

Determination of the quasi-stationary sea surface topography from a common adjustment of a geodetic and an oceanographic model

G.S. Vergos✉ and I.N. Tziavos

Department of Geodesy and Surveying, Aristotle University of Thessaloniki, University Box 440, 541 24, Thessaloniki, Greece, Fax: +30 31 0995948, E-mail: vergos@topo.auth.gr

Abstract. The determination of accurate marine geoid models from satellite altimetry data usually suffers from the absence and/or in-accuracy of appropriate models of the quasi-stationary sea surface topography (QSST). This is the case for the Mediterranean Sea and especially for its eastern part, where global models are inadequate since: a) The differences between the various solutions exceed the magnitude of the QSST itself and b) they are most commonly in the form of a low-degree spherical harmonics expansion of the QSST, which resolves wavelengths much longer than the extension of the area under study. From that rationale, the present study focuses on the determination of a QSST model in the eastern part of the Mediterranean Sea, from a geodetic point of view. This geodetically oriented QSST determination stands upon the simple principle that the quantity under determination can be derived as the difference between a purely altimetric and a purely gravimetric geoid model. From that initial solution an adjusted model is determined from its common adjustment with an oceanographic QSST model computed from in-situ oceanographic data. Finally, the circulation in the area under study is determined by estimating the velocities and the direction of the sea currents.

Keywords. Quasi-stationary sea surface topography, circulation, currents, velocities, adjustment.

1 Introduction

Since the early missions of GEOS-3 and SeaSat, altimeters onboard satellites have offered a tremendous amount of measurements of the sea surface resulting in the improved knowledge of the Earth's gravity field over oceanic regions. A direct consequence of that is the continuous development of Mean Sea Surface (MSS) models of the oceans, which are usually combined with satellite-only Earth Gravity Models (EGMs) to estimate models of the Quasi-Stationary Sea Surface Topography (QSST). The QSST is defined as the semi-constant over large periods of time deviation of the mean sea surface from the geoid. It reaches a maximum of +2.2 m and in closed sea areas has very small variations over large regions. This is why most QSST models developed during the last two decades are usually provided in terms of a spherical harmonics expansion of the QSST to low degrees, e.g., 20 (which corresponds to about 2000 km

full wavelength). It can be easily concluded that when the area under study is rather small or is characterised as closed, e.g., the Mediterranean Sea, then such global models are insufficient. Moreover, in areas like the aforementioned the differences between the presently available global QSST models largely exceed the magnitude of the signal under consideration itself. This signals both a significant uncertainty in the available models and a need for the development of reliable and accurate local estimates of the QSST for use in geodetic and oceanographic studies.

From a geodetic point of view, the QSST is needed for the reduction of the altimetric measurements from the sea surface to the geoid. This is so because the basic measurements of satellite altimeters, the sea surface heights (SSHs), refer to the sea surface and not the geoid itself. Therefore, the reduction of these observations to the geoid is necessary to determine a geoid and not a MSS model. Additionally, shipborne gravity measurements refer to the sea surface as well and need to be free-air reduced to the geoid to be used for the determination of a gravimetric geoid in the well-known Helmert scheme. The quantity needed for this reduction is the QSST, which is the "marine" counterpart of orthometric heights on land. It can be easily concluded that the QSST is significant for the precise and accurate determination of gravity-field related quantities, while local models are highly necessary as well to serve local to regional geoid modelling.

These form the basis for the present work, i.e., to investigate whether a determination of the QSST from a geodetic point of view, i.e., using traditional geodetic methods and quantities, is possible. Furthermore, from this initial solution an adjusted model is determined through a combination with a local oceanographic model of the QSST. Studies on a *geodetic determination* of the QSST have begun since the work by Engelis (1983) who presented in a very elegant way their feasibility (OSU83 QSST model). Consequently, there have been more works on a global determination of the QSST in terms of surface spherical harmonics (SH) (Engelis 1987), while Knudsen (1992) presented a local model for the North Sea. Then, Pavlis et al. (1998) used Proudman functions and data from the POCM-4 model to estimate the QSST to degree and order 20. Finally, Andritsanos et al. (2001) estimated QSST models and current velocities from an analysis of altimetric exact repeat mission data using the Fast Fourier Transform

based Multiple-Input Multiple-Output System Theory (MIMOST) method.

The area of the present study is the Eastern part of the Mediterranean Sea bounded between $33^\circ \leq \varphi \leq 38^\circ$ and $20^\circ \leq \lambda \leq 28^\circ$. This region was selected due to a) the fact that it is a closed sea, thus global models are insufficient due to both their low degree of expansion and range of differences and b) some well-known currents are present so they can provide a reasonable validation of the proposed method. The determination is based on well-known geodetic algorithms and uses purely “geodetic” data, i.e. satellite altimetry geoid heights and shipborne gravity anomalies. For the estimation of the QSST, the simple formula connecting altimetric and gravimetric geoid heights, i.e., that their difference gives the QSST, was employed. With this as a starting point, the use of low pass filtering (LPF) with a Wiener-type of filter and a blunder detection test is proposed to filter the resulting QSST field and lead to a better approximation of the SST. This filtering operation is necessary to reduce high-frequency oceanic effects contaminating geodetic mission (GM) altimetry, while the blunder removal is needed to smooth the differences between the altimetric and shipborne gravity data, due to blunders in the latter. After this initial model is developed, an adjusted one is estimated through a combination with a local oceanographic one. This adjustment procedure is based on the well known least squares principle, where the vector of the observation equations is formed by the differences of the geodetic and oceanographic QSST models. Various deterministic parametric models are tested in order to describe the differences of the observations and finally construct a corrector surface for the adjustment of the geodetic QSST model. As a final step, the direction and velocities of the ocean currents in the area are determined based on the principle of geostrophic flow.

2 Sea Surface Topography Modeling

For the determination of the QSST an altimetric and a gravimetric geoid model for the area were used. These models have been developed by Vergos (2006) and Vergos et al. (2005) and by combining all available altimetric data in the area under study for the former and a recently constructed high-resolution and high-accuracy gravity database for the latter. The development of these models will be briefly discussed since the models themselves and the methodology followed are well documented in Vergos (2006) and Vergos et al. (2005).

The altimetric geoid was estimated from a combination of ERS1 and GEOSAT GM data for the area under study. The well-known remove-compute-restore method was employed, while the EGM96 (Lemoine et al. 1998) global geopotential model was used as a reference surface. Finally, an altimetric geoid of $1' \times 1'$ resolution in both latitude and longitude was determined for the area under study.

For the determination of the gravimetric geoid model, an effort was made to collect all available marine, land and airborne gravity data for the area under study. Then, an editing and blunder detection and removal process, using least squares collocation, took place to construct a homogeneous and accurate gravity database. Finally, a gravimetric geoid model was estimated using EGM96 as a reference surface and the 1D FFT spherical Stokes convolution to evaluate Stokes’ function (Vergos 2006; Vergos et al. 2005). The statistics of the altimetric and gravimetric geoid models are summarized in Table 1.

Table 1. Statistics of the altimetric and gravimetric geoid models. Unit: [m].

MODEL	max	min	mean	σ
$N^{\text{gravimetric}}$	39.913	0.780	21.185	± 10.352
$N^{\text{altimetric}}$	40.206	1.057	21.376	± 10.484

Employing the so-derived geoid models for the area under study, a preliminary quasi-stationary sea surface topography model for the area was estimated as

$$\text{QSST} = N^{\text{alt}} - N^{\text{grav}} \quad (1)$$

where N^{alt} and N^{grav} are the altimetric and gravimetric geoid heights respectively. It should be noted that the gravity anomalies used to determine the gravimetric geoid are free-air reduced, i.e., reduced from the sea surface to the geoid. The statistical characteristics of this preliminary QSST are given in Table 2. From Table 1 it is evident that the QSST estimated presents some unreasonably large variations within the area (3.3 m) and reaches a maximum of 2.2 m. Therefore it is clear that blunders are present in the estimated field. Finally, from the resulting field it became evident that some noisy features were present thus low-pass filtering (LPF) was also needed to reduce these effects.

Table 2. Statistics of the preliminary QSST model before and after the 3rms test. Unit: [m].

	max	min	mean	σ
before	2.177	-1.112	0.224	± 0.326
after	0.977	-0.958	0.190	± 0.269

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 standard deviation of the preliminary field were removed. The statistics of the QSST model after this test are given in Table 2 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 that needs to be filtered. Furthermore, it is assumed that Kaula’s rule for the decay of the geoid power spectrum holds, i.e., that the geoid heights PSD decays like k^{-4} where k is the radial wavenumber. Finally, we arrive at the filtering function shown in Eq. 2, where ω_c is the cut-off frequency.

$$F(\omega) = \frac{\omega_c^4}{\omega^4 + \omega_c^4} \quad (2)$$

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 (noise reduction). 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 and 120 km and finally we selected a wavelength of 100 km (about 1° or harmonic degree 180) 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 the characteristics of the field as well. If we would select a longer wavelength, then, and if the area was significantly larger (e.g. the entire Mediterranean Sea) it would have been possible to identify larger in scale QSST features and distinguish them from smaller ones. The problem in this case is that shipborne gravity data in such high resolutions are not available for large regions.

The statistics of the final geodetic QSST field after the filtering are given in Table 3. Comparing the fields before and after the blunder removal and LPF it was concluded that the noise present in the preliminary model is reduced significantly, while blunders could not be identified. The QSST model estimated has been compared with a Mean Dynamic Topography (MDT) model computed for the entire Mediterranean Sea from an analysis of satellite altimetry and oceanographic data (Rio 2004). The latter is 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 model is given in Table 3 (last row). From the comparison it can be concluded that the two models agree reasonably well to each other (standard deviation at the ±20 cm level). The maximum and minimum values of the differences are found close to land areas only, where both models are inadequate, while in purely marine regions range between -0.2 to 0.2 m. This comparison gives evidence that the estimated geodetic QSST model is at least in good agree-

ment with existing regional oceanographic MDT models. Nevertheless, the magnitude of the QSST that the geodetic model provides, and the velocities of the ocean currents resulting from that, is quite large for the area under study. The presence of the oceanographic model provides the opportunity to *adjust* the geodetic one, i.e., minimize their differences in a least squares sense and thus provide a better estimate of the QSST for the area. The corrector surface resulting from this adjustment scheme can then serve for the transformation/adjustment of future geodetic QSST models available for the entire Mediterranean Sea.

Table 3. Statistics of the final geodetic QSST model. Unit: [m].

	max	min	mean	σ
QSST	0.675	-0.510	0.014	±0.238
MDT	0.096	-0.177	-0.047	±0.052
MDT-QSST	-0.635	0.478	-0.058	±0.200

3 Common Adjustment

In the common adjustment scheme of the QSST models the observation vector is of the form:

$$b_i = (N_i^{\text{alt}} - N_i^{\text{grav}}) - \zeta_i^{\text{c ocean}} = \zeta_i^{\text{c geod}} - \zeta_i^{\text{c ocean}} \quad (3)$$

where, $\zeta_i^{\text{c geod}}$ and $\zeta_i^{\text{c ocean}}$ denote the geodetic and oceanographic QSST models respectively. The observation vector entering the system of linear equations can then be describe as

$$b_i = \mathbf{a}_i^T \mathbf{x}_i + v_i \quad (4)$$

where, \mathbf{x} is the vector of the unknown parameters of the model selected and \mathbf{a} is the vector of the known coefficients of the parametric model selected to describe and minimize the errors in the observations and estimate values in new points as well. The parametric models used in the present study are the well-known four- and five-parameter similarity transformation ones (see Eqs. 5a, b) as well as polynomial models of degrees zero to three (see Eq. 5c).

$$\mathbf{a}_i^T \mathbf{x} = x_0 + x_1 \cos \varphi_i \cos \lambda_i + x_2 \cos \varphi_i \sin \lambda_i + x_3 \sin \varphi_i \quad (5a)$$

$$\mathbf{a}_i^T \mathbf{x} = x_0 + x_1 \cos \varphi_i \cos \lambda_i + x_2 \cos \varphi_i \sin \lambda_i + x_3 \sin \varphi_i + x_4 \sin^2 \varphi_i \quad (5b)$$

$$\mathbf{a}_i^T \mathbf{x} = \sum_{m=0}^M \sum_{n=0}^N x_q (\varphi_i - \varphi_o)^n (\lambda_i - \lambda_o)^m \cos^m \varphi_i \quad (5c)$$

In Eqs. 5a-c φ_i, λ_i denote the geodetic latitude and longitude of the point under consideration, φ_o, λ_o denote the mean latitude and longitude of the area under study. In Eq. 5c vector \mathbf{x}_q contains the q unknown coefficients, while q varies up to a maximum of $q=(M+1)(N+1)$. Depending on the choice of the parametric model 5a-c the design matrix \mathbf{A} of the system of normal equations ($\mathbf{b}=\mathbf{Ax}+\mathbf{v}$) is formed, so that the adjusted vector of unknown parameters $\hat{\mathbf{x}}$ is estimated as:

$$\hat{\mathbf{x}} = (\mathbf{A}^T \mathbf{P} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{P} \mathbf{b} \quad (6)$$

based on the minimization principle

$$\mathbf{v}^T \mathbf{P} \mathbf{v} = \mathbf{v}_{\zeta_c^{\text{geod}}}^T \mathbf{C}_{\zeta_c^{\text{geod}}}^{-1} \mathbf{v}_{\zeta_c^{\text{geod}}} + \mathbf{v}_{\zeta_c^{\text{ocean}}}^T \mathbf{C}_{\zeta_c^{\text{ocean}}}^{-1} \mathbf{v}_{\zeta_c^{\text{ocean}}} = \min \quad (7)$$

In Eqs. 6 and 7 \mathbf{P} and \mathbf{C} are the weight and covariance matrices of observations, and \mathbf{v} the vector matrix of errors. The adjusted geodetic QSST $\zeta_c^{\text{adj}}_{\text{geod}}$ is then estimated as:

$$\zeta_c^{\text{adj}}_{\text{geod}} = \zeta_c^{\text{geod}} + \mathbf{a}_1^T \mathbf{x} \quad (8)$$

All aforementioned parametric models have been tested in order to select the most appropriate one, according to (a) the final differences between the adjusted geodetic QSST model with the oceanographic one, (b) the goodness of fit through the coefficient of determination and the adjusted coefficient of determination (Fotopoulos 2003), and (c) parameter significance (Fotopoulos 2003; Kotsakis and Sideris 1999). Both the adjusted and simple coefficients of determination range between 0 and 1 and the closer they are to 1 the smaller the better the fit of the parametric model is. The adjusted coefficient of determination is superior to the simple one, since the latter is influenced significantly by the degrees of freedom of the system of linear equations, i.e., the smaller the degrees of freedom, (more parameters in the model) the closer R^2 is to 1 (see Fotopoulos 2003; Sen and Srivastava 1990).

Another criterion used to assess the parametric model performance and computed the adjusted geodetic QSST model was the condition number determined as the ratio between the larger and smaller eigenvalues of the matrix $\mathbf{A}^T \mathbf{A}$. Larger condition numbers translate into more unstable parametric models therefore the results of the prediction tend to vary more with new observations.

Finally, the significance of each model's parameters has been tested according to Dermanis and Rossikopoulos (1991). The entire procedure is based on first fitting to the data the highest order of the selected model and then eliminating the insignificant ones by testing a null hypothesis (backward elimination).

Following this methodology the parameters of the two similarity transformation models and the polynomial ones for degrees zero to three have been computed. The differences between the adjusted geodetic QSST models and the oceanographic one are summarized in Table 4 below. In that Table, A through D denote the zero, first, second and third order polynomial models, while E and F the four and five parameter similarity transformation ones. Characters in italics show the values of the corrector surface computed and regular ones the differences after the fit. From that table it is evident that the overall best fit is provided by the third order polynomial model, with a standard deviation (1σ) of the differences after the fit at the ± 9 cm level and a range of 60 cm. These large values refer to areas across the sea-

land boundary where both models suffer. Neglecting these regions, the range of the differences is at the 25 cm level with a 1σ of ± 3.5 cm.

Table 4. Differences between the adjusted geodetic QSST models and the oceanographic one and statistics of each corrector model. Unit: [m].

	max	min	mean	std
A (trend)			-0.058	
$\zeta_c^{\text{geod}} - \zeta_c^{\text{ocean}}$	0.596	-0.577	0.000	± 0.201
B (trend)	0.184	-0.298	-0.065	± 0.130
$\zeta_c^{\text{geod}} - \zeta_c^{\text{ocean}}$	0.571	-0.369	0.000	± 0.167
C (trend)	0.130	-0.755	-0.076	± 0.210
$\zeta_c^{\text{geod}} - \zeta_c^{\text{ocean}}$	0.499	-0.245	0.000	± 0.105
D (trend)	0.191	-0.737	-0.075	± 0.211
$\zeta_c^{\text{geod}} - \zeta_c^{\text{ocean}}$	0.481	-0.233	0.000	± 0.092
E (trend)	0.133	-0.532	-0.071	± 0.179
$\zeta_c^{\text{geod}} - \zeta_c^{\text{ocean}}$	0.553	-0.278	0.000	± 0.130
F (trend)	0.136	-0.614	-0.072	± 0.186
$\zeta_c^{\text{geod}} - \zeta_c^{\text{ocean}}$	0.558	-0.283	0.000	± 0.131

From that analysis it can be concluded that the model of preference is the 3rd order polynomial one, since it provides the smallest differences after the fit. During the adjustment for all models, the aforementioned statistical measures have been computed in order to test the goodness of fit of each one and the parameter significance. Table 5 summarizes the results acquired, from which it can be concluded that the 3rd order polynomial model provides the closest to one simple and adjusted coefficient of determination (0.68 and 0.74 respectively). This is much better compared to the second best four-parameter similarity transformation model (0.63 and 0.66 respectively). The results from the computation of the condition numbers are equivalent, strengthening the selection of the 3rd order polynomial model as the proper one. From the parameter significance test, all parameters were deemed as significant, while in the case of the five-parameter similarity transformation model it was concluded that the extra parameter compared to the four-parameter model is not significant. Taking these into account, the 3rd order polynomial model was selected to provide the corrector surface (see Fig. 2) with the characteristics presented in Table 4. The resulting adjusted geodetic QSST model is depicted in Fig. 2 and its statistics are presented in Table 6.

Table 5. Coefficient of determination, adjusted coefficient of determination and condition numbers for the various parametric models.

	A	B	C	D	E	F
R_a^2	0.44	0.51	0.56	0.68	0.63	0.59
R^2	0.46	0.54	0.62	0.74	0.66	0.60
co	1.6:10	4.4:10	6.7:10	2.6:10	1.2:10	7.3:10
n	2	3	4	5	6	7

4 Geostrophic Velocity Estimation

From estimation of the final adjusted geodetic QSST models for the area under study, the direction and velocities of the ocean currents can be determined. That was achieved by following the theory of geostrophic

flow, i.e., that the Coriolis force and the pressure gradient acting on the currents are in balance. This method is more related to oceanographic studies and products, but its main advantage is that it can quickly provide velocity estimates and takes into account the properties of the ocean as a fluid. One of its disadvantages is that it diverges close to coastal areas, thus making the current estimates in such regions unreliable. The equations of geostrophic flow in spherical approximation, are given as (Pond and Pickard, 2000)

$$u_s = -\frac{g}{fR} \frac{\partial H}{\partial \phi}, \quad v_s = \frac{g}{fR \cos \phi} \frac{\partial H}{\partial \lambda} \quad (9)$$

where u_s and v_s are the horizontal constituents of geostrophic flow, R is a mean earth radius (6371 km), ϕ and λ denote geographic latitude and longitude respectively, f is the Coriolis force and H the QSST previously estimated. Using Eqs. 11a and b, the north-south (u_s) and west-east (v_s) components of the currents' geostrophic velocities have been estimated for the area under study. Table 6 summarizes the statistics of the estimated velocities and the total velocity field (last row), while Fig. 2 depicts the direction and magnitude of the current velocities. From Fig. 2 we can clearly distinguish some well-known jets in the area like the Mid-Ionian (MIJ) and Mid-Mediterranean ones (Mid-MED Jet), the Western Cretan Gyre (WCG), the Ierapetra Anticyclone (IAC), Rhodes Gyre (RG) and the Cyclades Anticyclone (CAC). Furthermore, South of the island of Crete we can identify a small (in terms of magnitude) jet (dotted lines), which can be either a branch of the Mid-Mediterranean one or a jet by its own. Finally, there is a clear flow from the Aegean Sea (jets J1 and J2) which merge into the Western Cretan Anticyclone and probable "feed" the MIJ. On the other hand they can be part of the Eastern Cretan Anticyclone which is closer to mainland Crete and thus not depicted very well due to the problems of geostrophic theory close to coastal areas. The same currents are identified in the studies by Mazella et al. (2001) and Rio (2004) with the exception of the IAC which is only depicted in Mazella et al. (2001) as *known* to exist in the area under study. The fact that the small IAC and CAC can be clearly identified from the proposed methodology, gives good evidence that this "geodetic" estimation of the QSST can provide accurate and reliable estimates of the ocean circulation. From the geodetic part, the QSST can be used to reduce altimetric and marine-gravity measurements from the sea surface to the geoid.

Table 6. The final adjusted geodetic QSST model and the geostrophic velocities for the area under study. Unit: [m/s].

	max	min	mean	σ
QSST ^{adj geod}	0.332	-0.420	-0.040	±0.133
u_s	1.416	-1.239	-0.013	±0.283
v_s	1.440	-1.185	-0.012	±0.245
total field	1.445	0.000	0.313	±0.206

5 Conclusions

A method to determine the quasi-stationary sea surface topography from a purely geodetic point of view and using geodetic data has been presented. It is based on the simple relationship connecting altimetric and gravimetric geoid heights, a blunder removal and noise filtering procedure and finally an adjustment with an oceanographic model. From the results obtained it can be concluded that the proposed methodology provides accurate and reliable results, since it gives small differences w.r.t. a MDT model derived from altimetry and oceanographic data. Furthermore, from the current velocities estimated, it was possible to identify all known features of the circulation in the area under study like the Mid-Ionian and Mid-Mediterranean Jets, the Western Cretan Anticyclone, the Ierapetra and Cyclades Anticyclones and Rhodes Gyre, which were clearly identified and outlined in the final field.

Such a local QSST model is invaluable to geodetic studies for the reduction of altimetric sea surface heights from the sea surface to the geoid. Furthermore, it provides a reference surface for oceanographic studies, where other measurements can be referred. The results of the present study offer an encouraging prospect for the synergy between geodesy and oceanography with respect to sea level monitoring, sea surface topography determination and marine geoid modeling.

From the preliminary geodetic QSST model developed, it is evident that the initial estimate contains many errors since it gives very large values for both the QSST and the current velocities. This is clearly attributed to the errors in both the altimetric and gravimetric data and the differences in the vertical reference used for each data set. Therefore, the adjustment that followed is necessary not only to adjust the geodetic model to an oceanographic one, but to minimize the aforementioned errors as well. Given that the QSST signal has a long-wavelength nature and does not vary significantly especially in closed sea areas like the Mediterranean Sea, the corrector surface estimated can be used to adjust geodetic QSST models elsewhere in the Aegean Sea and the Mediterranean in general.

Acknowledgement

Funding for this research was provided from the Greek Ministry of Education in the frame of the EPEAEK II program «Pythagoras II – Support to Research Teams in the Universities».

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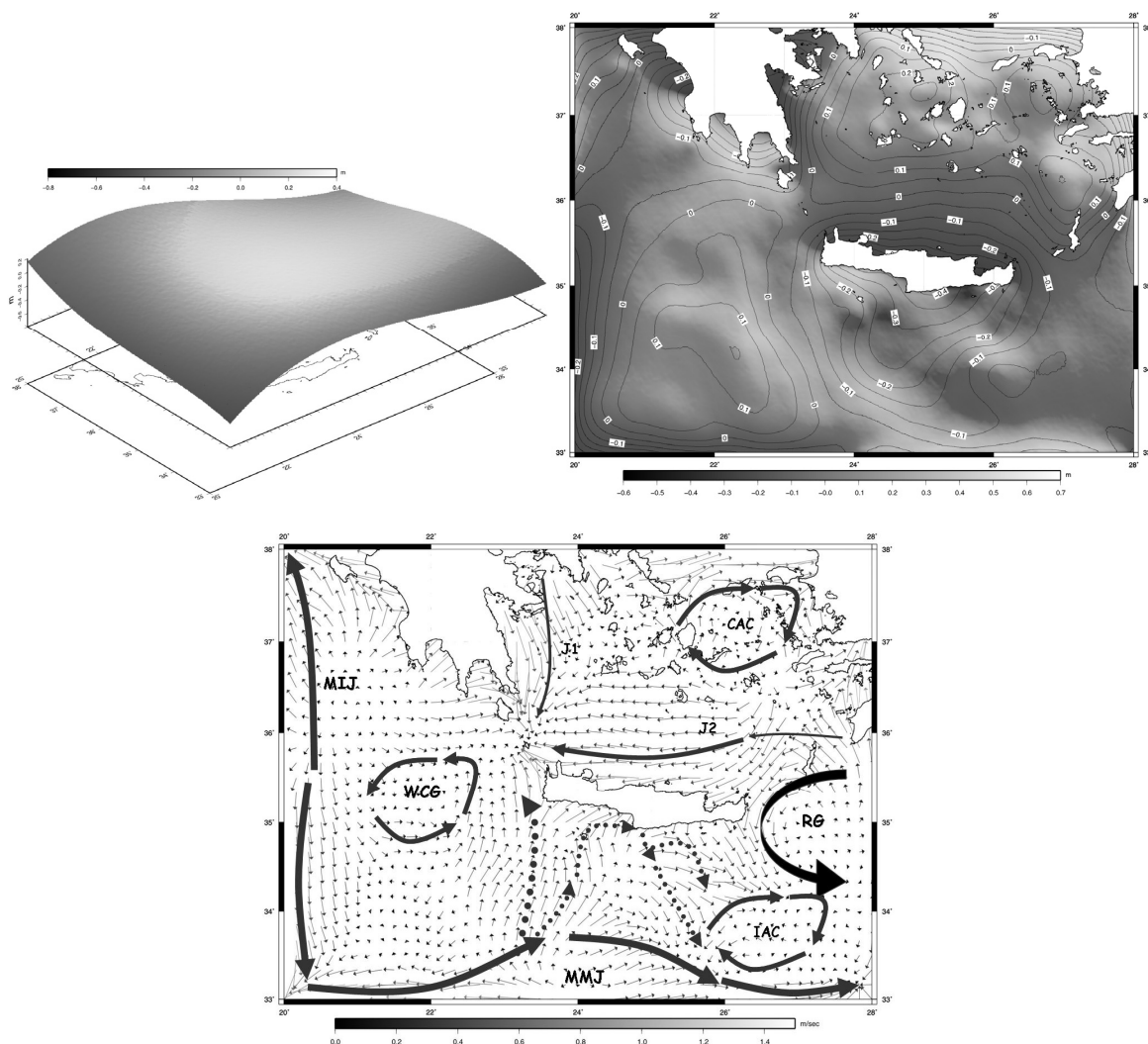


Fig. 2: The corrector surface (top left), the final adjusted geodetic QSST model (top right) and the direction and magnitude of the geostrophic currents (bottom).