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Original article

Features and Reasons for Spatial Heterogeneity of Mechanical Energy Flows in the Black Sea

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Abstract
Purpose. The work is aimed at determining the reasons for the spatial inhomogeneity of mechanical energy flows that arise during formation and evolution of the large-scale currents in the Black Sea. The uneven distribution of energy flows over the sea area was revealed in the analysis of time-averaged fields of the energy characteristics resulted from numerical simulation.
Methods and Results. The data of numerical experiments performed using the two-layer eddy-resolving model permitted to calculate the energy balance components in the eastern and western parts of the Black Sea. Averaging the energy characteristics over time and area within the selected areas made it possible to construct an integrated circuit of mechanical energy flows. To confirm the hypothesis on influence of the β-effect on the redistribution of energy flows, an additional experiment including the constant Coriolis parameter was carried out, and the energy balances were calculated by the method similar to the one applied in the first experiment.
Conclusions. It is revealed that under the impact of the β-effect, the energy flows are redistributed over the Black Sea basin area. In the eastern half of the sea, currents are pumped with wind energy and there is the process of formation of potential energy, which later, due to advection, is transferred to the west by the currents. In the western part of the sea, the potential energy that had been transported from the eastern half of the basin is converted into the kinetic energy of currents, a significant part of which dissipates due to bottom friction and horizontal turbulent viscosity. The rest of the kinetic energy is transported back to the basin eastern part by the current in the sea upper layer, where it again participates in the process of forming the potential energy.

Keywords: Black Sea, energy balance, energy conversions, large-scale circulation, β-effect, Rossby waves

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Introduction

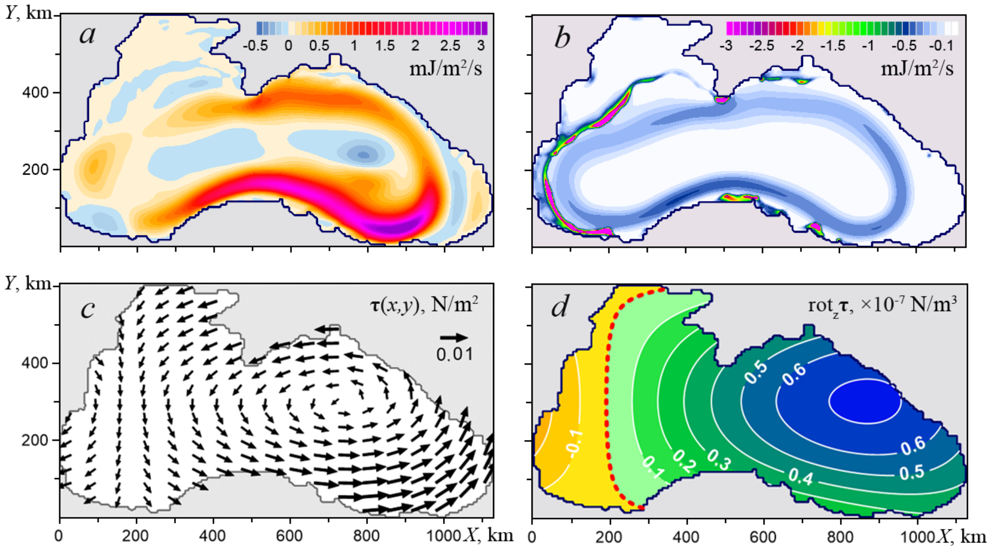
An essential point in the marine dynamics study is correct understanding of the processes of mechanical energy transformation that take place during formation and spatio-temporal evolution of current fields in seas and oceans. Mechanical energy refers to kinetic and potential energy. Energy conversion processes include energy transfer through sea surface or side boundaries, mutual transitions between kinetic and potential energy, energy dissipation due to bottom friction and turbulent viscosity and advective energy transfer by currents. These processes are described by the energy balance equations, which can be obtained from the equations of motion and formulas for kinetic and potential energy.

Many scientific works are devoted to the study of spatio-temporal variability of energy characteristics of sea currents. Some of them evaluate the components of mechanical energy balance [1–3], while others consider energy transitions between movements of various scales (large-scale currents and eddy formations) [4–8]. Calculation of energy flows between the kinetic and potential energy is also used to estimate contributions of the baroclinic and barotropic components to the instability of flows [9–11].

In the present paper, the results of numerical simulation within the two-layer eddy-resolving model [8, 12, 13] are used to analyze energy characteristics of the large-scale circulation in the Black Sea. This model is energetically balanced and qualitatively describes the Black Sea large-scale dynamic features, enables to consider the main factors that determine formation and variability of large-scale circulation and mesoscale eddy structures. These are vertical stratification of waters, nonlinearity of the advective terms in the equations of motion, the basin shape and coastline indentation, bottom topography and the β-effect [13]. Using a stationary or periodically changing wind to excite motion in the model, it is possible to obtain a solution of the problem to a statistically equilibrium mode, which is a condition that permits to consider and analyze the time-independent mean values of the studied parameters.

The possibility to obtain a statistically equilibrium solution is one of the reasons for choosing a two-layer model for calculations, but, on the other hand, the use of a simplified model may be a reason to criticize the conclusions made in this paper. Therefore, it makes sense to compare the results of calculating the energy parameters in the two-layer model with the results of similar calculations made using other, more "advanced" models. In this sense, the work [14] describing a numerical experiment on the Black Sea circulation modeling using the DieCAST model seems to be interesting and promising. The paper notes that over the period of 24 years, a quasi-periodic circulation regime was obtained in the model.

In [8], devoted to the study of energy conversions in a two-layer Black Sea model, inter alia, the fields of various energy characteristics averaged over a long time period were calculated. At the same time, significant differences in the spatial distribution of energy sources and sinks were noted. In particular, it was found that the energy flow entering the sea from the wind is concentrated in the eastern part (Fig. 1, *a*), and the areas where the maximum energy dissipation is observed are located in the western part along the northwestern shelf edge (Fig. 1, *b*). Thus, the sea receives energy mainly in the eastern part, and loses it in the western one.



F i g. 1. Spatial distribution of the time-averaged work of tangential wind stress (*a*) and average energy dissipation due to friction at the upper layer lower boundary (*b*), tangential wind stress (*c*) and wind vorticity (*d*)

The non-uniformity of wind pumping by the energy of large-scale Black Sea currents, the existence of which was previously mentioned in [15], is explained by the peculiarities of the tangential wind stress vorticity distribution over the Black Sea water area [15, 16]. As for the localization of zones with maximum energy dissipation by bottom friction along the continental shelf in the western sea part, there is no description and explanation of this phenomenon in scientific literature.

This work is devoted to discovering reasons for the spatial inhomogeneity of time-averaged energy flows in the Black Sea.

Materials and methods

The paper uses the results of numerical experiments carried out using a two-layer eddy-resolving model [8], in which the wind action was set by a stationary tangential wind stress field (Fig. 1, *c*, *d*) with an inhomogeneous vorticity over the area. The model parameters are as follows: spatial resolution (horizontal cell size) $\Delta x = \Delta y = 3000$ m; time step $\Delta t = 120$ s; horizontal turbulent viscosity coefficient parameterized by the biharmonic operator $A_B = 2 \cdot 10^8$ m^4/s; bottom friction coefficient proportional to the square of the velocity $r_H = 0.002$; linear friction coefficient between layers $r_L = 2 \cdot 10^{-6}$ m/s; reduced gravitational acceleration $g' = 0.032$ m/s^2; Coriolis parameter $f = f_0 + \beta y$, where $f_0 = 10^{-4}$ 1/s, $\beta = 2 \cdot 10^{-11}$ 1/s/m; upper layer thickness at rest $h_0 = 100$ m. The empirical coefficients of bottom friction and horizontal turbulent viscosity were selected based on the best agreement between the simulation results and observational data of the Black Sea circulation [17, 18].

The data necessary for energy characteristics calculation are the instantaneous sea level values, upper layer thickness and horizontal components of the current velocity at the computational grid nodes obtained in numerical experiments with a time discreteness of 1 day.

The following formulas were used to calculate the kinetic energy:

$$e_1 = \rho \frac{u_1^2 + v_1^2}{2}, \quad e_2 = \rho \frac{u_2^2 + v_2^2}{2}, \quad K_1 = h_1 e_1, \quad K_2 = h_2 e_2,$$

where e_1, e_2 is kinetic energy per unit volume of water in the upper and lower layers; ρ is the mean seawater density (the Boussinesq approximation consequence); (u_1, v_1), (u_2, v_2) are current velocity components in the layers; K_1, K_2 is kinetic energy of a water column of unit section in the upper and lower layers; h_1, h_2 is thickness of the layers.

The two-layer model energy is described by a system of energy balance equations consisting of equations for the kinetic energy of the upper and lower layers K_1, K_2 and an equation for the potential energy.

The energy balance equations for K_1, K_2 can be obtained by multiplying the equations of motion by the corresponding current velocity components, adding them and making simple transformations:

$$\begin{aligned} \frac{\partial K_1}{\partial t} + \frac{\partial u_1 h_1 e_1}{\partial x} + \frac{\partial v_1 h_1 e_1}{\partial y} &= W_{\mathrm{G1}} + W_\tau + W_{\mathrm{RL1}} + W_{\mathrm{AB1}}, \\ \frac{\partial K_2}{\partial t} + \frac{\partial u_2 h_2 e_2}{\partial x} + \frac{\partial v_2 h_2 e_2}{\partial y} &= W_{\mathrm{G2}} + W_{\mathrm{RL2}} + W_{\mathrm{RD}} + W_{\mathrm{AB2}}. \end{aligned} \tag{1}$$

The terms on the left side of the equations (1) are local derivatives with respect to time and divergence of kinetic energy flows in the upper and lower layers. On the right side of the equations, there are terms describing the work per unit time (power) of the forces included in the equations of motion. These works determine the corresponding energy flows and transitions: W_{G1}, W_{G2} is the work of hydrostatic pressure forces, equal to the transition between kinetic and potential energy in the upper and lower layers, respectively; W_τ is the work of the tangential wind stress, equal to the energy inflow from the wind (wind pumping); W_{RL1}, W_{RD} is energy dissipation due to friction force work on the lower boundary of the upper and lower layers; W_{RL2} is the energy input to the lower layer due to friction force work on the liquid boundary between the layers; W_{AB1}, W_{AB2} is energy dissipation due to the work of horizontal turbulent viscosity forces in the layers.

The potential energy balance equation is obtained by time differentiation of the potential energy of the position (P) of a unit section water column from the surface to the bottom:

$$P = -\int_{\zeta}^{H} \rho(z) gz dz = -\int_{\zeta}^{h_1+\zeta} \rho_1 gz dz - \int_{h_1+\zeta}^{H} \rho_2 gz dz,$$

$$P = -\rho_1 g \frac{(h_1+\zeta)^2}{2} + \rho_1 g \frac{\zeta^2}{2} - \rho_2 g \frac{H^2}{2} + \rho_2 g \frac{(h_1+\zeta)^2}{2},$$

$$P = -\rho_2 g \frac{H^2}{2} + \rho_2 g' \frac{(h_1+\zeta)^2}{2} + \rho_1 g \frac{\zeta^2}{2},$$

where H is the sea depth. After differentiating P with respect to t and using the Boussinesq and "hard cap" approximations, the equation needed is obtained

$$\frac{\partial P}{\partial t} - \rho g' \left(\frac{\partial u_2 h_2 h_1}{\partial x} + \frac{\partial v_2 h_2 h_1}{\partial y} \right) - \rho g \left(\frac{\partial U\zeta}{\partial x} + \frac{\partial V\zeta}{\partial y} \right) = -W_{\mathrm{G1}} - W_{\mathrm{G2}}, \quad (2)$$

where $U = u_1 h_1 + u_2 h_2$, $V = v_1 h_1 + v_2 h_2$ are the total flow components.

The flows W_{G1}, W_{G2} with different signs enter simultaneously into the balance equations of kinetic (equation (1)) and potential (equation (2)) energy, thereby providing an energy connection between the upper and lower layers.

The energy flows in equations (1) and (2) were calculated using the following formulas:

$$W_{\tau} = u_1 \tau^x + v_1 \tau^y,$$

$$W_{\mathrm{RL1}} = u_1 R_{\mathrm{L1}}^x + v_1 R_{\mathrm{L1}}^y, \qquad W_{\mathrm{RL2}} = u_2 R_{\mathrm{L2}}^x + v_2 R_{\mathrm{L2}}^y, \qquad W_{\mathrm{RD}} = u_2 R_{\mathrm{D}}^x + v_2 R_{\mathrm{D}}^y,$$

$$W_{\mathrm{G1}} = \rho g \left(u_1 h_1 \zeta_x + v_1 h_1 \zeta_y \right), \quad W_{\mathrm{G2}} = \rho g \left(u_2 h_2 \zeta_x + v_2 h_2 \zeta_y \right) + \rho g' \left(u_2 h_2 h_{1x} + v_2 h_2 h_{1y} \right),$$

$$W_{\mathrm{AB1}} = \rho \left(u_1 A_{\mathrm{B}} \nabla \left(h_1 \nabla (\Delta u_1) \right) + v_1 A_{\mathrm{B}} \nabla \left(h_1 \nabla (\Delta v_1) \right) \right),$$

$$W_{\mathrm{AB2}} = \rho \left(u_2 A_{\mathrm{B}} \nabla \left(h_2 \nabla (\Delta u_2) \right) + v_2 A_{\mathrm{B}} \nabla \left(h_2 \nabla (\Delta v_2) \right) \right),$$

where (τ^x, τ^y) are the tangential wind stress components on the sea surface; $\left(R_{\mathrm{L1}}^x, R_{\mathrm{L1}}^y\right), \left(R_{\mathrm{L2}}^x, R_{\mathrm{L2}}^y\right)$ are the components of friction forces at the interface between layers; $\left(R_{\mathrm{D}}^x, R_{\mathrm{D}}^y\right)$ are the bottom friction force components; A_{B} is the empirical coefficient of horizontal turbulent viscosity.

The study of instantaneous fields of energy characteristics is difficult due to the nonlinearity of the energy balance equations and significant variability of energy characteristics. One of the methods for studying such processes is calculation and analysis of their values averaged over time and/or space. A similar approach was used in [8], where energy characteristics were averaged over the entire sea area.

The analysis of the data averaged over the entire sea area did not allow to explain the spatial uneven distribution of energy flows. To do this, the Black Sea was conditionally divided into western and eastern parts along the meridian passing through Cape Sarych in Crimea (Fig. 2).

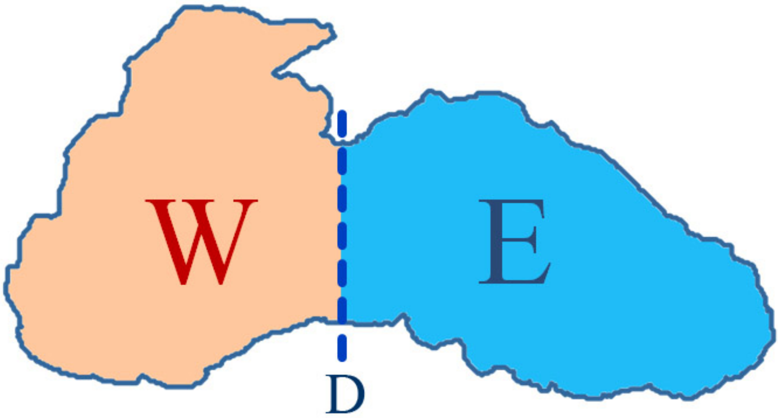


Fig. 2. Division of the Black Sea into the western (W) and eastern (E) parts along section D

Energy balances averaged over the area were calculated separately for the western and eastern sea parts (Fig. 3, K_1 balances in the top row, P balances in the middle row and K_2 balances in the bottom row).

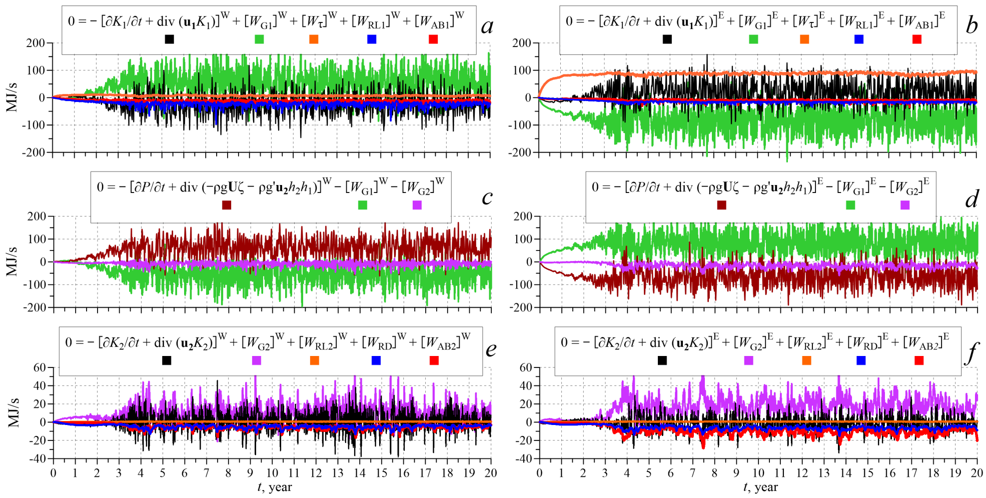


Fig. 3. Graphs of time changes of the water area average components of the energy balance for the western (left) and eastern (right) parts of the Black Sea. Expressions in square brackets with a superscript denote area averaging

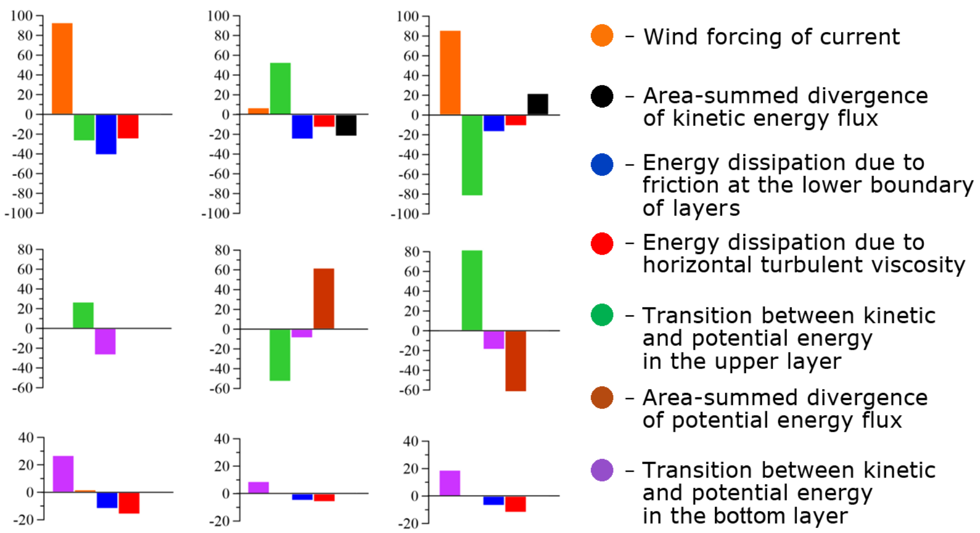
In the lower sea layer, the balances of the kinetic energy of the K_2 currents in the western and eastern basin parts (Fig. 3 *e*, *f*) are similar to each other, they show that the kinetic energy of the lower layer is formed due to the conversion from potential energy (purple curve). Energy dissipation in the lower layer goes on due to bottom friction (blue curve) and horizontal turbulent viscosity (red curve). The kinetic energy input into the lower sea layer due to the friction between the layers (orange curve) is negligible, which means that the friction at the boundary of the layers leads mainly to dissipation of the kinetic energy of the currents in the upper sea layer.

The differences between the energy balances K_1 (Fig. 3 *a*, *b*) and *P* (Fig. 3 *c*, *d*) in the western and eastern parts of the basin are significant.

In the eastern half of the sea (Fig. 3, *b*), the kinetic energy of currents K_1 is replenished due to the energy inflow from the wind (orange curve). Some part of K_1 is spent on dissipation (blue and red curves), but most of it goes into potential energy (green curve), which is then spent on replenishing the kinetic energy of the currents in the lower layer (purple curve) and on the divergence of the flow *P* (brown curve) (Fig. 3 *d*, *f*).

In Fig. 3, *b*, the attention is also drawn to the convergence graph of the kinetic energy flow K_1 (black curve), located in the region of positive values. Thus, it can be said that in the eastern sea part there is an additional source of kinetic energy in addition to the wind pumping, which is due to the convergence of the advective flow K_1.

In the western part of the sea, on the contrary, there is a divergence of the K_1 flow (Fig. 3, *a*, black curve) and a convergence of the *P* flow (Fig. 3, *c*, brown curve). The main source of kinetic energy K_1 replenishment in the western part of the basin (Fig. 3, *a*) is the transfer from potential energy (green curve). Energy dissipation due to bottom friction is twice as high as similar losses in the eastern half of the sea (blue curve).



F i g. 4. Time-averaged and area-aggregated components of the energy balance (MJ/s) in the experiment with the regard for the β-effect. The left column is the sea as a whole, the middle column – its western half, the right one – its eastern half. Top row – K_1 balances, middle row – *P* balances and bottom row – K_2 balances

To dispose of the time derivative in equations (1), the graphs shown in Fig. 3 can be averaged over a long time period and energy balances can be presented in the form of diagrams (Fig. 4). In Fig. 4, in addition to the average balances of the western and eastern halves of the sea, the averaged energy balances for the entire sea as a whole (left column) are shown. It can be seen that the energy balances in the eastern half of the sea in the direction of energy sources and sinks coincide with the overall balance. In the energy balance of the western part, the transition of energy between K_1 and P (green columns) is opposite to the analogous transition in the eastern part and in general across the sea.

The multidirectionality of energy transitions between K_1 and P in different halves of the sea (Fig. 4, middle row) is compensated by the total area divergence of the advective flow P (brown columns), which has opposite signs. In the K_1 balances of the eastern and western halves of the sea (Fig. 4, top row), opposite in sign components of the energy balance correspond to the total area of divergence/convergence of the advective flow K_1 (black columns).

To pass from the divergence of energy flows in formulas (1), (2) to energy flows through the D boundary separating the eastern and western parts of the Black Sea, the Ostrogradsky – Gauss formula is used. According to it, the integral of the divergence of the two-dimensional vector **F** field, extended to some S area, is equal to the **F** vector flow through the L contour, limiting this area:

$$\iint_{\mathrm{S}} (\mathrm{div}\,\mathbf{F})dxdy = \int_{\mathrm{L}} \left(\mathbf{F}\cdot\mathbf{n}\right)dl.$$

In the problem under consideration, taking into account the no-slip boundary conditions on the coast, this formula can be simplified by leaving only a part of the contour (*D* section) with non-zero flows through it on the right:

$$\iint_{\mathrm{W}} (\mathrm{div}\,\mathbf{F})dxdy = -\int_{\mathrm{D}} F^x dy, \quad \iint_{\mathrm{E}} (\mathrm{div}\,\mathbf{F})dxdy = \int_{\mathrm{D}} F^x dy,$$

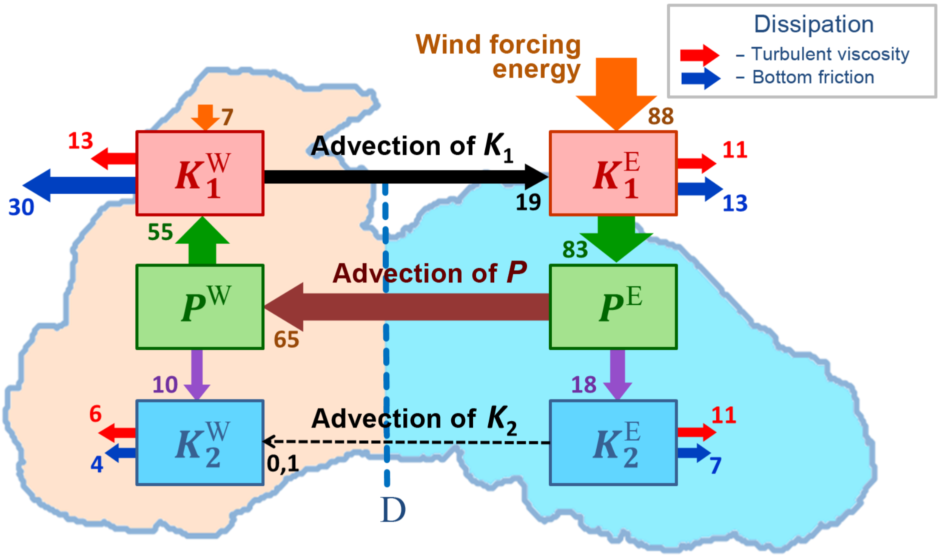
where F^x is the component of the flow along the X axis, normal to the Y axis. Then for the total advective P flow through the D section we obtain

$$\int_{\mathrm{D}} F_P^x dy = -\int_{\mathrm{D}} \rho\left(g(u_1h_1 + u_2h_2)\zeta + g'u_2h_2h_1\right)dy,$$

respectively, for advective kinetic energy flows through D we have

$$\int_{\mathrm{D}} F_{K_1}^x dy = \int_{\mathrm{D}} u_1h_1e_1dy, \quad \int_{\mathrm{D}} F_{K_2}^x dy = \int_{\mathrm{D}} u_2h_2e_2dy.$$

In view of the above, an integrated scheme of energy flows in the Black Sea was built under the condition of dividing the water area into two (Fig. 5). According to it, the wind energy entering the eastern half of the sea is used to increase the kinetic energy of the upper layer currents, which, in turn, is converted into potential energy due to the hydrostatic pressure gradient forces. Most of P from the eastern half of the sea is transported by the advective flow to the western one, and a smaller part is transferred into the kinetic energy of the currents in the lower layer.



F i g. 5. Scheme of average flows and energy conversions with the regard for the β-effect (numbers denote the energy flow values, MJ/s)

In the western half of the basin, the main source of K_1 replenishment is the conversion from potential energy carried by currents from the east. A small part of the potential energy also goes into K_2.

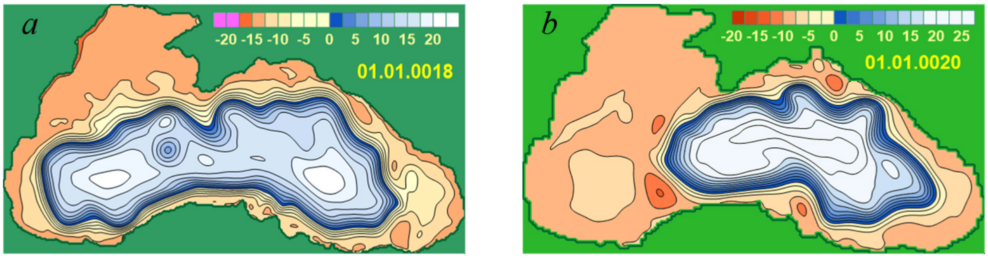
The kinetic energy of the upper layer currents in the western half actively dissipates, but a rather significant part of it is transferred back to the eastern half due to advection, thereby creating a mechanical energy circulation. The kinetic energy source in the eastern half of the sea in the form of an advective flow K_1 is approximately equal in magnitude to the energy dissipation in this area.

The energy loss in the considered numerical experiment happens due to the kinetic energy dissipation of the flows of the upper and lower layers due to bottom friction and horizontal turbulent viscosity. Moreover, in the dissipation structure in the upper layer, bottom friction predominates, and in the lower layer, turbulent viscosity prevails. The bottom friction of the upper layer in the western part makes the greatest contribution to the energy dissipation as a whole. The maximum energy sink areas are located along the continental slope along the northwestern and western shelf edge (Fig. 1, *b*).

The advective transfer of kinetic energy in the lower layer is directed from east to west, but its value is only 0.1% of the total energy inflow, which is commensurate with the accuracy of calculating the energy balance components in the model.

The most probable reason for the uneven distribution of averaged energy flows between the eastern and western parts of the Black Sea, according to the author, is the β-effect. Under the western boundary layer theory [19, 20], the Earth rotation and sphericity lead to an asymmetry of circulation cycles in the ocean, which is pronounced in the western intensification of currents. The energy transfer from east to west is carried out by Rossby waves, which belong to the class of gradient-eddy waves. In our previous numerical experiments [12], various types of long-term oscillations were obtained in the field of large-scale currents of the Black Sea in the form of barotropic, baroclinic and topographic Rossby waves, but no noticeable intensification of currents near the western coast was obtained.

To prove the hypothesis about the β-effect influence on the redistribution of energy flows in the Black Sea, an additional numerical experiment was carried out. It contained parameters similar to those used in the first experiment, but at $\beta = 0$. A visual representation of the circulation that took place in this experiment in a statistically equilibrium mode can be obtained from Fig. 6, *b*.



F i g. 6. Instantaneous sea level fields ζ, cm, in the experiment with (*a*) and without (*b*) the regard for the β-effect

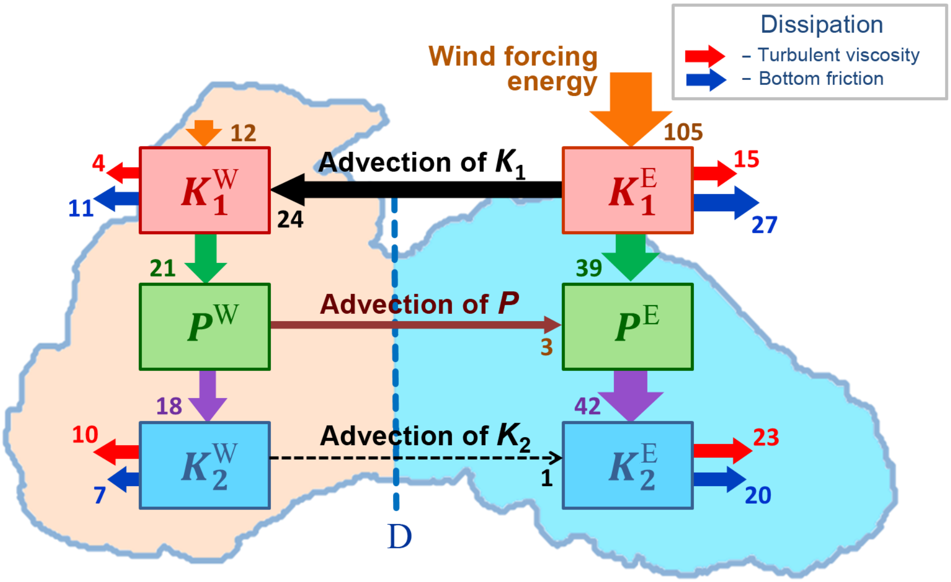
Due to the quasi-geostrophicity of the motions of the considered scales, the ζ fields give a good idea of the large-scale circulation in the upper layer. The ζ isolines coincide with the streamlines, and their maximum concentration corresponds to the Black Sea Rim Current core. In Fig. 6, *a*, the ζ field obtained in the experiment with allowance for the β-effect is shown for comparison. The main difference in circulation is that in the experiment with a constant Coriolis parameter, the Rim Current does not propagate to the western part of the sea, but is concentrated in the central and eastern parts. As shown by previous experiments, this circulation nature is explained by the choice of the tangential wind stress field over the sea (Fig. 1, *c*, *d*) and is determined primarily by the basin shape, bottom topography and influence of nonlinear advective terms in the equations of motion.

The scheme of energy flows and energy conversions (Fig. 7), constructed for the second experiment in a manner similar to that used in the first experiment (Fig. 4, 5), demonstrates the absence of an advective potential energy flow from the eastern half of the basin to the western one. In this case, an insignificant advective flow P in the opposite direction, which does not have a noticeable effect on other energy flows, is observed.

Contrary to the first experiment, at $\beta = 0$, energy conversions occur in the direction from K_1 to P in both halves of the basin.

At the same time the advective transfer of kinetic energy in the upper layer takes place from the eastern half of the basin to the western one. Obviously, this is due to the spatial unevenness of the wind stress field used, because of which more kinetic energy of currents is generated in the eastern half of the sea.

The wind energy pumping non-uniformity can also explain the large values of energy dissipation in the eastern half of the basin in the second experiment.



F i g. 7. Scheme of average fluxes and energy conversions in the experiment with no regard for the β-effect (see the notation in Fig. 5)

Thus, a comparison of the energy characteristics calculated from the results of two experiments, which differ only in taking into account/not taking into account the β-effect, confirms the earlier hypothesis about the influence of the combined effect of the Earth sphericity and rotation (β-effect) on the spatial redistribution of flows and conversions of mechanical energy in Black Sea.

Conclusion

After analyzing the data obtained as a result of numerical modeling within the framework of a two-layer eddy-resolving model, the significant differences in the energy sector of the eastern and western parts of the Black Sea were found.

In the eastern half of the sea, the main replenishment of the kinetic energy of the upper layer currents occurs due to the tangential wind stress work and in the western half, on the contrary, the energy dissipation processes due to bottom friction prevail. There is also a difference in the direction of the average transitions between potential and kinetic energy in different halves of the basin. In the east, the transformation of the kinetic energy of the upper layer currents into potential energy prevails, and in the west, on the contrary, potential energy is converted into kinetic energy. The observed imbalance in the spatial distribution of energy sources and sinks is compensated by the advective transfer of potential energy through the conditional boundary D from east to west.

The calculated advective flow of kinetic energy in the upper layer of the sea from the western to the eastern half is of interest. Considering that the kinetic energy in the western half is formed from the potential energy coming from the eastern part, where it was converted from the kinetic energy of the upper layer, it can be said that there is a mechanical energy circulation in the Black Sea.

It is important to understand that the constructed scheme of energy conversions reflects the average state of the energy characteristics. At certain moments of time, energy flows (transitions) can significantly differ from this scheme in magnitude and direction.

A comparative analysis of the energy balances obtained in the experiments carried out with and without taking into account the β-effect gives reason to believe that it is the β-effect being the cause of the spatial inhomogeneity features of energy flows in the Black Sea described above. This also indirectly confirms our earlier conclusion about the β-effect role in the distribution of the Rim Current to the entire perimeter of the deep-water part of the Black Sea.

In the present paper, some issues related to the structure of average advective energy flows between the eastern and western parts of the sea have not been considered. In particular, it is not clear how the flows are distributed along the D section and what scales of movement they belong to. The next work will be devoted to the answers to these and other questions.

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