The work of the main forces in the annual-averaged and seasonal-averaged energy balance of the Black Sea circulation

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Abstract. A numerical experiment with a high horizontal resolution for 2016 was carried out on the basis of a discrete eddy-resolving model, taking into account a real atmospheric forcing. The work of the main forces that support the baroclinic circulation of the Black Sea has been analyzed on the basis of the calculation results and in comparison with the energetics, obtained for other years (2011 and 2006). They included the wind work, buoyancy, pressure, turbulent friction, advection and turbulent diffusion. The wind force, buoyancy and vertical turbulent exchange brought contribution in the average annual balance of kinetic energy, the work of pressure and advection forces was small. The variability of potential energy was mainly specified by two factors - vertical turbulent diffusion and buoyancy work, which approximately compensated each other. The main contributions to the evolution of kinetic energy on the average seasons were made by four forces. These are the wind work, buoyancy, vertical and horizontal turbulent exchange. The most intensive work of wind forces was observed in the winter and autumn seasons, which was compensated by vertical turbulent friction. The buoyancy work was the most intense in the spring.

1. Introduction

A study of circulation in marine basins requires an assessment of the role of the main forces that generate and support a structure and dynamics of currents. Calculation and analysis of energetics, which includes the equations of the change rate of the kinetic (KE) and potential energies (PE), is the efficient method. The first analysis of the energetics of an idealized oceanic basin for a three-dimensional model was carried out in [1]. In the sequel, the energy approach was used to study large and mesoscale variability in the oceans and seas [2].

Numerical prognostic experiments were carried out taking into account real atmospheric forcing to study the circulation of the Black Sea for 2006 and 2011 in [4], [5]. The obtained results allowed us to assess the main forces that form and support the circulation of the Black Sea. Analysis of annual-averaged and seasonal-averaged energy cycles made it possible to determine general patterns in the behavior of the energy of the Black Sea.

A numerical model [6], used for all calculations, is a modern computational complex, based on the complete equations of ocean thermohydrodynamics in the Boussinesq approximation, hydrostatics and incompressibility of sea water. A finite-difference system of equations was approximated on the C-grid and had a second order spatial accuracy (up to an uneven step). A "leapfrog" scheme for time approximation, semi-implicit representation for pressure and TVD scheme for approximating the advective terms in the equations of motion [7] were used in the model. The biharmonic operator in the...
momentum, heat and salt transfer equations provided filtering of computational noise and stabilized a numerical solution. The spatial resolution of the model was 1.64 km along horizontal coordinates, 27 vertical z-levels were used. Vertical turbulent processes were parameterized on the basis of the theory of Mellor-Yamada 2.5 [8], the river runoff and water exchange through straits were taken into account. Discrete budget equations of the potential and kinetic energies were an exact consequence of the finite-difference equations of the model that ensured the exact correspondence of the calculated energy to the initial formulation. This paper presents the results of the prognostic calculation for 2016, which made it possible to calculate the energy budget and compare it with previous experiments for 2006 and 2011.

2. Energy equations

We introduce the following notations (H is the variable bottom relief):

\[ \langle \varphi \rangle_s \int \varphi dx dy, \quad \langle \varphi \rangle_v \frac{1}{V} \int_0^H \varphi dz dx dy, V = \int_0^H dz dx dy. \]

Then the equation of the change rate of the kinetic energy (KE) in symbolic form has the following form:

\[ \langle E_i \rangle_v - \langle \zeta \rangle_h - g \frac{\varphi}{2} + \text{Adv}(R + E) = \langle P \rangle_v + \langle \text{Adv}(P) \rangle_v + \langle \text{Diff}_{\text{Hor}}(P) \rangle_v + \langle \text{Diff}_{\text{Ver}}(P) \rangle_v + \langle \text{Fluxes} \rangle_s. \] (1)

The following notations were introduced: \( P = -g z \rho \) - potential energy, \( \zeta \) - sea level, \( R \) - pressure.

The last term in equation (2) describes the effect of the boundary conditions for the advection-diffusion equations of heat and salt on the sea surface. The terms in equations (1) and (2) were described repeatedly in detail in [4]. Then we omit the brackets.

3. Results of calculation

We considered the average annual balance for 2016. Result was presented in Figure 1. The change in the average kinetic energy per year was mainly specified by wind work, buoyancy, horizontal and vertical friction. That was a trivial result since the advection of the kinetic energy and pressure was small. We note that these terms are zero for a closed basin.

The change rate of potential energy was specified by the work of three forces. They were vertical diffusion, horizontal diffusion and the buoyancy work. It should be noted that the work of friction and vertical diffusion gave a relatively large contribution to the change of the total energy. Such a structure of the work of the main forces was confirmed by the results, previously obtained for 2006 and 2011.
Figure 1. Energy diagram for terms, averaged over the volume and for 2016 in equations (1) and (2). All the terms in this figure and the subsequent ones were normalized to $10^{-6}$.

The main contribution to the change rate of the kinetic and potential energies in the winter season (Figure 2) was given by the same forces. Advection of PE was added, which in absolute value was greater than horizontal turbulent diffusion. Turbulent friction, vertical and horizontal diffusion led to a decrease in the total energy. Unlike in 2006, the same effect took place in 2011. There was an increase in KE and a decrease in PE. The total energy decreased in sum.

Figure 2. Energy diagram for the terms, averaged over the volume and for the winter of 2016, in equations (1) and (2).

Unlike the winter season, there was an increase in PE, specified by the heating of the water surface (the term $\text{Fluxes}$ in Figure 3) and vertical diffusion ($\text{Diff}_{\text{ver}}$) in the spring period (Figure 3). The kinetic and potential energies increased on average in that season. The values of the main flows, besides $\text{Diff}_{\text{ver}}$, decreased noticeably in comparison with the winter season. The wind work and vertical friction decreased by approximately 4 times, the buoyancy - in 2.5, the work of the horizontal friction - in 3 times.
Figure 3. Energy diagram for the terms, averaged over the volume and for the spring of 2016, in equations (1) and (2).

In the summer period (Figure 4), the change rate of KE was formed similarly to the previous energy cycles. The influx of energy from the wind and specified by the buoyancy work was compensated by the vertical friction and horizontal friction. All four forces contributed to the change in the potential energy, and the work of the advection force, which was almost twice the buoyancy work, gave a noticeable influx of energy. These results convincingly confirm that a correct accounting of rivers and straits makes a significant contribution to the energy sector of the Black Sea circulation in certain seasons of the year within a relatively short period of integration.

Figure 4. Energy diagram for the terms, averaged over the volume and for the summer of 2016, in equations (1) and (2).

Energetics of the autumn period differed from the previous diagrams. Strong autumn winds led to the largest inflow into the kinetic energy in comparison with other periods of the year (Figure 5). The qualitative difference from balances in the winter, spring and summer seasons was that the buoyancy work had changed sign and there was an inflow of energy from the kinetic to the available potential energy. The contribution of vertical diffusion appreciably increased, which exceeded the annual average by approximately 10 times. That effect was manifested in 2016 and was not observed in 2006 and 2011.
4. Conclusion

The work of the main forces that support the baroclinic circulation of the Black Sea has been analyzed on the basis of the calculation results and in comparison with the energetics, obtained for other years (2011 and 2006). They included the wind work, buoyancy, pressure, turbulent friction, advection and turbulent diffusion. The wind force, buoyancy and vertical turbulent exchange brought contribution in the average annual balance of kinetic energy, the work of pressure and advection forces was small. The energy inflow from the wind was compensated by vertical turbulent mixing, the transition from PE to KE - by horizontal mixing. The same structure was observed for 2006 and 2011. The variability of potential energy was mainly specified by two factors - vertical turbulent diffusion and buoyancy work, which approximately compensated each other.

The main contribution to the evolution of kinetic energy on the average seasons was made by four forces. These are the wind work, buoyancy, vertical and horizontal turbulent exchange. There was a significant inter-seasonal variability. The most intensive work of wind forces was observed in the winter and autumn seasons, which was compensated by vertical turbulent friction. The buoyancy work was the most intense in the spring of 2006 and 2016.

The change rate of the potential energy was mainly determined by vertical turbulent diffusion and the buoyancy work. Their greatest influence took place in the spring and summer seasons. The work of the advection forces had a noticeable effect on the change rate of the seasonal-averaged potential energy in certain periods of the year. These results convincingly confirm that it is urgent to take into account rivers and straits adequately in order to describe the energetics of the Black Sea circulation, even integrating for a period of several months. Turbulent exchange and vertical turbulent diffusion played the most important role in all conducted calculations. Therefore, their parameterization plays a significant role in the model and requires a meticulous choice of the turbulence model.

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