Original article

Assessment of the Black Sea Steric Level Variability: New Approaches and Prospects for the Use of Satellite Information

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Abstract

Based on satellite altimetry and gravimetric data, the time series of steric level oscillations averaged over the Black Sea for 2002–2016 is reconstructed. The steric sea level oscillations were calculated as the difference between the total sea level measured by altimeters and the manometric (barystatic) component determined from gravimetric measurements GRACE. A good agreement was obtained between the steric component of the sea level and the estimates obtained from archival hydrological data and Argo floats. The maxima of the range of the seasonal variation of the steric component of the level are noted in the areas with maximum seasonal vertical displacements of the main pycnocline. Estimates of the steric level seasonal cycle were obtained, the range of oscillations was up to 12 cm. The minimum is reached in the winter period (March), and the maximum – in the summer period (August). It is noted that the seasonal cycle of the manometric component of the sea level is in good agreement with the seasonal cycle of the freshwater balance of the Black Sea constructed according to climatic hydrometeorological data. The estimate of the linear trend of the reconstructed steric oscillations is –0.6 ± 0.2 cm/year. This indicates that, despite the positive trend in water temperature in the main pycnocline and desalination of the surface layer, the contribution of the modern increase in salinity in all layers of the sea to the changes in water density in the Black Sea generally predominates.

Keywords: Black Sea, steric level, manometric level, water balance, altimetry, gravimetry, GRACE, climate

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Оценка изменчивости стерического уровня Черного моря: новые подходы и перспективы использования спутниковой информации

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Аннотация
На основе спутниковых альтиметрических и гравиметрических данных реконструирован временной ряд стерических колебаний уровня, осредненных по акватории Черного моря за 2002–2016 гг. Стерические колебания уровня моря рассчитывались как разница между общим уровнем, измеряемым альтиметрами, и манометрической (баристатической) составляющей, определяемой по гравиметрическим измерениям *GRACE*. Получено хорошее соответствие реконструированной стерической компоненты уровня моря оценкам, полученным по архивным гидрологическим данным и данным буев Арго. Максимумы размаха сезонного хода стерической составляющей уровня отмечаются в районах с максимальными сезонными вертикальными смещениями основного пикноклина. Получены оценки сезонного цикла стерического уровня с размахом колебаний до 12 см, минимум отмечается в зимний период (март), максимум – в летний период (август). Кроме того, выявлено хорошее соответствие сезонного хода манометрической компоненты уровня и пресноводного баланса Черного моря, рассчитанного по климатическим гидрометеорологическим данным. Оценка коэффициента линейного тренда реконструированных стерических колебаний составила –0.6±0.2 см/год. Это свидетельствует о том, что, несмотря на положительный тренд температуры воды в основном пикноклине и распреснение поверхностного слоя, вклад современного роста солености во всех слоях моря в изменения плотности воды в Черном море в целом преобладает.

Ключевые слова: Черное море, стерический уровень, манометрический уровень, водный баланс, альтиметрия, гравиметрия, *GRACE*, климат

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Introduction

The modern advanced stage of remote sensing development allows to realize continuous sea level monitoring, which permits to restore its steric component, which characterizes integral changes in the heat and salts content through the entire water column.

The steric oscillations of sea level H_{ster} are caused by changes in the density of sea water if the mass of a water column does not change. The manometric changes in a sea level H_{man} are caused by changes in the mass of a water column under the assumption that the sea water density remains unchanged [1, 2]. The steric and manometric components add up to give the resulting sea level [3]:

$$H = H_{\text{ster}} + H_{\text{man}}. \quad (1)$$

The resulting sea level is determined using tide-gauge or altimetry measurements. Satellite gravimetric measurements obtained as part of the Gravity Recovery and Climate Experiment (GRACE) project are used for the manometric component. The steric component can be estimated directly from CTD data or from satellite data using relation (1).

In seas that have limited connection with the World Ocean, such as the Black Sea, regional features of climate variability and their links to global changes are most pronounced. The lowest values of long-term oscillations in the steric level of the Black Sea (up to –6 cm), estimated from archival hydrological CTD data, are observed in the central part of the basin. Near the coast, the steric component of the level increases, the maximum occurs in the southeast of the sea (6–7 cm). The largest seasonal range of steric level oscillations is typical for the central (up to 20 cm) and southeastern (up to 16 cm) regions; the smallest range values are observed in the center of the eastern part of the Black Sea [4]. The contribution of the temperature component to steric oscillations of sea level is predominant, reaching the maximum in coastal areas (up to 90 %) [4].

The spatiotemporal steric oscillations variability in the Black Sea is directly related to their specific thermohaline structure, characterized by low surface salinity and sharp haline stratification. In the 0–50 m surface layer of the sea, water temperature brings in a more significant contribution to changes in density. With increasing depth, the spatial contribution of salinity to water density in the 50–300 m layer is comparable to the contribution of spatial temperature variability.

A distinctive feature of the hydrological structure of the Black Sea, which affects the vertical stratification of waters, is the presence of a cold intermediate layer (CIL), located at depths of 50–100 m. In the layer between the core and the lower boundary of the CIL, compensation occurs for the thermosteric and halosteric components of the sea water density. The maximum correlation of these characteristics is located at a depth of 250 m [5]. According to the Argo floats CTD data, salinity anomalies in the CIL were quite irregular in the period before 2010. Considerable temperature variations were also observed in the CIL. After 2010, there was a weak renewal of the CIL waters and an almost complete disappearance of the layer after 2014 [5].

There are various estimates of changes in the thermohaline characteristics of the Black Sea on the scale of interannual and interdecadal variability. Thus, according to the retrospective analysis [6], a long-term negative trend in water temperature was revealed in the 0–100 m layer, and a positive trend was revealed in the layer deeper than 200 m. In 1951–1995, salinity decreased in the upper layer of 0–50 m and increased in deeper layers, which enhanced the density stratification of waters.

According to [7], the decadal variability of temperature and salinity in the upper 0–50 m layer of the sea has a quasi-periodic nature, while in the winter and summer seasons temperature fluctuations differ in amplitude and phase characteristics. In addition, in paper [6], a negative linear trend of salinity in the 0–50 m layer is defined, which is consistent with the positive trend of the freshwater balance in the Black Sea. In recent decades, it was an increase in salinity and temperature in the layer of 75–300 m at the average rate of 0.05 PSU/10 years and 0.02 °C/10 years. The change in the sign of trends in interdecadal salinity variability occurs in the upper part of the pycnocline between the depths of 50 and 75 m. Since 2010, an increase in salinity has also been observed in the surface layer, which is explained by a decrease of the Azov-Black Sea basin freshwater balance.

In [8], three characteristic periods were defined based on the results of numerical modeling: 1960–1970, 1970–1995 and 1995–2015, characterized by different circulation states: weakening (1st period) and increasing intensity of cyclonic circulation (2nd and 3rd periods). An increase in temperature and salinity is observed in the permanent pycnocline layer, which is consistent with the results of [6, 7].

The aim of the work is to estimate the seasonal and interannual variability of the thermohaline structure of the Black Sea using the steric component of the sea level as an indicator. The novelty is in the use of the steric level for these purposes, which was reconstructed from satellite altimetric and gravimetric data on the Black Sea level, and in validation of the obtained assessments based on independent calculations from hydrological data.

Observational data

The following data were used in the work:

– oceanographic data archive of Marine Hydrophysical Institute (available at: http://bod-mhi.ru/ru/index.shtml) for a long period of 1923–2015 [9];

– Argo profiling floats data array for 2006–2015 provided by Copernicus Marine Environment Monitoring Service (CMEMS) (https://doi.org/10.48670/moi-00033);

– mean monthly values of gravimetric measurements of GRACE Release 06, GSFC v1.0, 1° × 1° grid (https://earth.gsfc.nasa.gov/geo/data/grace-mascons) for 2002–2016;

– mean monthly values of sea level anomalies from CMEMS altimetry data, grid 0.125° × 0.125°, product identifier SEALEVEL_BS_PHY_L4_REP_OBSERVATIONS_008_04

Research methods

In calculating the steric sea level values from sea water density profiles, a reanalysis of thermohaline fields of the Black Sea was used [9]. The thermosteric H_T and the halosteric H_S components of the steric sea level H_{ster} were calculated as follows:

$$H_{ster} = H_T + H_S,$$

$$H_T = -\int_{z_1}^{z_2} \alpha(z) T'(z) dz, \qquad H_S = \int_{z_1}^{z_2} \beta(z) S'(z) dz, \tag{2}$$

$$T'(z) = T(z) - \overline{T}, \qquad S'(z) = S(z) - \overline{S},$$

$$\alpha(z) = \frac{1}{\rho_0} \frac{\partial \rho(z)}{\partial T}, \qquad \beta(z) = \frac{1}{\rho_0} \frac{\partial \rho(z)}{\partial S},$$

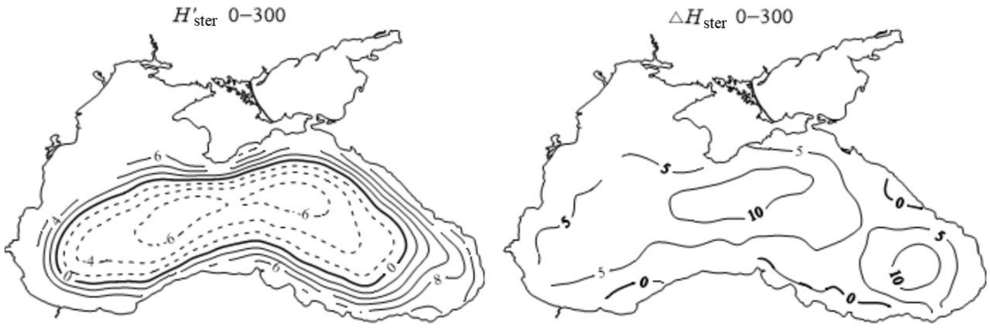
where H_{ster} is the steric level; H_T is the thermosteric level component; H_S is the halosteric level component; and $\overline{T}$, $\overline{S}$ are taken as climatic mean values of temperature and salinity of the Black Sea water. The thermal expansion coefficient α and the salinity compression coefficient β were calculated based on the Gibbs Seawater Oceanographic Toolbox TEOS-10 software package (http://www.teos-10.org/) using a polynomial expression as a function of absolute salinity, conservative temperature and pressure [10]. Since α and β do not change sign over a wide range of temperatures, salinity and pressure, with increasing temperature due to thermal expansion H_T increases, and with increasing salinity the halosteric component of the steric level H_S decreases due to salinity compression.

Results

Using the archive of long-term hydrological data (http://bod-mhi.ru/ru/index.shtml) for 1923–2015 [9] and formula (2) the steric level and its thermosteric and halosteric components were calculated.

A map of the mean annual values of the steric level of the Black Sea is presented in Fig. 1, *a*. The steric level is maximal at the periphery of the sea, where less saline and generally warmer waters predominate. The difference in steric level between the periphery and the central part of the sea is about 15 cm. The spatial distribution does not change qualitatively throughout the year, the level difference decreases from winter to summer.

For the deep-water part of the sea, the difference in steric level values between the maximum in August and the minimum in March can serve as a simple assessment of its seasonal variability. When approaching the continental slope, this difference decreases and even changes the sign (Fig. 1, *b*). This is due not so much to a decrease in the seasonal cycle amplitude, but to changes in its phase, which is explained by the peculiarities of oceanographic processes in the coastal zone.

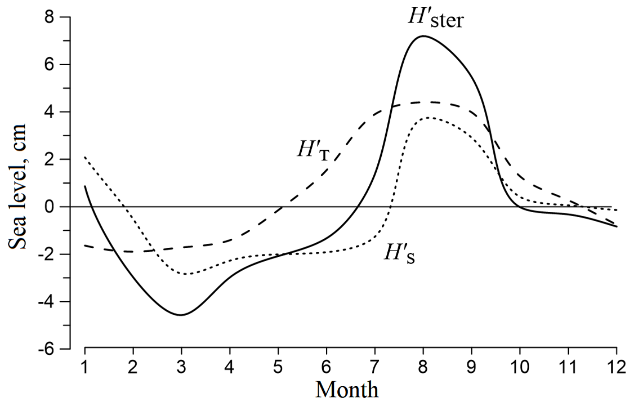


F i g . 1 . Mean annual values (cm) of the steric level of the Black Sea H'_{ster} (deviations from the basin mean) in the 0–300 m layer (*a*); difference values of the steric level in August and March, ΔH_{ster} (cm) in the 0–300 m layer (*b*)

Seasonal oscillations of the thermosteric and halosteric level components, which directly reflect changes in the total heat and salt contents of the layer, are almost synchronous in the deep-water part of the sea (Fig. 2). This ensures a stable seasonal cycle of the steric level over most of the sea area, corresponding to the mean seasonal cycle of *T*,*S* ratios in the upper layer of 0–50 m (Fig. 3, *a*). The steric level anomaly is positive from July to October, and it reaches a maximum of 7 cm in August. Moreover, the contribution of the thermosteric component to seasonal variability during this period exceeds the contribution of the halosteric component. In January, H_{ster} is also positive, but with a predominant contribution from the halosteric component (Fig. 2). The steric level becomes negative from February to June, reaching a minimum (–4.5 cm) in March; the contribution of the halosteric component predominates from February to May (Fig. 2).

A comparison of the mean annual values of steric sea level (deviations from the mean for the basin) in the layer of 0–50 m (Fig. 3, *a*) and in the layer of 50–300 m (Fig. 3, *b*) shows that the spatial structure of the distribution of mean long-term values in these layers has a qualitative correspondence, despite positive and negative decadal trends in temperature and salinity in the upper layer [6–8].

In the coastal zone, the relationship between the phases of the seasonal cycle of H_T and H_S can have significant regional differences, which depends on two main factors. The first of them is the spatiotemporal heterogeneity of river runoff and atmospheric precipitation, which affects the seasonal cycle of the steric level in the upper layer of the sea (Fig. 3, *c*). The Dnieper, Southern Bug, Dniester, and Danube rivers flow into the western part of the sea, generally providing more than 80 % of the river runoff into the Black Sea. The influx of the Azov Sea waters with low salinity through the Kerch Strait is also a factor in the desalination of surface waters in the central and western parts of the sea.

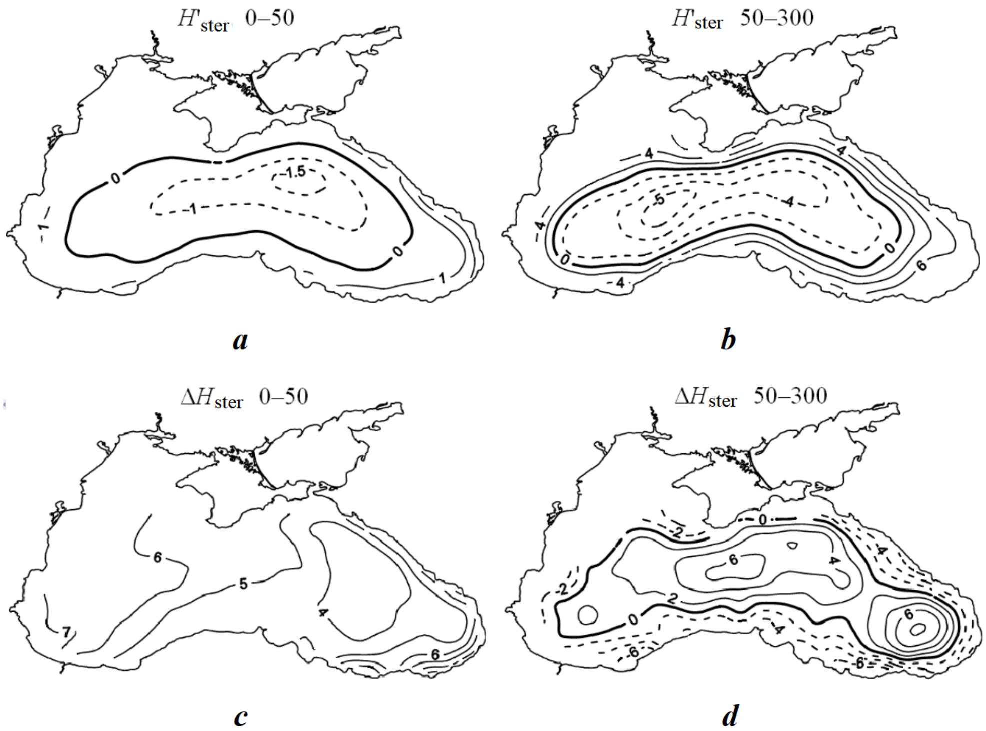


F i g . 2 . Seasonal cycle of the mean monthly anomalies (cm) of the steric sea level H'_{ster}, thermosteric H'_T and halosteric H'_s components in the central part of the Black Sea (deviations from the mean values for the year)

Taken together, this manifests itself in an increase in the steric level by more than 5 cm in the western part of the sea (Fig. 3, *c*). The second factor is the general circulation of the sea, which affects the thermohaline structure of waters in the layer of the main pycnocline through vertical movements. The maximum difference in steric level values, reaching 6 cm, occurs at the centers of cyclonic gyres and the Batumi anticyclone (Fig. 3, *d*).

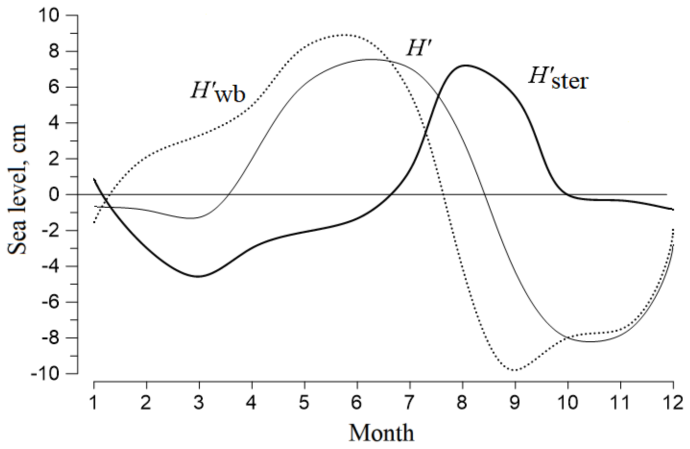
The results of calculations of the steric level oscillations make it possible to indirectly estimate the basin water balance as the difference between the resulting and steric levels. Fig. 4 presents such an assessment based on the steric level data in the central part of the sea and sea level measurements at coastal hydrometeorological stations (mean values from Sevastopol to Batumi). The assessment of the sea level component due to water inflow/outflow H_{wb} corresponds qualitatively to the conventional estimates of the Black Sea water balance [11]: the maximum occurs in May–June, the minimum occurs in September–October. It should be noted that comparison of the sea level measured in the coastal zone with the steric level in the deep sea is not entirely correct. As mentioned above, steric oscillations on the periphery of the sea have their own regional characteristics, so it seems more promising to use mean altimetry data over the entire basin as the resulting sea level [12].

Traditionally, sea level measurements are carried out at coastal tide-gauges (water level stations), unevenly distributed along the Black Sea coast.

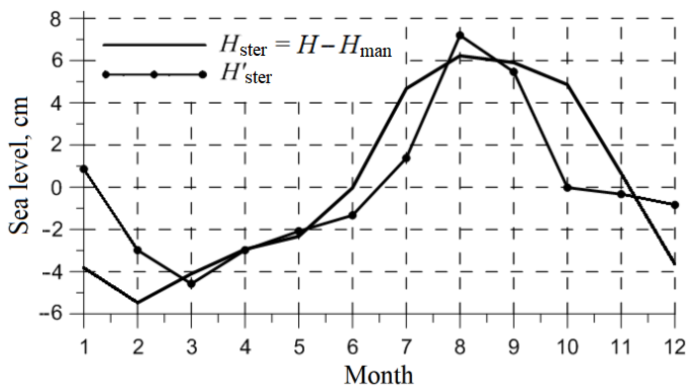


F i g . 3 . Mean annual values (cm) of the steric sea level (deviations from the basin mean) in the 0–50 m layer (*a*) and in the 50–300 m layer (*b*); the seasonal cycle (cm) of steric sea level as the difference in values in August and March for the 0–50 m layer (*c*) and the 50–300 m layer (*d*)

Satellite altimeter data are currently used to study sea level variability throughout the basin. According to altimetry data, an increase in the Black Sea level was observed from January 1993 to May 2017 at a mean rate of 2.5 ± 0.5 mm/year [12] against the background of fairly strong interannual variability. In addition, with the launch of a satellite within the framework of the GRACE project in 2002, it became possible to evaluate the contribution of the sea level manometric component H_{man} [12]. The GRACE data are in fairly good agreement with data on the ocean variability and can be used to assess the freshwater balance of the Black Sea and reconstruct the steric level of the Black Sea based on relation (1). To calculate steric oscillations of the Black Sea level based on relation (1) and estimates of their seasonal and interannual variability, satellite altimetry data H and GRACE RL06 H_{man} data for 2002–2016 were used [3, 13]. As a result, the seasonal cycle of the steric sea level H_{ster}, reconstructed from satellite data, was calculated, which corresponds quite well to the seasonal cycle of the Black Sea steric level H'_{ster}, calculated from archival hydrological CTD data (Fig. 5).



F i g . 4 . Seasonal cycle of the mean monthly values of the steric sea level H'_{ster}, and the sea level according to the tide-gauge measurements at coastal stations H' and sea level component due to the water balance H'_{wb} as difference between H' and H'_{ster}



F i g . 5 . Seasonal cycle of the mean monthly values of the steric sea level H'_{ster} according to hydrological observations and the steric sea level according to the altimetry data H and GRACE H_{man} as estimates of the $H_{ster} = H – H_{man}$

The plot of the reconstructed steric level has a smoother shape in the period from June to November, the maximum in August coincides in time with the maximum of the steric level H'_{ster} according to hydrological observations, and the minimum in the seasonal cycle occurs a month earlier than H'_{ster} – in February (Fig. 5). The seasonal cycle of the manometric level according to GRACE data, averaged over the entire sea area, gives more adequate estimates of the water balance component of the sea level in comparison with the preliminary assessment of H_{wb} based on coastal data (see Fig. 4 and 6). The H_{wb} graph has a maximum in June, a month later than H_{man}, and a minimum in September, which coincides with H_{man}; the values of their amplitudes are close (see Fig. 4 and 6). The maxima of the seasonal cycle of both plots in Fig. 6 coincide in April – May, and the minima for the freshwater balance according to the climate data falls on August [11], and for the manometric level H_{man} – on September (a month later) (Fig. 6). This is apparently due to the fact that the seasonal cycle of H_{man} according to GRACE data was averaged for 2002–2016 and actually belongs to a different climatic period. In addition, differences in the phase and amplitude of the seasonal cycle of H_{man} and the freshwater balance are due to the fact that variations in the water balance of the sea are influenced not only by its freshwater balance (rivers, precipitation, evaporation), but also by water exchange through the straits (Fig. 6).

The sea level according to the altimetry data H and the manometric component of sea level H_{man} according to GRACE RL06 GFSC data, averaged over the Black Sea, are characterized by significant interannual variability (Fig. 7). The maxima and minima of level oscillations and its manometric component coincide in phase, and the difference in their amplitudes gives the steric component of the sea level (Fig. 7, 8).

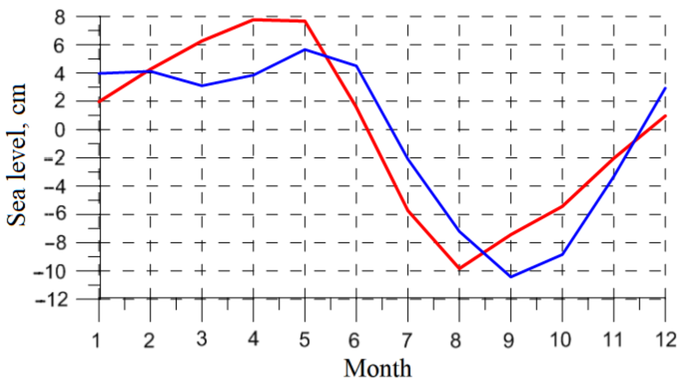
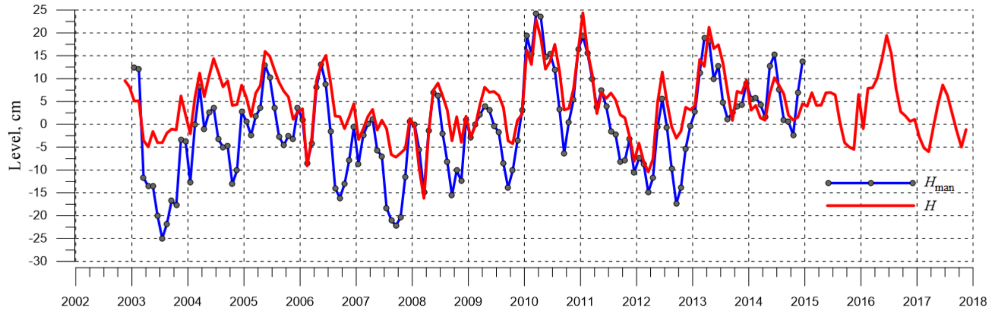


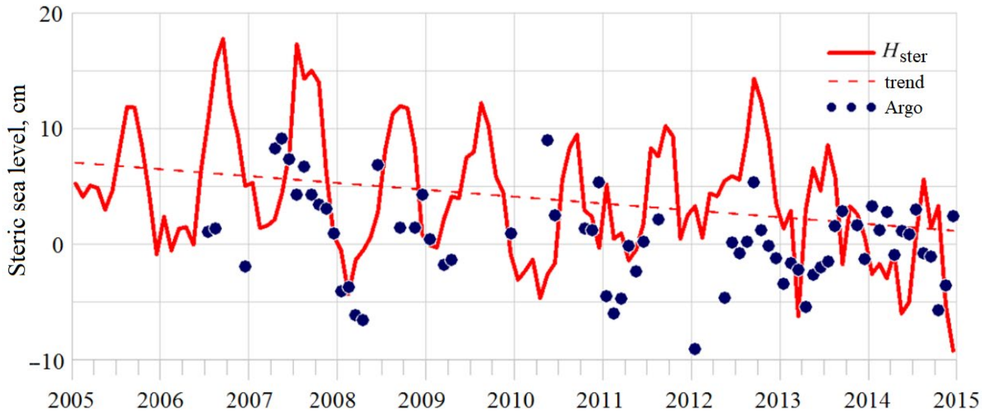
Fig. 6. Seasonal cycle of monthly average values of the Black Sea freshwater balance according to climate data [11] (red line) and manometric level H_{man} (GRACE RL06 GSFC 2003–2016) (blue line)



F i g . 7 . Mean level of the Black Sea according to altimetry data H and manometric component of sea level H_{man} from GRACE RL06 GFSC data

There are several periods with different modes of mean sea level variability: 2004–2006 and 2012–2013 with a pronounced seasonal cycle with an amplitude of up to 15 cm; 2007–2009 – with the absence of a summer maximum level in 2007 and small amplitudes of up to 10 cm; 2010–2011 – with maximum amplitudes up to 25 cm; 2012–2013 and 2014–2015 – with the minimum amplitudes for the entire period of 2003–2018 (less than 10 cm) (Fig. 7). The coincidence of the sea level maxima and the manometric component in amplitude and phase in 2010 and 2011 indicates that in these years the main contribution to the sea level was provided by the water balance component (Fig. 7). The authors of [14] D. L. Volkov and F. V. Landerer also came to the conclusion that the maximum sea level and manometric component in 2010 and 2011 were caused by the maximum moisture content in the Black Sea drainage basin, which led to an increase in the total river flow.

Based on relation (1) using basin sea level averaged according to the altimetry data H and the manometric component of sea level H_{man} according to GRACE RL06 GFSC data, the mean reconstructed steric level H_{ster} for the Black Sea was obtained (Fig. 8). The steric component is also characterized by significant interannual variability with different modes of oscillation: 2005–2009 and 2012 – quasi-regular oscillations of the steric level with an amplitude of up to 15 cm; 2010–2011 and 2013–2015 – violation of quasi-regularity of oscillations and a decrease in amplitude to 5 cm (Fig. 8). In addition, the trend of the reconstructed steric level is negative (–0.59 ± 0.21 cm/year). The estimates of interannual oscillations in the H_{ster} level reconstructed from the satellite data are confirmed by calculations of the mean steric level based on CTD data from Argo profiler floats No. 4900542, 6900805, 2901200 (Fig. 8). The trajectory of the Argo float No. 4900542 passed through the deep-water part of the sea, then the float was in the Batumi anticyclone for a long time. Floats No. 6900805 and 2901200 made



F i g . 8 . Reconstruction of the sea mean steric level $H_{ster} = H - H_{man}$ and mean steric level according to Argo floats No. 4900542, 6900805, and 2901200

several revolutions in the deep-water part of the sea approximately along the Rim Current. Despite the incomplete coverage of the Black Sea with data from these floats, the steric level calculated from their CTD profiles can be considered as an independent instrumental assessment confirming the general trend of interannual changes in the H_{ster} level reconstructed from satellite data. The range of steric oscillations according to Argo floats is approximately twice smaller than that of H_{ster}, and, accordingly, the negative trend is also smaller: −0.22 ± 0.05 cm/year (Fig. 8).

Discussion

The importance of studying sea level variability, including its steric and manometric components, is due to the direct connection of the sea level with the basin water balance and the sea thermohaline structure. The use of satellite altimetry and gravimetric data revealed that the contribution of these both components to the interannual variability of the Black Sea level is approximately the same. The inland Black Sea is a suitable case study for conducting methodological work on the joint use of altimetry and gravimetric data as an alternative to conventional assessments of steric oscillations and basin water balance. However, the variability of the manometric level component is additionally affected by the Black Sea drainage basin soil moisture. To eliminate these errors, our work used GRACE RL06 GSFC data obtained based on the calculation method using mascons [15]. Another approach to correcting the influence of the signal from the variability of soil moisture is to use the hydrological reanalysis models [16] and take into account the soil moisture signal of the Black Sea drainage basin according to GRACE data for land [14, 16].

Our estimates of interannual variability and negative trend in the steric level of the Black Sea reflect the integral effect of thermohaline changes throughout the entire water column. In the seasonal cycle for the upper 300-meter layer, the contribution of the thermosteric component of the steric level in the summer period is 1–2 cm higher than the contribution of the halosteric component, and vice versa in the winter period (see Fig. 2). In recent decades, according to numerical modeling and field observations, a negative linear trend in salinity (–0.02 PSU/year) in the 0–50 m layer has been identified, which is due to a positive trend in the fresh water balance of the Black Sea. There are not statistically significant trends in the Black Sea surface temperature in recent years [8]. With increasing depth between the CIL core and its lower boundary, thermosteric and halosteric effects compensate each other [5]. In the 75–300 m layer, positive trends in salinity and temperature have been observed in recent decades at an average rate of 0.05 PSU/10 years and 0.02 °C/10 years [7]. Instrumental measurements revealed that for the northeastern part of the Black Sea, climate changes led to a noticeable increase in salinity in the upper 200-meter layer, as well as an increase in temperature in the layers located below the temperature minimum layer (CIL) [17]. Thus, in the layer below 50–75 m, a simultaneous increase in salinity and temperature leads to multidirectional trends in the steric component of sea level oscillations.

Nevertheless, the trends in the steric level reconstructed from satellite data, reflecting changes in the entire sea water column from the surface to the bottom, and the trends from Argo floats CTD profiles in the 0–500 m layer have negative values (Fig. 8). This means that, integrally over depth in the layer below 50 m, an increase in salinity leads to a decrease in the steric level throughout the sea, exceeding the positive contribution of the thermosteric component from an increase in temperature. The inflow of more saline and warm waters into the deep layers of the Black Sea occurs through the system of Turkish straits. However, determining the water fluxes through the Bosphorus using traditional methods is attended with great difficulties. In the future, it will be possible to estimate water exchange through the straits using the sea level according to the altimetry data and the manometric level component according to GRACE data [16].

Conclusions

Based on satellite altimetry and gravimetric data, the time-series of steric oscillations in the Black Sea level for 2002–2016 was reconstructed. Its comparison with the steric level estimates calculated from archival hydrological data confirmed good agreement between them. The estimates of the seasonal cycle of the steric level were obtained: the range of oscillations reaches 12 cm, the minimum occurs in the winter period (March), the maximum occurs in the summer period (August). The seasonal cycle of the steric level reconstructed from satellite data has a smoother shape compared to the calculations of the steric level H'_{ster} from archival hydrological data. The reconstructed steric level attains its maximum in August and coincides in time with the maximum H'_{ster}, and the minimum occurs a month earlier than H'_{ster} – in February. For the seasonal cycle of the manometric component of sea level, according to GRACE data, good agreement was obtained with the seasonal cycle of the Black Sea freshwater balance, calculated from hydrometeorological observations.

The maximum difference in the steric level H'_{ster} between the periphery and the center of the sea was about 15 cm. The regions of the maximum range of the seasonal cycle in the steric level have been identified. These areas correspond to the areas of maximum seasonal vertical displacements of the main pycnocline. A comparison of the mean annual values of steric sea level (deviations from the basin mean) in the 0–50 m layer and in the 50–300 m layer shows that, despite the opposite directional decadal trends in temperature and salinity, the spatial distribution of the long-term mean values in these layers is qualitatively consistent.

The steric level H_{ster} reconstructed from satellite data is characterized by significant interannual variability with periods of various oscillation modes with timescale about 3 years and amplitude changes from 5 to 15 cm. In 2010–2011 and 2013–2015, there was a violation of the quasi-regularity of steric oscillations and a decrease in their amplitude under 5 cm. The estimate of the linear trend of the reconstructed steric level has a negative sign and amounts to –0.59 ± 0.21 cm/year. The steric level was also calculated from Argo floats CTD profiles, which provided an independent instrumental estimate confirming the general trend of interannual changes in the reconstructed steric level H_{ster}. The range of steric oscillations according to Argo floats is approximately twice smaller than that of H_{ster}, and, accordingly, the negative trend coefficient is smaller (−0.22 ± 0.05 cm/year). The general negative trend in the steric component of the Black Sea level indicates that among the thermohaline properties impacts on the sea level, the contribution of an increase in salinity prevails over the contribution of an increase in water temperature. In addition to the regional heat and water balance, changes in the thermohaline structure of waters and the steric component of sea level are affected by the inflow of saline and warm waters into the Black Sea through the system of Turkish straits. In the future, it seems possible to estimate water exchange through the Bosphorus using the discussed approach of combining altimetry and gravimetric measurements.

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Vladimir N. Belokopytov – calculation and analysis the Black Sea steric level and their thermosteric and halosteric components based on the archive of long-term hydrological data.

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