Numerical analysis of the Black Sea energy budget in 2011

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Abstract. The paper analyzes the results of the annual-averaged and seasonal-averaged variability of the Black Sea energetics in 2011. Energetic features were computed by equations describing the change rate of the kinetic and potential energy. They corresponded precisely to the finite-difference equations of the ocean model developed in the Marine Hydrophysical Institute of the Russian Academy of Sciences. A numerical experiment was run with a horizontal resolution of 1.6 km and took into account the real atmospheric forcing SKIRON for 2011. It was discovered that on average over the year the most significant components of the integral energy budget were the wind work, the dissipation due to friction, and the change of potential energy due to vertical diffusion. Seasonal variability of energy fluxes was determined by the contribution from wind and dissipation due to friction in the autumn-winter period. As a result, the vertical mixing processes enhanced and the RIM Current got stronger. In the spring and summer seasons the main energy processes were the buoyancy work and vertical turbulent diffusion due to increase in the vertical density gradient.

1. Introduction

The work of the main forces forming the circulation features in the oceans and seas was described by the budget equations of kinetic (KE) and potential energy (PE). Model and field estimations of the currents mean kinetic energy, eddy energy, available potential energy (APE) allow us to make conclusions about the generation mechanisms and dynamics of jet currents, fronts and eddies of various scales. The energetic cycle of the World Ocean was simulated in [1], where the transformations between the mean KE and APE were calculated. The authors showed that APE sank due to eddy-induced overturning circulation and the mean KE was reduced due to the vertical redistribution of geostrophic currents momentum, herewith both processes were caused by baroclinic mesoscale eddies. An analysis of energy conversions was compiled in [2] during the investigation of the generation mechanisms of the hydrophysical parameters anomalies in the Arctic Ocean. The assessment of the kinetic energy balance is used in numerical ocean models select stopping criteria for the adaptive calculations of the hydrodynamical characteristics [3]. The numerical calculations of the energetics of the Black Sea climatic circulation was first carried out in [4] and as a result the most energy-active sea zones were identified. Examination of the energy budget in the semiclosed basins with vertically separated exchange flows at the strait was presented in [5]. In this paper it was shown that the change rate of the volume-integrated mechanical energy of semiclosed seas (including the Black Sea) is directly related to the wind work, surface heat fluxes, and buoyancy fluxes. Authors concluded that the buoyancy work is one of the main factors forming the mesoscale variability in such seas.
The aim of our research was to calculate of the Black Sea energetics considering the real atmospheric forcing and to perform qualitative and quantitative estimations of the annual-averaged and seasonal-averaged contributions of the physical processes in KE and PE variations in 2011. Note that, unlike in [4], in the presented work the horizontal resolution was increased, account the water exchange on the open boundaries was taken into (in the river mouths and straits), and real forcing was used. In future it will allow us to compare the results for various years [6] and to investigate the inter-annual variability of the energy characteristics in the Black Sea.

Increase of the model resolution let to simulate mesoscale and submesoscale eddies in the velocity fields which have not been obtained in the experiments with resolution of 5 km (as in [7]). Also the variability of the sea surface height and surface currents were reconstructed more realistic especially under extreme storms. The resolution of small scales lets to more accurately calculate the energy redistribution over the movements spectrum. This is confirmed by the fact that the contribution of the turbulent dissipation term in the total energy balance has not decreased despite more quantity of eddies which were reproduced. Therefore, lower resolution had a reason for incorrect description of the energy sink in the subgrid scales.

2. Energetic model equations
The problem was solved by the eddy-resolving z-model of the Marine Hydrophysical Institute RAS (MHI-model) which is based on the motion equations in quasi-static approximation and the budget equations of temperature and salinity. Formulation of the problem, differential equations and their finite-difference equivalents, the stages of model development are described in detail in [7]. The discrete energetic equations are a consequence of the finite-difference model equations, which provides exact implementation of conservation laws at the discrete level.

To compute the circulation energetic characteristics, the MHI-model was supplemented with a subroutine for calculation of the components of KE and PE budgets [4]. The symbolic notation of the KE change equations has the following form:

\[ E_i + \text{Adv}(P + E) = \Pi \leftrightarrow E + F_{\text{Bfr}}(E) - \text{Diss}_{\text{Ver}}(E) - \text{Diss}_{\text{Hor}}(E), \]

where \( \text{Adv}(P) \) – advection of pressure, \( \text{Adv}(E) \) – advection of KE, \( \Pi \leftrightarrow E \) – buoyancy work, \( F_{\text{Bfr}}(E) \) – KE change due to wind action and bottom friction, \( \text{Diss}_{\text{Ver}}(E) \) – KE change due to vertical internal friction, and \( \text{Diss}_{\text{Hor}}(E) \) – KE change due to horizontal friction, including internal horizontal friction and lateral friction. Integration of eq. (1) over the basin volume, denoted by angle brackets, gives:

\[ <E_i>_\psi + <\text{Adv}(E)>_\psi + <\text{Adv}(P)>_\psi = <\Pi \leftrightarrow E>_\psi + <\tau \rightarrow E>_S - <\text{Diss}_{\text{Ver}}(E)>_\psi - <\text{Diss}_{\text{Hor}}(E)>_\psi. \]

The contributions of the advective terms is not equal to zero after integration, because the river inflows and the water exchange through the straits were taken into account in the model. The term \( F_{\text{Bfr}}(E) \) gives the contributions on the sea surface and on the bottom. For analysis simplicity the term describing the energy dissipation due to bottom friction was introduced in term of \( <\text{Diss}_{\text{Ver}}(E)>_\psi \).

And wind contribution was allocated in the separate term \( <\tau \rightarrow E>_S \) too.

According to [4] the PE change is determined by this equation:

\[ \Pi_t + \text{Adv}(\Pi) = -\Pi \leftrightarrow E + \text{Diff}_{\text{Hor}}(\Pi) + \text{Diff}_{\text{Fluxes}}(\Pi) + \text{Diff}_{\text{Ver}}(\Pi) + \text{Diff}_{\text{Ver}}^{\text{Bot-Sur}}(\Pi) + \text{Diff}_{\text{Ver}}^{\text{Add}}(\Pi), \]

where \( \text{Adv}(\Pi) \) – advection of PE, \( \text{Diff}_{\text{Hor}}(\Pi) \) – PE change due to horizontal turbulent diffusion, \( \text{Diff}_{\text{Fluxes}}(\Pi) \) – PE change due to buoyancy fluxes and internal vertical turbulent diffusion, \( \text{Diff}_{\text{Ver}}^{\text{Bot-Sur}}(\Pi) \) – PE change due to the difference between bottom and surface density, \( \text{Diff}_{\text{Ver}}^{\text{Add}}(\Pi) \) –
PE change due to the depth heterogeneity of the vertical turbulent diffusion coefficient, and $\text{Diff}^{\text{Add}} _{\text{Ver}} (II) −$ additional term due to nonlinear dependence of density from the temperature and salinity. For further analysis the PE change due to heat and salinity fluxes from the atmosphere was allocated in a separate component denoted as $\langle \text{Fluxes} \rangle _S$. The vertical diffusion in the system was determined by the sum of the fourth, fifth and sixth terms in eq. (3). Eq. (3) takes the next form after integration over the volume:

$$
\langle \Pi _V > _V + < \text{Adv} (II) > _V = - < \Pi _V \leftrightarrow E > _V + < \text{Fluxes} > _S + \\
+ < \text{Diff}^{\text{Hor}} _{\text{Hor}} (II) > _V + < \text{Diff}^{\text{Ver}} _{\text{Ver}} (II) > _V .
$$

(4)

3. The numerical experiment setting

To calculate the hydrophysical and energetic characteristics of the Black Sea circulation, the numerical experiment was carried out under the next parameters. The boundary conditions included the wind stress fields, latent, sensible, long-wave heat fluxes, solar radiation, evaporation and precipitation obtained from the SKIRON atmospheric reanalysis with a spatial resolution of 0.1° [8]. The fields of sea surface temperature were assimilated every day. The water exchange through the straits and the inflows of the main rivers was taken into account in accordance with the mean climatic data. The climatic fields of level, temperature, salinity and current velocities were given by [9]. The fields of level, temperature, salinity and current velocities obtained in [9] with a horizontal resolution of 5 km were set in the initial time moment corresponding to December 31, 2010. All boundary and initial fields were linearly interpolated on the model grid. At the initial moment the agreement procedure of hydrophysical and atmospheric fields was applied. The boundary conditions were fixed and the calculation of the model equations was carried out. As agreement criteria, we used the volume-integrated divergence of the horizontal velocity characterizing the similarity degree of the numerical velocity to geostrophic velocity. The criteria were decreased by an order after 4 days of model time. Therefore we assume that the velocity field was adapted to the density field, i.e. there was a quasi-geostrophic adjustment.

The experiment was carried out on a regular spatial grid with a horizontal step of 1.6 km, 27 vertical z-levels were used, and the time step was equal to 96 sec. Note that horizontal resolution of the model is less than the baroclinic Rossby’s deformation radius [10], which is about 8 km in the Black Sea coastal zones. So we can reproduce the mesoscale and submesoscale eddies that are often detected on satellite images and field observations [11], [12]. The vertical turbulent coefficients were calculated in accordance with the Mellor-Yamada parameterization 2.5 [13]. The coefficients near the biharmonic operators in the terms that describe the horizontal turbulent viscosity in the motion equations and the horizontal turbulent diffusion in the transport equations of temperature and salinity are $10^{16} \text{cm}^2\text{sec}^{-1}$, $5 \times 10^{14} \text{cm}^2\text{sec}^{-1}$, respectively. The experiment was run for the period from January 1 to December 31, 2011. Complete problem statement, boundary and initial conditions, description of the subroutine for calculation of the energy budget components are presented in detail in [6].

4. Results of the numerical experiment

As a result we obtained three-dimensional arrays of hydrophysical fields, one-dimensional arrays of all terms in eq. (2) and (4), and three-dimensional arrays of the spatial distribution of terms in eq. (1) and (3) for every day of the investigative period. The paper presents the analysis results of the Black Sea volume-integrated energetics in 2011. The angle brackets are skipped in the text and figures below.

4.1. Intra-annual variability

We considered the volume-integrated energetic characteristics (terms of eq. (2) and (4)) averaged over the year. Figure 1 presents a scheme of the directions and magnitudes of the energetic fluxes composing the KE and PE budgets. On average over 2011 there was an accumulation of KE and PE, alongside this the rate growth of PE was five times higher than of KE. The exchange between KE and PE was implemented through the buoyancy work $\Pi \leftrightarrow E$. At the mean over the year its value was
positive and the share of the total PE having converted in KE was about 50 percent. The wind work $\tau \rightarrow E$ gave the maximum contribution to KE. Input from the wind was compensated by 72 percent by the vertical friction $\text{Diss}_{\text{ver}}$. The advective terms $\text{Adv}(P)$ and $\text{Adv}(E)$ are small, however, but not equal to zero because the river inflow and exchange through the Kerch Strait and the Bosphorus Strait were taken into account in the MHI-model. KE decreased due to the horizontal friction $(\text{Diss}_{\text{hor}})$ and the absolute value of this term was three times higher than the contribution from the buoyancy work.

The vertical diffusion $\text{Diff}_{\text{ver}}$ gave the main contribution to the integral PE balance and the magnitude of this term exceeded other components more than four times. $\text{Diss}_{\text{hor}}$ was mainly determined by the stratification and variability of vertical turbulent diffusion coefficient with depth. Horizontal diffusion $\text{Diff}_{\text{hor}}$ was almost five times less than vertical. This result indicates that PE increased mainly due to vertical diffusion processes and their enhancement was a consequence of the significantly heterogeneous vertical structure of the density fields in 2011. It will be illustrated below.

Figure 1 demonstrates that the contribution to the PE budget due to fluxes of heat and salt from the atmosphere composed about 20 percent of the PE balance. Its value is negative so the fifth part of the PE was lost to heating of near-water layer of atmosphere. Thus, the integral KE balance was determined by the contribution from wind and dissipation due to friction, while the integral PE balance was determined the vertical diffusion on average over 2011.

![Figure 1. Annual-averaged components of the energy budget (10\(^{-6}\) erg cm\(^{-3}\)·sec\(^{-1}\)).](image)

4.2. Seasonal variability

The terms in eq. (2) and (4) were averaged over the seasons to investigate seasonal variability. The analysis of obtained values allowed us to identify the most energetically significant contributions depending on the time of a year. The results are presented in Table 1.

| 2011  | $\tau \rightarrow E$ | $\Pi \rightarrow E$ | $\text{Diss}_{\text{ver}}$ | $\text{Diff}_{\text{ver}}$ | Fluxes |
|-------|----------------------|---------------------|--------------------------|---------------------------|--------|
| winter| 18.9                 | 0.3                 | -14.5                    | -2.3                      | -1.9   |
| spring| 6                    | 1.8                 | -3.7                     | 13.8                      | 1      |
| summer| 3                    | 2.6                 | -2.5                     | 15.6                      | 1.4    |
| autumn| 17.6                 | 0.7                 | -12.1                    | -0.2                      | -2.1   |

It can be seen that the maximum contribution to KE from the wind was detected in winter and autumn, its partial compensation occurred due to vertical friction. The increase in wind work resulted in an intensification of the modeling velocities in the RIM Current zone in the cold period, which agrees...
well with the published data and field observations [14]. The buoyancy work and the vertical turbulent diffusion effects grew in spring and summer because of the seasonal variability of the density field (intensification of the river inflows and warming of the upper sea layer). These processes took place along with the relaxing wind field. The PE change due to fluxes of heat and salt from the atmosphere indicates that in the autumn and winter of 2011 the sea gave up more heat to the atmosphere than it had received in the spring and summer.

The integral profiles of temperature, salinity and conventional density averaged over the seasons were analyzed. Averaged profiles over the winter and summer of 2011 are presented in Figure 2. It shows that the profiles of salinity and conventional density are qualitatively identical in winter and the vertical temperature gradient is less than 2°C in the upper 300-m layer (Figure 2, a). Such a structure of the density field was a result of intensive winter convection and cooling. At this time the components $\Pi \leftrightarrow E$ and $\text{Diff}_{\text{ver}}$ were minimal. The significant increase in the temperature and conventional density gradients was observed in the summer compared to the winter: in the upper 50-m layer the temperature variation was equal to 17°C and the density variation was equal to 3.5 conventional units (Figure 2, b). So, during the warm year period the density of the upper quasi-homogeneous layer (and therefore its PE) was determined more by temperature than salinity. The rising of the stratification led to the situation when the terms $\Pi \leftrightarrow E$ and $\text{Diff}_{\text{ver}}$ reached their maximum values. As is clear from Table 1, the magnitude of these terms increased almost an order compared to the winter period. Thus, in the summer of 2011 the change rate of PE increased, despite the fact that the direct PE decreased.

![Figure 2](image.png)

**Figure 2.** Averaged temperature, salinity, and conventional density profiles: a – over the winter of 2011; b – over the summer of 2011.

5. Conclusion

In the result of the present research we learned that the total energy in the Black Sea increased in 2011. The growth of KE occurred due to the wind work in the autumn-winter period. Our analysis of hydrodynamic characteristics showed that enhancement of the vertical mixing processes and the intensification of the RIM Current were observed inside the marine system at this time. The heating of the upper sea layers led to the increase in the vertical density gradients in the warm months and it caused the growth of contributions due to the buoyancy work and the vertical diffusion. Thus, in 2011 the Black Sea integral energetics was determined by influences of the wind work, the buoyancy work, the friction processes, and the vertical turbulent diffusion.

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