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Original article

Mechanisms of Variability of the Black and Marmara Seas Circulation Based on Numerical Energy Analysis

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Abstract
Purpose. The study is purposed at analyzing the physical mechanisms of formation of the Black and Marmara seas circulation structures based on the numerical experiments with climatic boundary conditions.
Methods and Results. To investigate the reasons for the formation of circulation features, the energetic approach was applied that permitted to calculate the work of the forces affecting the marine environment. Location in the same geographical region determines similarity of atmospheric conditions for the Black and Marmara seas, and a clearly pronounced two-layer water stratification in both basins is related to a significant difference in salinity of the Black Sea and Mediterranean waters. To analyze the mechanisms of circulation variability, the mean and eddy fields formed under the impact of climatic atmospheric forcing and calculated using a numerical model of sea dynamics were considered. Wind influence, thermohaline fluxes on the sea surface, buoyancy work, friction, and diffusion were quantitatively assessed based on calculation of the Lorenz energy cycle components. The common features were found in the mechanisms of mesoscale variability, and the differences – in the mechanisms of large-scale circulation variability.
Conclusions. It is shown that the main source of energy for the Black Sea mean circulation is wind stress work, and as for the Marmara Sea, the dominant factor is buoyancy work. For both basins, variability of the eddy kinetic energy characterizing the mesoscale dynamics is conditioned by baroclinic instability. At that, about a quarter of the available potential energy in the Black Sea, and about a half of it in the Marmara Sea is transformed into the eddy kinetic energy.

Keywords: Black Sea, Marmara Sea, circulation, kinetic energy, available potential energy, Lorenz energy cycle, dissipation, baroclinic instability, buoyancy, wind stress

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1. Introduction

The Black and Marmara seas are internal basins, where water exchange with the ocean is limited by narrow straits. Along with the Sea of Azov, they form the so-called Euxine Cascade, where the circulation structure is determined mainly by atmospheric forcing and water exchange through the straits. A number of modern papers is devoted to the numerical study of water dynamics of the entire cascade [1, 2] and its separate basins (for example, [1] [3, 4]) focusing on simulation methods

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[1] Copernicus Monitoring Environment Marine Service. *Black Sea Physical Reanalysis (CMEMS BS-Currents) (Version 1): Data Set.* 2020. [online] Available at: https://doi.org/10.25423/CMCC/BLKSEA_MULTIYEAR_PHY_007_004 [Accessed: 30 May 2023].

for the observed circulation characteristics. There are far fewer studies, especially for the Marmara Sea, that discuss circulation variability mechanisms and quantify the influence of specific physical processes on the thermohaline and dynamic structure of waters.

The study of circulation energy is an important tool for analyzing the eddy and current formation mechanisms. Since the energy balance enables to estimate contributions of forces to the considered processes, it is possible to determine physical reasons for the formation and evolution of circulation features based on these estimates. It is the very approach that was used in [5], where, using the basin energy analysis, the influence of atmospheric forcing and flows through straits in such semi-enclosed seas as the Mediterranean, Red, Black and Baltic was studied. Numerical analysis of the equations for the rate of kinetic and potential energy change for the Black Sea is presented in [6–8]. Some elements of the eddy kinetic energy budget of the Black Sea, calculated from the modeling results, are considered in [9].

The studies of the Marmara Sea dynamics at different time intervals note that wind forcing and flows through the straits are the dominant factors determining the structure and spatiotemporal variability of the mesoscale features of its circulation and describe some sea energy features. Thus, [10] shows that in some years the kinetic energy in the northern Marmara Sea can be comparable to the energy of the current entering from the Bosporus, and further direction of the jet depends on the wind stress maximum location. In a recent study based on the SHYFEM model [4], it was calculated that the flow from the Bosporus forms an anticyclonic circulation in the Marmara Sea and the eddy kinetic energy reaches high values near the jets emerging from the Bosporus and Dardanelles straits as well as on the downwind side of the islands. In the past few years, calculations of the Marmara Sea circulation were also carried out based on the model developed at Marine Hydrophysical Institute (MHI). The influence of momentum fluxes through the Bosporus and Dardanelles straits as well as atmospheric fluxes was assessed; analysis of the kinetic energy budget was carried out [11].

Unlike the papers concerning the Black Sea, publications on the Marmara Sea dynamics did not evaluate the relationship of all redistribution cycle components of various energy types in the basin (Lorenz energy cycle) and did not determine the quantitative relationships between various types of incoming and expended energy. Climatic circulation has been simulated, and calculations and comparative assessments of the energy cycles in these basins have been carried out to study variability mechanisms in the circulation of inland seas with straits using the example of the Black and Marmara seas. A numerical analysis of the Lorenz cycle components for the Marmara Sea has been presented for the first time.

2. Methods and data

The numerical experiments were carried out using a nonlinear eddy-resolving model developed at MHI [12]. The model is built in a Cartesian coordinate system based on a complete system of ocean thermohydrodynamic equations in the Boussinesq and hydrostatics approximations. The sea level is calculated under the assumption that the linearized kinematic condition is satisfied on the free surface, the vertical velocity is calculated from the continuity equation. Density depends nonlinearly on temperature and salinity according to Mamaev's formula [2]. Tangential wind stresses, heat fluxes, precipitation and evaporation rates are specified as boundary conditions on the free surface. Free-slip conditions are set on solid lateral boundaries for tangential velocity components and the absence of normal fluxes of momentum, heat and salt. Friction on the bottom is not taken into account. The model takes into account river inflows and water exchange through straits. Dirichlet conditions are set on liquid sections of the boundary, so the velocity is calculated from the flux rates in rivers and straits, the temperature and salinity are specified. The vertical turbulent exchange is parameterized using the Pacanowski–Philander approximation [13]. The horizontal turbulent viscosity and diffusion coefficients are constant. The stages of the model development, the numerical implementation features of the equations and a detailed description of the model are presented in [12].

The Black Sea model

Modelling of the Black Sea climatic circulation was carried out using the following parameters of the MHI model. The model domain is represented by a uniform grid of 698 × 390 nodes with a horizontal resolution of 1.64 km, which is approximately (1/48)° longitude and (1/66)° latitude. The lower left grid node corresponds to a point with coordinates 27.34°E, 40.81°N. Vertically, 27 z-horizons with depths of 2.5; 5; 10; 15; 20; 25; 30; 40; 50; 62.5; 75; 87.5; 100; 112.5; 125; 150; 200; 300; 400; 500; 700; 900; 1100; 1300; 1500; 1700; 2100 m are specified. The basin bathymetry is based on EMODnet [3] data. The time step is 96 s. In accordance with the conclusions of [14], the spatial resolution of the MHI model of 1.64 km enables a clear simulation of mesoscale circulation features, since this value is significantly smaller than the Rossby deformation radius (15–20 km).

Monthly mean values of total heat flux [15] and moisture flux (the difference between precipitation and evaporation) [16] were used on the sea surface. The tangential wind stress fields are built for each day using surface pressure distributions [17]. The monthly mean water fluxes at the mouths of the Danube, Dnieper, Dniester, Sakarya, Kizil-Irmak, Yeshil-Irmak, Rioni rivers, in the Kerch Strait and the Upper Bosporus current are specified [18]. To comply with the law of mass conservation in the basin, the flux rate in the lower Bosporus current is calculated under the assumption that the total water flux rate for the year is equal to zero (the sum of the flux rates of rivers, straits and the difference between precipitation and evaporation). Salinity at river mouths is 7‰, the monthly mean temperature is given according to the atlas [18]. Temperature and salinity in the Lower Bosporus current correspond to the annual mean characteristics – 12 °C and 35 ‰, respectively.

The initial field (sea level, temperature, salinity and horizontal velocities) for January 1 of the climatic year was built by interpolating the experiment results [19]

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[2] Mamayev, O.I., ed., 1975. *Temperature – Salinity Analysis of World Ocean Waters*. Amsterdam: Elsevier, 374 p. (Elsevier Oceanography Series). doi:10.1016/s0422-9894(08)x7055-2

[3] EMODnet Bathymetry WMTS Service. *European Marine Observation and Data Network*. [online]. Available at: https://www.emodnet-bathymetry.eu [Accessed: 30 May 2023].

into 1.64 km grid points. The experiment was conducted on a 5 km grid with assimilation of climatological temperature and salinity profiles. Note that the experiment [19] was performed at the same atmospheric forcing as the calculation analyzed. The integration of the model equations was carried out for one year period. The output data of the model are the daily mean fields of sea level, temperature, salinity and velocity components.

The Marmara Sea model

The MHI model [12] adapted for the Marmara Sea was used to simulate climatic circulation of the specified basin. Dirichlet conditions on liquid boundaries were applied in the Bosporus and Dardanelles straits. Climatic values of temperature, salinity and velocity in the straits were determined according to the data given in [20, 21]. On the free surface, the monthly mean climatic fluxes of heat, moisture and daily mean tangential wind stress were specified. They were obtained by averaging *ERA*5 atmospheric reanalysis data [4] for the 30-year climate period of 1991–2020 [5]. The bottom topography was taken the same as in the model implementation [11].

The calculated domain was located between 40.28° and 41.11°N, 26.68° and 29.50°E and contained 178×104 nodes, which is approximately 1.22 km and 0.83 km in zonal and meridional directions, respectively. Vertically, 18 z-levels were specified with depth values from 2.5 to 1100 m (calculated horizons 2.5; 5; 10; 15; 20; 25; 30; 40; 50; 62.5; 75; 100; 150; 300; 500; 700; 900; 1100 m). The time step was 30 s.

The initial field was constructed in accordance with the data from [11]. The calculation was carried out for several annual periods with climatic atmospheric fluxes repeating from year to year. The period of adjustment of the thermodynamic fields of the Marmara Sea to atmospheric conditions was monitored by the evolution of the calculated integral characteristics. After the solution reached a quasi-periodic regime with an annual period (after 1000 model days), the resulting three-dimensional hydrophysical fields were recorded as climate ones.

Lorenz energy cycle

Numerical assessments of the influence of basic physical processes, such as thermohaline and wind forcing, dissipation, buoyancy fluxes and current instability, on the circulation structure were carried out based on the calculation of the Lorenz energy cycle [22] components using the following formulas:

$$K_m = \frac{1}{2}\int_V \rho_0(\bar{u}^2 + \bar{v}^2)dV, \qquad K_e = \frac{1}{2}\int_V \rho_0\overline{(u'^2 + v'^2)}dV,$$

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[4] Copernicus Climate Change Service. *ECMWF Reanalysis v5 (ERA5)*. 2023. [online] Available at: https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5 [Accessed: 29 October 2023].

[5] WMO, 2017. [*WMO Guidelines for Calculating Climate Normals*]. Geneva: WMO, 21 p. [online] Available at: https://library.wmo.int/doc_num.php?explnum_id=4168 [Accessed: 17 November 2023] (in Russian).

$$P_m = \frac{1}{2}\int_V \frac{g}{n_0(z)}\overline{\rho^*}^2 dV, \qquad P_e = \frac{1}{2}\int_V \frac{g}{n_0(z)}\overline{\rho^{*\prime 2}} dV, \tag{1}$$

$$n_0(z) = \frac{\partial < \overline{\rho} >}{\partial z}, \qquad \rho^* = \rho - < \overline{\rho} >,$$

where K_m is kinetic energy (KE) of the mean current; K_e is eddy kinetic energy; P_m is mean available potential energy (APE); P_e is eddy available potential energy; $\rho_0 = 1000$ kg·m^{-3}; ρ is local density; ρ^* is local density anomaly; $< \overline{\rho} >$ is local density area-averaged over layer; u and v are zonal and meridional velocity components; $\int_V dV$ is volume integral; g is gravity acceleration. The stroke denotes deviation from the time average, the bar above the symbol indicates time averaging; the averaging interval is equal to one year for all values. The rates of energy conversion C between the components of the energy cycle can be written as

$$C(K_e, K_m) = \int_V \rho_0 (\overline{u'\mathbf{u}'} \cdot \nabla \overline{u} + \overline{v'\mathbf{u}'} \cdot \nabla \overline{v}) dV, \qquad C(P_e, P_m) = \int_V \frac{g}{n_0} \overline{\rho'\mathbf{u}'} \cdot \nabla_h \overline{\rho} dV,$$

$$C(P_m, K_m) = \int_V g \overline{\rho}\,\overline{w} dV, \qquad C(P_e, K_e) = \int_V g \overline{\rho' w'} dV, \tag{2}$$

where $\mathbf{u}'$ are horizontal velocity components; w is vertical velocity component; ∇ is Hamiltonian operator. It is true for the transformation rate that if $C(X, Y) > 0$, then X is transformed into Y and vice versa. The energy conversion between K_m and K_e is due to barotropic instability caused by the velocity shear and the energy transfer from P_m through P_e to K_e is due to baroclinic instability. The buoyancy work describes transformation of energy between P_m and K_m.

Energy generation G is provided by the mean and eddy parts of the wind stress work and buoyancy fluxes on the sea surface for KE and APE, respectively:

$$G(K_m) = \int_S \left(\overline{\tau_x}\,\overline{u} + \overline{\tau_y}\,\overline{v}\right) dS, \qquad G(K_e) = \int_S \left(\overline{\tau_x' u'} + \overline{\tau_y' v'}\right) dS,$$

$$G(P_m) = \int_S \frac{g}{n_0(z)} \overline{\rho^*}\,\overline{Q} dS, \qquad G(P_e) = \int_S \frac{g}{n_0(z)} \overline{\rho^{*\prime} Q'} dS, \tag{3}$$

where τ_x, τ_y are components of the tangential wind stress vector; Q is buoyancy flux on the surface; $\int_S dS$ is the integral over the surface layer area.

Dissipative terms D are calculated from the energy budget equations under the assumption that on average per year the energy change rate is zero. Note that according to the estimates of the terms of the equation for the KE change rate, which was obtained as an exact consequence of the differential formulation of the problem (Fig. 1 in [7, p. 77]), for the Black Sea climatic circulation, energy dissipation occurs mainly due to horizontal and vertical internal friction with little friction on the bottom. The paper [23] also shows that taking or not taking into account the bottom friction affects only the time when climatic circulation reaches a quasi-periodic regime. Therefore, ignoring friction on the bottom, allowed in the MHI model, does not lead to the kinetic energy increase. The conditions for carrying out numerical experiments are such that, on average, the total system KE changes by no more than 10% per year.

3. Results

Based on the modelled fields of thermohydrodynamic characteristics, the energy cycle components for the Black and Marmara seas were calculated using formulas (1)–(3). Preliminary estimates of the vertical distribution of KE and APE density in the Black Sea showed that about 80% of the mean KE and 90% of the mean APE were concentrated in the upper 200-meter layer. These data are consistent with the results presented in [18]. Thus, in the Black Sea, no more than 20% of the KE can be transferred from the upper layer to the underlying horizons through the vertical velocity shear. There is no significant APE flux from the upper layer, which is associated with a weakening of vertical diffusion processes and a decrease in buoyancy fluxes below the permanent pycnocline.

For the Marmara Sea, estimates of the mean KE and APE showed that the KE density in the upper 30-meter layer is approximately 1.5 times higher than in the underlying layer (61 and 39%). The difference between this ratio and the ratio for the Black Sea can be explained by the presence in the Marmara Sea under the permanent pycnocline of a reverse current directed from the Mediterranean Sea to the Black Sea at a velocity approximately twice as weak as in the upper layer. At the same time, in the Black Sea, mean velocities decrease with depth and under the pycnocline their values are an order of magnitude lower than near the surface. According to the calculations of the mean APE density in the Marmara Sea, 80% of the APE is concentrated in the upper 30 m layer. This is explained by the fact that the density of the waters of the lower layer of the Marmara Sea is due to highly saline Mediterranean waters entering through the Dardanelles Strait with significantly lower vertical gradients.

Therefore, for both seas, the majority of both kinetic and available potential energy is concentrated in the upper layers, including the pycnoclines.

Lorenz energy cycle for the Black Sea

Fig. 1 shows the Lorenz energy cycle for the climatic circulation of the Black Sea (values are indicated rounded to the nearest hundredth). The energy cycle components are presented for the upper active layer 0–200 m, which includes the main features of the thermohaline structure of the Black Sea [24]: seasonal thermocline (15–20 m), cold intermediate layer (30–100 m) and the main halocline layer (75–150 m). As can be seen from Fig. 1, 66% of the total KE of climatic circulation is provided by the mean current and 33% – by eddy movements. In this case, the main source of KE is the wind stress work – the contribution $G(K_m)$ is the largest among all climate circulation energy sources. Qualitatively, this result corresponds to the generally accepted idea that it is the wind forcing that forms large-scale basin circulation in the Black Sea [25–27].

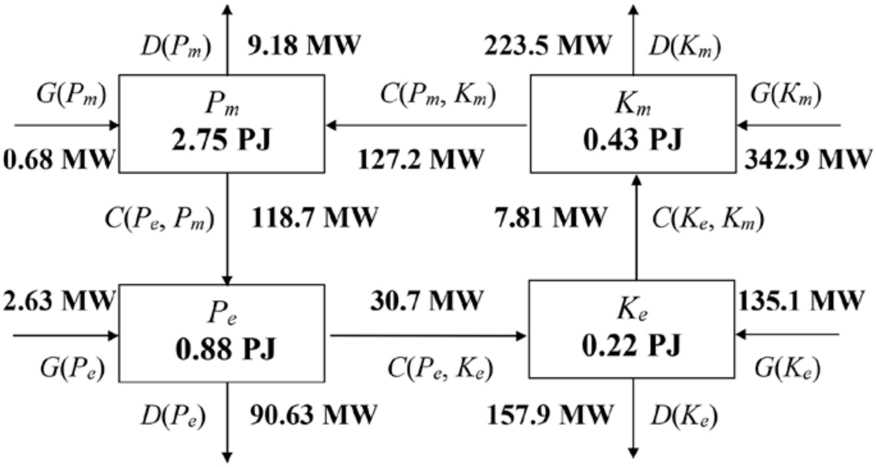


Fig. 1. Diagram of the Lorenz energy cycle for climatic circulation in the upper 200-m layer of the Black Sea

Eddy KE is supported by two sources: the time-varying part of the wind stress work $G(K_e)$ and the baroclinic instability $C(P_e, K_e)$. However, the contribution of the latter is almost four times less than the contribution from the wind. Energy flux $C(K_e, K_m)$, caused by barotropic instability, is minimal and directed from the eddy motion to the mean current. This indicates that for a quasi-stationary circulation regime, evolution of the main mesoscale eddies of the Black Sea (Sevastopol and Batumi anticyclones) is not related to the mean large-scale circulation.

Mean large-scale circulation maintains mean APE reserve, which is demonstrated by the $C(P_m, K_m)$ flux direction. The main part of this energy is transformed further into eddy APE. Generational and dissipative contributions to the P_m change budget are relatively small. The $D(P_e)$ flux magnitude indicates that almost 74% of the incoming energy is dissipated due to diffusion processes. However, the remaining 26% goes into eddy KE. Thus, for the climatic circulation in the upper 200-meter layer of the Black Sea, baroclinic instability processes contribute to transformation only 26% of the existing APE into eddy KE. If K_e budget is considered separately, then, according to Fig. 1, vertical dissipation completely compensates for the energy influx from the wind ($D(K_e) > G(K_e)$); therefore, it is baroclinic instability that plays the main role in the evolution of mesoscale eddy movements.

Lorenz energy cycle for the Marmara Sea

Similar to the Lorenz cycle study in the Black Sea, the upper layer including surface waters with the most active dynamics and permanent pycnocline layer was selected for the Marmara Sea. Therefore, in this basin, the components of the climatic energy cycle were calculated to the 30 m depth. Some energy characteristics and seasonal circulation of this layer for real atmospheric conditions in 2008 were studied in [11]. For the climatic circulation of the Marmara Sea, a diagram of the Lorenz energy cycle is shown in Fig. 2 (values are rounded as in Fig. 1).

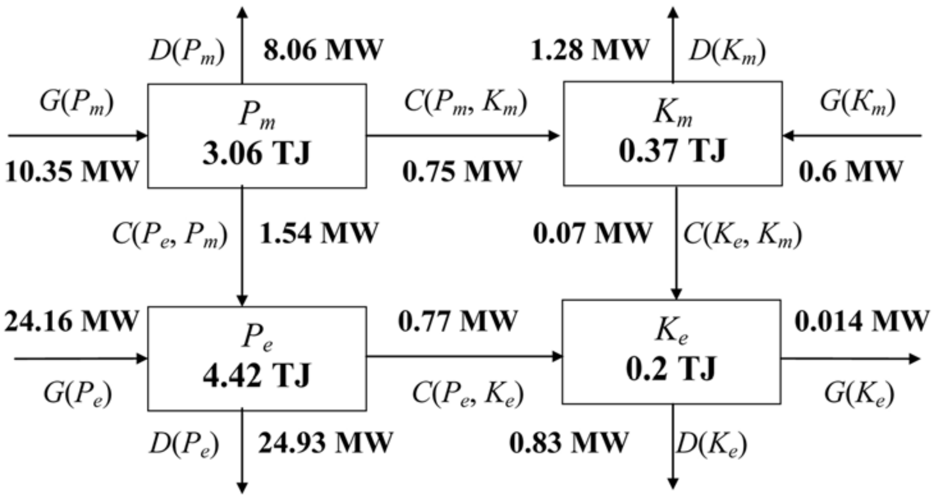


Fig. 2. Diagram of the Lorenz energy cycle for climatic circulation in the upper 30-m layer of the Marmara Sea

The ratio of energy cycle components shows that the contribution of mean KE flux to the climatic circulation of the Marmara Sea is approximately 65% and another 35% is provided by eddy movement energy. Unlike the Black Sea, where the main KE source is the wind, the greatest contribution to the generation of the mean Marmara Sea KE is made by the buoyancy work (56 %), exceeding the wind stress work (44%).

Eddy KE is supported by two sources: the mean KE flux transformation (barotropic instability) and the APE transformation (baroclinic instability) with the contribution of the latter dominating and amounting to 91%. Energy fluxes replenishing the eddy KE budget are almost completely dissipated due to internal vertical friction (98%) and another 2% are lost due to wind friction when the direction of wind pulsations is opposite to the direction of current velocity pulsations.

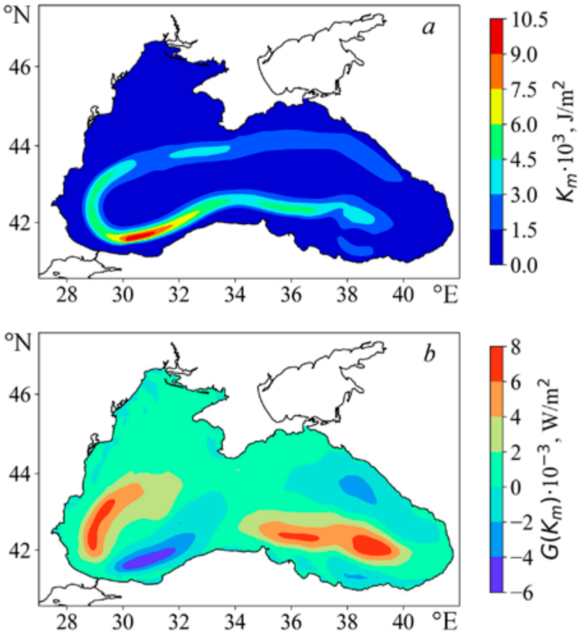
The generation and dissipative components of the P_m and P_e budget prevail. Additional estimates of the $G(P_m)$ and $G(P_e)$ terms without taking into account the influence of straits showed that in this case there is a significant (by about two orders of magnitude) underestimation of the energy influx. Therefore, the main contribution to APE generation comes from flows through the Bosporus and Dardanelles straits. The incoming mean APE is partially spent on the buoyancy work (7%), and goes partly into the eddy APE due to baroclinic instability (15%), the rest dissipates. The $C(P_e, P_m)$ flux is the largest in absolute value among the energy conversion rates in Fig. 2. The analysis shows that in the eddy APE budget about 50% of the $C(P_e, P_m)$ flux is converted into eddy KE against the background of mutual $G(P_e)$ and $D(P_e)$ compensation.

It should be noted that the components of the budgets for changes in the mean and eddy APE are an order of magnitude larger in absolute value than the KE, and energy conversion from APE provides the main influx both into K_m through the buoyancy work, and into K_e due to baroclinic instability. Accordingly, in the upper Marmara Sea layer, the climate circulation is formed to a greater extent by the APE transformation generated by fluxes through the straits. Buoyancy fluxes formed by thermohaline atmospheric forcing are of little significance in the energy balance of the Marmara Sea. This conclusion is consistent with the results of [28], where it was shown that a realistic circulation is formed even without taking into account atmospheric forcing, but when the flows through the straits are specified.

4. Discussion

The obtained qualitative and quantitative assessments of the Lorenz energy cycle for the climatic circulation of the upper active layer of the Black Sea from a physical viewpoint can be interpreted as follows. The main energy source in the Black Sea is wind. Cyclonic vorticity of the wind field forms a large-scale cyclonic gyre. According to Fig. 3, the zones of extreme values of the contribution from the wind and from the KE of the mean current coincide.

Approximately 2/3 of the incoming energy from the wind is dissipated as a result of vertical friction and the remaining part is converted into mean APE. That is, on average per year, the cyclonic circulation maintains density stratification with the upwelling of denser waters in the sea center and the descent of less saline waters at the basin periphery. Compared to energy influx from the mean current, the contribution of sea surface thermohaline forcing to APE variability is negligible. As a result of the action of baroclinic instability processes, about a quarter of APE is transformed into eddy KE. In this case, due to mutual compensation of the components describing the eddy KE generation and dissipation, mesoscale circulation variability is determined by baroclinic instability processes.

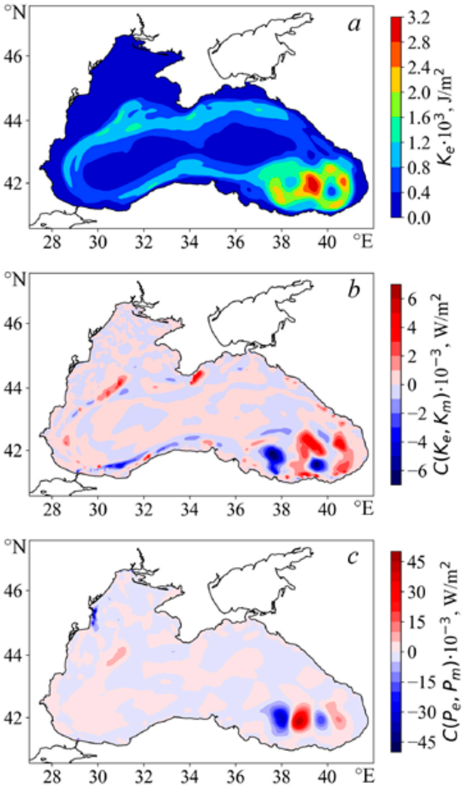


F i g. 3. Spatial distribution of the mean current kinetic energy (*a*) and contribution of the wind stress work (*b*)

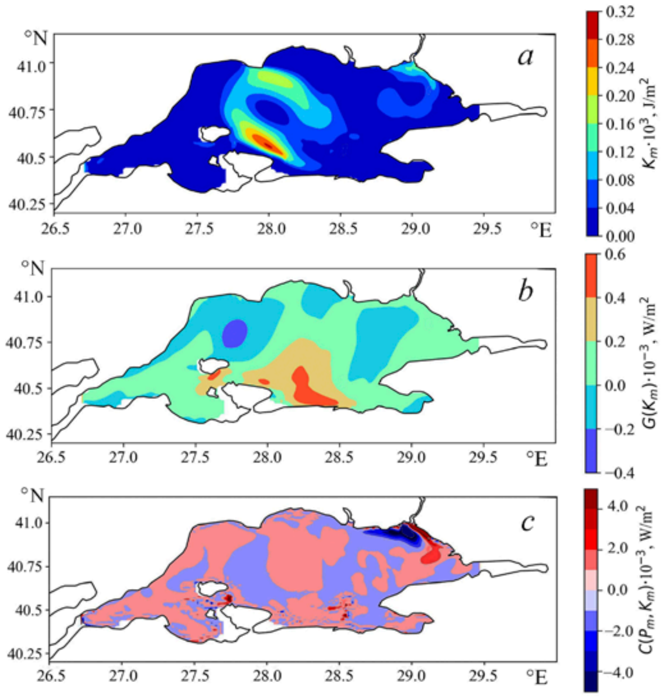
Fig. 4 shows spatial distributions of the vertically integrated K_e, $C(K_e, K_m)$ and $C(P_e, P_m)$. Apparently, the maximum eddy KE is localized in the stationary zone of the Batumi anticyclone (southeastern corner of the sea in Fig. 4, *a*). Here, the region of the most intense energy exchange is observed due to barotropic (Fig. 4, *b*) and baroclinic (Fig. 4, *c*) instability processes. In this case, the extreme values of the $C(P_e, P_m)$ parameter are approximately seven times greater than $C(K_e, K_m)$.

As follows from the diagram in Fig. 2, the mean current in the Marmara Sea is supported by the contributions of wind stress and buoyancy works. Fig. 5 shows the fields of the mean APE, and mean wind stress and buoyancy works integrated in the upper 30-meter layer.

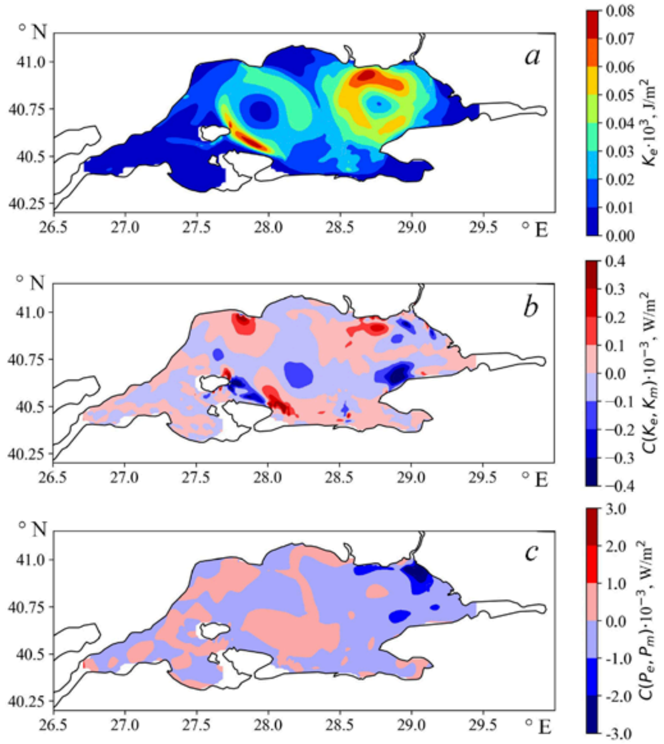
Apparently, the increased K_m values north of 40.75°N (Fig. 5, *a*) correspond to the zone of $C(P_m, K_m)$ positive values (Fig. 5, *c*). In the area of maximum K_m to the northeast of Kapıdağ Peninsula (central part of the southern coast), increased $G(K_m)$ values are observed (Fig. 5, *b*), which in absolute value are approximately an order of magnitude less than the contribution of buoyancy work. Fig. 2 and 5 indicate that the climatic circulation in the upper Marmara Sea layer is largely gradient in nature. An intense APE transformation not only in the area of the straits but also in the central sea part is apparently associated with a difference in sea level height [29] as well as with a significant difference in water salinity [20, 21] between the Black and Mediterranean seas.



F i g. 4. Spatial distribution of the eddy kinetic energy (*a*), and the barotropic (*b*) and baroclinic (*c*) instability contributions



F i g. 5. Spatial distribution of the mean current kinetic energy (*a*) and the contributions of wind stress work (*b*) and buoyancy work (*c*)



F i g. 6. Spatial distribution of the eddy kinetic energy (*a*), and the barotropic (*b*) and baroclinic (*c*) instability contributions

Eddy KE, which characterizes mesoscale variability, is replenished due to energy conversion as a result of barotropic and baroclinic instability. Moreover, in the Marmara Sea as well as in the Black Sea, the energy transformation from available potential into eddy kinetic energy is an order of magnitude greater than the energy influx from the mean current. Fig. 6 shows maps of vertically integrated K_e, $C(K_e, K_m)$ and $C(P_e, P_m)$. Two K_e maxima are clearly expressed in Fig. 6, *a*: to the southwest of the Bosporus and to the northeast of Kapıdağ Peninsula.

According to Fig. 6, *c*, eddy energy (and therefore mesoscale variability) in the eastern part of the sea is caused by APE transformation ($C(P_e, P_m) < 0$). The second K_e maximum is formed by comparable magnitude $C(K_e, K_m)$ and $C(P_e, P_m)$ contributions. Comparison of Fig. 5, *a*, 6, a and 6, *b* shows that the area near Kapıdağ Peninsula is the zone of the most intense energy transfer from the mean current to the eddies.

5. Conclusion

The present work provides a numerical estimation of the Lorenz energy cycle in the Black and Marmara seas. Circulation modelling in both basins was carried out based on the numerical eddy-resolving MHI model with high spatial resolution. To identify the general variability mechanisms in the circulation of inland seas with limited water exchange, the water dynamics in the layer from the surface to the lower boundary of the permanent pycnocline, formed under conditions of climatic atmospheric forcing, is considered. The physical interpretation of the presented estimates of the energy cycle is consistent with the hydrophysical features of the seas under consideration known from the literature.

In both cases the ratio between the mean and eddy KE is about 65 and 35% of the total KE despite geomorphological differences between the basins. At the same time, common features were found in the mesoscale variability mechanisms and differences in the mechanisms of large-scale circulation variability. Thus, the main energy source for the mean circulation of the Black Sea is the wind stress work and the main source of energy for the Marmara Sea is the buoyancy work. In other words, in the Black Sea the mean current structure is determined directly by external (wind) influence, and in the Marmara Sea – by internal APE redistribution supported by the inflow of waters with different thermohaline characteristics through the straits. The analysis showed that in the Marmara Sea the mean APE change rate due to water exchange through the straits is two orders of magnitude greater than the rate under the influence of atmospheric forcing.

The eddy KE change rate, which characterizes mesoscale variability, for both basins is determined by baroclinic instability. At the same time, the energy influx into the eddies due to barotropic instability is less in both the Black and Marmara seas. Let us note that as a result of baroclinic instability processes in the Black Sea about a quarter of APE is transformed into eddy KE, and in the Marmara Sea – about a half.

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