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Mean dynamic topography of the black sea, computed from altimetry, drifters measurements and hydrology data

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Abstract

Mean Dynamic Topography (MDT) is a crucial parameter for estimating dynamic topography, and, therefore, geostrophic circulation from satellite altimetry Sea Level Anomalies (SLA). In this work we use drifting buoy measurements, hydrographic profiles and SLA to reconstruct MDT of the Black Sea by "synthetic" method. Obtained mean dynamic topography shows higher gradients of sea level and resolves a lot of mesoscale processes in comparison to previous works, mostly based on climatic hydrological measurements.

Verification of dynamic topography determined by altimetry SLA and estimated MDT, with independent dynamic heights and drifter buoy velocities shows good quantitative and qualitative coincidence for all Black Sea basin and improvements compare to previous fields of MDT.

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

1 Introduction

Satellite altimetry is a unique instrument for ocean dynamic topography and geostrophic circulation estimation from remote sensing data. Moreover, for the first time in history it provides regular 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 unprecedented accuracy ~2 cm (Cheney et al., 1994). One of the main problems in using altimetry data for oceanology is determination of full dynamic topography (the sea level above the geoid) from altitude data. For this, first, altitude of altimeter is subtracted from the height of satellite orbit, which is counted from reference ellipsoid – rough approximation of Earth form. The result is 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 geoid G from SSH. Unfortunately, today, the shape of geoid is still unknown with accuracy required for oceanology. That is the reason why indirect method of determining dynamic topography is used. For this, mean SSH for the period 1993–1999 years is subtracted from each measurement of SSH. Geoid variations are supposed small with respect to level variations induced by ocean dynamic. Sea level anomalies h' (SLA) from SSH measurements may be described as:

$$h' = \mathrm{SSH} - <\mathrm{SSH}>_{1993-1999} = G + h - <G+h>_{1993-1999} = h - <h>_{1993-1999} \tag{1}$$

and full dynamic topography as:

$$h = h' + <h>_{1993-1999} \tag{2}$$

here $<>$ – mean time averaging, $<h>_{1993-1999}$ – is called mean dynamic topography (MDT).

For the Black Sea there is no MDT designed specially for altimetric measurements. Existing fields is based on climate hydrological data over 1954–2004 years (Belokopytov, 2003) and modeled dynamic heights, also over another time periods (Knysh et al., 2002). These fields can result in too smooth solutions and, moreover, different periods of used data could result in errors for determining dynamic topography.

One of the main tasks in the framework of project ECOOP was reconstruction of Mean Dynamic Topography for the Black Sea in order to improve quality of altimetry-estimated fields of dynamic topography and corresponding geostrophic velocities.

In our work we use the concept of so called "synthetic" methodic, which is based on combination of altimetric anomalies and in-situ data. This concept was already established for the world ocean (Rio and Hernandez, 2004) and Mediterranean Sea (Rio et al., 2007) and other areas and shows it's superiority over other methodics (Hernandez et al., 2001). We use drifting buoy velocity measurements and hydrographic profiles to compute a set of along-track synthetic estimates of MDT of the Black Sea and then extrapolate it on the whole basin. Drogue of drifter was centered at 15 m depth. These buoys were constructed to reduce wind slippage and Stokes drift so that they closely follow the currents at their drogues depth.

2 Data and methods

2.1 "Syntethic" method

The core idea of "synthetic" method is based on the definition of sea level anomaly. As SLA is the difference between dynamic topography and MDT, we can determine "synthetic" estimate $H(r)$ of MDT as difference between quasi-synchronous in-situ measurement of full dynamic signal $h_{\text{is}}(t,r)$ and altimetric sea level anomaly $h'(t,r)$ (Rio and Hernandez, 2004):

$$h_{\text{is}}(t,r) - h'(t,r) = H(r) \tag{3}$$

One can also use in-situ velocity measurements $u_{\text{is}}(r,t), v_{\text{is}}(r,t)$ and velocity anomalies *u'(r,t), v'(r,t)* computed from SLA through geostrophic equations to estimate mean synthetic velocities *U(r), V(r)*:

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

$$u_{\text{is}}(t,r) - u'(t,r) = U(r) \tag{4}$$

Mean velocities allow us to compute gradients of MDT as

$$U(r) = -\frac{g}{f}\frac{\partial H(r)}{\partial y}; \quad V(r) = \frac{g}{f}\frac{\partial H(r)}{\partial x}, \tag{5}$$

Here f is coriolis parameter for the Black Sea, g – gravitational acceleration. After integrating one can receive "synthetic" estimations of MDT.

One of the main advantages of this method is ability of using all available in-situ data from 1991 year to our days to determine MDT estimates. Future measurements may be used to improve MDT and, therefore, to receive more accurate dynamic topography from altimetry with required resolution.

2.2 Data

2.2.1 Altimetry

In this work we used along-track sea level anomalies from Topex/Poseidon mission for the period from April 1993 to December 2005. Data was received from CLS (AVISO) (http://www.aviso.oceanobs.com). All standard correction was applied (Le Traon and Ogor, 1998). These data were specially designed in CLS for Black Sea region with 40 km filtering distance cut-off and sampling (1 point over 3 is conserved). Obtained SLA measurements have precision about 3–4 cm, temporal resolution 10-days and spatial 7 km.

2.2.2 Drifting buoys

Data consist 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 tracked by the Argos Data Collection and Location System (DCLS) installed on NOAA polar-orbiting satellites. A temporal resolution of the data is 1–6 h. Total quantity of estimated location measurements is 103 000. Most of the drifters are captured by the Rim current, so the main part of measurements is on the periphery of the Sea.

2.2.3 Dynamic Heights

Hydrographic profiles of temperature and salinity were obtained from Oceanographic data bank of Marine Hydrophysical Institute (ODB of MHI) and include all data,

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collected for whole basin of the Black Sea for 1992–2003 years. Dynamic heights referenced to a depth 500 m were estimated from hydrographic profiles by dynamic method by the "Hydrologist" software (Belokopytov, 2005). Total array consist of 3100 measurements.

2.2.4 Climatic MDT (CMDT)

To compare our results on different stages we use mean dynamic sea level computed from numerical modeling with assimilation of climatic array of hydrological data averaged for period 1973–1992 years (Knysh et al., 2002). Black Sea dynamics is mainly described by the cyclonic Rim Current that is generated by wind circulation. That is why, the mean dynamic topography is higher on periphery and small in the center of Black Sea (Fig. 1).

3 Computation of synthetic MDT

3.1 Computation of along-track synthetic MDT from drifter measurements

3.1.1 Drifter data processing

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

$$\frac{d\mathbf{v}}{dt} + \mathbf{k} \times f\mathbf{v} = -g\nabla h + \frac{1}{\rho}\frac{d\tau}{\partial z} + A \tag{6}$$

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

In order to estimate geostrophic velocity from drifters data inertial oscillations were filtered out by applying 17-hours low-pass filter.

The Ekman component were filtered out, by using an assumption that only geostrophic part of velocity exist for drifters measurements during weak winds ($<5\,\mathrm{m\,s^{-1}}$). This assumption is reasonable for buoys with 15-m drogue depth. In this work we use NCEP (National Centers for Environmental Prediction) 1×1 geographical degree data on 6-h regular grid for 1998–2005 years (http://oceandata.sci.gsfc.nasa.gov/Ancillary/Meterological/).

3.1.2 Reconstruction of along-track synthetic MDT

First, a set of geostrophic velocities anomalies u', v' were computed from SLA data through geostrophic balance equation. Along-track anomalies allow to determine only velocities projection normal to direction of track. Then quasi-synchronous measurements of buoys velocities were chosen and project on the same direction. The intervals of selection were 25 km and 5 days. These values approximately correspond to scales of synoptical spatial and temporal variability of processes in the Black Sea.

Then a set of mean synthetic velocities U, V, consisted of 755 values, was computed by subtraction using Eq. (4). Estimates of MDT were done for all points of altimetric tracks, with existing quasi-synchronous measurements of buoys velocities and SLA. If there have been more then one estimate of MDT in one point, all estimates were averaged.

Synthetic velocities were approximated along track by polynomials of degree 5–7. Figure 2 illustrates the synthetic velocities and its approximations along tracks No. 83 and No. 220 and, for comparison, velocities, computed from climatic MDT. Computed polynomials were integrated to estimate along-track mean dynamic topography (Fig. 3).

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

Let sea level for each cross point is for track number i is l_{ij} and for track j is l_{ji}, respectively. The main idea is found such C_j that sum D

$$D = \sum_{i}^{N} S_i = \sum_{i}^{N} \sum_{j}^{N} ((l_{ij} + C_i) - (l_{ji} + C_j)) \tag{7}$$

is minimal. For this on the zero step of the algorithm all C_j were equal to mean track j sea level. Then on next step k differences S_i were obtained and number M of track with maximum S were determined. Constant C_M was computed as

$$C_M^k = C_M^{k-1} - < S_{1..N}^{k-1} >_i \tag{8}$$

Received set of coefficients $C_{1..M..N}$ was used on the next step $k+1$. On step $k = 1000$ values of sum S_i and D became less than 10^{-5} m.

Finally mean dynamic topography along track of Topex/Poseidon was computed from measurements of the drifter buoys velocities (Fig. 4)

3.2 Computation of along-track synthetic MDT from dynamic heights

3.2.1 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 total amount of water in the basin. So in fact, dynamic heights is the difference between full dynamic topography and water balance W

$$h_{\text{is}} = h - W \tag{9}$$

In order to determine this part of signal we compute water balance of the Black Sea by spatially averaging all the altimetric SLA and then interpolating it on 10-days regular

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grid $L(t) = \langle h'(r,t) \rangle_r$. Computed array(fig) describes total change of water amount in the basin W plus steric effect S_t.

$$L = W + S_t, \tag{10}$$

Amplitudes of steric effect in the Black Sea are small, about 4 cm, and have well-defined annual period (Goryachkin and Ivanov, 2009). We use simple approximation by sinusoid with amplitude 4 cm, period 1 year and minimum on 28 February to subtract steric effect in our work:

$$S_t = 0.04 \times \sin\left(\frac{2 \times \prod \times (N_\mathrm{d} - 28)}{365} - \frac{\prod}{2}\right) \tag{11}$$

where N_d is number of the day in the year Then, dynamic heights were processed as follows:

$$h = h_\mathrm{is} + L - S_t \tag{12}$$

to be consistent with altimetric measurements.

3.2.2 Reconstruction of along-track synthetic MDT

Synthethic MDT estimates were determined as differences between quasi-synchronous measurements of full dynamic topography generated from hydrologic measurements and altimetric SLA (the intervals of selection were the same as for drifting buoys 25 km and 5 days). Then they were approximated by polynomials of 5–7 degrees. The result (Fig. 5) is along-track synthetic MDT. Unfortunately, time period after 1992 year characterized by small available amount of hydrological observations, that is why MDT based on this data was reconstructed only for few tracks.

4 Results

Computed from drifters and dynamic heights along-track estimates of synthetic MDT were averaged and interpolated (extrapolated) on the whole Black Sea basin. The result is synthetic mean dynamic topography (SMDT) with 1/8° resolution shown on Fig. 6. Reconstructed MDT, as well as the climatic MDT show cyclonic circulation of the Black Sea with higher sea level on periphery and lower in the center. But synthetic mean dynamic topography reveals two separate cyclonic cells in contrast to one cyclonic cell with two cores in CMDT: one on the west and one on the east parts of the basin, which is consistent with modern studies about Black Sea. Besides, eastern cyclone has two cores on the west and south of eastern part of the sea.

The other main difference between synthetic MDT and climatic field is higher gradients of sea level that will result in higher current velocities of the sea.

Third important feature of constructed MDT is existence of a lot of mesoscale anticyclonic eddies situated between Rim current and coast of Black Sea. Most of them are already well-known and discussed in previous studies (Korotaev et al., 2003). Despite, both climatic and synthetic MDT reproduce strongest "Batumi" and "Sevastopol" eddies, on SMDT one can see also note the existence in SMDT of other related with coast line shape mesoscale features so called – Bosphorous, Kizilirmak, Sakarya, Synop and Trabzon eddies on the south of the Black Sea; Crimean anticyclone on the north; and Kali–Akra Eddy on the north-west coast. Strong anticyclonic area was detected near Kerch Strait. In the terms of sea level they look like areas with higher sea level. These results demonstrate that estimated mean dynamic topography resolves mesoscale processes in the Black Sea better then previous fields of MDT.

5 Validation

5.1 Dynamic heights

For validation purpose we use independent measurements of dynamic heights h_{dyn} from ODB of MHI for 2002–2009 years for different areas of Black Sea. These data were compared with measurements of full altimetry dynamic topography, computed as sum of along-track SLA and two different mean dynamic topographies (estimated

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synthetic and climatic). The intervals of selection between two measurements were 25 km and 5 days. Total amount of 78 quasi-synchronous dynamic heights were chosen.

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

$$h_{\text{is}} = h_{\text{dyn}} - S_t;$$

$$h_1 = \text{SMDT} + \text{SLA} - L;$$

$$h_2 = \text{CMDT} + \text{SLA} - L;$$

where L, S_t – defined in Sect. 3.2.1. Scattergram (Fig. 7) illustrate better coincidence of in-situ h and altimetric h_1, computed with usage of synthetic mean dynamic topography for all statistical quantities. Correlation is 0.78 and 0.73 with CMDT and SMDT, respectively, RMS differences is 0.045 m and 0.046 m. The most noticeable improvement is on regression slope, that is 0.996 (almost one) in case we use synthetic MDT to reconstruct dynamic topography and 0.802 for climatic MDT.

5.2 Drifting buoys velocities

All available drifters data (more than 106 000 of velocities measurements for 2001–2008 years) were used for validation. Altimetric velocities were computed from dynamic topography 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). For comparison, altimetric velocities were linearly interpolated on a position and time of each drifter's measurement. Inertial oscillations from drifter velocities were filtered out by applying 17-hours low-pass filter. No Ekman component were removed.

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Statistical analysis was made for each drifter separately. For 34 from 54 drifters coefficients of correlation for zonal of velocity is more than 0.7 and more than 0.6 for meridional. Mean correlation coefficient for all drifters are almost the same for SMDT and CMDT and are equal to 0.68 for zonal velocity and 0.61 for meridional. We should also mention that correlation coefficients 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 2 MDT and is equal to 0.088 m s^{-1} and 0.09 m s^{-1} for SMDT and CMDT, respectively. Besides, drifter drogue depth is situated on the 15 m depth, in cases with strong winds and small geostrophic currents Ekman drift may have a significant influence on drifter trajectories, and can be one a reason for rather high values of RMS for some drifters.

The main advantage of synthetic mean dynamic topography is seen when analyzing differences between drifters and altimetry mean velocities. Mean drifting buoys velocity is 0.199 m s^{-1}, which is consistent with Rim current velocity (Poulain et al., 2003). Average amplitude of altimetric velocities is equal to 0.168 m s^{-1} for SMDT and 0.146 m s^{-1} for CMDT. For each individual drifting buoy differences of in-situ mean amplitude and altimetric mean amplitude is less for SMDT. The Fig. 8 below shows scattergram of mean amplitudes of buoys velocities and altimetric one, 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 made a conclusion that synthetic mean dynamic topography with higher gradients of sea level better reconstructs real amplitudes of velocities in the Black Sea.

6 Conclusions

At the present work, Mean Dynamic Topography of the Black Sea for a period 1993–1999 years, was computed using in-situ measurements of drifting buoys velocities,

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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 methodic is similar to one applied for a global ocean in (Rio and Hernandez, 2004).

As a final result, we obtain Synthetic Mean Dynamic Topography for the Black Sea on 1/8° regular grid. Obtained SMDT was validated by using independent hydrological observations and all available drifting buoys data.

Intercomparison of SMDT and CMDT demonstrates SMDT better coincidence with in-situ data, especially in the terms of amplitudes.

Results of this work will be useful for a lot of oceanographic applications, for example, the oceanic transport estimation or assimilating of altimetry data in circulation models etc.

"Synthetic" method allow to improve mean dynamic topography in future when there will appear new in-situ measurements.

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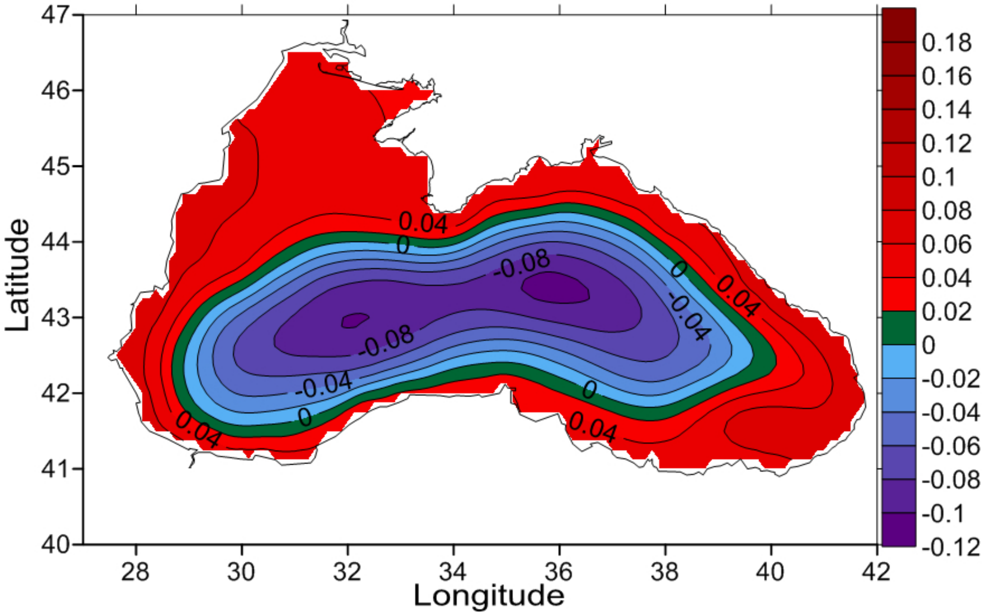

Fig. 1. Mean topography (averaged for 1973–1992 years) computed from dynamic model with assimilation of climatic data (Knysh et al., 2002).

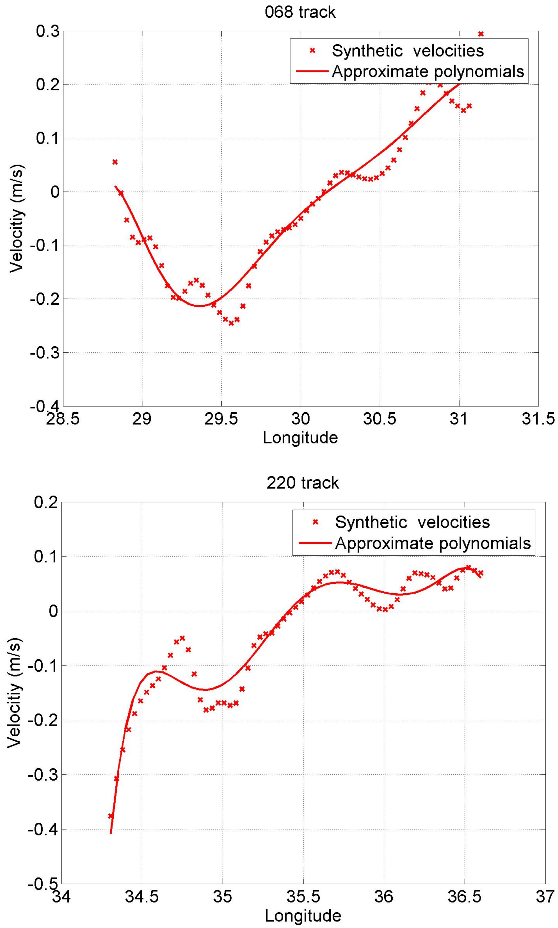

Fig. 2. Synthetic velocities computed in Black Sea along tracks No. 68 and No. 220 of Topex/Poseidon from drifters measurements and SLA and their polynomial approximations.

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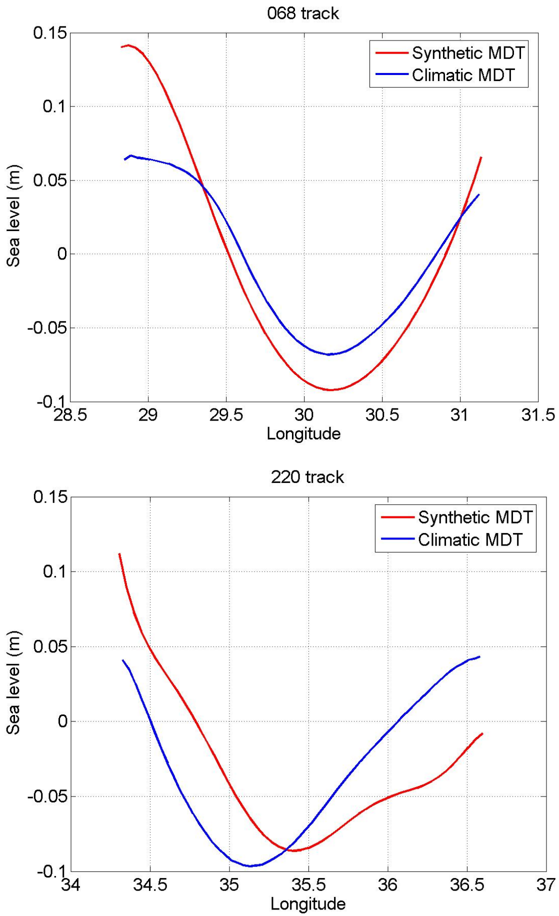

Fig. 3. Synthetic MDT computed in Black Sea along tracks No. 83 and No. 220 of Topex/Poseidon from drifters measurements and SLA and, for comparison, climatic MDT along the same tracks.

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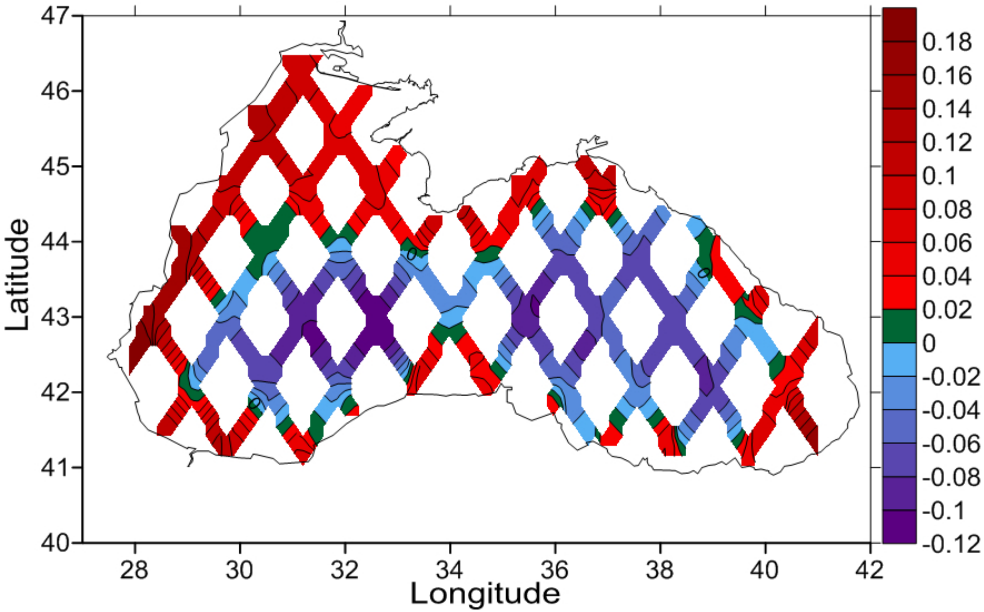

Fig. 4. Along-track mean dynamic topography computed from SLA and drifting buoy measurements.

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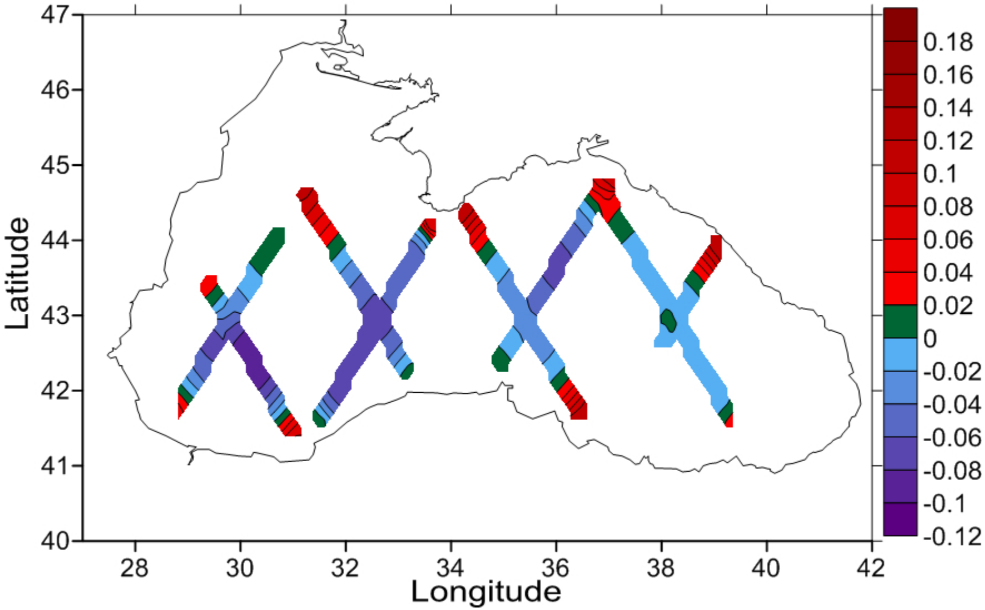

Fig. 5. Along-track mean dynamic topography computed from SLA and hydrographic profiles.

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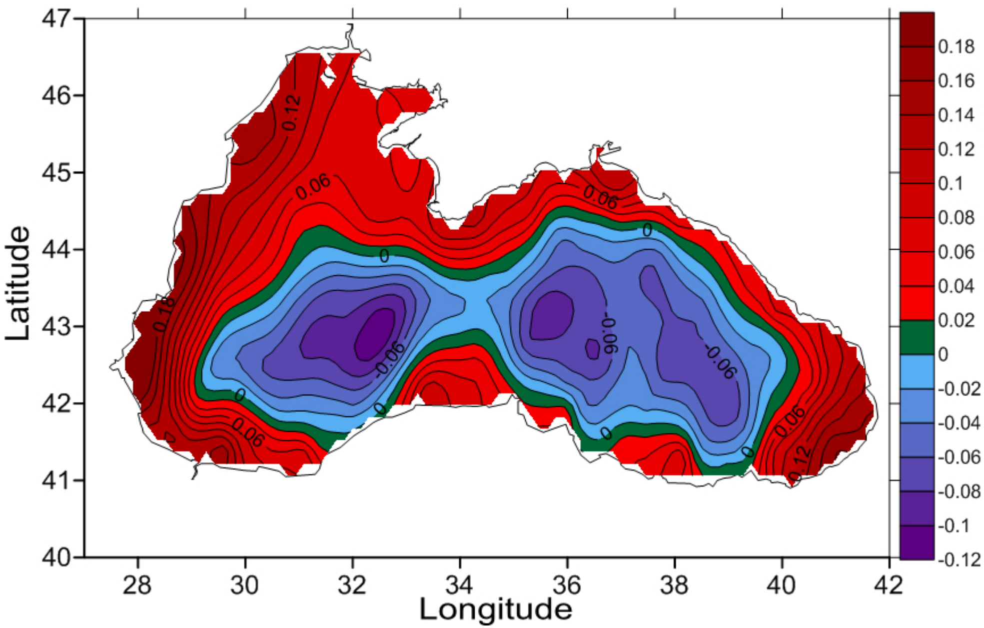

Fig. 6. Synthetic Mean Dynamic Topography computed in this paper.

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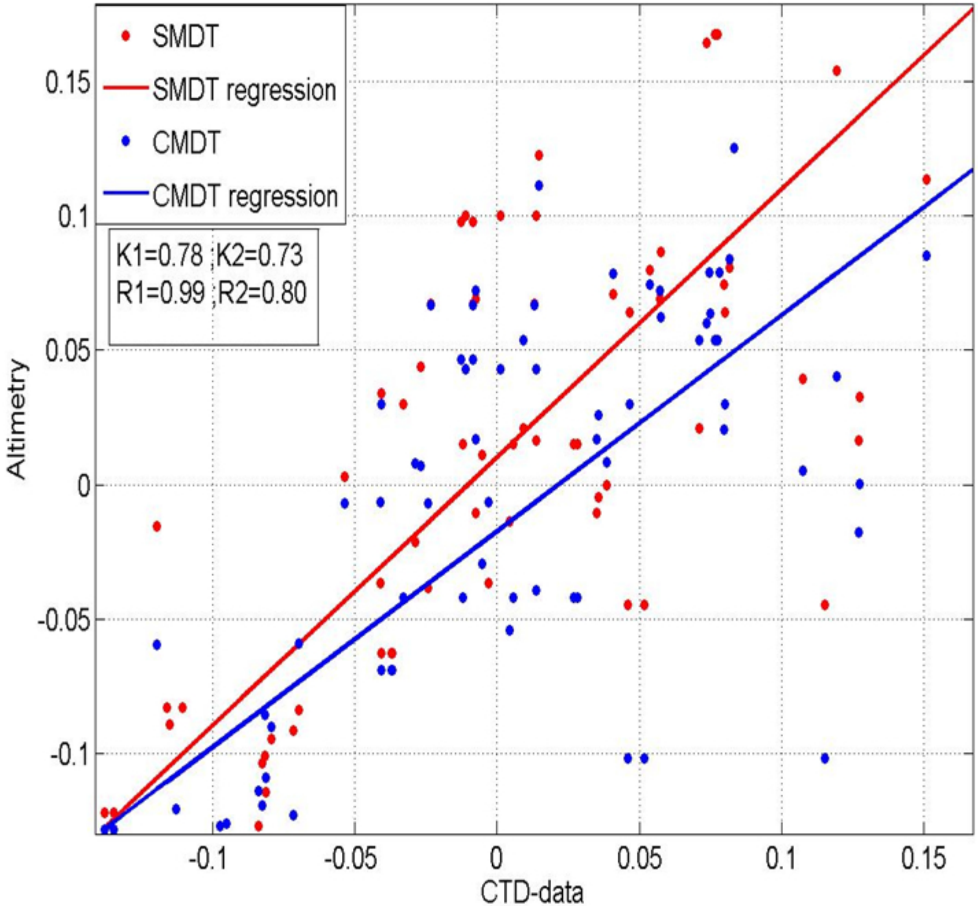

Fig. 7. Scattergram of transformed altimetric dynamic heights h_1, h_2, reconstructed with use of SMDT and CMDT, respectively, and in-situ dynamic heights h_{is}.

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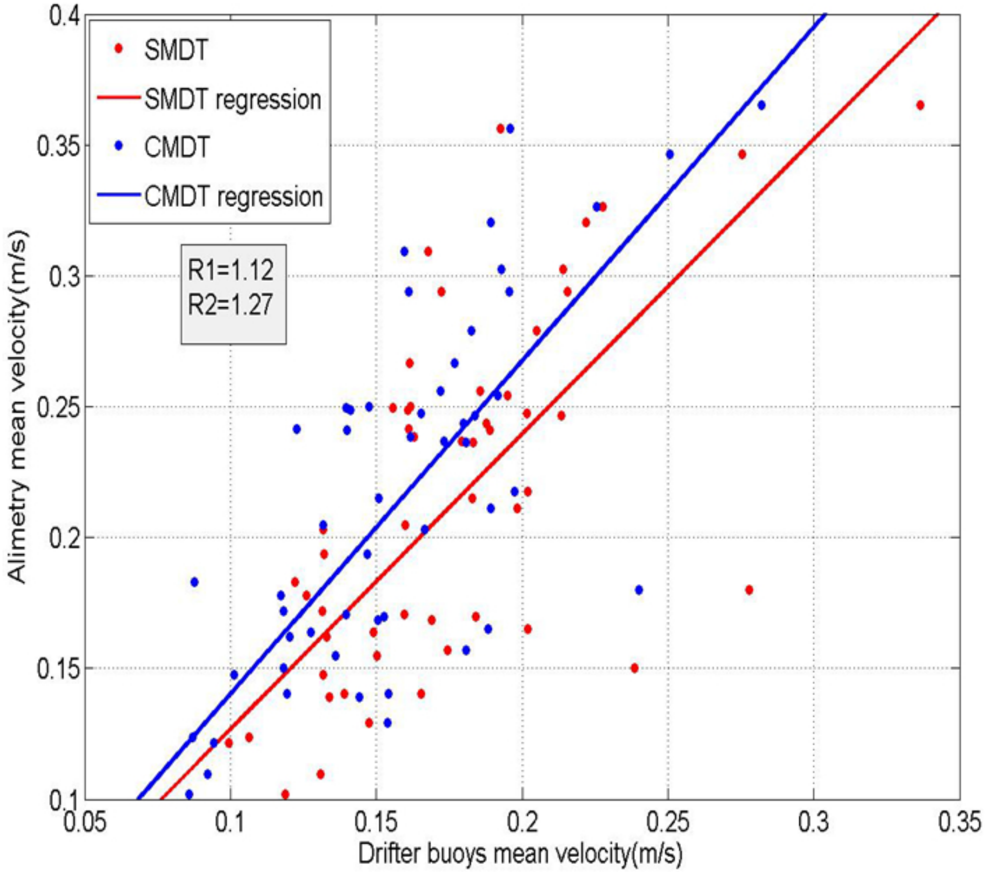

Fig. 8. Scattergram of mean amplitudes of drifting buoys and altimetric velocities, reconstructed using SMDT and CMDT.

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