 3 it can be concluded that the estimated MSS model give smaller differences w.r.t. the TG gravimetric geoid heights compared to KMS01. These differences range from only -11 cm (for Bourgas) to almost -2.6 m for the TG station in Shabla. For the latter KMS01 gives a very large difference as well (~-2 m), so it may be possible that the estimated gravimetric geoid height at that station is wrong. Apart from the differences at the Shabla station, the rest appear very satisfactory, since they reach a minimum of -68 cm. These large differences can be due to a) the fact that the altimetric data were not reduced for the sea surface topography and b) datum inconsistencies between the altimetric models and the gravimetric geoid estimated for the TG stations. This is especially evident for the Varna TG station (difference of 14.2 cm after the fit), which was used for the definition of the Bulgarian height system and its connection to the Baltic system. This difference is very close to the one between the Baltic and Black Sea height systems. After the fit of the transformation model the differences range between 9 mm and 35 cm for the estimated MSS model and 1.3 cm and 48 cm for KMS01. This is very encouraging for the methodology followed to determine the MSS model.

Table 3. Differences between the TG geoid height, the estimated MSS model and KMS01. Unit: [m].

	N^{TG}-N^{MSS}		N^{TG}-N^{KMS01}	
Constanza	-0.675	*-0.029*	-0.445	*-0.040*
Shabla	-2.590	*-0.185*	-1.970	*-0.251*
Varna	-0.588	*0.142*	0.112	*0.192*
Irakli	-0.539	*0.354*	0.317	*0.480*
Bourgas	-0.108	*-0.278*	0.549	*-0.378*
Ahtopol	-0.465	*-0.012*	0.046	*-0.017*
Mykolaiv	-0.324	*0.009*	-0.245	*0.013*

From the minimization of the differences between the TG geoid heights and the MSS model a corrector surface has been determined (see Fig. 8) which corresponds to the 6 parameters estimated by Eq. 1. The translation parameter between the TG geoid heights and the MSS model estimated is 70 cm. This trend is very large to be attributed to either the height difference between the Black Sea and the Baltic Height systems, the QSST in the Black Sea and the datum inconsistencies between the MSS and quasi-geoid models. A first guess would be that the Shabla station influences the entire adjustment, therefore that TG was removed and the differences between the quasi-geoid heights and the determined MSS were once again minimized. When employing Eq. 1 with six observations, this leads to a system with a unique solution, so no actual adjustment can take place. Therefore, a 1st order polynomial was used, which is described by the first three x_i parameters of Eq. 1. The differences after the fit at each station were now found to be -0.156 m, -0.085m, -0.088 m, 0.368 m, -0.107 m and 0.068 m for the Constanza, Varna, Irakli, Bourgas, Ahtopol and Mykolaiv TG station, which clearly depicts

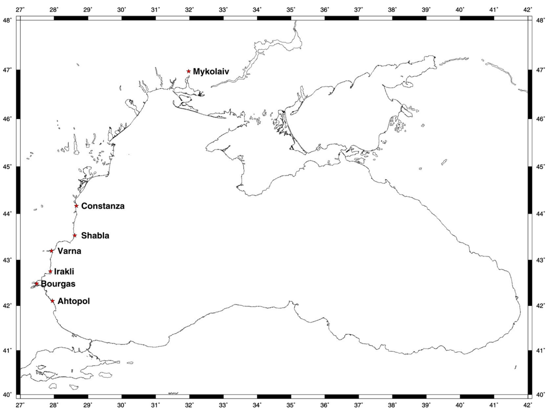

Figure 7: Distribution of TG stations in the Black Sea.

that the Shabla station influenced strongly the rest of the estimated residuals. The new corrector surface is depicted in Fig. 6 as well, while the estimated translation parameter (x_1) between the TG quasi-geoid heights and the MSS heights was now estimated at the 42.5 cm ±5.8 cm level. This result corresponds very well to the combined effect of the height difference between the Black Sea and the Baltic Height systems (27 cm), the QSST in the Black Sea and the datum inconsistencies between the MSS and quasi-geoid models.

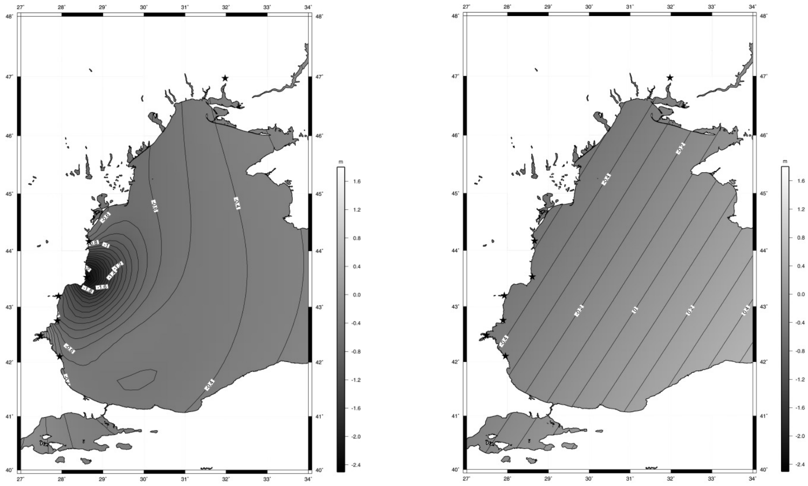

Figure 7: 2nd order (left) and 1st order (right) corrector surfaces between gravimetric quasi-geoid heights and altimetric geoid heights.

5. Conclusions

A method of estimating a mean sea surface model has been presented based on an analysis of single- and multi-satellite datasets employing various gridding algorithms. The combination of altimeter data from as many satellites as possible is preferable, since it manages to overcome the problems caused by the large cross-track spacing of ERM data, i.e., the discontinuities introduced in the estimated MSS model from the few observations available. Additionally, least squares collocation (employing a local covariance function) is preferred against weighted means and splines in tension to estimate the final grid, since it gives the more rigorous results without introducing artifacts in the final field. Furthermore, LSC manages to depict the short-wavelength features of the gravity field of the area while WM especially smoothes the estimated MSS model significantly.

From the analysis of the variations in the sea level, it was concluded that there is no detectable significant changes in the time period studied (1993-2001), since variations at the sub-mm level cannot be regarded as important. It is also worth mentioning that the sea level in the area under study has a seasonal pattern which is evident throughout the nine years covered by the present study. Additionally, it was possible to detect the response of the sea in the region to El Niño but not to La Niña, probably due to the small magnitude of the latter.

Finally, from the comparisons between the MSS model estimated and TG quasi-geoid heights it became evident that the model determined is comparable to KMS01 and in some cases better than that since the differences it provides are smaller.

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