Ocean Sci., 7, 745–753, 2011
www.ocean-sci.net/7/745/2011/
doi:10.5194/os-7-745-2011

Ocean Science

Mean Dynamic Topography of the Black Sea, computed from altimetry, drifter measurements and hydrology data

A. A. Kubryakov and S. V. Stanichny

Marine Hydrophysical Institute of NAS of Ukraine, 99011 Sevastopol, Ukraine

Received: 1 March 2011 – Published in Ocean Sci. Discuss.: 4 April 2011
Revised: 27 September 2011 – Accepted: 18 October 2011 – Published: 8 November 2011

Abstract. Mean Dynamic Topography (MDT) is a crucial parameter for estimating dynamic topography, and, therefore, geostrophic circulation from satellite altimetry measurements. In this work we use drifting buoy measurements, hydrographic profiles and along-track Sea Level Anomalies (SLA) to reconstruct MDT of the Black Sea by the "synthetic" method. Obtained MDT shows a lot of mesoscale features, which are not present in previous MDT fields of the Black Sea, mostly based on climatic data. Moreover, gradients of sea level in the synthetic MDT are significantly higher compared to other fields, which is evidence of more intense currents in the basin.

Validation of determined MDT field with independent dynamic heights and drifter buoy velocities shows good quantitative and qualitative coincidence over all Black Sea basin and improvements compare to previous fields.

New Black Sea MDT will improve quality of altimetry-derived geostrophic velocities and lead to better understanding of the spatial and temporal features of the upper layer dynamics.

1 Introduction

Satellite altimetry is a unique instrument for measuring ocean dynamic topography and geostrophic circulation from remote sensing data. It provides regular high-quality data for whole World Ocean since 1991, which can be used to analyze the ocean processes and their variations on different scales.

Satellite altimeter measures altitude above the sea surface with accuracy ∼2 cm (Cheney et al., 1994). One of the main problems in using altimetry data for marine science is the determination of full dynamic topography (the sea level above the geoid) from the measured altitude data. For that, first, altitude of altimeter is subtracted from the height of satellite orbit, which is counted from the reference ellipsoid – rough approximation of Earth form. The result is the so-called sea surface height (SSH) – height of the sea above reference ellipsoid. It consists of two terms, – marine geoid G and dynamic topography h. The direct method of h estimation is, therefore, simple subtraction of the geoid G from SSH. Unfortunately, today, the shape of the geoid is still unknown with accuracy required for oceanography (see, for example Le Provost, 2002). That is the reason why an indirect method of determining full dynamic topography is used, based on Sea Level Anomalies (SLA). It is organized as follows: first, SSH, averaged for the referenced period T (in our case T is 1993–1999), is subtracted from each measurement of SSH. Geoid variations are assumed to be small with respect to sea level variations induced by ocean dynamic. Sea level anomalies h' from SSH measurements defined as:

$$h' = \mathrm{SSH} - <\mathrm{SSH}>_T = G + h - <G+h>_T = h - <h>_T, \quad (1)$$

and full dynamic topography is:

$$h = h' + <h>_T \quad (2)$$

here $<>$ – mean time averaging, $<h>$ – is called the mean dynamic topography (MDT).

The sea level anomalies used in this study are computed by SSALTO DUACS and they are referenced to a 1993–1999 mean profile (http://www.aviso.oceanobs.com/). Therefore, to reconstruct the absolute dynamic topography, the mean dynamic topography for the same time period 1993–1999 is needed.

Absolute dynamic topography allows to calculate geostrophic velocities, which are essential parameters for a lot of oceanological tasks, through geostrophic balance equations:

$$u_\mathrm{g} = -\frac{g}{f}\frac{\partial h}{\partial y}; \quad v_\mathrm{g} = \frac{g}{f}\frac{\partial h}{\partial x} \quad (3)$$

Correspondence to: A. A. Kubryakov
(arskubr@gmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Here x – longitude, y – latitude, u_g, v_g – zonal and meridional geostrophic velocities, f – Coriolis parameter, g – gravitational acceleration.

Today, there are a lot of different works dedicated to estimation of MDT for different areas of the world ocean, for example (Rio et al., 2011; Maximenko et al., 2009; Dobricic, 2005). For the Black Sea there was no MDT designed specially for altimetric measurements. Existing fields are based on climatic hydrological data, averaged over 1954–2004 (Belokopytov, 2003) and modeled fields of dynamic topography, with in-situ data assimilation, also averaged for another time period (Knysh et al., 2002). Due to the low spatially-temporal resolution of hydrological data, such methods can result in too smooth solutions. Moreover, different periods of averaging result in errors in MDT estimation, as Black Sea dynamics have strong interannual variability (Knysh et al., 2011).

That is why, one of the main tasks in the framework of project ECOOP was the reconstruction of mean dynamic topography of the Black Sea. Determined MDT will improve quality of altimetry-estimated fields of dynamic topography and corresponding geostrophic surface currents and increase the accuracy of such calculations.

In this work we use the concept of the so called "synthetic" method, which is based on the combination of altimetric sea level anomalies and in-situ data. This concept was already established for the World Ocean (Rio et al., 2004), and for regional studies in the Mediterranean Sea (Rio, 2007) and other areas (Challenor et al., 1996; Snaith et al., 2003) and shows its superiority over other methods (Hernandez et al., 2001). We use SLA, drifting buoy velocity measurements and hydrographic profiles to compute along-track synthetic MDT of the Black Sea and then extrapolate it on the whole basin.

2 Black Sea upper-layer circulation

Black Sea is an almost enclosed basin, which is connected with the Mediterranian Sea through narrow Straits of Bosphorus. The main feature of the Black Sea circulation is cyclonic Rim Current, surrounding entire basin, which is induced by wind circulation in the area (Zatcepin et al., 2003) (see scheme on Fig. 1). Rim Current form two large cyclonic gyres in the western and eastern part of the Black Sea.

A number of quasi-permanent nearshore anticyclonic eddies exist between the coast and Rim current (Ovchinnikov and Titov, 1990). Zones with predominant anticyclone vorticity are shown at Fig. 1. So-called Sevastopol and Batumi eddies are the most intense areas with mesoscale activity, where strong non-stationary anticyclones are formed.

The Black Sea is a stratified basin with strong mesoscale activity (Zatcepin et al., 2003) and typical baroclinic Rossby radius 15–25 km, so spatial resolution of the reconstructed MDT should be in correspondence with typical scale of the surface currents.

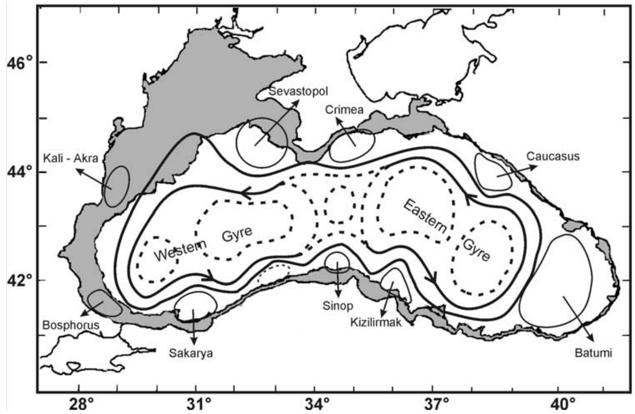

Fig. 1. The schematic diagram for the main features of the upper layer circulation derived from synthesis of past hydrographic studies prior to 1990 and altimetric data (reproduced from its original given by Korotaev et al. (1993)).

3 Data and methods

3.1 "Syntethic" method

The core idea of "synthetic" method is based on the definition of sea level anomaly. It is clear from Eq. (2) that we can determine synthetic estimate $H(r)$ of MDT at position r as the difference between quasi-synchronous in-situ measurement of full dynamic topography $h_{is}(t,r)$ and altimetric sea level anomaly $h'(t,r)$ at position r and time t (Rio and Hernandez, 2004):

$$h_{is}(t,r) - h'(t,r) = h_{is}(t,r) - (h(t,r) - H(r)) = H(r) \quad (4)$$

The time period of the obtained synthetic MDT $H(r)$ depends on the time period to which the used SLA are referenced. Since we use SLA from SSALTO DUACS we get through Eq. (2) a MDT representing 1993–1999 time period.

Also, one can use in-situ velocity measurements $u_{is}(r,t), v_{is}(r,t)$ and velocity anomalies $u'(r,t)$, $v'(r,t)$ computed from SLA through geostrophic Eq. (3), to estimate mean synthetic velocities $U(r)$, $V(r)$:

$$v_{is}(t,r) - v'(t,r) = V(r)$$

$$u_{is}(t,r) - u'(t,r) = U(r) \quad (5)$$

and, then, to compute gradients of MDT from equations:

$$U(r) = -\frac{g}{f}\frac{\partial H(r)}{\partial y}; \quad V(r) = \frac{g}{f}\frac{\partial H(r)}{\partial x}, \quad (6)$$

After integrating Eq. (6) one can receive "synthetic" estimations of MDT.

One of the major advantages of this method is the ability to use all available in-situ data from 1992 to present day for MDT determination. In Eq. (4), the time period of the obtained MDT is the time period to which the SLA are referenced, whatever is the time measurement of the in-situ data and the altimetry data. That is why any in-situ data may be used, also outside the period 1993–1999. Future measurements can be used to improve MDT and therefore, to retrieve more accurate dynamic topography from satellite altimetry data.

3.2 Data

3.2.1 Altimetry

In this work we used along-track Sea Level Anomalies from the Topex/Poseidon mission for the period from April 1993 to December 2005. SLA are computed relative to a 1993–1999 mean profile. Data were received from Collecte Localisation Satellite (CLS) (AVISO) (http://www.aviso.oceanobs.com). All standard corrections were applied (Le Traon and Ogor, 1998). These data were specially designed in CLS for the Black Sea region with 40 km filtering distance cutoff and sampling (1 point over 3 is conserved) . Precision of SLA measurements is about 3–4 cm, temporal resolution is 10 days and the spatial resolution is 7 km.

3.2.2 Drifting buoys

Data consists of measurements of 49 drifters deployed in Black Sea between 1999 and 2003. Main instrument is SVP-B buoy and its modifications (Motyzhev et al., 2000). Drogue of drifter was centered at 15 m depth. These buoys were constructed to reduce wind slippage and Stoke's drift, so that they closely follow the currents at their drogue's depth. Buoys were satellite-tracked by the Argos Data Collection and Location System (DCLS) installed on National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. Temporal resolution of the data is 1–6 h. Obtained dataset consists of more than 103 000 location measurements. Most of the drifters are captured by the Rim Current, so the most measurements are on the periphery of the Black Sea.

3.2.3 Dynamic heights

Profiles of temperature and salinity were obtained from Oceanographic data bank of Marine Hydrophysical Institute (ODB of MHI) and include all data, collected over whole basin of the Black Sea for 1992–2003. Dynamic heights, referenced to a depth of 500 m, were estimated from hydrographic profiles by dynamic method with help of the "Hydrologist" software (Belokopytov, 2005). Total dataset consist of more than 3100 measurements.

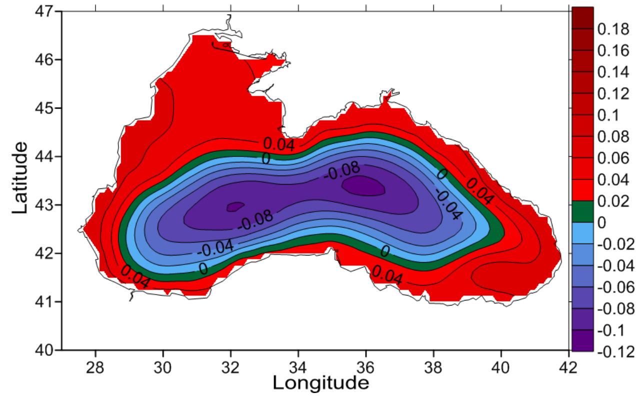

Fig. 2. Mean topography (averaged for 1973–1992) calculated by dynamic model with assimilation of climatic data (Knysh et al., 2002).

3.2.4 Climatic MDT (CMDT)

To compare our results on different stages we use mean dynamic sea level calculated from numerical modeling with assimilation of climatic array of hydrological data, averaged for the period 1973–1992 (Knysh et al., 2002) (Fig. 2). Calculations were made using the 3-D non-linear primitive equation model, developed in (Demyshev and Korotaev, 1992).

4 Computation of synthetic MDT

4.1 Computation of along-track synthetic MDT from drifter measurements

4.1.1 Drifter data processing

Velocities of drifting buoys were computed from position measurements by central difference scheme and then interpolated on 1 h regular intervals. Buoy velocity, which can be described by the following equation:

$$\frac{d\boldsymbol{v}}{dt} + \boldsymbol{k} \times f\boldsymbol{v} = -g\nabla h + \frac{1}{\rho}\frac{d\tau}{\partial z} \quad (7)$$

varies because of three main factors – geostrophic current, caused by gradients of dynamic topography (first term in right part), Ekman wind-driven component (second term) and other ageostrophic phenomena, that is generally inertial oscillations; here τ is wind stress, ρ – density, z – depth, $\boldsymbol{k}=\{-1,1,0\}$.

In order to estimate the geostrophic component from the full buoy velocity all other components should be filtered out. Time period of inertial oscillations in the Black Sea is:

$$T = 12(\mathrm{h})/\sin\varphi \sim 17\mathrm{h}, \quad (8)$$

here φ is latitude, that varies from 41° N to 45° E. Hence, inertial oscillations were filtered out by applying 17 h low-pass filter.

We use an assumption that the wind-driven component is negligible in situations with weak wind velocities ($<5\,\mathrm{m\,s^{-1}}$). This assumption is reasonable for buoys with 15 m drogue depth. All other situations were filtered out. In this work we use NCEP (National Centers for Environmental Prediction) $1^\circ \times 1^\circ$ wind on 6 h regular grid for 1998–2005 (http://oceandata.sci.gsfc.nasa.gov/Ancillary/Meterological/).

4.1.2 Reconstruction of along-track synthetic MDT

First, a set of geostrophic velocity anomalies u', v' were computed from SLA data through geostrophic balance Eq. (3). Along-track anomalies allow to determine only the projections of velocity normal to the direction of track. Then, quasi-synchronous measurements of drifter velocities were chosen and projected on the same direction. The intervals of selection between measurements were 25 km and 5 days. These values approximately correspond to the scales of synoptic spatial and temporal variability of processes in the Black Sea.

Differences between full velocity and anomalies define mean synthetic velocities U, V through Eq. (5) in along-track point, where quasi-synchronous measurements existed. All estimates of synthetic velocity existed in the same along-track point were averaged. Finally, there were retrieved 755 values of U, V in unique track points.

Synthetic velocities were approximated along each track by polynomials of degree 5–7. Figure 3 illustrates the synthetic velocities and its approximations along tracks No. 68 and No. 220. Computed polynomials were integrated to estimate along-track mean dynamic topography (Fig. 4).

Constants of integration $C_{1..N}$ (here N–number of tracks) were determined by minimization of the sea level differences in track cross-points for estimated profiles of MDT. This is mandatory condition, which provides us smooth solutions without sharp gradients of the sea level in the tracks cross-points. Minimization was made on the base of recursive function.

Sea level for track number i is l_i; sea level for cross-point between track i and j is l_{ij} for track number i and l_{ji} for track number j, respectively. The main idea is found such C_i that sum D of cross-point differences for each track:

$$D = \sum_{i}^{N} S_i = \sum_{i}^{N}\sum_{j}^{N}((l_{ij}+C_i)-(l_{ji}+C_j))^2 \quad (9)$$

is minimal. On the zero step of the algorithm ($k = 0$) all constants C_i are equal to mean sea level on track i:

$$C_i^0 = \langle l_i \rangle \quad (10)$$

On the next step ($k = 1$) differences S_i are computed for each track. Then we determine the number of track M which correspond to the maximum value of sum S_M. Constant C_M for the track number M is computed as

$$C_M^k = C_M^{k-1} - \langle S_M^{k-1} \rangle \quad (11)$$

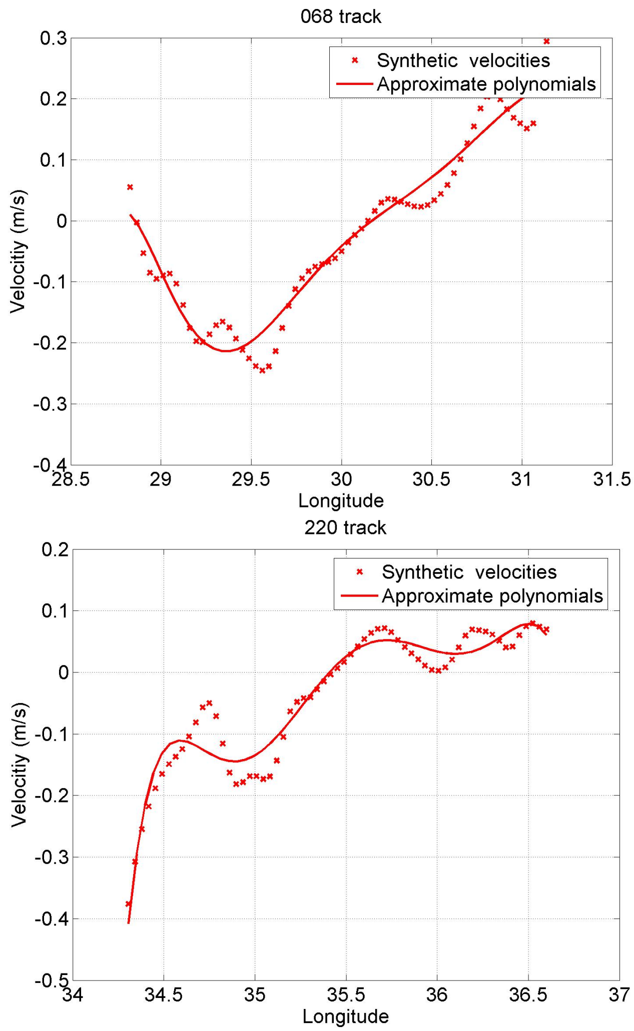

Fig. 3. Synthetic velocities computed in Black Sea along tracks No. 68 and No. 220 of Topex/Poseidon from drifters measurements and SLA and their polynomial approximations.

The set of coefficients $C^k_{1..M..N}$ is used on the next step ($k = k+1$). On step $k = 1000$ values of sum S_i and D became less than 10^{-5} m.

Using described above algorithm of minimization, along-track mean dynamic topography of the Black Sea was computed from SLA and drifter buoys velocities (Fig. 5)

4.2 Computation of along-track synthetic MDT from dynamic heights

4.2.1 Dynamic heights processing

Dynamic heights h_{is} computed from hydrologic data have to be processed to be consistent with altimetry sea level. They missed all the variance associated to eustatic variations of the sea level, i.e. induced by change of the total amount of water

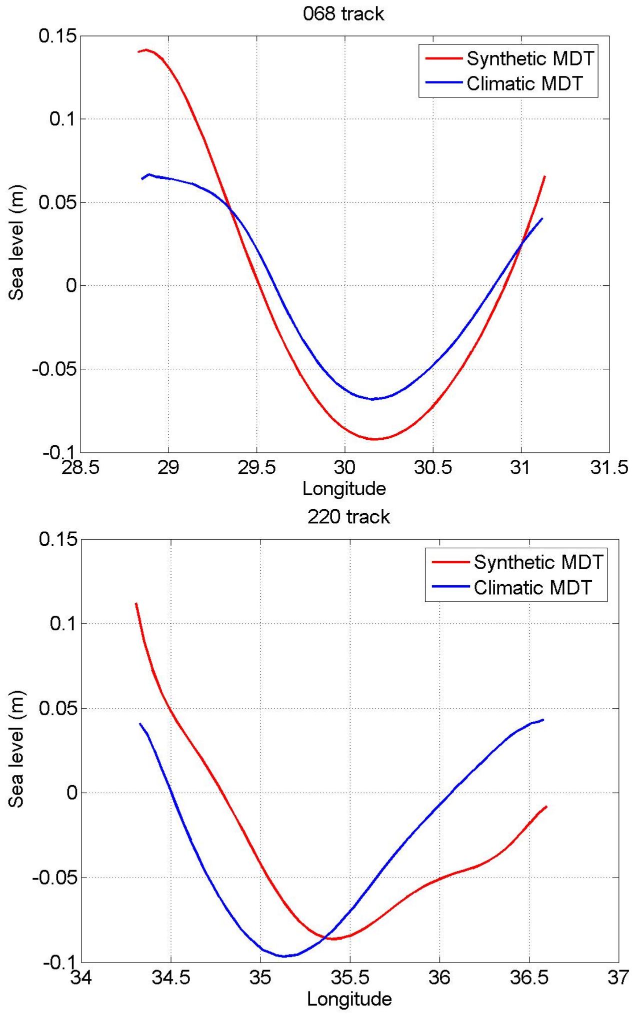

Fig. 4. Synthetic MDT computed in Black Sea along tracks No. 68 and No. 220 of Topex/Poseidon from drifters measurements and SLA and, for comparison, climatic MDT along the same tracks.

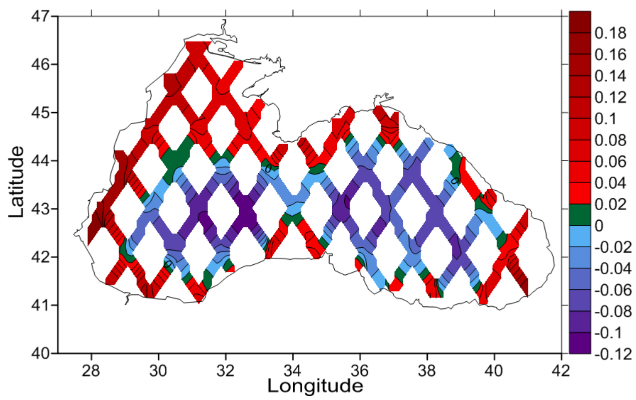

Fig. 5. Along-track mean dynamic topography computed from SLA and drifting buoy measurements.

in the basin. So, in fact, dynamic heights is the difference between absolute sea level signal and water balance W

$$h_{\mathrm{is}} = h - W \qquad (12)$$

In order to determine W we compute total change of the Black Sea volume by spatially averaging all altimetric SLA measurements and then interpolating it on 10-days regular grid $L(t) = < h'(r,t)>_r$. Computed array describes total change of water amount in the basin W plus steric effect S_t.

$$L = W + S_t, \qquad (13)$$

Amplitudes of steric effect in the Black Sea are small, about 4 cm, and have a well-defined annual period (Goryachkin and Ivanov, 2006). Here we simply approximate steric effect by a sinusoid with amplitude 4 cm, period 1 yr and minimum on 28 February:

$$S_t = 0.04 \times \sin\left(\frac{2 \times \pi \times (N_{\mathrm{d}} - 28)}{365} - \frac{\pi}{2}\right) \qquad (14)$$

where N_{d} is number of the day in the year. Then, dynamic heights were processed as follows:

$$h = h_{\mathrm{is}} + L - S_t \qquad (15)$$

to be consistent with altimetric measurements.

4.2.2 Reconstruction of along-track synthetic MDT

Two datasets were used to compute synthetic estimates of MDT: full dynamic topography calculated from hydrologic measurements through Eq. (15) and altimetric sea level anomalies h'. Differences between quasi-synchronous measurements were computed (the intervals of selection were 25 km and 5 days) and approximated along each track by polynomials of 5–7 degrees. Total amount of synthetic heights consisted of 771 values, which correspond to 225 estimates of MDT in unique track points. The result is along-track synthetic MDT shown on Fig. 6.

Unfortunately, only a small amount of hydrological data is available in the Black Sea after 1992 year. That is the reason why along-track synthetic MDT, based on this type of data, was reconstructed only for few Topex/Poseidon tracks.

5 Results

Along-track estimates of synthetic MDT computed from drifters and dynamic heights were combined as follows: first, we add a constant to each mean profile of MDT, computed from the dynamic heights, so that they fit best mean dynamic profiles, computed from drifters. After that, weights were computed (depending on number of measurements used) for each point of each mean profile, computed from drifters and TS-measurements. Then, estimates of MDT for each point were averaged with corresponded weights

$$\mathrm{H}_p = \frac{(n_{\mathrm{dr}} \times H_{\mathrm{dr}} + n_{\mathrm{dyn}} \times H_{\mathrm{dyn}})}{n_{\mathrm{dr}} + n_{\mathrm{dyn}}} \qquad (16)$$

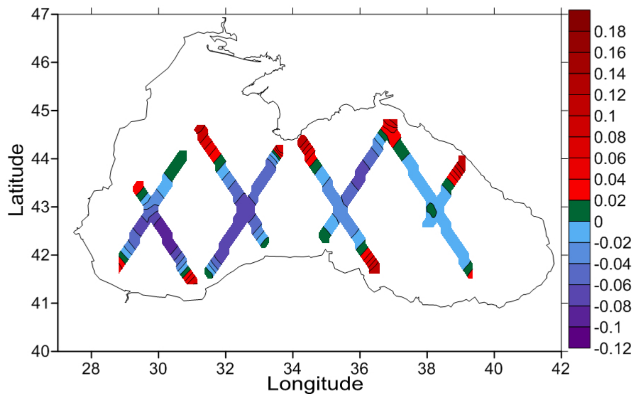

Fig. 6. Along-track mean dynamic topography computed from SLA and hydrographic profiles.

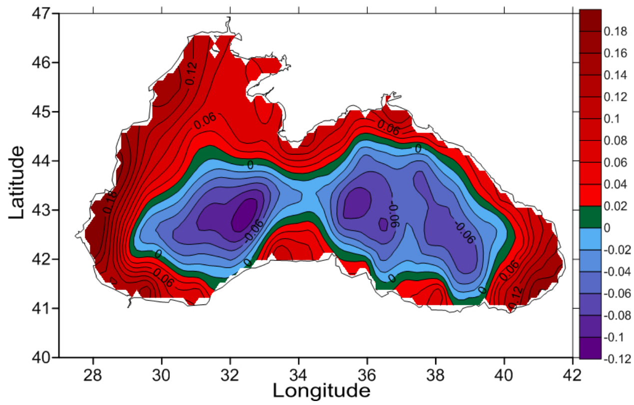

Fig. 7. Synthetic Mean Dynamic Topography computed in this paper.

here p – number of point, n_{dr}–number of buoy measurements used for MDT computation in along-track point p, n_{dyn} – the same for hydrologic data, H_{dr} and H_{dyn} is MDT estimates in point p from buoys and hydrology, respectively. After that, another minimization procedure, described in Sect. 4.1.2, was made with combined along-tracks estimates. Combined along-track MDT was interpolated (extrapolated) on the whole Black Sea basin. The result is synthetic mean dynamic topography (SMDT) with 1/8° resolution shown in Fig. 7.

SMDT, as well as the climatic MDT, defines cyclonic circulation of the Black Sea with higher sea level on the periphery and lower in the center. Synthetic mean dynamic topography reveals two separate cyclonic cells in the west and east part of the basin, in contrast to one cyclonic cell in CMDT. This fact is consistent with modern studies about the Black Sea (Ovchinnikov and Titov, 1990). Besides, the eastern cyclone in SMDT has two cores on the west and south of eastern part of the sea.

Gradients of sea level in SMDT field are significantly higher than gradients in CMDT. This fact is evidence of higher velocities in the Rim current, than estimated earlier from altimetry data.

Synthetic mean dynamic topography reveals existence of many mesoscale features with anticyclonic vorticity on the periphery of the basin, which are not presented on the climatic field. In terms of dynamic topography they looked like zones with higher sea level (see Fig. 7). Most of them are already well-known (see Fig. 1) and discussed in previous studies (Korotaev et al., 2003).

Despite, both climatic and synthetic MDT reproduce the strongest anticyclone zone in the south-east of the Black Sea, corresponding to quasi-stationary Batumi gyre, on reconstructed MDT one can see other areas with strong mesoscale activity: there is a so-called Sevastopol “eddy” on the west of Crimea peninsula; Danube “eddy” in the north-west, Bosphorous in the south-west; Sakarya in the south-south-west; strong Synop and Kizilirmak on the south; Kerch on the north-east; Crimea on the north of the Black Sea (see Fig. 1). Also SMDT reveals strong anticyclone area near city Ordu with center in 38° E, 41.5° N in the south-south-east part of the Black Sea. We should say here that all mentioned above “eddies” are not real stationary anticyclone gyres, but areas with dominant anticyclone vorticity in time-averaged circulation. All these results demonstrate that estimated synthetic mean dynamic topography resolves mesoscale processes in the Black Sea better then climatic MDT.

6 Validation

6.1 Validation with dynamic heights

For validation purposes we use independent measurements of dynamic heights h_{dyn} from ODB of MHI for 2002–2009. This dataset was compared with measurements of full dynamic topography, computed as sum of along-track SLA and two different mean dynamic topographies (estimated synthetic and climatic) . The intervals of selection between two measurements were 25 km and 5 days. 78 independent quasi-synchronous dynamic heights were chosen for comparison.

Two datasets have to be transformed to be consistent before comparison. As it was explained in Sect. 4.2.1 , one needs to take into account contribution of eustatic factors of sea level change. In order to exclude influence of these factors on comparison we analyze arrays h_{is}, h_1 and h_2 defined as follows:

$$h = h_{is} - S_{t;} h_1 = H_{Synthetic} + h' - L; h_2 = H_{Climatic} + h' - L; \quad (17)$$

where L, S_t were defined in Sect. 4.2.1.

Statistical comparison showed that absolute dynamic topography, computed from altimetry data, is in a good agreement with in-situ measurements. Synthetic MDT is preferable for dynamic topography reconstruction compare to climatic MDT (Fig. 7). Correlation coefficients between in-situ and altimetry data are 0.78 and 0.73 for SMDT and CMDT,

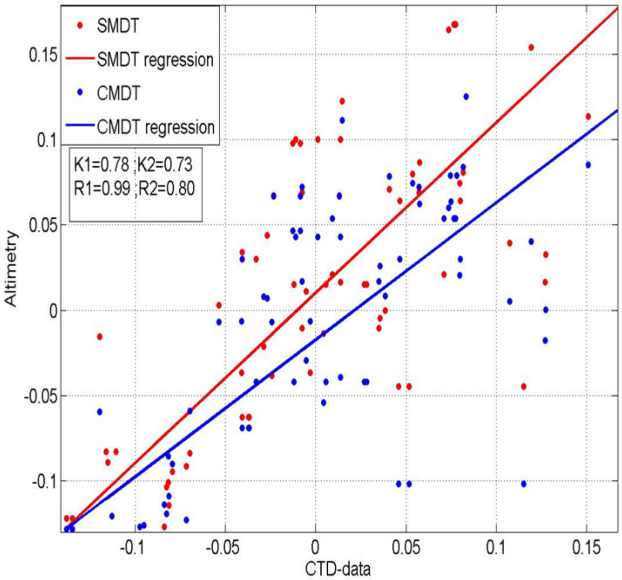

Fig. 8. Scattergram of transformed altimetric dynamic heights $h1, h2$, reconstructed with use of SMDT and CMDT, respectively, and in-situ dynamic heights h_{is}.

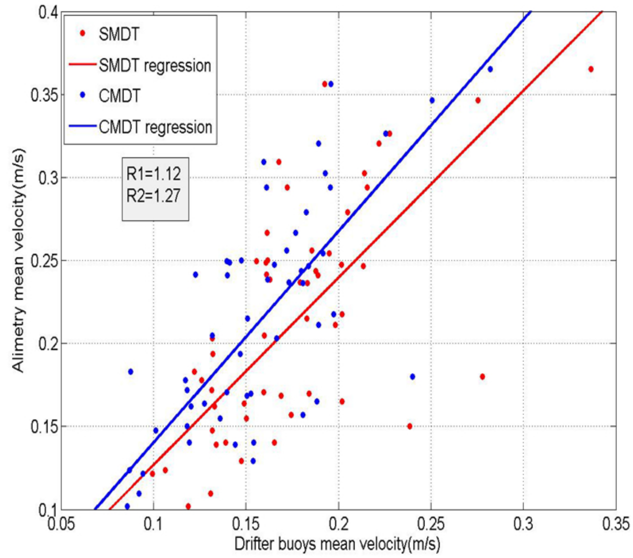

Fig. 9. Scattergram of mean amplitudes of drifting buoys and altimetric velocities, reconstructed using SMDT and CMDT.

respectively, RMS differences is 0.045 m and 0.046 m. The most noticeable improvement is seen, when analyzing regression slope, that is 0.996 (almost one) in the case of synthetic MDT and 0.802 for climatic MDT.

6.2 Validation with drifting buoys velocities

All available drifters data (more than 106 000 of velocity measurements for 1999–2008) were used for validation. Inertial oscillations were filtered out from buoys velocities by applying 17 h low-pass filter. Ekman wind-driven current component was not removed.

Altimetric velocities were computed from dynamic topography, defined as sum of MDT and SLA, through geostrophic balance equation. Here we use weekly maps of SLA on a 1/8° regular grid, computed from ERS1-2, Topex/Poseidon, Jason-1 and GFO missions for the same period (Le Traon et al., 1998). Altimetric velocities were linearly interpolated on a position and time moment of each drifter's measurement.

Statistical analysis was made for the whole dataset and for each drifter separately. Correlation coefficients for the whole dataset are almost the same for SMDT and CMDT and are equal to 0.73 for zonal velocity and 0.63 for meridional. For 34 from 54 drifters coefficients of correlation for zonal velocity is more than 0.7; for meridional more than 0.6. We should also mention that correlation coefficients had grown on 0.1–0.15 when we used 7-days smoothing of drifter velocities, that is consistent with altimetry maps temporal resolution, and became rather high – more than 0.8 for zonal component for 32 drifters of 54, and more than 0.7 for meridional component for 29 buoys.

Mean RMS differences are also almost the same for two MDT and are equal to 0.088 m s^{-1} and 0.09 m s^{-1} for SMDT and CMDT, respectively. Despite the drifter drogue is situated on the 15 m depth, Ekman drift may have a significant influence on drifter trajectories in situations with strong winds and weak geostrophic currents, and can be one of the reason for rather high values of RMS for some drifters.

The main advantage of synthetic mean dynamic topography is seen when analyzing mean amplitudes of drifters and altimetry velocities. Mean drifting buoys velocity is 0.185 m s^{-1}, which is consistent with Rim current velocity (Poulain et al., 2005). Average amplitude of altimetric velocities is equal to 0.160 m s^{-1} for SMDT and 0.141 m s^{-1} for CMDT. Differences of in-situ mean amplitudes and altimetric mean amplitudes is less for SMDT for the whole dataset and for almost each individual drifting buoy. The Fig. 8 below shows scattergram of mean amplitudes of buoys and altimetric velocities, reconstructed using two different MDT. Regression coefficient is 1.12 for synthetic MDT, which is much closer to one, compare to 1.27 for climatic MDT. We can make a conclusion that higher gradients of sea level in SMDT allow us to better reconstruct amplitudes of real velocity fields from altimetry data.

We should also mention that altimetry-derived velocities, computed with both MDT, are less than in-situ buoys measurements. This fact could be explained by a contribution of Ekman drift velocity in buoy measurements, which is not resolved from altimetry data.

7 Conclusions

Mean Dynamic Topography of the Black Sea for a period 1993–1999 was computed using in-situ measurements of drifting buoys velocities, hydrological data and sea level anomalies. Estimated field is necessary for reconstruction of dynamic topography and geostrophic velocity fields from altimetry measurements in this region. The concept of the used method is similar to one applied for a global ocean in (Rio and Hernandez, 2004), but it provides estimates of MDT, based on along-track altimetry data, without usage of the background field.

As a final result, we obtain Synthetic Mean Dynamic Topography of the Black Sea on 1/8° regular grid. Computed SMDT shows higher gradients of sea level and, therefore, higher current velocities in the Black Sea compared to climatic MDT. Besides, SMDT reveals existence of many mesoscale features on the periphery of the basin, which are not presented on the climatic field. Validation with independent hydrological observations and drifting buoys data shows improvements compare to CMDT, especially in terms of amplitudes.

Results of this work will be useful for a lot of oceanographic applications, for example, the heat and salt transport estimation, assimilating of altimetry data in numerical models, etc.

The "synthetic" method, applied in our work, allows one to improve MDT in future each time new in-situ measurements are available.

Acknowledgements. We would like to thanks Claire Dufau, (Collecte Localisation Satellites (CLS), France) for altimetry data providing and countenance during the work. This work was partly supported by EU FP6 ECOOP project.

Edited by: P. Oddo

References

Belokopytov, V. N.: Seasonal variability of thermohaline and hydrological and acoustic structure of the Black Sea water, Marine Hydrophys. J., 8, 12–23, 2003 (in Russian).

Belokopytov, V. N.: Ocean Station Tool: Software package for processing and analysis of oceanographic data, Proc. Intern. Marine Data and Information Conference – IMDIS, 31 May – 3 June, 67 pp., 2005.

Challenor, P. G., Read, J. F., Pollard, R. T., and Tokmakian, R. T.: Measuring Surface Currents in Drake Passage from Altimetry and Hydrography, J. Phys. Oceanogr., 26, 2748–2759, 1996.

Cheney, R., Miller, L., Agreen, R., Doyle, N., and Lillibridge, J.: TOPEX/POSEIDON: The 2-cm solution, J. Geophys. Res., 99, 24555–24563, 1994.

Demyshev, S. G. and Korotaev, G. K.: Numerical energy-balanced model of baroclinic currents in the ocean with bottom topography on the C-grid, in: Numerical models and results of intercalibration simulations in the Atlantic ocean, Moscow, 163–231, 1992 (in Russian).

Dobricic, S.: New mean dynamic topography of the Mediterranean calculated from assimilation system diagnostics, Geophys. Res. Lett., 32, L11606, doi:10.1029/2005GL022518, 2005.

Goryachkin, Y. N. and Ivanov, V. A.: The Black Sea Level: Past, Present and Future, MHI NASU, Sevastopol, 210 pp., 2006. (in Russian).

Hernandez, F., Schaeffer, P., Rio, M.-H., Tamagnan, D., and Le Traon, P.-Y.: Mean dynamic topography for satellite altimetry: Two approaches, from oceanographic data or satellite gravimetry, Journees lux-embourgeoises de geodynamique, 89, 19–25., 2001.

Knysh, V. V., Demyshev, S. G., and Korotaev, G. K.: Method of reconstructing the climatic seasonal circulation of the Black Sea on the basis of assimilation of hydrologic data in models, Marine Hydrophys. J., 2, 36–52, 2002 (in Russian).

Knysh, V. V., Korotaev, G. K., Moiseenko, V. A., Kubryakov, A. I., Belokopytov, V. N., and Inyushina, N. V.: Seasonal and interannual variability of Black Sea hydrophysical fields reconstructed from 1971–1993 reanalysis data, Izv. Atmos. Ocean. Phy., 47, 399–411, 2011.

Korotaev, G., Oguz, T., Nikiforov, A., and Koblinsky, C.: Seasonal, interannual, and mesoscale variability of the Black Sea upper layer circulation derived from altimeter data, J. Geophys. Res., 108, 3122, doi:10.1029/2002JC001508, 2003.

Le Provost, C. and Bremond, M.: Resolution needed for an adequate determination of the mean ocean circulation from altimetry and an improved geoid, Space Sci. Rev., 108, 163–178, 2002.

Le Traon, P.-Y. and Ogor, F.: ERS-1/2 orbit improvement using TOPEX/Poseidon: The 2-cm challenge, J. Geophys. Res., 103, 4, 8045–8057, 1998.

Le Traon, P.-Y., Nadal, F., and Ducet, N.: An improved mapping method of multisatellite altimeter data, J. Atmos. Ocean. Tech., 15, 522–533, 1998.

Maximenko, N., Niiler, P., Rio, M.-H., Melnichenko, O., Centurioni, L., Chambers, D., Zlotnicki, V., and Galperin, B: Mean dynamic topography of the ocean derived from satellite and drifting buoy data by three different techniques, J. Atmos. Oceanic Technol., 26, 1910–1919, 2009.

Motyzhov, S. V., Poulain, P.-M., Zatsepin, A. G., Fayos, C., Kostianoy, A. G., Maximenk, N. A., Poyarkov, S. G., Soloviev, D. M., and Stanichny, S. V.: DBCP Technical Document Series World Meteorological Organization, Geneva, 17 ,116–128, 2000.

Ovchinnikov, I. M. and Titov, V. B.: Anticyclonic vorticity of the currents in the coastal zone of the Black Sea, Doklady AN SSSR, 314, 1236–1239, 1990 (in Russian).

Poulain, P.-M., Barbanti, R., Motyzhev, S., and Zatsepin, A.: Statistical description of the Black Sea near-surface circulation using drifters in 1999–2003, Deep-Sea Res. Pt. I, 52, 12, 2250–2274, 2005.

Rio, M.-H. and Hernandez, F.: A mean dynamic topography computed over the world ocean from altimetry, in situ measurements, and a geoid model, J. Geophys. Res., 109, C12032, doi:10.1029/2003JC002226, 2004.

Rio, M.-H., Poulain, P.-M., Pascal, A., Mauri, E., Larnicol, G., and Santoleri, R.: A mean dynamic topography of the Mediterranean Sea computer from altimeter data, in situ measurements and a general circulation model, J. Mar. Sys., 65, 484–508, 2007.

Rio, M. H., Guinehut, S., and Larnicol, G.: New CNES-CLS09 global mean dynamic topography computed from the combination of GRACE data, altimetry, and in situ measurements, J. Geophys. Res., 116, C07018, doi:10.1029/2010JC006505, 2011.

Snaith, H. M., Alderson, S. G., Allen, J. T., and Guymer, T. H.: Monitoring the eastern Alboran Sea using combined altimetry and in situ data, Philos. T. R. Soc. Lon., 361, 1802, 65–70, 2003.

Zatsepin, A. G., Ginzburg, A. I., Kostianoy, A. G., Kremenetskiy, V. V., Krivosheya, V. G., Stanichny, S. V., and Poulain, P.-M.: Observations of Black Sea mesoscale eddies and associated horizontal mixing, J. Geophys. Res., 108, 3246, doi:10.1029/2002JC001390, 2003.