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Computation of a new Mean Dynamic Topography for the Mediterranean Sea from model outputs, altimeter measurements and oceanographic in-situ data

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Abstract

The accurate knowledge of the ocean Mean Dynamic Topography (MDT) is a crucial issue for a number of oceanographic applications and in some areas of the Mediterranean Sea, important limitations have been found pointing to the need of an upgrade. We present a new Mean Dynamic Topography (MDT) that was computed for the Mediterranean Sea. It takes profit of improvements made possible by the use of extended datasets and refined processing. The updated dataset spans the 1993–2012 period and consists of: drifter velocities, altimetry data, hydrological profiles and model data. The methodology is similar to the previous MDT Rio et al. (2007). However, in Rio et al. (2007) no hydrological profiles had been taken into account. This has required the development of dedicated processing. A number of sensitivity studies have been carried out to obtain the most accurate MDT as possible. The main results from these sensitivity studies are the following: moderate impact to the choice of correlation scales but almost negligible sensitivity to the choice of the first guess (model solution). A systematic external validation to independent data has been made to evaluate the performance of the new MDT. Compared to previous version, SMDT-MED-2014 features shorter scales structures, which results in an altimeter velocity variance closer to the observed velocity variance and, at the same time, gives better Taylor skills.

1 Introduction

The accurate knowledge of the ocean Mean Dynamic Topography (MDT) is a crucial issue for a number of oceanographic applications based on the use of altimeter Sea Level Anomalies. The MDT may be calculated as the filtered difference between an altimeter Mean Sea Surface (MSS – Schaeffer et al., 2012; Andersen et al., 2009) and a geoid model. However, due to the lack of an accurate geoid, the computation of the MDT at short scales with sufficient accuracy is not trivial. The recent release of geoid models based on the use of GOCE data (Pail et al., 2011) or a combination of GOCE and GRACE data (Bruinsma et al., 2013) has led to significant improvements for the calculation of the ocean MDT at scales down to 125 km (Mulet et al., 2012). However, in the Mediterranean Sea, where the Rossby radius is of the order of 10 km, and the basin geometry characterized by narrow straits, numerous islands, this resolution is not sufficient to capture the small details and sharp coastal gradients of the circulation. A possible way to go is to use so-called combined geoid models, where the missing short scales of the geoid are provided by altimeter measurements (by turning the altimeter MSS, which is the sum of the geoid and the MDT, into gravity anomalies, that are then used in the calculation of the combined geoid). This has been done recently by Menna et al. (2013), showing potential improvement of the resulting MDT. However, this approach is based on the use of an a priori MDT solution, and the independency of the final result to the choice of the a priori solution may therefore be questionable. Another approach is to combine different sources of information, including model outputs, in-situ measurements and altimeter data. This was done for instance by Rio et al. (2007) and the resulting field is displayed in Fig. 1.

Recent studies (e.g. Bouffard et al., 2010) have identified limitations and inaccuracies of the MDT developed by Rio et al. (2007) pointing out the necessity of an update. In the frame of SOCIB activities (Tintoré et al., 2013), an improved solution is presented in this paper, which has been made possible by the recent availability of updated time series of drifter data, simulations and new methodology enabling the inclusion of in situ profiles (Argo, CTD,. . .). The paper is organized as follow: first, we will describe in more details the methodology (Sect. 2) used and then present the different datasets that have been used for the calculation (Sect. 3). Then, in Sect. 4 we will describe the different processing steps that have been applied on the data to obtain synthetic observations of the MDT and the corresponding mean geostrophic velocities as described in the methodology section. The calculation of the MDT is based on a multivariate objective analysis and a number of sensitivity tests to different analysis parameters has been carried out, whose results are presented in Sect. 5. The final MDT of the Mediterranean

Sea is described in Sect. 6 and validated in Sect. 7. Finally, we will end with a number of concluding remaks and perspectives.

2 Method

We have used the three steps methodology described in Rio and Hernandez (2004) and Rio et al. (2005, 2007, 2011). The first step is to compute a large scale estimate of the MDT (the so-called first guess). This can be achieved by averaging the outputs from an ocean model (Rio et al., 2007) or by filtering the difference between an altimeter MSS and a geoid model (Rio et al., 2004, 2005, 2011). Next, “synthetic” estimates of the MDT ($\langle h\rangle$) and the associated mean geostrophic currents ($\langle u_\mathrm{g}\rangle$, $\langle v_\mathrm{g}\rangle$) are calculated. These are simply obtained (Eq. 1), for a given time t and geographical position r, by subtracting from the instantaneous in-situ measurements of the ocean dynamic topography $h(t,r)$ or the ocean geostrophic surface current $u_\mathrm{g}(t,r)$, $v_\mathrm{g}(t,r)$, the time variable ($h'_\mathrm{a}(t,r)$, $u'_\mathrm{a}(t,r)$, $v'_\mathrm{a}(t,r)$) component as measured by altimetry.

$$\begin{aligned}
\langle h\rangle(r) &= h(t,r) - h'_\mathrm{a} \\
\langle u_\mathrm{g}\rangle(r) &= u_\mathrm{g}(t,r) - u'_\mathrm{a}(t,r) \qquad (1)\\
\langle v_\mathrm{g}\rangle(r) &= v_\mathrm{g}(t,r) - v'_\mathrm{a}(t,r)
\end{aligned}$$

The synthetic estimates are then used to improve the large scale solution (both for mean heights and mean geostrophic velocities) from the direct method through a multivariate objective analysis. In this formulation, first introduced in oceanography by Bretherton (1976), the MDT $\langle h\rangle(r)$ is obtained at the spatial position r as a linear combination (Eq. 2) of the observations $O(r_i)$. The observations are the synthetic estimates obtained through Eq. (1).

$$\langle h\rangle(r) = \sum_{i=1}^{N} \alpha_i O(r_i) \text{ where } \alpha_i = \sum_{j=1}^{N} \mathbf{A}^{-1}_{i,j} C_{r,j} \qquad (2)$$

A is the observations covariance matrix and $\boldsymbol{C}$ is the covariance vector between the observations and the estimated field. Under a number of hypotheses (homogeneity and isotropy), the covariance between two locations i and j only depends on the distance d_{ij} between the observations:

$$\mathbf{A} = (\langle\sigma^2\rangle\boldsymbol{C}(d_{ij}) + \langle\varepsilon_i\varepsilon_j\rangle)_{i,j=1,N} \text{ and } \boldsymbol{C}_r = (\langle\sigma^2\rangle\boldsymbol{C}(d_{ij}))_{j=1,N}$$

where σ^2 is the a priori MDT variance, $\boldsymbol{C}(r)$ is the a priori correlation function of the MDT field and ε_i is the error on the observation located at r_i.

As in Rio and Hernandez (2004), we plan to use the correlation function introduced by Arhan and Colin de Verdiere (1985)

$$\boldsymbol{C}(r) = \left(1 + r + \frac{1}{6}r^2 - \frac{1}{6}r^3\right)e^{-r}$$

where

$$r = \sqrt{\left(\frac{x}{x_0}\right)^2 + \left(\frac{y}{y_0}\right)^2}$$

and x_0 and y_0 are the zonal and meridian correlation radii of the MDT in the study area.

A linear relationship (i.e. geostrophy) links the mean dynamic height and the mean geostrophic velocities. As a consequence, the correlation function between the mean heights and the mean velocities can be deduced by the derivation of the MDT correlation function $\boldsymbol{C}(r)$ (see Appendix A from Rio and Hernandez, 2004).

In theory, the mean of the estimated field needs to be zero (Bretherton et al., 1976). In practice, this hypothesis is fulfilled by first removing from the observations the large scale a priori solution computed through the direct method. After inversion, the large scale field is added back to the estimated field.

For each grid point where the optimally filtered field is computed, the weights on the surrounding observations therefore depend both on the distance to the grid point and on the observation error. The distance dependence is fully defined through the covariance field (variance and correlation radii) of the MDT. This method therefore requires the knowledge of both observation error and the a priori MDT covariance field. The a priori covariance information of Mediterranean Sea MDT will be determined using a modelled MDT.

3 Data

3.1 Model outputs

Outputs from two numerical models have been used to compute the first guess for the MDT computation. The first modeled MDT was computed averaging over the 1993–1999 period outputs from the MFS model (Adani et al., 2011), while the second MDT uses outputs from a NEMO model configuration (Beuvier et al., 2010). They are displayed in Fig. 2a and b respectively.

3.2 Hydrological profiles

The hydrological profiles that have been used for this study were collected by IMEDEA(CSIC-UIB) and SOCIB (Ruiz et al., 2009, 2012; Bouffard et al., 2010; Pascual et al., 2010; Heslop et al., 2012) and the CTD profiles by IEO (IBAMar database, López Jurado et al., 2005; Alemany et al., 2010). This includes also Argo floats and CTD measurements from the EN3 database for the period ranging from 1993–2012. The number of available profiles in 0.25° by 0.25° boxes is displayed in Fig. 3.

3.3 Drifter velocities

We used a processed dataset of geostrophic drifter velocities for the Mediterranean Sea for the period 1993–2011 computed by Poulain et al. (2012). Drifter velocities have been low-pass filtered (36 h) and sampled at 6 h intervals. The wind-driven Ekman drifts have been removed using an ad hoc statistical regression using local wind products. We used all data until June 2011 for the MDT computation and kept the data from July to December 2011 for validation. The number of velocities available in 1/8° boxes is displayed in Fig. 4.

4 Computation of the synthetic datasets

4.1 Computation of the synthetic mean heights

The hydrological profiles listed in Sect. 3.2 were used to compute dynamic heights relative to 350 m as displayed in Fig. 5. The reference depth choice results from making a compromise between the number of profiles available (the deeper the reference depth, the less the profiles available) and the dynamical content of the calculated dynamic heights (the deeper the reference depth, the more complete the captured baroclinic content).

The use of these dynamic heights to compute synthetic mean heights of the Mediterranean Sea requires:

1. to extract the temporal variability from the instantaneous dynamic height. The resulting quantity is therefore the mean dynamic height relative to the reference depth (350 m).
2. to add the missing mean component, i.e. the mean dynamic height at 350 m relative to the bottom and the barotropic contribution to the mean height (not measured by change in temperature and salinity).

To achieve point 1, the idea is to interpolate at the position of the measured dynamic height the sea level anomaly (SLA, h') measured by altimetry and to extract from this SLA the steric contribution of the first 350 m (or 450 m), Dh'_{350} (or Dh'_{450}) through the use of a parameter α_{350} such that

$$\mathrm{Dh}'_{350} = \alpha_{350}\mathrm{SLA}$$

α_{350} is determined through least squares fit between the altimeter SLA and observations of Dh'_{350} computed subtracting from the instantaneous dynamic heights relative to 350 m a mean field. This mean field was obtained by smoothing the observations using an objective analysis. Then α_{350} was obtained through lease square fit over a 3 months moving window. The coefficients range between 0.3 and 0.6 and, due to stratification, are maximal in summer and minimal in winter: for a stratified fluid in rotation, the ratio between horizontal and spatial scales is of the order of N/f, where N is the Brunt–Välsälä frequency and f is the Coriolis parameter. During summer, when stratification is important, the vertical coupling is reduced and the baroclinic flow dominates, and the dynamic heights calculated from the temperature and salinity variations explain an important part of the full Sea Level Anomaly measured by altimetry. Once the temporal variability of the dynamic heights relative to 350 m has been removed using $\alpha_{\mathrm{obs}/350\,\mathrm{m}}$, we need to add the missing mean component, i.e. the mean dynamic height at 350 m relative to the bottom and the barotropic contribution to the mean height (not measured by change in temperature and salinity). This missing component is estimated as the difference between the MFS modelled MDT (Fig. 2a) and the mean dynamic heights relative to 350 m computed from observations. The MFS model is used here to be consistent with the first guess used for the MDT calculation (see Sect. 5.2). Due to the small number of profiles (Fig. 3), we decided to compute the mean synthetic heights in 0.25° by 0.25° boxes. The mean dynamic heights relative to 350 m and computed in 0.25° by 0.25° boxes are displayed in Fig. 6a. After adding the missing component, the mean synthetic heights that will be used for the MDT computation are displayed in Fig. 6b. An error estimate is also obtained for each 0.25° by 0.25° boxes. It is calculated as the box variance divided by the number of observations in the box. The obtained error is displayed in Fig. 6c. It is lower than 2–3 cm in most places.

4.2 Computation of the synthetic mean velocities

We extracted from each geostrophic drifter velocity the temporal variability by subtracting the geostrophic velocity anomalies as measured by altimetry. We used the AVISO

SLA maps computed specifically for the Mediterranean Sea area. The obtained "synthetic" mean geostrophic velocities computed in 1/8° by 1/8° boxes are displayed in Fig. 7.

In order to highlight the efficiency of the method to remove the temporal variability of the drifter velocities, we have computed the variance in 1/8° by 1/8° boxes of the geostrophic velocities (top plots of Fig. 8) and compared it to the variance obtained using the "synthetic" mean geostrophic velocities (bottom plots of Fig. 8). We checked that for both components of the velocity, the variance is reduced once the temporal variability has been removed.

Finally, an error is estimated in each 1/8° by 1/8° box. It takes into account:

- the individual velocity error estimates, computed as the sum of two contributions: the altimeter velocity anomaly errors (equal to 30 % (resp. 40 %) of the zonal (resp. meridian) velocity on one side and the drifter geostrophic velocity error on the other side. This drifter geostrophic velocity error depends on the drifter type and is given in Table 2 of the paper by Poulain et al. (2012). It ranges between 2 and 5 $\mathrm{cm\,s^{-1}}$.
- the variance in the box where synthetic mean velocities are computed.

In each box, the error is taken as the maximum of the two above contributions divided by the number of observations in the box. The resulting error field is shown in Fig. 9.

5 Sensitivity tests

In order to discriminate between the different MDTs obtained using different parameters (first guess, correlation scales...) we have compared our different solutions to independent mean synthetic velocities from drifter data. This independent dataset is made of 2492 6 h velocity measurements spanning the period from July to December 2011 (this represents 1 % of the total drifter dataset). They were processed as described in Sect. 4 to extract the mean geostrophic component of the current, but they were not included for the SMDT-MED-2014 calculation.

They sampled the Balearic Islands area, the northern tip of the Tyrrhenian Sea and the Ionian jet.

5.1 Sensitivity tests to the objective analysis input parameters

The a priori MDT covariance is a key parameter of the objective analysis that is used to map the MDT from the mean synthetic heights and velocities.

The correlation radii have been obtained directly from the drifter mean geostrophic velocity information.

In effect, the correlation for the zonal (meridional) mean geostrophic velocities $U(V)$ is given by Eq. (3) (resp. Eq. 4) below:

$$\langle U,U\rangle = \sigma_U^2 \cdot \frac{\left(\frac{x}{x_0}\right)^2 \cdot F(r) + \left(\frac{y}{y_0}\right)^2 \cdot G(r)}{r^2} \tag{3}$$

$$\langle V,V\rangle = \sigma_V^2 \cdot \frac{\left(\frac{x}{x_0}\right)^2 \cdot G(r) + \left(\frac{y}{y_0}\right)^2 \cdot F(r)}{r^2} \tag{4}$$

where $F(r) = \left(1 + r - \frac{1}{4}r^2\right)e^{-r}$ and $G(r) = \left(1 + r - \frac{7}{4}r^2 + \frac{7}{4}r^3\right)e^{-r}$ and $r = \sqrt{\left(\frac{x}{x_0}\right)^2 + \left(\frac{y}{y_0}\right)^2}$.

The correlation radii x_0 and y_0 were determined by least square fit in 1° by 1° boxes. Slightly different results where obtained using the analysis of the zonal drifter velocities (Eq. 3) or the meridional drifter velocities (Eq. 4). Better comparison to independent drifter velocities were obtained using the zonal analysis as highlighted in Table 2, so that we used the correlation scales from Eq. (3) for the final MDT calculation. These scales are shown in Fig. 10.

The variance used was also computed from the drifter velocities variance using Eq. (3) or Eq. (4)

$$\sigma_h^2 = \sigma_U^2 \cdot \left(\frac{f}{g}\right)^2 \cdot \frac{3}{2} \cdot y_0^2 = \sigma_V^2 \cdot \left(\frac{f}{g}\right)^2 \cdot \frac{3}{2} \cdot x_0^2 \tag{5}$$

Slightly different results were obtained for σ_h^2 when starting from σ_U^2 or σ_V^2 in Eq. (5). We chose to take the maximum of the variance obtained. The final variance field is displayed in Fig. 8.

5.2 Sensitivity tests to the first guess

We have computed two different MDTs using as first guess the 1993–1999 mean from either the MFS or the NEMO model (Fig. 2). The top left plot of Fig. 13 shows the height difference between these two first guess. Important differences are visible, mainly in the Alboran Basin, the Ionian Basin and the Levantine Basin. Differences amplitude can reach up to 20 cm but is lower than 8 cm in most places. For this sensitivity study, we have used only the synthetic mean velocities as input of the objective analysis. The top right plot of Fig. 13 shows the height differences between the two obtained MDTs. They are much lower than the differences between the two first guess (see the Alboran Sea for instance), with amplitudes lower than 2–3 cm. In addition the height differences are rather large scale, meaning that the impact on mean geostrophic velocities is low. Indeed, it is lower than 1 cm s^{-1} in most places (bottom plots of Fig. 13).

Consequently, the statistical comparison to independent drifter velocities shows very few impact when one first guess is used instead of another (Table 1). Slightly lower Root Mean Square (RMS) differences are obtained using the MFS model compared to the NEMO model (17.5 cm s^{-1} instead of 17.7 cm s^{-1} for the zonal component, 15.4 cm s^{-1} instead of 15.6 cm s^{-1} for the meridian component).

In both cases, the altimeter zonal (resp. meridian) velocity variance is overestimated (resp. underestimated) compared to the drifter zonal (resp. meridian) velocity variance.

Finally, we have used the MFS model mean as first guess.

6 The SMDT-MED-2014

The synthetic mean heights and velocities have been finally used to improve the MFS model mean through a multivariate objective analysis based on the parameters described in the previous section. The resulting SMDT-MED-2014 is displayed in Fig. 14. A detailed view of the corresponding mean geostrophic currents is given for 5 different areas of the Mediterranean Sea in Fig. 15 (Alboran Sea and Algerian Current; Balearic Islands; North West Mediterranean Basin; Thyrrhenian Sea and Adriatic Sea; Ionian Sea; Levantine Sea).

For comparison, for each area, we have also displayed the mean velocities as measured by drifters (first column), the previous SMDT05 solution from Rio et al. (2007) (second column), and the MDT from the MFS model, used here as first guess (third column).

Depending on the area, the mean currents are either reinforced (Liguro-Provençal current, coastal Adriatic currents, Algerian currents) compared to the initial first guess, or weakened (coastal current along the Spanish South Eastern coasts). The Alboran gyres are nicely resolved, while they were not captured by the MFS model. The previous SMDT07 solution featured a strong unrealistic current along the Spanish Catalan coasts, which has almost disappeared in the new SMDT-MED-2014, in agreement with the MFS model and the drifter mean velocities. The Ligurian current is also strongly modified in the new solution compared to the SMDT07, and the same holds for the Bonifacio gyre in the Tyrrhenian Sea, in good agreement with the drifter velocities.

7 Validation using independent in-situ measurements

7.1 Comparison to independent drifter velocities

To validate the obtained SMDT-MED-2014 and quantify the improvements made compared to the previous solution, we have used the same independent synthetic mean velocity dataset as for the sensitivity studies.

Results are given in Table 3. The use of the new SMDT-MED-2014 shows clear improvements compared to the SMDT07 solution, with reduced RMS differences to drifter velocities.

7.2 Comparison to independent hydrological profiles

We use a dataset of 912 independent CTD profiles not included in the previous computations to perform a comparison with the SOCIB-CLS MDT. The profiles come from cruises carried out during the period 2001–2012 in the area of the Balearic Sea by IEO (IBAMar López Jurado et al., 2005; Alemany et al., 2010) and IMEDEA and SOCIB (Bouffard et al., 2010; Pascual et al., 2010; Ruiz et al., 2012; Heslop et al., 2012). For all CTD profiles, the dynamic height was computed with a common reference level of 350 m. This is compared to the absolute dynamic topography (ADT) obtained by adding the gridded SLA fields to the previous MDT computed by Rio et al. (2007) and the SMDT-MED-2014 and then interpolated onto the position and time of the dynamic height profiles. The new SMDT-MED-2014 presents a better agreeement with hydrological profiles as it is shown in the Taylor diagram (Fig. 16). The correlation increases from 0.54 to 0.60, the rms differences decrease from 5.34 cm to 4.47 cm and the standard deviation (std) of the ADT gets also closer to the dynamic height std (4.27 cm) with SMDT-MED-2014 (5.41 cm) than with the previous version (6.34 cm). The fact that ADT std is still larger than the in situ std, may give an indication of the missing baroclinic (below 350 m) and barotropic component of the dynamic height computation.

7.3 Comparison to Sea Surface Temperature

A qualitative validation of the improvements achieved with the new SMDT-MED-2014 can be also analyzed through the comparison with Sea Surface Temperature (SST) maps. Here we present one example in the Ligurian Basin (Fig. 17). They correspond to the mean SST fields averaged over one particular year (2007) and the equivalent mean circulation as derived from the addition of SLA and MDT using the previous MDT computed by Rio et al. (2007) and the SMDT-MED-2014. For the SST we use the reanalysis produced by Marullo et al. (2007), which consists of a daily SST series obtained through an optimal interpolation of infrared AVHRR data with a $1/16^{\circ}$ resolution.

SST gradients give an indication of the mean surface cyclonic circulation of the Ligurian Sea, revealing the continuity along the coast of Corsica, the protrusion in the Gulf of Genova and the propagation along the French Mediterranean slope. The SST pattern also shows to cold cores, one centered at 6° E and the second one at $7^{\circ}30'$ E. The SMDT07 solution also shows a general cyclonic circulation with higher values along the coast, although the protrusions close to Gulf of Genova is less pronounced than in the SST field and only one of the two cores is present (at around 6° E although the shape is quite different). Note also that there is a disruption of the circulation in the vicinity of Nice (at about 7° E), with a gradient of ADT almost perpendicular to the slope, indicating that the associated surface geostrophic currents are towards the coast and not parallel as it is expected from the SST patterns and also from previous studies (e.g. Pascual et al., 2013). On the contrary, the SMDT-MED-2014 solution shows a remarkable agreement with the SST fields. The cyclonic circulation is reinforced with a marked protrusion towards the Gulf of Genova, the two small cyclones are present with the same position and shape as SST data, and the artifact of associated currents towards the coast in the area of Nice has been corrected.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

8 Conclusion

A new MDT was computed for the Mediterranean Sea, that is available for calculating absolute altimetric heights and geostrophic currents, and that may be used to assimilate altimeter Sea Level Anomalies into operational forecasting systems of the Mediterranean Sea. It is based on the same methodology than the previous MDT computed by Rio et al. (2007). A number of improvements have been made possible by the use of extended datasets and refined processing. The new dataset consisted of an updated dataset of drifter velocities provided by OGS and a dataset of hydrological profiles provided by IMEDEA. In Rio et al. (2007) no hydrological profiles had been taken into account. This has required the development of dedicated processing. However, the impact of using these data, that are not very numerous, remains low at the moment.

A number of sensitivity study has been carried out to obtain the most accurate MDT as possible. The main currents and main stationary structures of the Mediterranean Sea are found to be nicely resolved by this new MDT, with an improved description of important currents as the Liguro-Provençal current, or known structures as the Bonifacio gyre, compared to the previous SMDT07 solution. Also, spurious currents present in the SMDT07 solution have now disappeared (along the Spanish Catalan coast for instance). A systematic external validation to independent data (drifters, hydrological profiles, SST) has been made to evaluate the different parameter choices and validate the final SMDT-MED-2014. However, only few independent data were available for validation so that the MDTs were tested mainly in the Balearic Islands area and the North Ionian Jet.

For the future, further work about the definition of the correlation scales is needed, as well as an enhanced validation exercise, in particular in other parts of the basin. In addition, further work is needed to investigate the possibility to use the future release of GOCE geoid models (that will be available in mid 2014) to compute a model-independent first guess in the Mediterranean Sea. Due to the high geoid error level compared to the rather low oceanic signal variance in the Mediterranean Sea, this will require the development of sophisticated filtering techniques.

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Table 1. Rms differences between the processed independent drifter velocities and the altimeter velocities calculated using 2 different MDT solutions, starting either from the NEMO or the MFS model as first guess.

	SMDT V_{synth} EbNEMO	SMDT V_{synth} EbMFS
$U_{\text{Drifter}} - U_{\text{Exp}}$	17.68	17.51
$V_{\text{Drifter}} - V_{\text{Exp}}$	15.60	15.39

Table 2. Rms differences between the processed independent drifter velocities and the altimeter velocities calculated using 2 different MDT solutions, based on the use of correlation scales deduced from the analysis of the zonal or the meridional drifter velocities.

	SMDT RcDrifter U,U	SMDT RcDrifter V,V
RMS($U_{\text{Drifter}} - U_{\text{Exp}}$)	16.7	17.0
RMS($V_{\text{Drifter}} - V_{\text{Exp}}$)	15.3	15.4

Table 3. RMS differences of altimeter velocities obtained using the old and the new MDT solutions to independent geostrophic velocities.

	SMDT07	SMDT-MED-2014
$U_{\text{Drifter}} - U_{\text{Exp}}$	15.95	15.0
$V_{\text{Drifter}} - V_{\text{Exp}}$	14.94	14.1

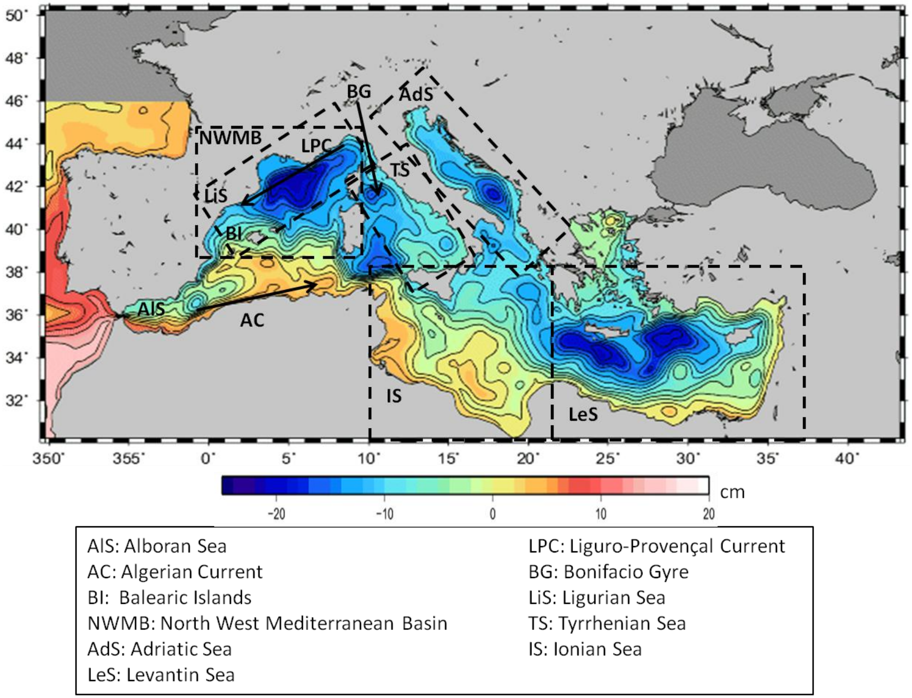

Fig. 1. The Mean Dynamic Topography computed by Rio et al. (2007). The different sub-basins and currents mentioned in this paper are defined here.

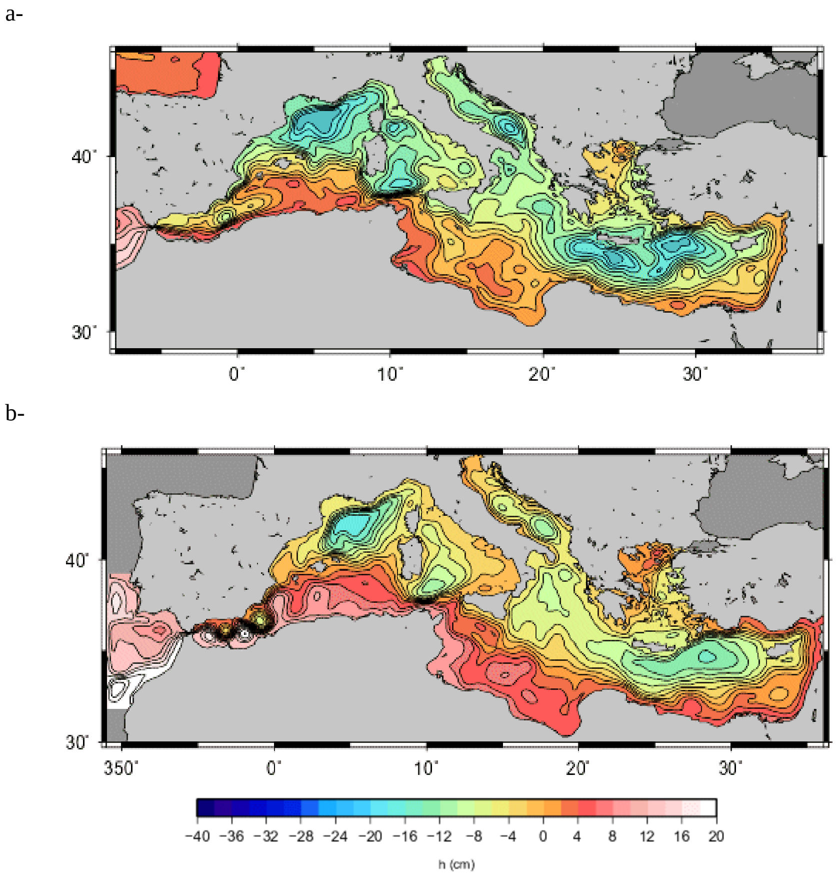

Fig. 2. The Mean Dynamic Topography of the Mediterranean Sea for the period 1993–1999 calculated averaging model outputs from **(a)** the MFS model and **(b)** the NEMO12 model.

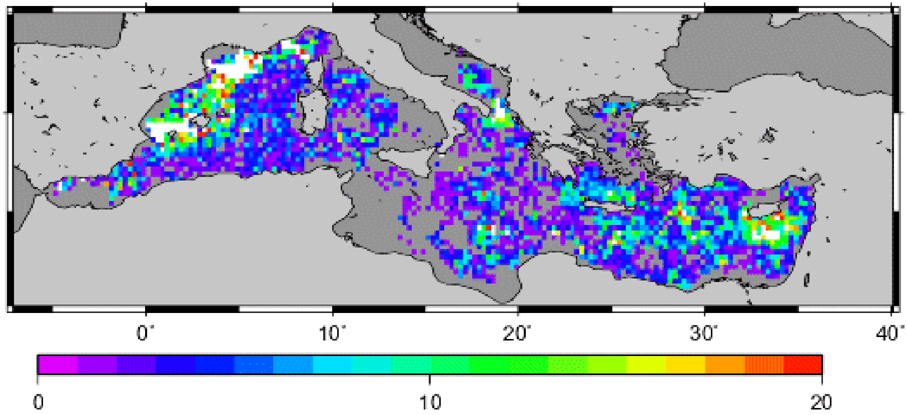

Fig. 3. Number of hydrological profiles (0–350 m) in 0.25° by 0.25° boxes. Numbers in white boxes are greater than 50. Boxes with no data are in grey.

OSD
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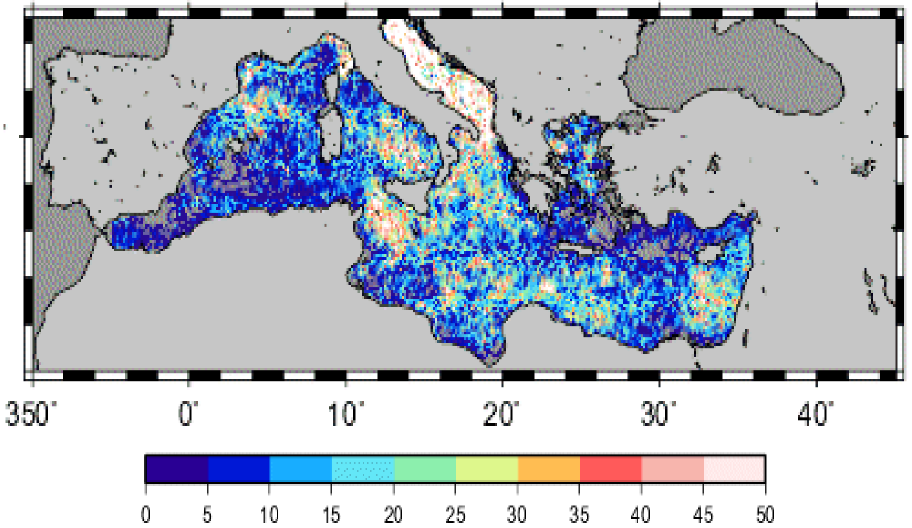

Fig. 4. Number of drifter velocities in 1/8° boxes. Numbers in white boxes are greater than 50. Boxes with no data are in grey.

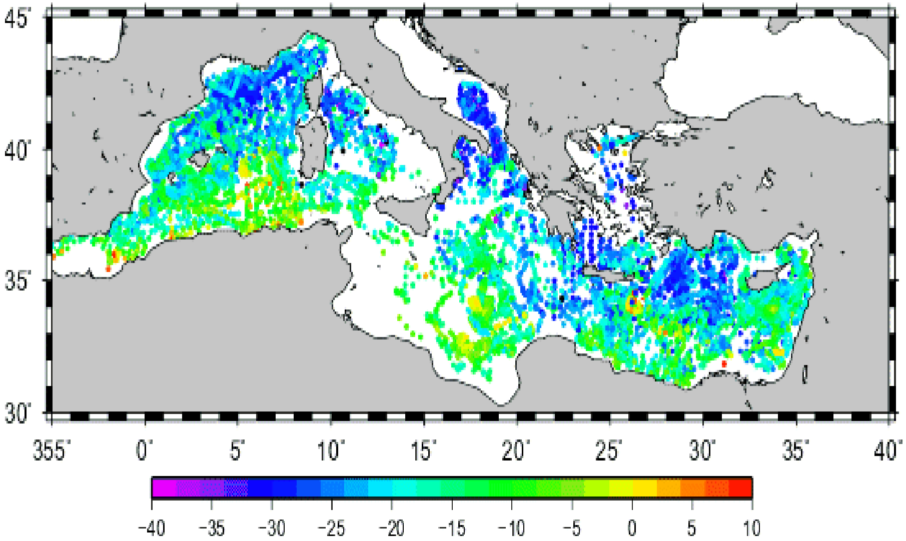

Fig. 5. Dynamic Heights computed relative to 350 m from the T/S profiles available for this study. White stands for no data. Unit is cm.

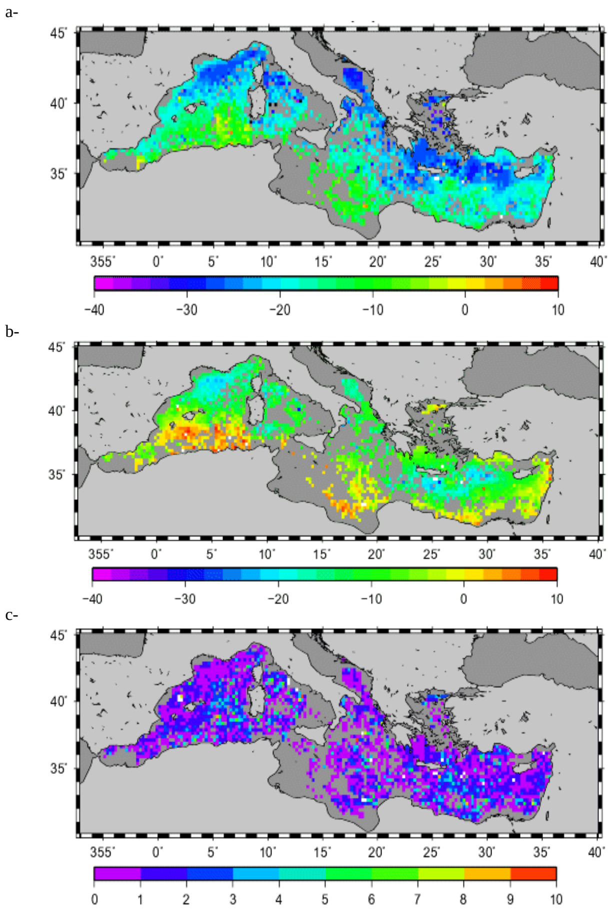

Fig. 6. (a) The mean synthetic dynamic heights relative to 350 m. **(b)** the synthetic mean dynamic topography estimates and **(c)** the corresponding errors. Unit is cm.

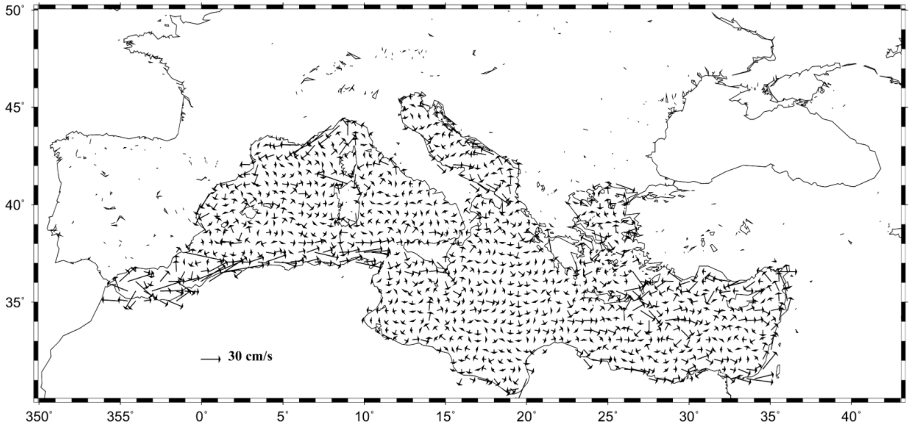

Fig. 7. The synthetic mean velocities computed from drifter velocities and altimetry in 1/8° boxes.

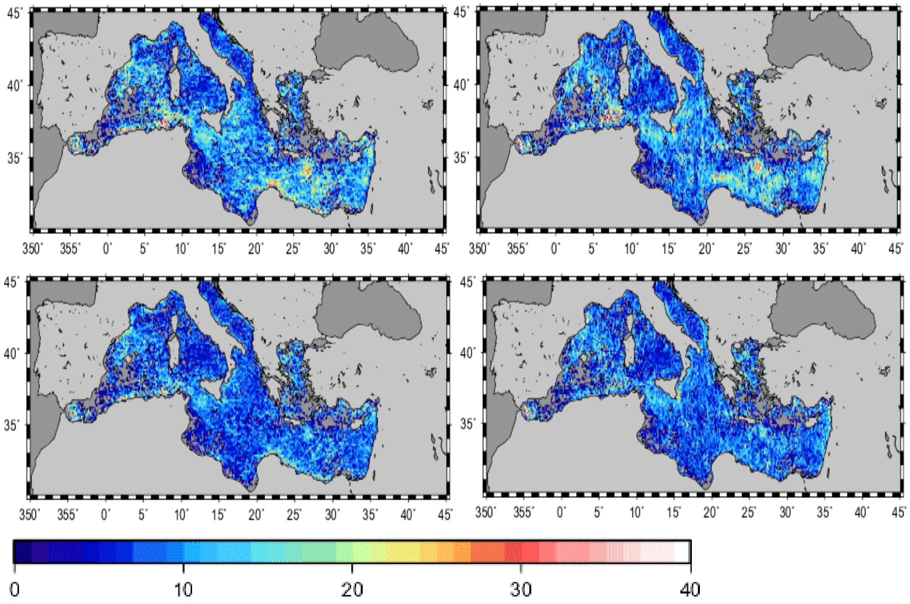

Fig. 8. Variance computed in 1/8° boxes of (top) the geostrophic drifter velocities and (bottom) the synthetic mean velocities for the zonal (left) and meridian (right) component. Units are $\mathrm{cm\,s^{-1}}$.

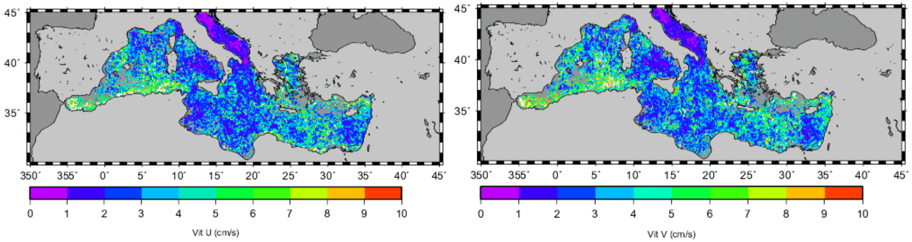

Fig. 9. Error on the mean zonal (left) and meridional (right) velocities.

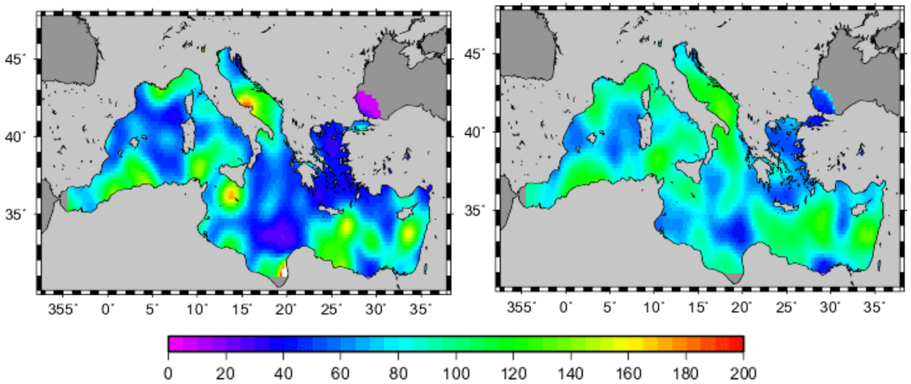

Fig. 10. Zonal (left) and meridian (right) correlation scales computed using the zonal velocities covariances. Scales have been filtered using a 200 km low pass filter. Units are km.

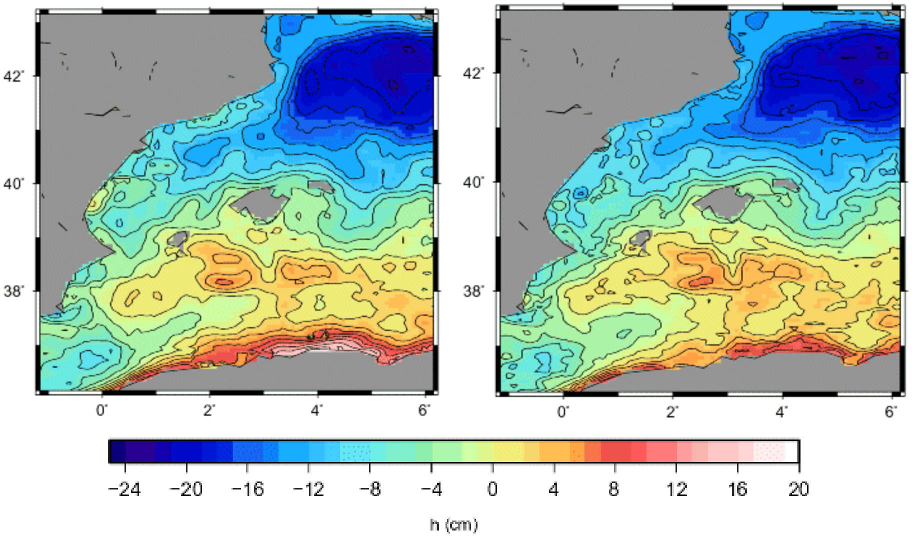

Fig. 11. Mean Dynamic Topography computed in the Balearic Islands area using different correlation scales: (left) from the drifters ($\langle U,U \rangle$ component), (right) from the drifters ($\langle V,V \rangle$ component).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▌
▶▌
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

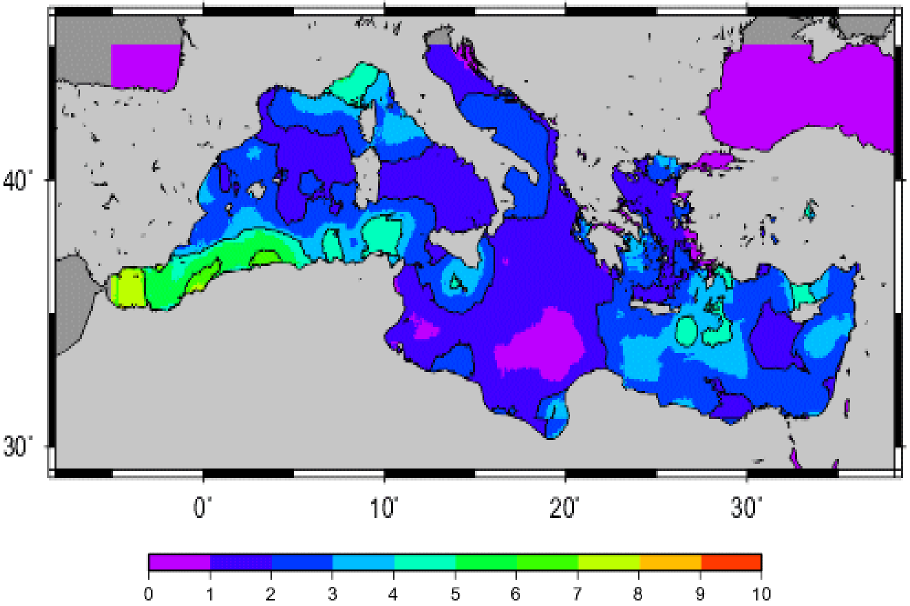

Fig. 12. A priori variance of the Mediterranean MDT computed in 1° boxes from the drifters. Unis are cm^2.

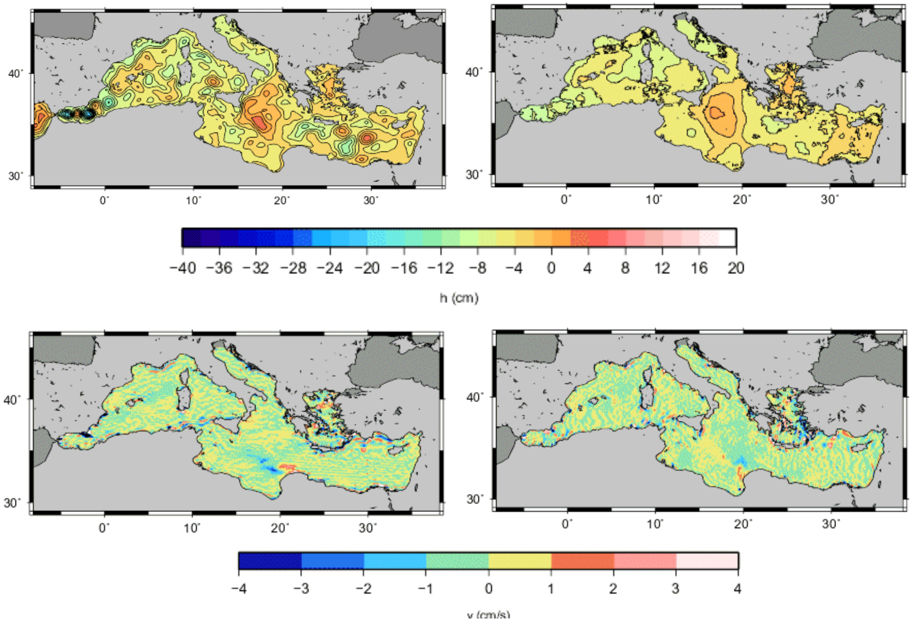

Fig. 13. Top Left: Height difference between the MFS and the NEMO modelled MDT. Height (top right), zonal velocity (bottom left) and meridional velocity (bottom right) differences between the Mediterranean Mean Dynamic Topography obtained from the inversion of the mean geostrophic velocities using the MFS or the NEMO first guess.

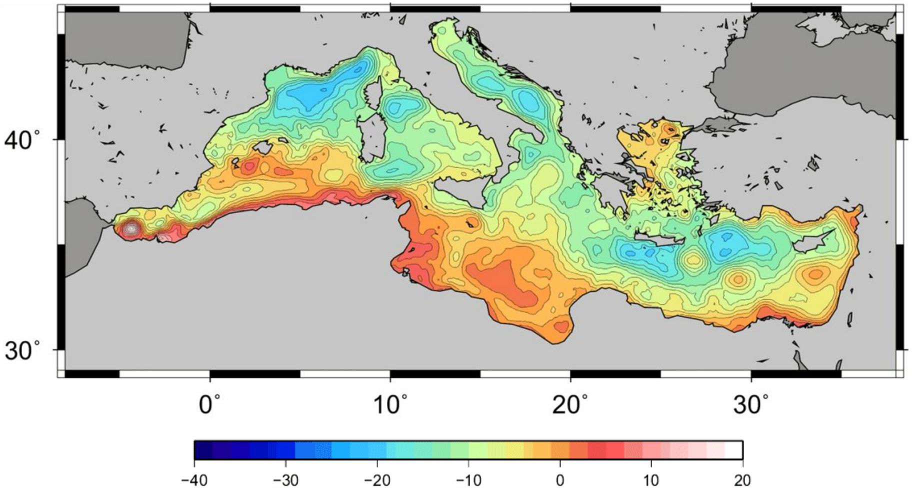

Fig. 14. The SMDT-MED-2014. Units are cm.

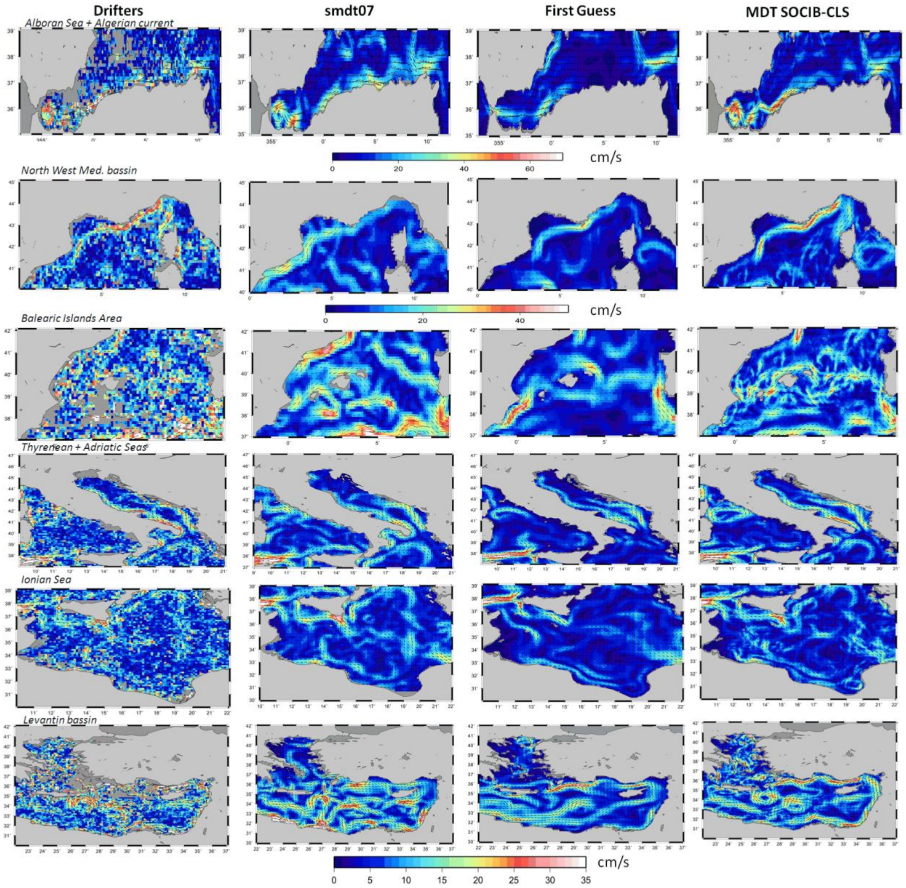

Fig. 15. mean circulation in different parts of the Mediterranean Sea as seen by 1st column: the drifters; 2nd column: the previous SMDT07 solution; 3rd column; the MFS model first guess used for the computation of the SMDT-MED-2014; 4th: the SMDT-MED-2014.

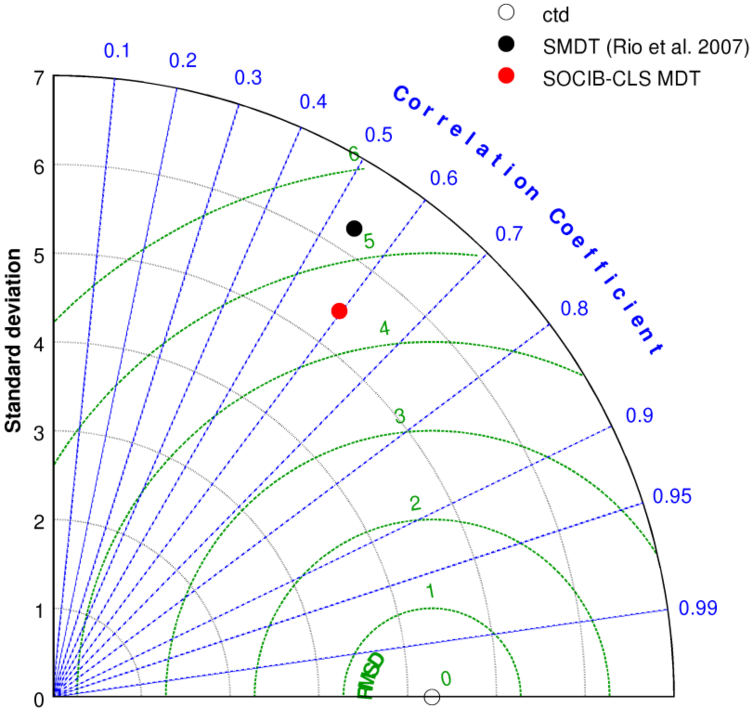

Fig. 16. Taylor diagram displaying a statistical comparison with CTD of the SMDT07 solution and the SMDT-MED-2014 solution.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

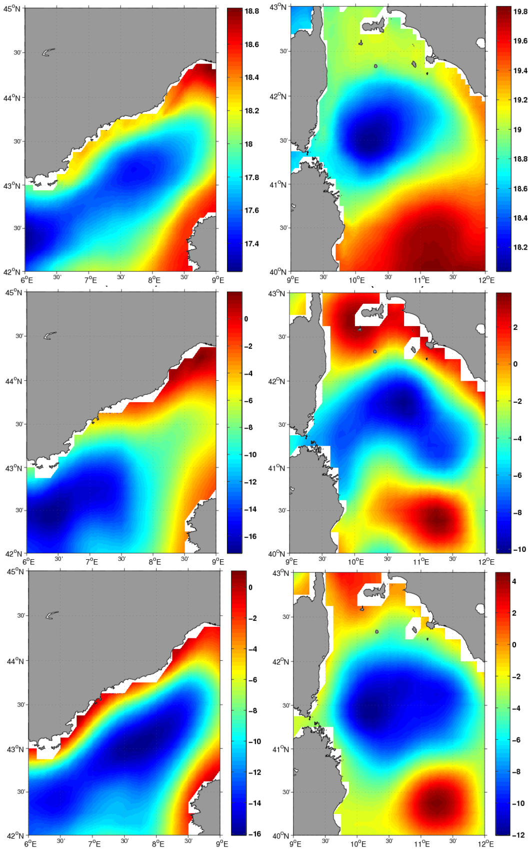

Fig. 17. First row: mean SST patterns (in °C) corresponding to the annual 2007 average for the Ligurian basin (left) and Thyrhenian basin (right). Second row: mean circulation as derived from the previous SMDT solution. Third row: mean circulation as derived from the SOCIB-CLS-MDT solution.