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Mean surface geostrophic circulation of the Mediterranean Sea estimated from GOCE geoid models and altimetric mean sea surface: initial validation and accuracy assessment

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ABSTRACT Different combinations of the EGM2008 global model and the GOCE space-wise solution are used to estimate the geodetic mean dynamic topography and the corresponding surface geostrophic circulation of the Mediterranean Sea. In order to assess the accuracy of the GOCE-derived products for oceanographic applications, the mean currents obtained from the geoid models are compared with the mean surface geostrophic velocities measured by drifters and satellite altimetry data. The mean dynamic topographies based on GOCE data combined with EGM2008 generally describe the main circulation patterns and dynamical features in the Mediterranean Sea, except in few coastal regions and in the semi-enclosed Adriatic and Aegean Seas, and improve the results obtained with previous geoid models. The root mean square differences between the geostrophic velocities and the GOCE/EGM2008-derived currents are smaller than 10 cm/s in all the sectors of the Mediterranean basin, whereas they are larger than 12 - 15 cm/s using the EGM2008 solution. The minimum discrepancies and the best complex correlation coefficient are achieved from the EGMSPWbc solution based on an order-wise block diagonal approximation of the GOCE error covariance structure.

Key words: GOCE, Mediterranean Sea, mean dynamic topography, ocean circulation.

1. Introduction

The Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite mission was launched in March 2009 with the objective of measuring the Earth geoid at spatial scales of 100 km with an accuracy of 1 cm. As indicated by its name, one of the primary scientific goal of the GOCE mission is the global determination of the ocean's geostrophic currents (Bingham *et al.*, 2011; Le Traon, 2011). The GOCE mission provides a more accurate global picture of the Earth's gravity field than ever before (Haines *et al.*, 2011), with a huge impact on geophysics. An accurate knowledge of the marine geoid allows the absolute dynamic topography values to be computed from satellite altimetric measurements. Without an accurate geoid only the variable part of the ocean Dynamic Topography (DT), defined as Sea Level Anomaly (SLA), can be deduced from altimetric heights with the accuracy (2-3 cm) required for ocean circulation studies. The direct subtraction of a geoid model (i.e., the geoid height above a reference ellipsoid) from an altimetric mean sea surface (i.e., the mean sea level over a given period of time above the reference ellipsoid) results in an estimate of the ocean Mean Dynamic Topography (MDT) over the considered time period. This MDT can be then added to the altimetric SLA to obtain the ocean absolute DT. The DT is directly related to ocean circulation through the geostrophic approximation.

An initial assessment of the performance of GOCE in terms of ocean MDT and associated geostrophic currents has been provided in the North Atlantic (Bingham *et al.*, 2011), Southern Ocean (Albertella *et al.*, 2012) and global ocean (Mulet *et al.*, 2012). The estimates of mean circulation from GOCE improve the results obtained with previous geoid models, especially at spatial scales smaller than 200 km. GOCE data have been also combined with other existing geoid models in order to provide more accurate representations of surface currents than those obtained for each model alone. For example, solutions derived from the combination of GRACE and GOCE data results in a significant improvement of the low/medium degrees (Pail *et al.*, 2010; Janjić *et al.*, 2012) and permits to better resolve the oceanic circulation than the Earth Gravity Model 2008 (EGM2008) solution (Mulet *et al.*, 2012). Larger improvements with respect to EGM2008 are obtained also combining GOCE and GRACE data with altimeter and terrestrial gravity data (Bruinsma *et al.*, 2010; Mulet *et al.*, 2012).

However, semi-enclosed seas, such as the Mediterranean Sea, are the real challenge for the use of GOCE data, since the spatial scales of the oceanic structures are smaller than in the open ocean and, in many areas, smaller than the expected resolution of GOCE (Rio, 2011). The study of the Mediterranean geostrophic circulation is particularly complex and requires the knowledge of a geoid with an extremely high resolution and accuracy. The objective of this study is to carry out a validation of GOCE global models in the Mediterranean Sea in order to quantify their performances for oceanographic applications. For this purpose, different combinations of the EGM2008 global model [based on GRACE, altimeter and terrestrial gravity data; see Pavlis *et al.* (2012)] containing the high frequencies of the gravitational field, and the GOCE space-wise solution (based on 1 year of GOCE data) are used to estimate the geodetic MDTs in the Mediterranean Sea. The combinations between GOCE, GRACE and ground data, also including EGM2008 [e.g., in the recent EIGEN-6C model: Förste *et al.* (2011)], are generally based on normal equations that, in the case of EGM2008, are computed under the hypothesis of cylindrical symmetry and therefore do not take into account local dishomogeneities due to the original data density and quality. This information is at least partially used in the combination method proposed in this paper. On the other hand, the proposed solutions based on a direct combination between GOCE and EGM2008 coefficients, just using an approximation of the GOCE full error matrix and the EGM2008 coefficient variances, can be similar to other solutions delivered to the geodetic community depending on the calibration/approximation of the covariance matrices (i.e., the inverse of the normal matrices) and on the adopted regularization strategy. The currents derived from these MDTs are compared to those derived from the EGM2008 solution only and to the surface geostrophic currents obtained from the combination of *in situ* data, altimetry products and model outputs (Rio *et al.*, 2007; Poulain *et al.*, 2012).

The paper is organized as follows: a brief description of the different geoid models, the mean tide model, the methodologies employed to estimate the geodetic MDTs and the associated surface geostrophic currents, are presented in section 2; the main qualitative and quantitative results are discussed in section 3; the conclusions are summarized in section 4.

2. Data

2.1. Geoid models

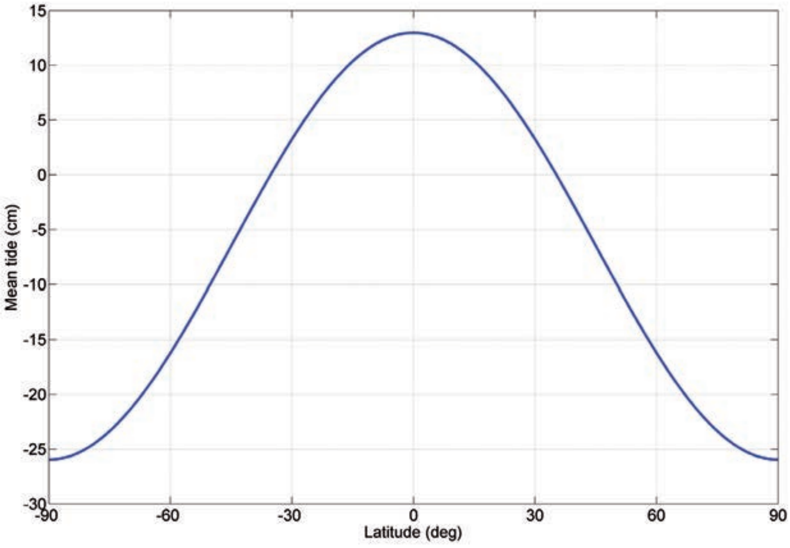
A combination of two Earth gravitational global models, namely EGM2008 (Pavlis *et al.*, 2012) and GO_CONS_GFC_2_SPW_R2 (Migliaccio *et al.*, 2011; Pail *et al.*, 2012), were computed to estimate a geoid with high accuracy and resolution. The global models are usually released in terms of coefficients of a spherical harmonic truncated series V_{lm}:

$$V(r, \vartheta, \lambda) = \frac{GM}{R} \sum_{l=0}^{L} \sum_{m=0}^{l} \left(\frac{R}{r}\right)^{l+1} V_{lm}\, Y_{lm}(\vartheta, \lambda) \qquad (1)$$

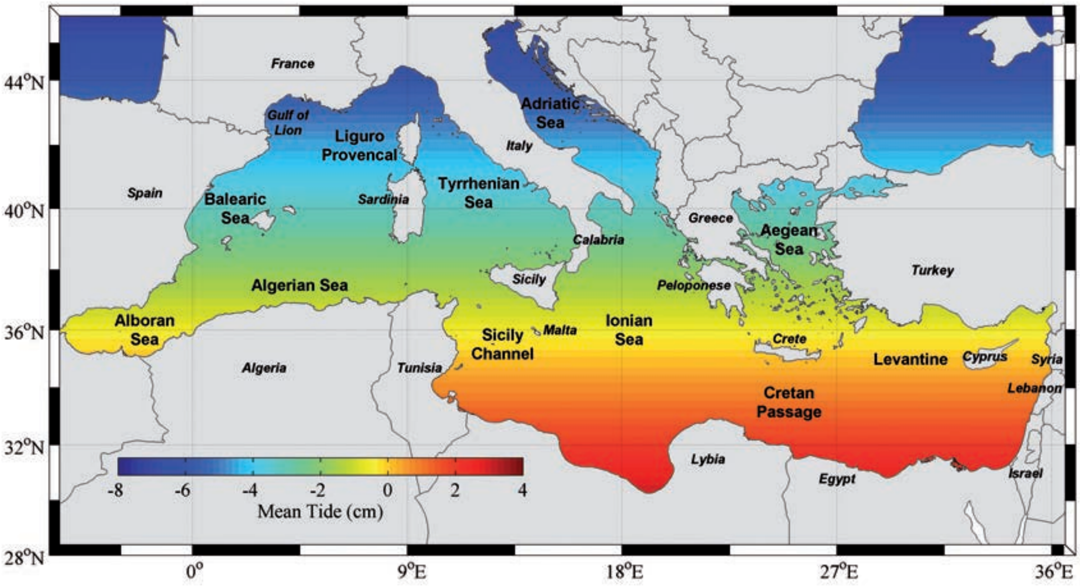
where V is the gravitational potential (r, ϑ, λ are the radial coordinate, spherical colatitude and longitude, respectively), G is the gravitational constant, R is a reference radius of the Earth and $Y_{lm}(\vartheta, \lambda)$ are the fully normalized spherical harmonics of degree l and order m (Heiskanen and Moritz, 1967). The EGM2008 coefficients are computed from a combination of the GRACE data (Mayer-Gürr *et al.*, 2010) and a global gravity anomaly database of 5´ x 5´ resolution. In particular this database has been constructed by merging information coming from different sources, e.g., radar altimetry offshore and ground gravity observation onshore. Note that in order to compute gravity anomaly from altimetry data an a-priori MDT model is used in EGM2008. The GRACE observations give information at low frequencies (up to degree 120 corresponding to a resolution of about 170 km), while higher frequencies (up to degree 2159 corresponding to a resolution of about 10 km) are recovered from ground data. Due to the different height data used in the acquisition of these ground observations, the resulting global geoid can be affected by local biases, or in general, by long period distortions. In addition, the model is delivered with two, not fully consistent, sources of information on its error: spherical harmonic coefficient variances and a geographical map of error variances, e.g., in terms of geoid undulation. The inconsistency is due to the fact that coefficient variances lead to a latitude dependent error shape, while the actual error in EGM2008 is mainly dependent on the original gravity data quality and spatial distribution. On the other hand, the provided geographical map of error variances does not give any information on covariances, being the hypothesis of uncorrelated errors too approximate.

On the contrary, the GO_CONS_GFC_2_SPW_R2 model (up to degree 240 corresponding to a resolution of about 80 km) is based only on GOCE satellite data and therefore it does not contain any biases. Moreover, for this model the full error covariance matrix is available. Note that GOCE observations provide the currently most accurate description at middle-low frequencies of the gravitational field (centimetric accuracy in terms of geoid up to degree 200).

In this framework a combination between the two models can improve the EGM2008 (at least at middle-low frequencies) and gives an optimal data set for the study of MDT.



a



b

Fig. 1 - Global mean tide pattern as function of the latitude (a). Geography of the Mediterranean Sea and structure of the mean tide over the Mediterranean area (b).

2.2. Mean tide model

The mean tide consists of a permanent deformation of the Earth leading to a constant high tide at the equator and low tide at the poles (Fig. 1a), which includes both the direct effect of the luni-solar Tide-Generating Potential (TGP) and the indirect effect of the Earth's response to this potential. It is a time-independent term, expressed as a function only of the latitude, and originates from the time average of the zonal second degree TGP of the Moon and the Sun being different from zero. Hence, the tide-free geoid needs to be corrected into the so-called mean geoid to account for these constant contributions and to represent the real mean sea level.

The mean tide effect ΔN_{MT} to be added to the tide-free geoid undulations is computed from the zonal second degree Love number $k_{20} = 0.3019$ for an anelastic solid Earth from IERS-TN36 Standards (Petit and Luzum, 2010) as specified hereunder:

$$\Delta N_{MT} = (1+k_{20}) \frac{\overline{V}_2^{TGP}}{g}, \tag{2}$$

where g is the gravity acceleration on the Earth's surface and $\overline{V}_2^{TGP}$ is the time average of the zonal second degree luni-solar TGP, determined according to the formulation of Poutanen *et al.* (1996). In Fig. 1b the mean tide distribution is shown over the Mediterranean area.

2.3. Other data

The geodetic MDTs were calculated by subtracting the derived geoid heights from the Mean Sea Surface (MSS) (i.e., the direct method); the MSS and the geoid must be represented relative to the same reference ellipsoid (Bingham *et al.*, 2008; Haines *et al.*, 2011). The altimetric MSS used in this work is the CNES-CLS11, computed using a 15-year dataset of TOPEX/POSEIDON, ERS-2, GFO, JASON-1, ENVISAT mean profiles. As explained by Schaeffer *et al.* (2012), all these data were pre-processed, in order to be less contaminated by the seasonal part of the ocean variable signal, were corrected from the ocean variability and were referenced to the 1993 - 1999 period. This MSS resolves spatial scales smaller than 10 - 20 km. More details about the CNES-CLS11 are available at the web page: http://www.aviso.oceanobs.com/.

In order to quantitatively select the method that reproduces the more realistic MDT in the Mediterranean Sea, the GOCE- and EGM2008-derived geodetic currents were compared to the geostrophic currents of Rio *et al.* (2007) and Poulain *et al.* (2012). The currents of Rio *et al.* (2007) are estimated using the DT outputs from MFSTEP (Mediterranean Forecasting System: Toward Environmental Predictions) model (Demirov *et al.*, 2003), locally improved with the mean geostrophic circulation obtained combining drifter velocities and altimetric data; the time span covered by these currents is from 1993 to 1999. The currents of Poulain *et al.* (2012) are obtained combining 18-years (1992 - 2010) of drifter data with the concurrent satellite SLA. The relationship between the drifter velocities and the satellite-derived anomalies of geostrophic velocities can be used to compute the geostrophic circulation in all the time periods in which the satellite data are available, also in the periods without the drifter observations. In this work, in order to use the same temporal coverage of the MSS, the MDTs and the Rio *et al.* (2007) data sets, we have selected the currents of Poulain *et al.* (2012) over the period 1993 - 1999 (Fig. 2).

3. Methods

3.1. EGM2008 and GOCE combination

In the present work, the gravity field information derived from the GO_CONS_GFC_2_SPW_R2 model is used to improve the accuracy of EGM2008 in the low-medium degrees (say between 100 and 200) in the Mediterranean area. The key-issue is to setup the error covariance matrices of the two models for an optimal combination. Naturally the combination involves just the degrees below 240, while higher frequency components (from degree 241-2159) are directly taken from EGM2008. The combination is based on a least squares adjustment and the correct coefficients, $\hat{V}_{lm}$, are estimated as:

$$\hat{V}_{lm} = \left(A^T Q^{-1} A\right)^{-1} A^T Q^{-1} \begin{bmatrix} V_{lm}^{GOCE} \\ V_{lm}^{EGM08} \end{bmatrix} \tag{3}$$

where V_{lm}^{GOCE} and V_{lm}^{EGM08} are the coefficients obtained by GOCE and EGM2008 respectively, $A = \begin{bmatrix} I \\ I \end{bmatrix}$ with I the identity matrix and Q is given by:

$$Q = \begin{bmatrix} C_{\delta V_{lm}^{GOCE} \delta V_{lm}^{GOCE}} & 0 \\ 0 & C_{\delta V_{lm}^{EGM08} \delta V_{lm}^{EGM08}} \end{bmatrix} \tag{4}$$

where $C_{\delta V_{lm}^{GOCE} \delta V_{lm}^{GOCE}}$ and $C_{\delta V_{lm}^{EGM08} \delta V_{lm}^{EGM08}}$ are the covariance matrix of GOCE and EGM2008 error, respectively. As for the stochastic model, two hypotheses have been considered in order to estimate the $\hat{V}_{lm}$ coefficients: the first one (EGMSPWcv) uses only the coefficient error variances for GOCE and EGM2008 (each coefficient is therefore independent from one another), while the second one (EGMSPWbc) is more refined and it is based on an order-wise block diagonal approximation of the GOCE error covariance structure. The block covariances give a more accurate description of the error stochastic structure since coefficients of the same order but different degrees show a significant correlation (especially for low orders).

The main corrections are for coefficients in the degree range between 70 and 210 where GOCE is expected to be superior to EGM2008. The resulting corrections have a maximum value of about 40 cm.

3.2. Estimation of the geodetic MDTs from geoid

The tide-free geoid solutions EGMSPWcv, EGMSPWbc and EGM2008 were first combined with the mean tide effect and then subtracted from the altimetric MSS:

$$\text{MDT} = \text{MSS} - (\text{Geoid} + \text{Mean Tide}) \tag{5}$$

The MDTs, estimated from the different geoid solutions, are representative of the MSS for the reference period (1993 - 1999).

3.3. Estimation of the geostrophic currents

A geostrophic current is an oceanic flow in which the pressure gradient force is balanced by the Coriolis effect due to the Earth's rotation. The geostrophic balance is:

$$\begin{cases} fv = \dfrac{1}{\rho}\dfrac{\partial p}{\partial x} \\ -fu = \dfrac{1}{\rho}\dfrac{\partial p}{\partial y} \end{cases} \tag{6}$$

where u and v are the zonal and meridional currents, ρ is the surface water density, p is the pressure and f is the Coriolis parameter. At the surface $p = \rho g \eta$, where η is the DT height, thus there is a direct relationship between the DT and the surface geostrophic currents:

$$\begin{cases} fv = g\dfrac{\partial \eta}{\partial x} \\ -fu = g\dfrac{\partial \eta}{\partial y} \end{cases} . \tag{7}$$

From Eq. (7) the components of surface geostrophic currents can be readily derived as follow:

$$v = \frac{g}{f}\frac{\partial \eta}{dx}, \quad u = -\frac{g}{f}\frac{\partial \eta}{dy} . \tag{8}$$

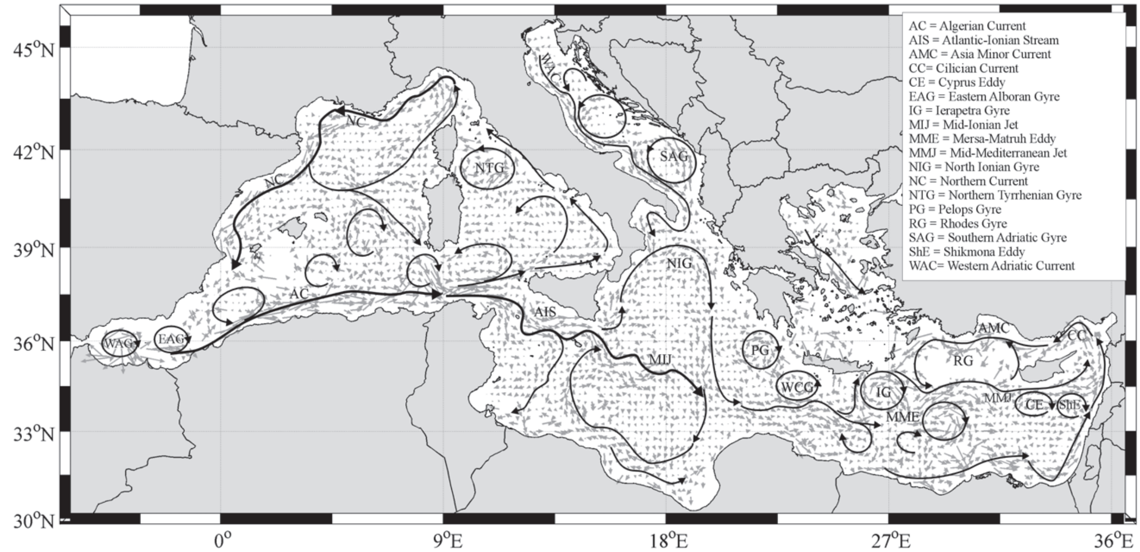


Fig. 2 - Mean surface geostrophic circulation in the Mediterranean Sea in the period 1993 - 1999 (bright grey) organized in bins of 0.25° x 0.25°. Black lines emphasize the main currents and sub-basin eddies (adapted from Poulain *et al.*, 2012).

4. Results

Fig. 2 depicts a schematic diagram of the surface geostrophic circulation in the Mediterranean Sea based on the results of Poulain *et al.* (2012). The current field (bright grey) has been obtained combining *in situ* drifter data and satellite altimetry data to build a regularly sampled dataset of observations, covering the period 1993 - 1999. The black arrows summarize the main currents and sub-basin eddies of the Mediterranean Sea. This scheme can be useful to the reader in order to follow the features of mean circulation discussed hereafter and to identify the main currents.

4.1. Qualitative description of geodetic MDTs and corresponding surface geostrophic circulation

The raw geodetic MDT obtained from 1 year of GOCE-only geoid data (Fig. 3a) is clearly dominated by short scale noise, resulting from the strong difference in spectral content between the MSS (spatial scales down to 10 - 20 km) and the geoid model (spatial resolution of ~ 80 km) (Rio, 2011). The oceanographic signal derived by this MDT is not able to correctly reproduce the Mediterranean circulation features. On the other hand, the geodetic MDTs obtained from the EGMSPWbc, EGMSPWcv and EGM2008 solutions (Figs. 3b, 3c, 3d, respectively) in the period 1993 - 1999 generally reproduce the main characteristics of the large scale circulation in the Mediterranean Sea described in Rio *et al.* (2007): a large cyclonic cell in the Liguro - Provençal sub-basin, an anticyclonic cell and a central eastward cross-basin current in the Ionian Sea, a cyclonic circulation in the centre of the Levantine sub-basins.

In order to examine in detail the basin and sub-basin features of the circulation derived from the geodetic MDTs in Figs. 3b, 3c, 3d, we have divided the Mediterranean Sea into different sectors (Figs. 4 to 8) and we have compared qualitatively the current field of each sector with the results of Poulain *et al.* (2012) depicted in Fig. 2. The current fields are organized in geographical bins of 0.25° x 0.25°.

The Liguro - Provençal cyclonic cell is composed of two cyclonic structures in the EGMSPWbc solution (Figs. 3b and 4a), located between 40° - 42° N, 2° - 4° E and 40.5° - 42.5° N, 6° - 8° E, respectively, with speeds between 10 cm/s and 30 cm/s (Fig. 4a). The anticyclonic feature centred near 40° N and 5.5° E (Figs. 3b and 4a) is in agreement with the mean map of Poulain *et al.* (2012) (Fig. 2). The EGMSPWcv and EGM2008 solutions (Figs. 3c, 3d, 4b and 4c) show a single cyclonic structure in the Liguro - Provençal basin with intensities of 10 - 20 cm/s and 10 - 15 cm/s, respectively. In the EGM2008 solution the cyclonic cell extends southward, towards the Algerian Sea (Fig. 3d). The Northern Current is partly resolved by the EGMSPWbc and EGM2008 solutions (Figs. 4a and 4c), whereas it is not resolved by the EGMSPWcv solution (Fig. 4b).

The signatures of western and eastern Alboran sub-basin anticyclones are recognizable in the three combined MDTs (Figs. 3b, 3c, 3d and 5) with maximum intensities of 40 cm/s, as described in Poulain *et al.* (2012). The eastward flow along the Algerian coast, as well as the anticyclonic eddies resulting from its instability, are partially reproduced using the EGMSPWbc solution (Fig. 5a). The narrow Algerian Current is not resolved by the other solutions; in particular it flows in the wrong direction (westwards) using the MDT derived from EGM2008 (Fig. 5c).

The inflow of surface water in the Tyrrhenian Sea and the Northern Tyrrhenian Gyre are well reproduced by the EGMSPWbc solution (Fig. 6a), whereas the NW-ward flow along the Italian peninsula is just outlined. The anticyclonic eddy located between 39° - 41° N and 11° - 13° E (Fig. 3b) has been observed in previous studies as a persistent feature of the circulation (Astraldi and Gasparini, 1994; Rinaldi *et al.*, 2010). The main circulation patterns of the Tyrrhenian basin are not well documented using the EGMSPWcv and the EGM2008 solutions (Figs. 6b and 6c). The general circulation in the Adriatic Sea, characterised by three cyclonic circuits and by a

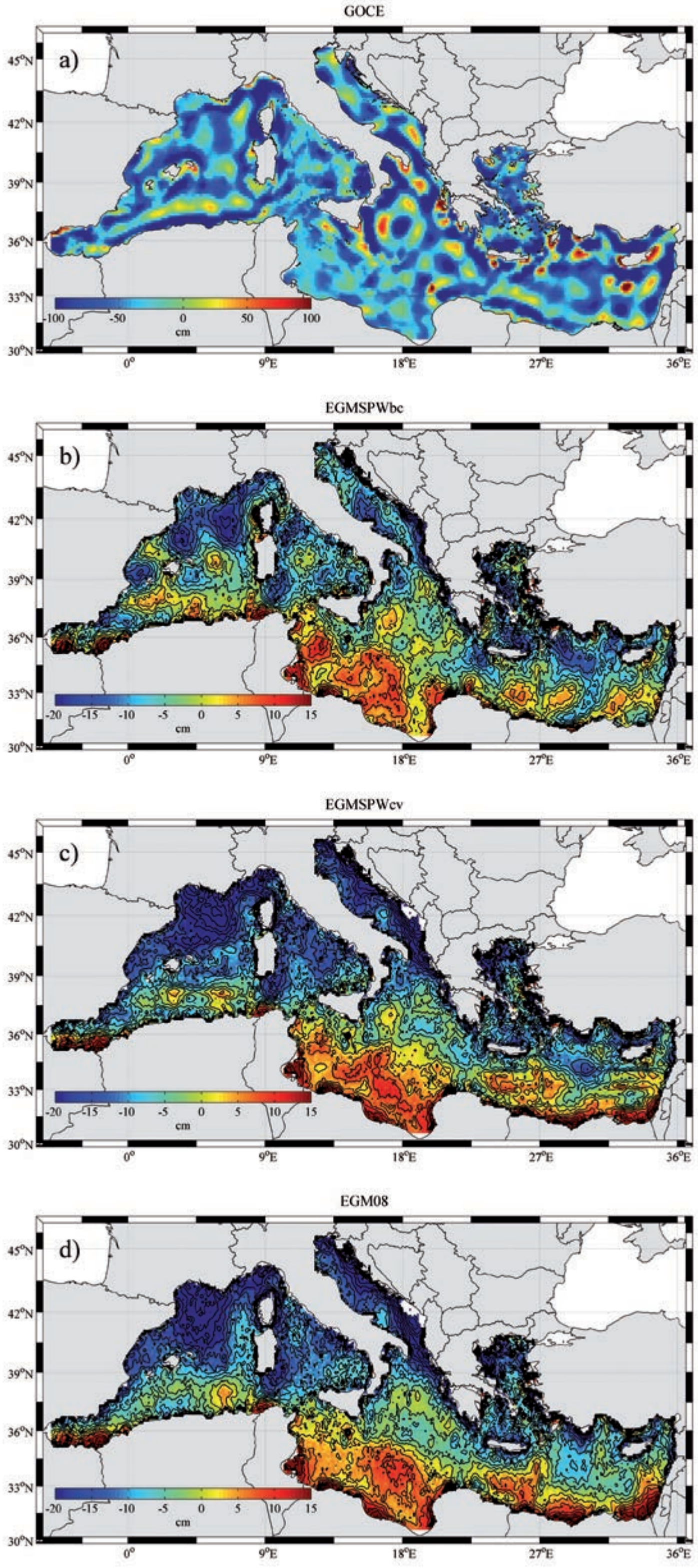


Fig. 3 - The mean dynamic topography of the Mediterranean Sea in the period 1993 - 1999 obtained from GOCE (a), EGMSPWbc (b), EGMSPWcv (c), EGM2008 (d).

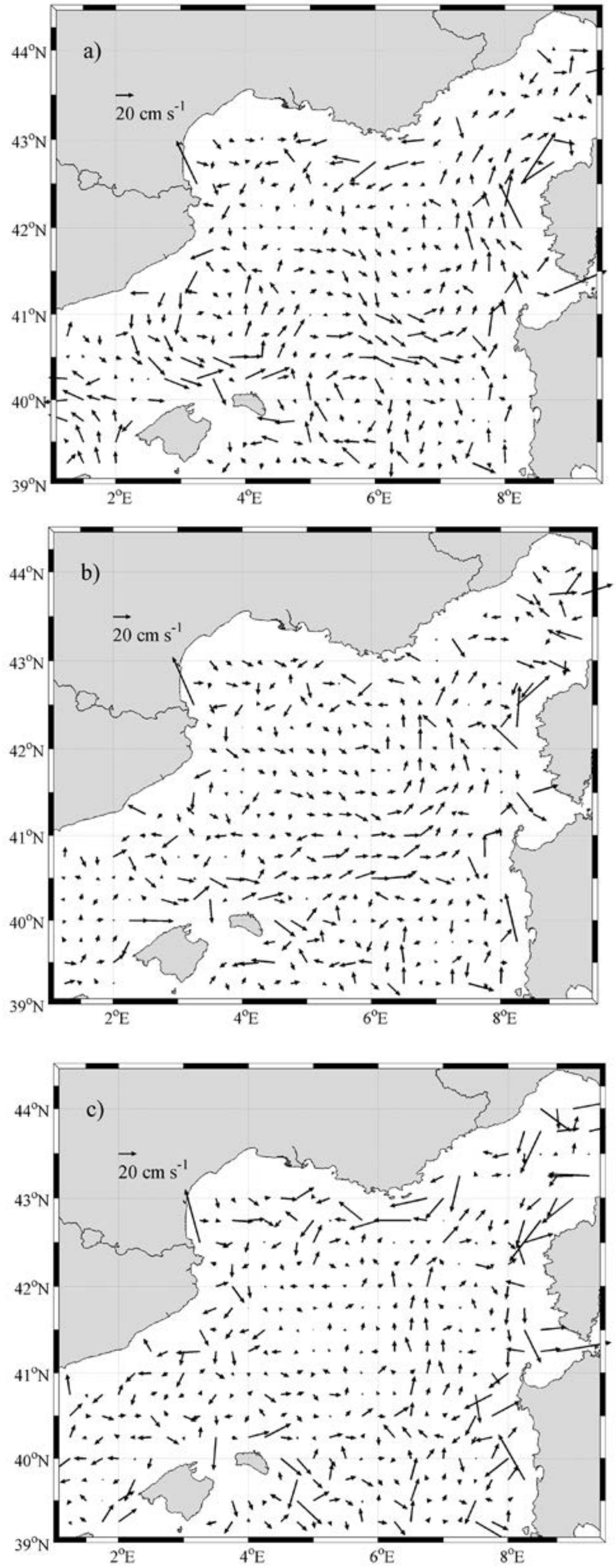


Fig. 4 - Geostrophic currents in the Liguro–Provençal sub-basin derived from EGMSPWbc (a), EGMSPWcv (b), EGM2008 (c).

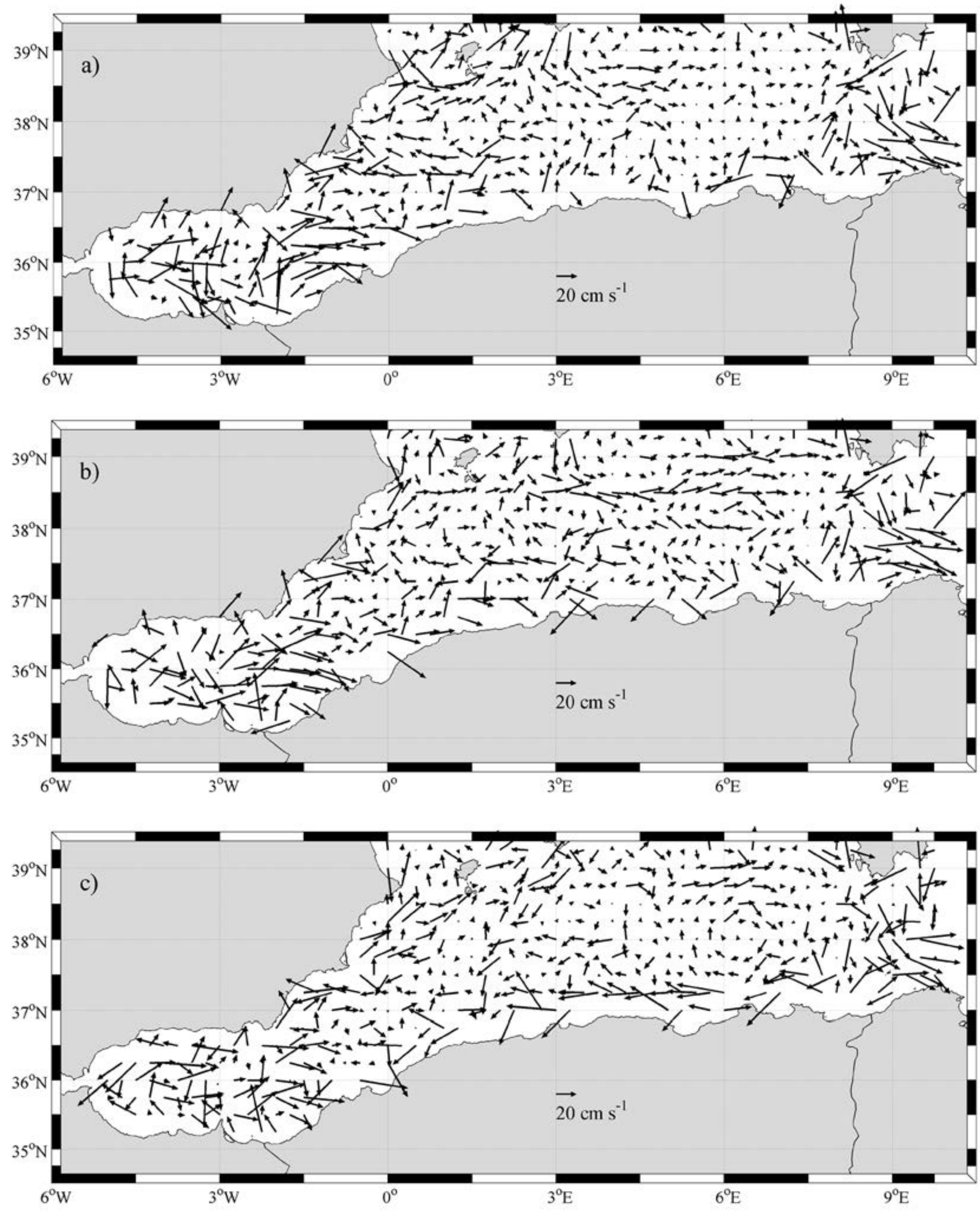


Fig. 5 - Geostrophic currents in Algerian sub-basin derived from EGMSPWbc (a), EGMSPWcv (b), EGM2008 (c).

strong south-eastward coastal current on the western side (Poulain *et al.*, 2011; see Fig. 2), is not retrieved using any of the geodetic MDTs (Fig. 6).

The zonal meandering of the Atlantic - Ionian Stream flowing eastwards in the Sicily Channel is well reconstructed from the EGMSPWbc and EGMSPWcv solutions (Figs. 7a and 7b), as well as the anticyclonic circulation in the Northern Ionian (North Ionian Gyre). The GOCE/EGM2008-derived currents show the southward branch of this anticyclonic structure

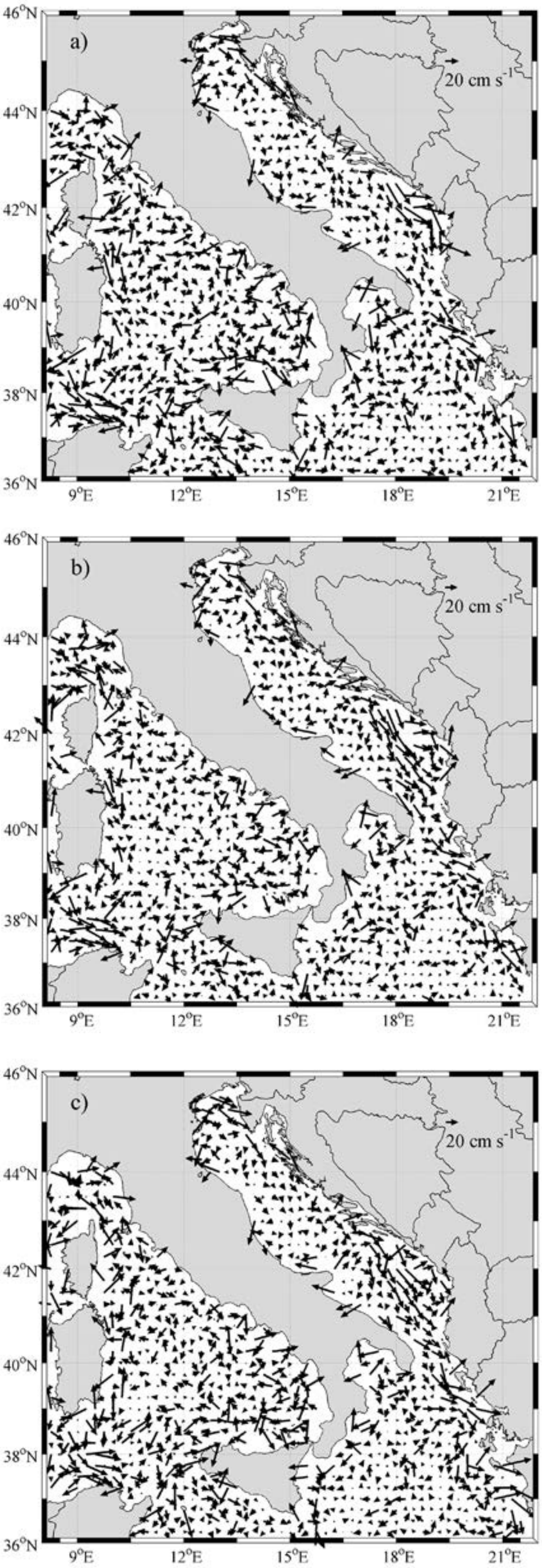


Fig. 6 - Geostrophic currents in the Tyrrhenian and Adriatic seas derived from EGMSPWbc (a), EGMSPWcv (b), EGM2008 (c).

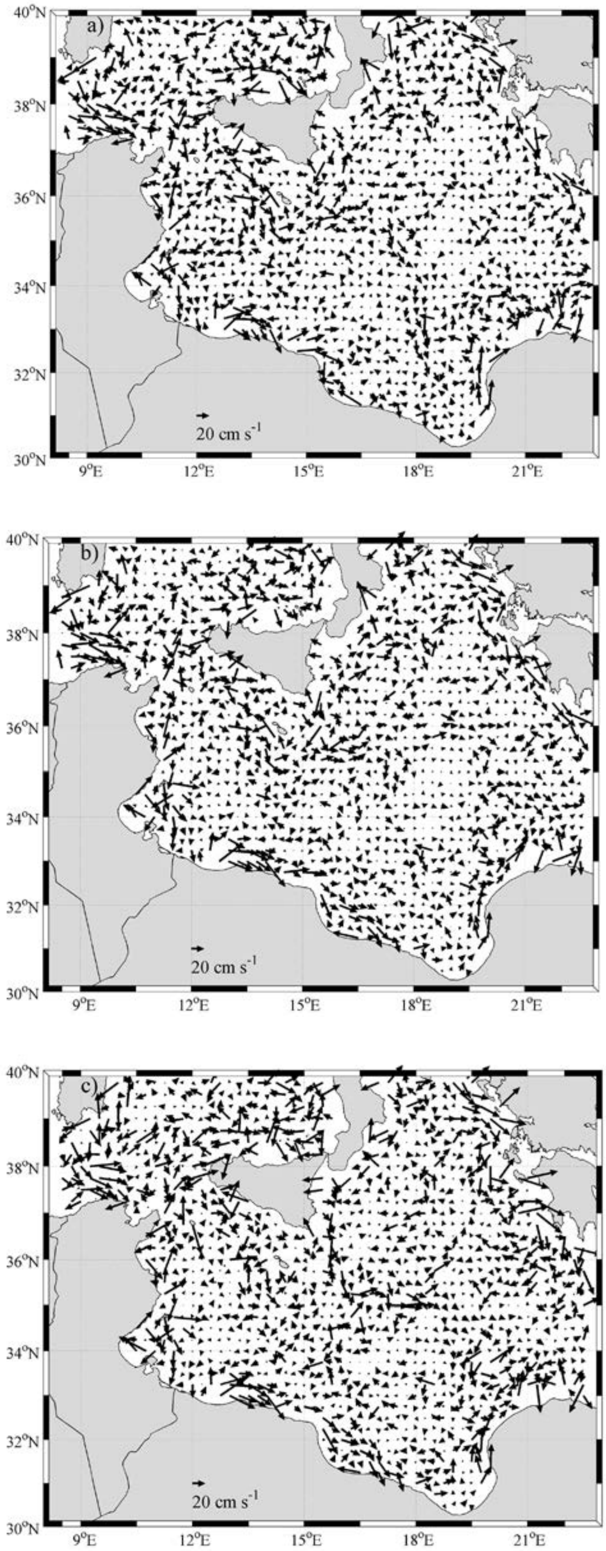


Fig. 7 - Geostrophic currents in the Sicily Channel and Ionian Sea derived from EGMSPWbc (a), EGMSPWcv (b), EGM2008 (c).

along the Greek slope (Figs. 7a and 7b), whereas in Poulain *et al.* (2012) this SE-ward flow is a meridional jet centred at 19°30' E (Fig. 2). The Atlantic - Ionian Stream and the Mid-Ionian Jet are actually the northern rim of another anticyclonic circulation located in the Southern Ionian (Fig. 2); the southern part of this anticyclonic circulation is roughly sketched in the geodetic maps (Figs. 7a and 7b). The Pelops eddy is better reproduced by EGMSPWbc solution (Figs. 3b and 7a). The EGM2008 solution depicts a southward flow along the Sicilian and Calabrian coasts (Fig. 7c), in contrast with the main circulation described by GOCE/EGM2008-derived maps (Figs. 7a and 7b) and by the mean currents of Poulain *et al.* (2012).

The surface circulation of the Levantine sub-basin consists of complicated flow patterns, characterised by regions with strong eddy kinetic energy, strong offshore and along-slope currents and several multi-scaled eddies (Menna *et al.*, 2012). This complex circulation cannot be simply reconstructed, therefore the geodetic currents provide a circulation field where only a few features can be considered realistic. The Libyo - Egyptian and the Asia Minor Currents are partially reproduced by the geodetic EGMSPWbc and EGMSPWcv solutions, as well as the cyclonic and anticyclonic eddies generated by the instability of the along-slope currents (Figs. 8a and 8b). Dynamical features as the Mersa - Matruh and Ierapetra anticyclones and the Rhodes and western Cretan cyclones are better reproduced by the EGMSPWbc solution (Fig. 8a). The northward along-slope current that flows off the Lebanon and Syria coasts is not resolved and moves in the wrong direction in all the geodetic solutions. Furthermore, the accuracy of GOCE/EGM2008-and EGM2008-derived geoids are not sufficient to retrieve the complex surface circulation in the semi-enclosed Aegean Sea.

4.2. Quantitative validation of geodetic MDTs in terms of geostrophic velocities

In order to validate the accuracy of the different geodetic MDTs in the Mediterranean Sea, the corresponding mean geostrophic velocities were compared to the velocities of Poulain *et al.* (2012) and Rio *et al.* (2007). Comparisons were done computing the Root Square Differences (RSD) between the geostrophic velocities in each geographical bin (0.25° x 0.25°) and the Root mean square differences (RMSD) in each sector of the Mediterranean basin.

The discrepancies between the currents from Poulain *et al.* (2012) and the currents derived from the EGMSPWbc and EGMSPWcv solutions show similar values: the RSD of the geostrophic velocities (not shown) are smaller than 10 cm/s in the regions far from the coast, except in some bins of the Ionian and Levantine sub-basins where the they are as large as 15 cm/s; whereas the RSD are larger than 20 cm/s in the main coastal currents (Algerian, Libyo-Egyptian and Asia Minor Currents). The zonal and meridional RMSD in each sector of the Mediterranean Sea are displayed in Table 1; for both the velocity components the mean differences are ~ 5 cm/s, except in the zonal component of the Algerian sub-basin (8 cm/s), and in the Adriatic and Aegean Seas (between 6 and 10 cm/s). The mean square differences expressed in percentage of variance show that the best results are obtained using the EGMSPWbc solution.

The RSD estimated between the currents of Poulain *et al.* (2012) and the currents derived from EGM2008 are larger than 20 cm/s in the main coastal currents, in the centre of the Liguro–Provençal, Tyrrhenian, Ionian and Levantine sub-basins, in the Alboran Sea and along the Greek and Peloponnese slopes (not shown). The mean values of the zonal and meridional RMSD (Table 1) are larger than 10 cm/s in each sector of the basin; mean differences larger than 15 cm/s are

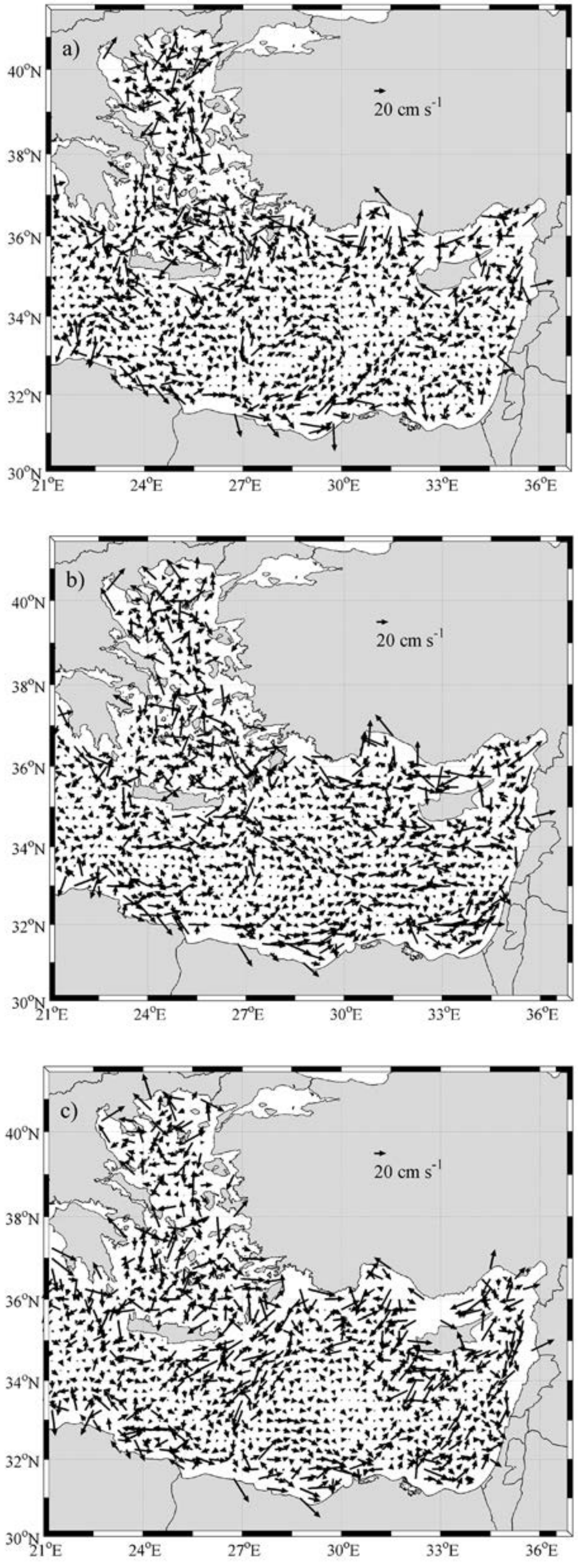


Fig. 8 - Geostrophic currents in the Levantine sub-basin and Aegean Sea derived from EGMSPWbc (a), EGMSPWcv (b), EGM2008 (c).

Table 1 - RMSD estimated in each sector of the Mediterranean Sea: 1) between the geostrophic velocities of Poulain *et al.* (2012) and the velocities derived from the geodetic MDTs; 2) between the geostrophic velocities of Rio *et al.* (2007) and the velocities derived from the geodetic MDTs. Values in brackets indicate the mean square differences in percentage of variance.

		RMSD cm/s (% of variance)					
		Poulain 2012 vs EGMSPWbc	Poulain 2012 vs EGMSPWcv	Poulain 2012 vs EGM2008	Rio 2007 vs EGMSPWbc	Rio 2007 vs EGMSPWcv	Rio 2007 vs EGM2008
Liguro Provençal	u	4.45 (25)	4.62 (27)	10.60 (140)	5.49 (40)	5.19 (36)	12.62 (213)
	v	4.86 (28)	4.69 (27)	11.30 (154)	5.03 (63)	4.36 (47)	10.76 (290)
Algerian	u	8.13 (27)	8.49 (29)	15.26 (94)	8.51 (42)	9.22 (50)	16.03 (150)
	v	5.35 (24)	5.37 (24)	12.19 (126)	5.23 (38)	5.44 (41)	10.91 (165)
Tyrrhenian	u	5.36 (37)	5.62 (40)	12.54 (201)	5.25 (34)	5.45 (37)	12.22(186)
	v	5.47 (60)	5.01 (52)	12.47 (321)	6.10 (88)	5.65 (76)	12.25 (356)
Adriatic	u	6.24 (90)	6.69 (104)	12.09 (340)	6.02 (71)	6.63 (86)	13.80 (372)
	v	7.23 (62)	10.15 (123)	12.33 (182)	7.16 (103)	10.11 (206)	12.71 (326)
Ionian	u	4.18 (15)	5.39 (24)	10.71 (96)	4.60 (23)	5.18 (29)	11.30 (140)
	v	4.01 (34)	4.12 (36)	10.12 (217)	5.02 (74)	4.70 (65)	10.77 (343)
Levantine	u	5.05 (24)	6.45 (40)	9.27 (83)	6.06 (38)	6.76 (48)	13.03 (177)
	v	5.51 (38)	5.27 (34)	11.78 (173)	5.04 (52)	5.93 (72)	13.57 (377)
Aegean	u	8.63 (80)	9.29 (93)	15.47 (259)	9.68 (305)	10.20 (336)	19.96 (321)
	v	8.26 (66)	9.23 (83)	17.24 (289)	10.25 (263)	6.09 (186)	18.11 (205)

observed in the zonal component of Algerian sub-basin and in the Aegean Sea. The mean square differences expressed in percentage of variance show larger values than those obtained from GOCE/EGM2008-derived solutions.

The RMSD estimated from the currents of Rio *et al.* (2007) depict similar discrepancies compared with the currents of Poulain *et al.* (2012); larger values (Table 1) are observed for the EGM2008 solution, in particular in the Levantine sub-basin and in the Aegean Sea (13 - 20 cm/s).

The RMSD and the amplitude of the complex correlation coefficients (Kundu, 1976), estimated with respect to the dataset of Poulain *et al.* (2012) over the whole Mediterranean Sea, are summarized in Table 2, together with the standard deviation of each data set. The minimum zonal and meridional discrepancies and the smallest standard deviation are obtained using the EGMSPWbc solution, with a correlation coefficient of ~ 0.6. Both the combined GOCE/EGM2008-derived currents show a lower RMSD with respect to the MDT obtained using the EGM2008 solution alone. The mean difference between the velocity components of Poulain *et*

Table 2 - RMSD and magnitude of the complex correlation coefficient estimated between the geostrophic velocities of Poulain *et al.* (2012) and the velocities derived from the geodetic MDTs, or the speeds of Rio *et al.* (2007). The Standard Deviation (STD) of each dataset is reported.

		EGMSPWbc	EGMSPWcv	EGM2008	Rio 2007	Poulain 2012
RMSD	u	5.93	6.37	12.11	5.70	0
(cm/s)	v	5.48	6.12	12.47	5.63	0
STD (cm/s)		9.26	10.84	12.76	6.09	7.25
CorrCoeff		0.56	0.41	0.22	0.67	1.00

Table 3 - RMSD and magnitude of the complex correlation coefficient estimated between the geostrophic velocities of Rio *et al*. (2007) and the velocities derived from the geodetic MDTs.

		EGMSPWbc	EGMSPWcv	EGM2008
RMSD (cm/s)	u	6.39	6.87	14.38
	v	6.26	6.05	12.71
CorrCoeff		0.51	0.38	0.19

al. (2012) and of Rio *et al*. (2007) is of ~ 5.7 cm/s and the correlation coefficient is of ~ 0.7.

For comparison, the same statistics are also performed between the geostrophic components of Rio *et al*. (2007) and the geoid-derived datasets (Tables 1 and 3). The results confirm that the minimum discrepancy and the best correlation coefficient are obtained using the EGMSPWbc solution.

5. Concluding remarks

The MDTs derived from different combination of EGM2008 and GOCE space-wise solutions have been used to estimate the mean geostrophic circulation in the Mediterranean Sea in the period 1993 - 1999. The comparison of these geodetic currents with independent data, obtained from *in situ* oceanographic measurements and altimetric products, allows to assess the performance of GOCE measurements in the semi-enclosed sea.

The main characteristics of the large scale circulation in the Mediterranean Sea are generally depicted by the MDTs derived from the combination of GOCE and EGM2008, and are in agreement with the synthetic MDT obtained by Rio *et al*. (2007). At basin and sub-basin scale, the currents obtained from the geoid models reproduce many dynamical features of the surface circulation and some coastal currents, especially in the western basin and in the Ionian Sea. In contrast, the GOCE/EGM2008-derived circulations in the semienclosed Adriatic and Aegean Seas are totally unrealistic.

The accuracy of the different geodetic MDTs in the Mediterranean Sea and of the corresponding mean geostrophic speeds has been assessed by comparing them with the mean circulation maps of Rio *et al*. (2007) and Poulain *et al*. (2012). The minimum RMSD (5.93 cm/s for the zonal component and 5.48 cm/s for the meridional component) and the best correlation coefficient (0.56) are achieved using the EGMSPWbc solution. More generally, the currents resulting from the combination of EGM2008 model and GOCE space-wise solutions improve the estimates derived using only the EGM2008 solution.

The combination of GOCE mission data with the previous geoid models enhances the quality of the description of the Mediterranean Sea circulation based on geodetic and altimetry data, especially for the sub-basin scale features and for the along–slope currents. It is hoped that the continuation of the GOCE mission will provide improved geoid models based on more accurate data to resolve the mean mesoscale features and to further improve the study of the coastal ocean circulation mainly in the small, semi-enclosed and marginal seas.

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