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MARINE PHYSICS

Monthly Mean Characteristics of the Intra-Annual Variability of the Caspian Sea Water Circulation from an Eddy-Resolving Thermohydrodynamical Model

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Abstract—We studied the seasonal variability of the water circulation in the Caspian Sea with the use of an improved model of the thermohydrodynamical processes. In comparison with recent studies [4], in the model proposed, the problem is solved over a finer spatial grid using 6-h atmospheric conditions. The explicit description of the mesoscale processes and high-frequency oscillations with time scales of $\sim 10^2$–10^4 s allowed us to widen the set of phenomena represented by the model. We analyzed the monthly mean characteristics of the water circulation, the eddy generation in the jet alongshore currents, the three-dimensional structure of the upwelling, the currents off the Kura River, and the currents along the eastern coast of the sea. The results of the modeling are compared with the data of field observations of the large-scale and mesoscale phenomena in the Caspian Sea. The subsurface cyclonic currents (below 20–50 m) in the deep-water parts of the sea are the most stable during a year. The seasonal variability of the surface currents is caused by the wind variability and momentum exchange with the subsurface currents.

1. INTRODUCTION

As it follows from numerous measurements, the hydrodynamics of seas and oceans are characterized by a wide spectrum of variability. However, present-day measurement methods and facilities, such as autonomous buoys, long-term anchored meters, and so on, allow only a small part of the spatiotemporal variability of the sea condition to be measured directly in the sea. At present, only satellite measurements can provide more or less complete information on the synoptic dynamics. These data, however, are restricted to the surface characteristics. Hence, no quantitative description of the water circulation and understanding of its dynamics and interactions can be obtained with the use of the measurements alone. Numerical models are necessary as a means for interpretation of the observation data and understanding the sea dynamics [22].

All this is true for the study of the circulation of the Caspian Sea water. Among the statistically reliable data on the sea condition available, we should indicate the monthly mean data on the thermohaline structure of the upper 100-m layer of the sea [8] and the data on the spectral characteristics of the currents [1, 9]. The most reliable data are probably the data on the diurnal, annual, and interannual variability of the sea level standing. From the data of the measurements of the biochemical parameters, the anticyclonic eddies off the southern Caspian coast were revealed [6]. The satellite images of the sea surface temperature allow us to reveal in more detail the spatiotemporal characteristics of the upwelling along the eastern coast of the middle Caspian Sea [20] that are known from field observations. In addition to the data of routine oceanographic field observations collected during this century and their interpretation, the studies with the use of models of the sea hydrodynamics carried out during recent years allow a better understanding of the character of the large-scale circulation of the sea water [4, 5, 10, 21].

The characteristic features of the hydrophysical regime in the Caspian Sea and its variability should be taken into account while developing a sea thermodynamical model. First, the Caspian Sea is enclosed and is not connected with the World Ocean. Therefore, the characteristic most sensitive to the variability of external forcing is the water balance. Second, in the Caspian Sea, in contrast to the marginal seas, the vertical stratification of the water is primarily determined by thermal factors. As a result, the vertical stratification and currents in the upper ($\sim$100 m) layer (above and below the pycnocline) are highly sensitive to the variability (diurnal and synoptic scales) of the atmospheric effect. Third, the Caspian Sea is a shallow-water sea—two thirds of the sea area is located over a shelf with depths less than 100 m. All the above-said determines the basic requirements of the sea dynamics model to be developed. They include the following: the model should be able to describe the characteristic dynamical features of the sea (the near-shore jet currents, eddy dynamics, upwelling, and vertical stratification), the sea level variability (therefore, the variability of the water mass), and be able to operate in the synoptic atmospheric forcing mode.

The present study is a continuation of the study of the variability of the thermohydrodynamical processes in the Caspian Sea with the use of the Model of Enclosed Sea Hydrodynamics (MESH) [15]. The study of the large-scale characteristics of the annual variability of the sea hydrodynamics with the use of MESH [2, 4] showed that the surface water circulation in the Middle and Southern Caspian Sea is not cyclonic for the period of a year and that the currents along the eastern coast of the Middle Caspian Sea are double-layered. In [2], the seasonal variability of the sea level and its dependence on the parameters of the near-water layer of the atmosphere and on the sea surface temperature were also studied. The sea surface temperature depends on both the sea–air interaction and three-dimensional thermohydrodynamical processes. The set of the processes associated with the mesoscale variability of the sea characteristics and its role in the water circulation cannot be described within the frameworks of the previous model, in particular, due to the insufficient spatial resolution and the use of monthly mean atmospheric conditions. In the present study, we attempt to widen the spectrum of the processes described by the model. In particular, we present the results of modeling of the sea hydrodynamics with a more precise description of the topographic eddied and frontal zones. The use of a finer spatial grid with respect to the vertical provides a better description of the thermohydrodynamical processes in the upper sea layer. It is of particular importance that, in the present study, we specify the synoptic atmospheric conditions at the upper boundary. This allows us to represent the thermohydrodynamical characteristics of the sea in a regime close to the on-line mode.

It is known that the use of synoptic atmospheric forcing results in the generation of high-frequency processes in the model solution. The temporal dispersion of the atmospheric forcing plays an important role in determining the momentum and heat fluxes and, hence, in the generation of the upper mixed layer and sea surface temperature, which, in turn, affects the evaporation from the sea surface and the sea level dynamics. The effect of the time averaging of the atmospheric forcing on the representation of the hydrodynamic processes by the model is considered in a series of studies. In particular, a one-dimensional problem on the intensification of turbulence in the upper sea level under a squall wind and the decaying turbulence after the stop of the wind is considered in detail in [18].

Being subjected to synoptic atmospheric forcing, the model generates inertial oscillations, which make a substantial contribution to the solution variability. In the models of sea hydrodynamics, the inertial oscillations are frequently not taken into account due to the use of smoothly varying atmospheric conditions or due to their removal through numerical filtering. The effect of the inertial oscillation on the vertical exchange was studied in [12], where different three-dimensional processes associated with storms and the after-storm effects are discussed. A brief review devoted to this issue is also presented there. As can be seen from the analysis of the results of this model, when we resolve the explicit inertial oscillations, they affect the large-scale characteristics of the solution, in particular, the vertical mixing and, hence, the sea surface temperature, evaporation, and sea level changes.

In the present study, we mainly analyze the monthly mean characteristics of the water circulation and, partially, the instant characteristics of the eddy structures. The high-frequency thermohydrodynamical sea processes, the variability of the sea level, and the variability of the currents in the Northern Caspian Sea will be considered in other papers.

2. FORMULATION OF THE NUMERICAL EXPERIMENT

The MESH used in the present study is a coupled model of the sea thermohydrodynamics, the air–sea interaction, and the thermodynamics of the sea ice [2, 4, 15]. The model is based on the complete three-dimensional set of equations of the geophysical hydrodynamics. We used the hydrostatic approximation, the Boussinesq approximation, and the assumption on the sea water incompressibility. The movable upper boundary of the sea is described by the equation of free surface in a quasi-linear approximation, which allows the description of both high-frequency oscillations and the variations of the mean sea level caused by the nonzero water balance. The predicting equations in the model are the equations for the horizontal components of the velocity, the equations for the heat and salt transport, and the equations for the free surface. In the present study, the MESH includes a parametrization of the vertical mixing according to the Mellor–Yamada scheme of the 2.5 level [16], which requires solving two additional prognostic equations. The applicability of the parametrization for the model of the Caspian Sea was discussed in [3]. The MESH is a z-level model with approximation over the longitudinal, latitudinal, and depth coordinates. While developing the finite-difference approximation of the model equations, we paid particular attention to satisfying the conservation laws and the integral equations inherent in the differential set of equations. These laws are the laws of conservation of mass, heat, and salinity, and the equation of the evolution of the sum of the kinetic and potential energy. In more detail, the numerical model was described in [2, 15].

To specify the boundary conditions at the sea surface and in the model of the air–sea interaction, we used the data of the ERA-15 ECMWF reanalysis of the atmospheric circulation [13] carried out in the period from 1979–1993. The analysis of the atmospheric forcing, ERA-15, used in the present study for different areas was carried out in [14, 17, 19]. It can be concluded that the data of the reanalysis well agree with the measuring data. The seasonal variability of the monthly mean winds over the Caspian Sea was considered in [4] in detail. The model of the seasonal variability was integrated in the regime of annually recurrent conditions at the boundaries. Because in 1979–1993 the sea level varied significantly due to the unbalance in the external conditions, we chose a year when the annual variation of the level was minimum for this period in order to introduce the minimum perturbation to the model solution at the beginning of a year [4]. An analysis of the sea level marks measured at the gauge stations in Makhachkala, Fort Shevchenko, Krasnovodsk, and Baku showed that the minimum value of the mean level from the beginning of January to the end of December was in 1982. Thus, we used the conditions of 1982 as the external conditions for the model.

At the upper boundary of the domain in the MESH, we used the momentum flux, the fluxes of the explicit and latent heat, the fluxes of the solar and long-wave radiation, and the mass fluxes (the precipitation, evaporation, and the freezing and melting of ice) as the boundary conditions. The momentum flux, the fluxes of the explicit and latent heat, as well as the evaporation are calculated in a submodel of the air–sea interaction based on the Monin–Obukhov theory. The initial data for the calculation of the fluxes are the air temperature and humidity at a level of 2 m, the temperature at the sea surface, the wind velocity at a level of 10 m, the atmospheric pressure at the sea level, and the current velocity and temperature in the upper water level used in the model. To specify the conditions in the near-water atmospheric layer, we used the data with a 6-h discreteness and a 1.25° spatial resolution. The effect of the riverine runoff in the MESH was taken into account by setting the current velocities, temperature, and salinity (equal to zero) of the riverine waters over the open segments of the side boundary. In total, we took into account the inflow of four rivers (the Volga, Ural, Terek, and Kura rivers). The Volga River is assumed to flow in by three main branches. In 1980, the strait connecting the sea with Kara Bogaz Gol Bay was closed. Therefore, the model has no side sink. At the solid sides of the domain and the bottom, we specified the insulation condition for the heat and salt, the nonpenetration condition, and the slip condition.

The horizontal resolution of the model grid is 1/24 × 1/18 degree or about 4 km. In vertical, the grid is nonuniform: within the depth range 0–35 m, the grid interval was 2 m; within 35–75 m it was equal to 5 m; and below 75 m, the grid step increased from 25 to 100 m. In total, the basin was divided into 38 horizontal layers with 27 levels in the upper 100-m layer.

The initial data for the construction of the coastline and bathymetry are the maps of the region on a 1 : 750 000 scale, the maps of the Republic of Kalmykia on a 1 : 200 000 scale, and the data of the GLOBE project (www.globe.gov). In the present study, the topography of the sea bottom and the coastline correspond to the mean sea level located at a mark of −27.9 m.

3. LARGE-SCALE CIRCULATION OVER THE DEEP-WATER PARTS OF THE SEA

The seasonal variability of the monthly averaged characteristics of the seawater is caused by the seasonal variability of the main external factors: the wind and heat flux between the atmosphere and the sea and the inflow of fresh water from the rivers. Let us recognize the main regimes characteristic of the deep-water parts of the sea.

The negative heat fluxes between the atmosphere and the sea (from September to February) result in intensification of the vertical mixing, an increase in the thickness of the upper mixed layer, and formation of the vertically homogeneous currents. The winter mixing reaches a depth of 100 m in the Middle Caspian Sea and 50 m in the Southern Caspian Sea.

The positive heat fluxes (from March to August) result in an increase in the buoyancy in the upper sea layers, a decrease in the thickness of the upper mixed layer, a sharpening of the pycnocline (under the conditions of the Caspian Sea, this is primarily determined by the thermal factors), and, hence, a decrease in the exchange processes through the pycnocline and formation of two-layered currents over the vertical. The currents in the upper layer of the open parts of the sea far from the coasts are generated by the wind forcing (Ekman currents) and by baroclinic gradients. Below the upper ~20-m (in the summer) –50-m (in the winter) Ekman layer, the currents are determined mainly by the baroclinic factors.

Let us begin the analysis of the horizontal water circulation with the abyssal layers, as the currents here are more structurized and stable in time than those in the surface layers. According to the modeling results, the currents during a year in the subsurface (below 20–50 m) layers in the abyssal parts of the sea feature a cyclonic character (Fig. 1). This seems to be caused by the inflow of desalinated waters to the shelf for the period of a year, by the more intensive heating of the shelf waters in the summer, and by the more intensive vertical exchange over the shelf. The possible reason for the abyssal cyclonic vorticity of the currents is the influx of vorticity to the abyssal sea layers caused by the water downwelling. In the winter period, the abyssal currents are more intensive, which is probably associated with the enhancement of the cyclonic vorticity caused by wind forcing.

The cyclonic water gyres over the deep-sea basins in the Middle and Southern Caspian Sea are associated with the ventilation of the abyssal waters. The extreme values of the velocity of the downwelling over the periphery of the cyclone, as follows from the model, exceed 1 m/day. The velocities of the upwelling at the cyclonic center are smaller by an order of magnitude. The horizontal temperature field characteristic of the cyclonic circulation features the presence of cold water from the near-bottom layers at the center of the cyclone

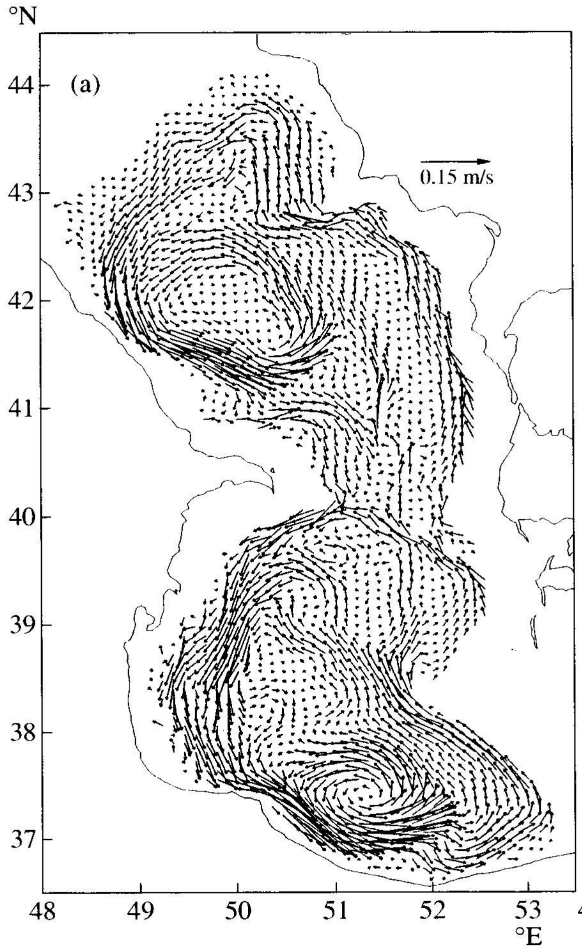

Fig. 1. Monthly mean currents (m/s) at a level of 50 m in (a) December and (b) July.

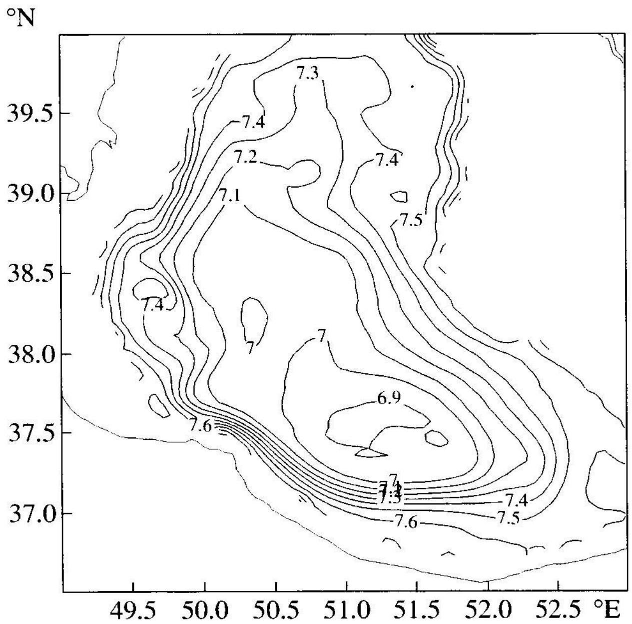

Fig. 2. Distribution of monthly mean temperature (°C) in the Southern Caspian Sea in June at a level of 150 m.

and warm water down welled from the shelf zone over the slope at its periphery (Fig. 2).

The seasonal variability of the surface currents is affected by the wind variability and vertical exchange with the subsurface currents. The extent of the influence of these factors is determined by the variability of the vertical exchange processes.

In the winter months, the vertical mixing is maximum and, as a consequence, the surface currents are predominantly entrained by deep-water cyclonic gyres in the Middle and Southern Caspian Sea. The wind convergence at the centers of the deep-sea subbasins results in cyclonic Ekman currents. In the winter period, the momentum transfer from the surface to the deep layers is intensified. As a result, in December and January, in the Middle and Southern Caspian Sea, surface currents generate cyclonic gyres (Fig. 3a). The "baroclinic abyssal" components of the gyres (eddies over the deep-sea areas) and wind components (northward currents over the eastern shelf) should be recognized. The replacement of the divergence wind regime by the predominantly northerly and northeasterly winds changes the wind component of the currents, which results in the

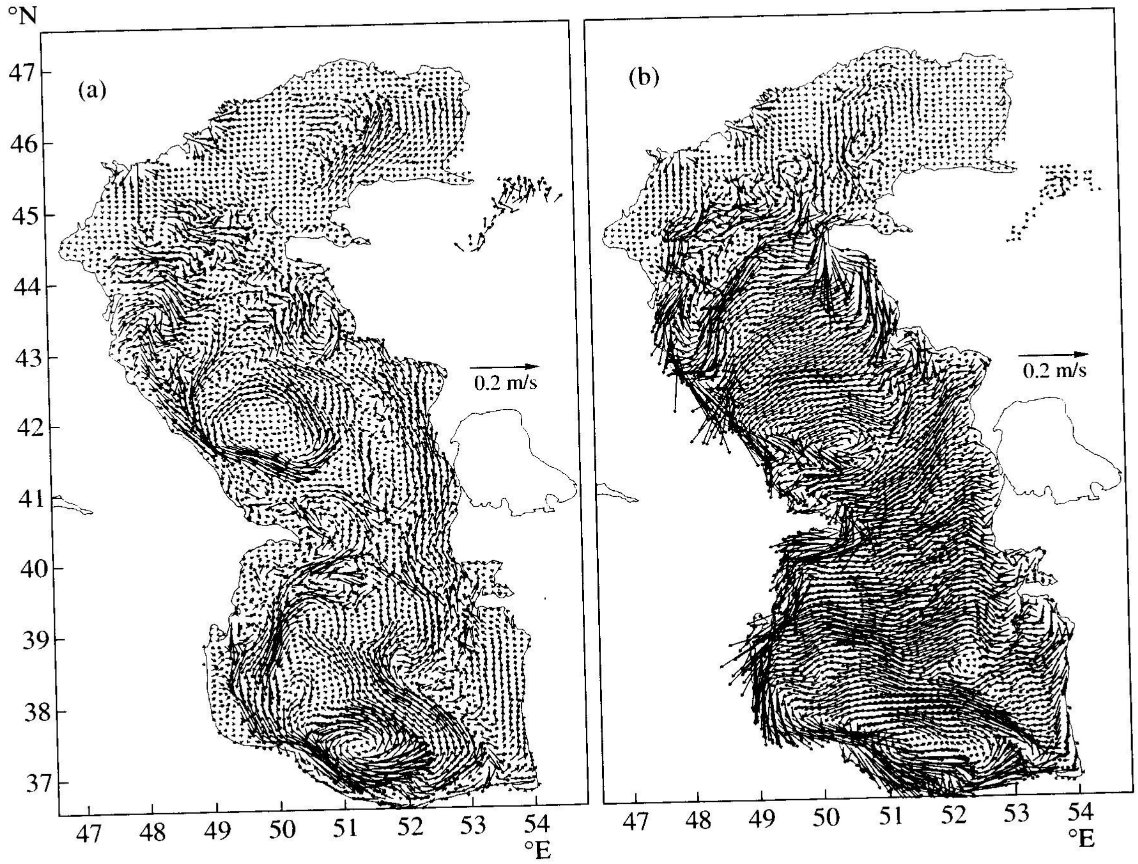

Fig. 3. Monthly mean currents (m/s) at the sea surface in (a) December and (b) July.

turn of the surface currents over the eastern shelf from the northward to the southward direction. Over the deep-sea basins, the baroclinic component determines the cyclonic eddies (CE).

With the heating of the sea surface waters, the formation of the thermocline, and the decrease in the vertical mixing, the currents acquire a two-layered structure. The effect of the deep-sea currents on the surface ones is weakened, and the surface circulation is increasingly determined by the wind. The CE over the abyssal water in the Middle Caspian Sea is gradually weakened, and, by June, its eastern northward-directed segment disappears. In July, due to the domination of northerly winds, the surface currents in most of the Middle and Southern Caspian Sea (excluding the near-shore regions) are directed toward the west and southwest (Fig. 3b). In the southern part of the Southern Caspian Sea, the wind divergence generates a CE whose vorticity is similar to that of the subsurface baroclinic eddy.

4. CURRENTS OVER THE SEA SHELF

4.1. Western Shelf of the Middle and Southern Caspian Sea. Actually, all year round, the desalinated waters of the Northern Caspian are transported southward along its western coasts. In the autumn–winter period, the greater part of the water mass in the region of 41.5° N turns southwestward, leaves the near-shore area, and, flowing along the shelf edge, turns around the

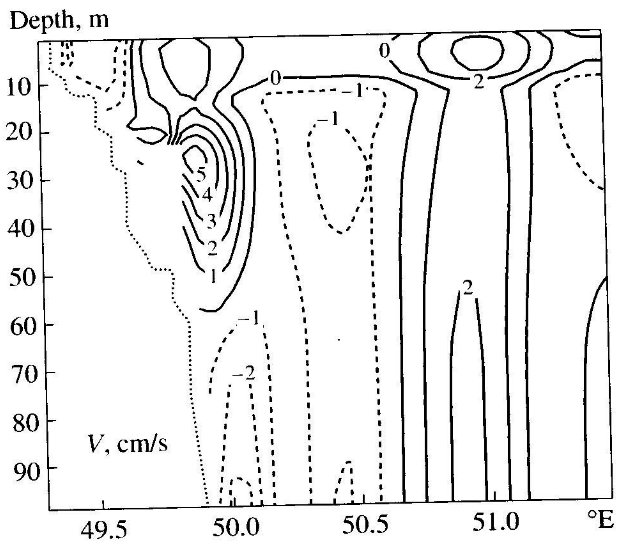

Fig. 4. Vertical section of the field of monthly mean meridional velocity component along 39.5° N in August. The positive values of the meridional velocity point the north.

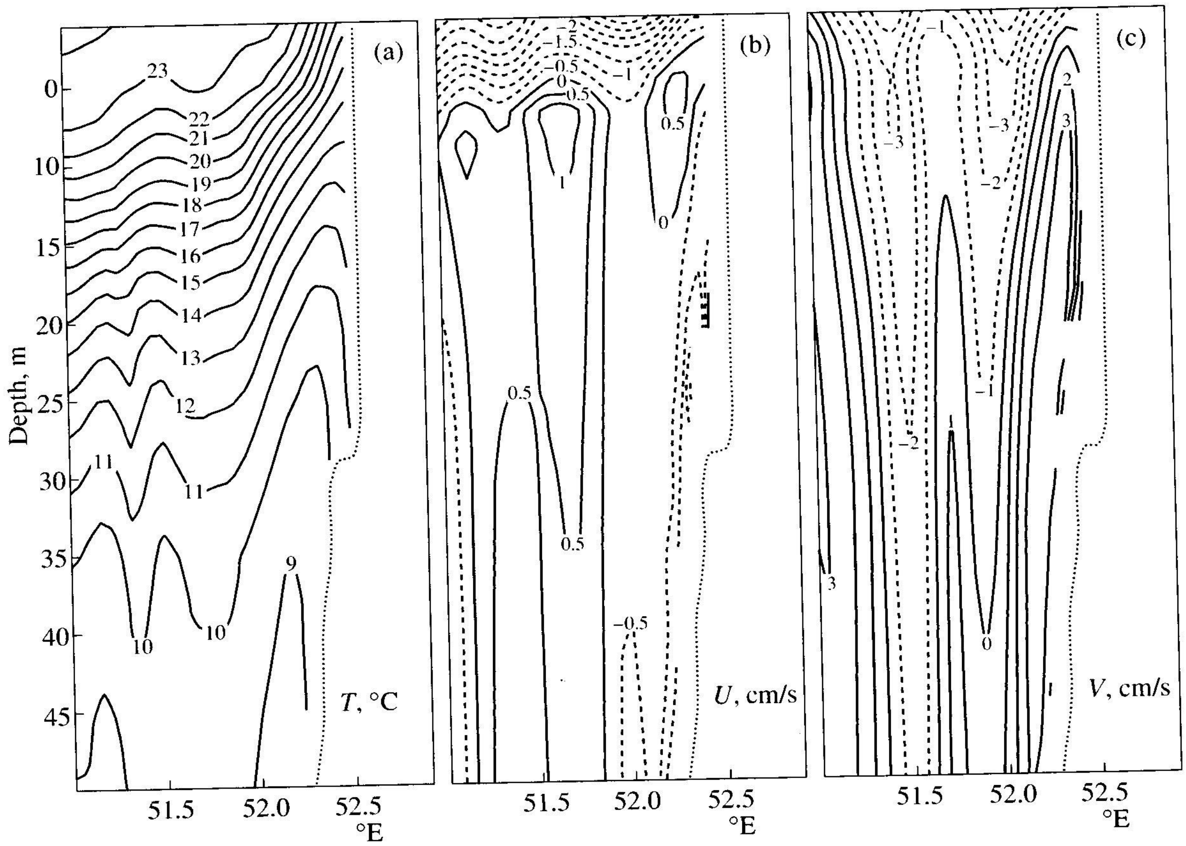

Fig. 5. Vertical sections of the monthly mean fields of (a) temperature, (b) zonal, and (c) meridional components of velocity along 42° N in July. The positive values of the meridional velocity point the north, and those of the zonal velocity point the east.

deep-sea basin of the Middle Caspian Sea. Such a flow pattern is broken down in the summer time, when the surface water, which is isolated by the stable stratification, is forced to move westward by northerly winds and a large-scale cyclone exists under the thin 10- to 20-m upper mixed layer. In August, the surface current along the western coast changes its direction for the northward one.

Off the western coast of the Apsheron Peninsula and north of it up to 41.5° N, the surface current is variable throughout the year. In the first half of the year, from January to May, it flows southward, while, from August to November, it flows northward and occupies the entire width of the shelf band. The change in the direction of the water flow in August is caused by the enhancement of the easterly component of the wind, which generates the northward Ekman transport. The annual mean circulation pattern in this region shows that southward flow slightly dominates in a narrow (about 20 km) near-shore band, while the northward flow dominates further away up to the edge of the shelf.

In the winter time, in the northwestern area of the southern subbasin of the sea, we observed a meandering jet current (Fig. 3a). East of the southern alongshore current, an anticyclonic eddy (ACE) is generated, which is traced down to a depth of 50 m and looks like a region of reduced water salinity, which indicates the presence of less saline waters of the Middle Caspian Sea in the ACE transported by the southern current. The near-shore waters to the right of the jet current are colder and more saline. Meandering of jet currents can also be observed in other regions of the Middle and Southern Caspian Sea (e.g., in the southwestern region of the Southern Caspian Sea (Fig. 7a), which will be discussed below)

In the literature, descriptions of an anticyclonic gyre in the northwestern part of the Southern Caspian Sea from the estuary of the Kura River to the Apsheron Peninsula (the Kura anticyclone) can frequently be encountered. The measurements of the currents at the Kura River delta front and throughout the western coast of the Southern Caspian Sea provide contradictory information. For instance, according to Klevtsova [7], the recurrence of the southward currents off the entire western coast is 60–100%. The measurements carried out by Tsitsarev [11] in 1961–1965 revealed the domination of northward currents in the near-shore zone. Meanwhile, over the slope, the current flows southward [9], which indicates the anticyclonic character of the water circulation in the northwestern part of the Southern Caspian Sea. The results of the modeling indicate that an ACE in the monthly mean water circulation in

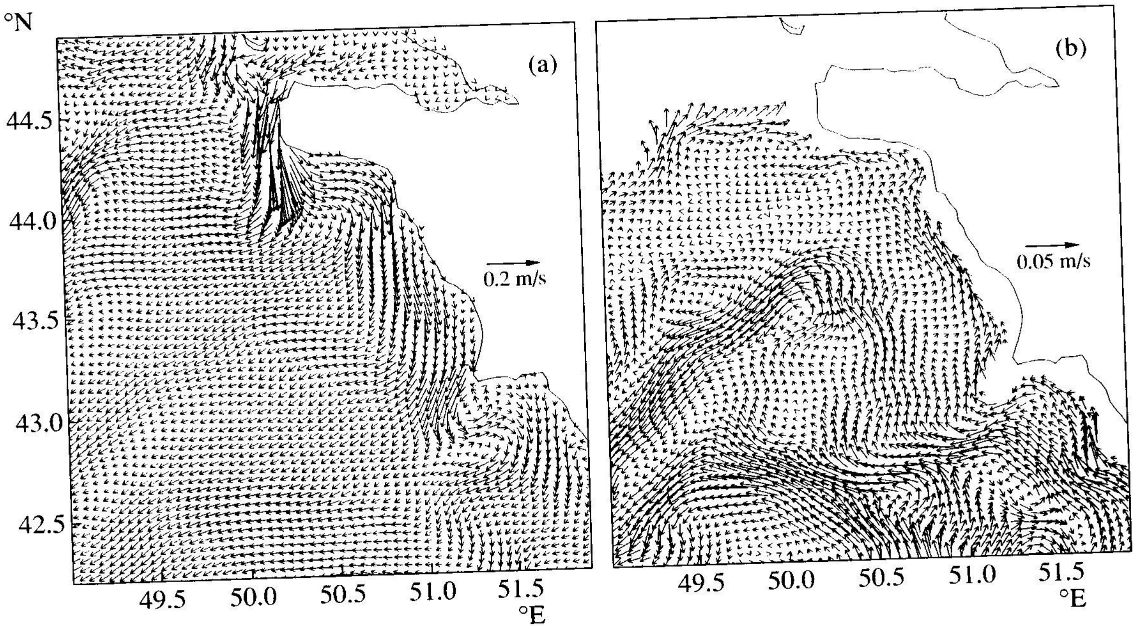

Fig. 6. Monthly mean currents (a) at the surface and (b) at a level of 27 m in July.

this region can be observed in December (Fig. 3a) and in August–October. It should be noted that, from August to October, in the subsurface layer near the western coast between the estuary of the Kura River and Apsheron Peninsula, a quasi-steady northward current is observed, as is shown in Fig. 4, where the distribution of the meridional component of the current velocity averaged over August in the section along 39.5° N is presented. The northward subsurface current over the shelf and the weaker southward current at the same level (20–40 m) generate an ACE. When the wind weakens or changes its direction for the easterly or southerly direction, the subsurface ACE is traceable at the surface for several days. According to the model, this ACE is not a permanent phenomenon in this region. Moreover, the alongshore surface currents north and south of the Kura River estuary flow predominantly southward.

4.2. Eastern Shelf of the Middle and Southern Caspian Sea. One of the most striking phenomena in the sea is the summer upwelling along the eastern coast of the Middle Caspian Sea, which is caused by the offshore flow of the surface water due to the northwesterly wind and upwelling of the cold water from the near-bottom layers. The mean water temperature in the vicinity of the coast is lower by 7–10°C than that in the deep-sea regions. The maximum values of the velocity of the vertical water motion reach 1 m/day. Figure 5 shows the water temperature and velocity components in the zonal section along 42° N averaged over July. The offshore current in the upper layer 5–7 m thick and the counterflow at a depth of 5–15 m and deeper generate an upwelling. Below the countercurrent, a northwestward near-bottom counter-countercurrent is generated and, hence, a downwelling along the eastern slope at depths below 20–30 m appears. The field of meridional velocities demonstrates a southward alongshore surface current and a northward alongshore current under it. It should be noted that the vertical structure of the zonal velocity component is three-layered. In the near-bottom layer, the current flows in the same direction as the surface current does, i.e., away from the coast. Near the shore, there is an upwelling in the 0- to 10-m layer and a downwelling in the 10- to 30-m layer.

Another characteristic feature of the currents over the eastern shelf of the Middle Caspian Sea is the strong alongshore southward current. In the northern part of the shelf, along the Mangyshlak Peninsula, the current flows southward in all the seasons. The two-layered current system in this region (a southward current at the surface and a northward near-bottom current), which is revealed by the measurements [1], is observed in the model only in July and August (Fig. 6); the monthly mean velocities of the near-bottom current do not exceed 3 cm/s.

Off the southern part of the eastern coast of the Middle Caspian Sea, the surface alongshore current is rather intensive (it has monthly mean velocities of 10–20 cm/s), but it can flow both southward (January–June, October–November) and northward (December). The velocity field can sometimes be rather irregular over the vertical. Only in February and March does the subsurface current (at depths of 20–50 m) steadily flow southward. In July and August, when northeasterly and easterly winds cause a strong offshore drift of the surface waters, a northward jet current in the near-bottom lay-

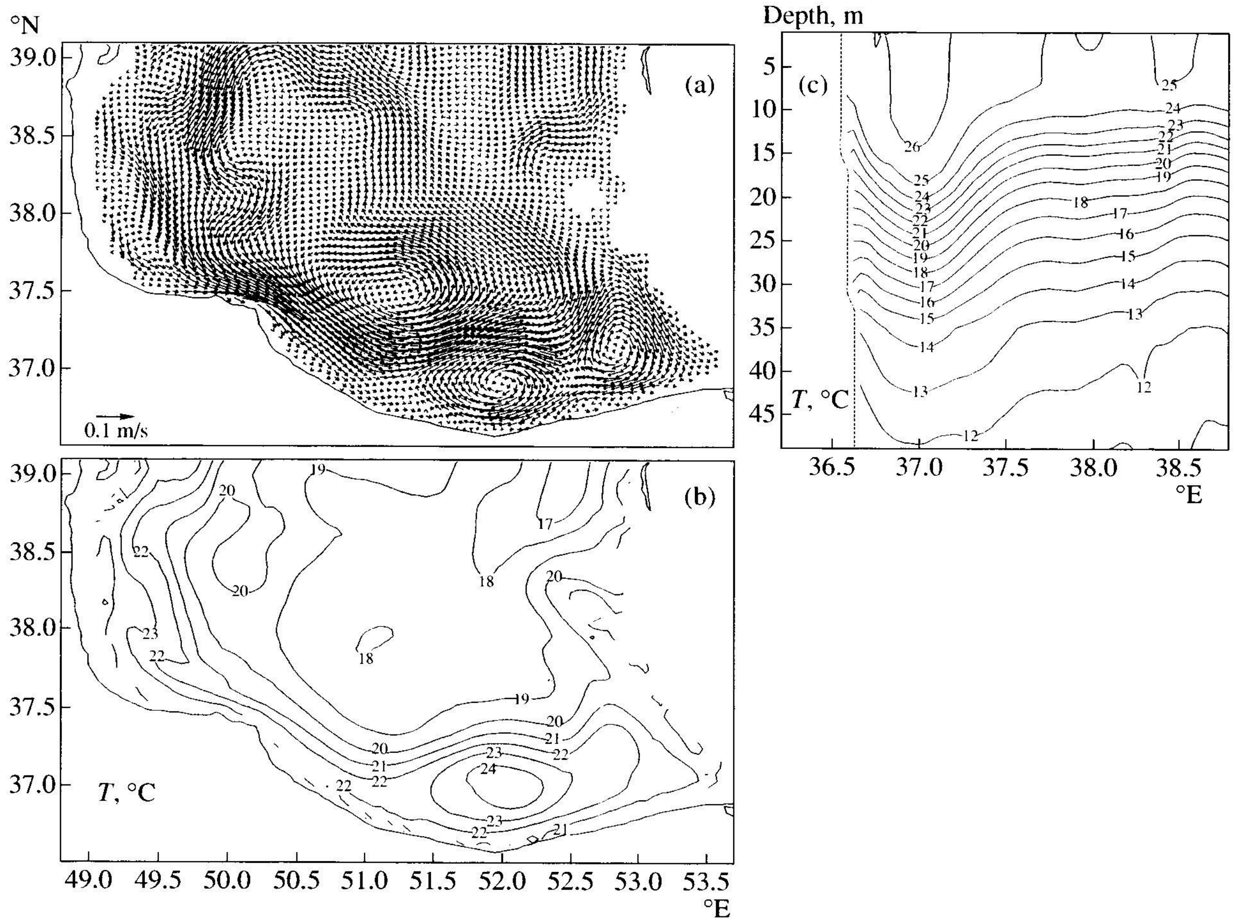

Fig. 7. (a) Currents and (b) temperature at a level of 19 m averaged over September and (c) vertical section of the temperature field along the 52° E meridian.

ers is induced. The vertical structure of the velocity field in this region is insufficiently known. On the one hand, the climatic surface temperature fields reveal an anomaly of warm waters at the surface [8]. This phenomenon is frequently interpreted as a result of the transport of the waters from the Southern Caspian Sea, i.e., a northward current from the Apsheron barrier should exist along the eastern coast. The modeling results [4], however, show that, since February, the surface current here flows southward. An analysis of the results obtained with the present model shows that, in December, the currents flow northward throughout the water column over the shelf zone, while in January, the surface waters turn to the south and the subsurface southward current over the shelf is weak. Meanwhile, a permanent northward current exists over the shelf slope, which represents a segment of the undersurface large-scale cyclonic eddy in the Middle Caspian Sea, which transports northward the warm waters of the Southern Caspian Sea. In the subsurface layers, the warm waters flow toward the shore, and, due to the diffusion and upwelling, look at the surface like a tongue of warm waters.

4.3. Currents over the Southern Shelf of the Southern Caspian Sea. According to the model, developed eddy dynamics are characteristic of different sea areas. There is, however, only a few field observations that evidence eddy formation in the Caspian Sea. Among them, the seasonal surveys in 1994–1996 in the Southern Caspian Sea [6] should be noted.

The results of numerical calculation indicate a large-scale cyclonic gyre that occupies almost the entire subbasin and generates a series of mesoscale eddies at its periphery, some of which are associated with the characteristic topographic features and exist for more than a month, as it can be seen from the map of the monthly mean surface currents (Fig. 3a). A small steady-state mesoscale CE was observed at the southernmost site of the Caspian Sea from May to July and in the second half of the autumn. During the other months, the near-shore current is directed from the east to the west and the above-mentioned cyclonic gyre moves away from the coast and merges with the large-scale cyclonic circulation. The instant current patterns indicate selected short-term and moving eddies at the shelf edge in the eastern and northwestern subbasins.

Based on the data of observations, a system of steady-state eddies in the southeastern region of the Southern Caspian Sea with a distinguishable strong ACE and a similar system of eddies in the southwestern region of the subbasin are described [6]. The authors assumed that the abyssal waters of the Southern Caspian Sea are generated in the ACE. This assumption is validated by the measurements of the concentrations of oxygen, phosphates, nitrates, and silicon. In our model, the ACE can be observed near the shelf edge in the southeast and, less distinguishable, in the southwest nearly all the way through a year (Figs. 3a, 7). Figure 7 shows the current velocities and water temperatures at a level of 19 m and the temperature section along the 52° E meridian, which indicate that two ACE in the southeast are responsible for the down welling of warm waters and a CE in the central part of the Southern Caspian Sea is responsible for the upwelling of cold waters. The less distinguishable ACE near the western edge of the shelf causes a downwelling of warm water. It should be noted that, among the three ACE mentioned above, only the easternmost eddy can represent a source of generation of abyssal waters (according to the present model) as it is quasi-steady and exists virtually all through a year. It disappears from the surface only in the summer months, when the waters are steadily stratified and the surface layer is isolated. Meanwhile, in other seasons, the ACE in the southern part of the subbasin is replaced by an equally intensive CE. In this case, the downwelling of the surface water is observed at the periphery of the CE along the steep slope of the shelf.

5. CONCLUSIONS

The results of numerical calculations of the thermohydrodynamical processes in the Caspian Sea are presented. The principal differences of the model considered from the previous model [4] lie in the more detailed spatial grid in both the horizontal and vertical directions, the use of 6-h atmospheric conditions, and the parametrization of the vertical mixing according to the 2.5 Mellor–Yamada level. Thus, the model is capable of describing a wider class of the processes and phenomena. According to the model, the synoptic atmospheric forcing generates high-frequency processes with time scales of $\sim 10^2$–10^4 s.

An analysis of the monthly mean characteristics of the water circulation shows that the most stable currents for the period of a year are the currents in the subsurface (below 20–50 m) layers in the deep-sea parts, which feature a cyclonic character. The most probable mechanism forcing the large-scale cyclonic vorticity of the subsurface currents in the deep-sea regions is the baroclinicity of the sea caused by the fresh water supply to the shelf and the summer heating of the waters over it. The local injection of vorticity also contributes to the intensification of the cyclonic circulation in the subsurface layers [10], especially in the winter period, when the wind convergence and intensive vertical exchange over the Middle and Southern Caspian Sea encourage the near-shore downwelling.

The generation of the surface system of currents is affected by the variability of the wind and the vertical momentum exchange with the subsurface currents and is characterized by strong variability throughout a year. The cyclonic character of the large-scale water circulation in the Middle and Southern Caspian Sea is observed only in December and January. In the summer months, the currents in the upper layer have predominantly Ekman's origin due to the forcing by the dominating southerly and southwesterly winds. Meanwhile, the surface waters flow southwestward and westward (Fig. 3).

The three-dimensional structure of the currents along the eastern and western coasts of the sea, the upwelling, and the currents at the Kura River delta front is proved by the analysis of the data of field observations of the large-scale and mesoscale phenomena in the Caspian Sea.

A comparative analysis of the model solution and observation data, in particular, with respect to the annual trend in the sea level changes (this problem was not considered in this paper) and to the characteristics of the summer upwelling along the eastern coast of the Middle Caspian Sea, shows both qualitative (in spatial distribution and lifetime) and quantitative (in the value of the temperature gradient) agreement with the data of field observations of the characteristics of the alongshore jet currents, their vertical structure, and the dynamics of the eddies near the southern coast of the sea. This allows us to conclude that the present model satisfactorily describes the characteristic thermohydrodynamical processes in the sea.

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REFERENCES

1. A. L. Bondarenko, *Currents of the Caspian Sea and Formation of the Salinity Field in the Waters of the North Caspian* (Nauka, Moscow, 1993) [in Russian].
2. R. A. Ibraev, Doctoral Dissertation in Mathematics and Physics (IVM RAN, Moscow, 2002) [in Russian].
3. R. A. Ibraev and D. G. Kurdyumov, "Sensitivity of the Seasonal Variability of the Water Circulation in the Caspian Sea to the Parametrization of the Vertical Mixing in the Hydrodynamical Models," Fiz. Atmos. Okeana **39** (6), 849 (2003).

4. R. A. Ibraev, E. Ozsoy, and K. Shrum, "Seasonal Variability of the Circulation and Sea Level in the Caspian Sea: Analysis of the Results of Modeling and Observation Data," in *Trans. of the International Seminar "Changes in the Ecosystem of the Caspian Sea under the Conditions of the Intensification of the Economic Activity"* (KaspNIRKh, Astrakhan', 2002), Inf. Bull. No. 3, pp. 8–19.
5. R. A. Ibraev, A. S. Sarkisyan, and D. I. Trukhchev, "Seasonal Variability of the Circulation of the Caspian Sea Waters Restored the Benguela Upwelling the Mean Annual Hydrological Data," Fiz. Atmos. Okeana **37** (1), 103 (2001).
6. D. N. Katunin and V. V. Sapozhnikov, "Multidisciplinary Studies of the Ecosystem of the South Caspian Sea," Okeanologiya **37** (1), 152 (1997).
7. N. D. Klevtsova, "Currents of the Western Coasts of the Middle and Southern Caspian," in *Coll. of Papers of Bak. GMO* (FOL UGMS AzSSR, Baku, 1968), No. 4, pp. 153–159 [in Russian].
8. A. N. Kosarev and V. S. Tuzhilkin, *Climatic Thermohaline Fields of the Caspian Sea* (GOIN, MGU, Moscow, 1995) [in Russian].
9. *The Seas of the USSR. Hydrometeorology and Hydrochemistry of the Seas*, Vol. VI: *The Caspian Sea*, Issue 1, Ed. by F. S. Terziev, A. N. Kosarev, and A. A. Kerimov (St. Petersburg: Gidrometeoizdat, 1992) [in Russian]
10. V. S. Tuzhilkin, A. N. Kosarev, D. I. Trukhchev, and D. P. Ivanova, "Seasonal Features of the General Water Circulation in the Deep-Water Part of the Caspian Sea," Meteorol. Gidrol., No. 1, 91 (1997).
11. A. N. Tsitsarev, "Features of the Drift Currents in the Area off the Kura River," in *Coll. of Papers Bak. GMO* (FOL UGMS AzSSR, Baku, 1967), No. 3, pp. 50–57 [in Russian].
12. E. A. D'Asaro, *Ocean Storms—A Three-Dimensional, Severe Storm, Air–Sea Interaction Experiment: Overview and Core Program (Manuscript)* (Applied Physics Lab., Univ. of Washington, DC, 1985).
13. J. K. Gibson, P. Kallberg, S. Uppala, *et al.*, "ERA-15 Description (Version 2, January 1999)," ECMWF Re-Analysis Project Report Series, No. 1 (1999).
14. B. Huang and J. Shukla, "A Comparison of Two Surface Wind Stress Analyses over the Tropical Atlantic during 1980–1987," J. Clim., No. 9, 906 (1996).
15. R. A. Ibrayev, "Model of Enclosed and Semi-Enclosed Sea Hydrodynamics," Russ. J. Numer. Anal. Math. Modelling **16** (4), 291 (2001).
16. G. L. Mellor and T. Yamada, "Development of a Turbulence Closure Model for Geophysical Fluid Problems," Rev. Geophys. Space Phys. **20**, 851 (1982).
17. S. Nigam, C. Chung, and E. DeWeaver, "ENSO Diabatic Heating in ECMWF and NCEP-NCAR Reanalyses, and NCAR CCM3 Simulation," J. Clim. **13**, 3152 (2000).
18. R. A. Richardson, G. G. Sutyrin, D. Herbert, and L. M. Rothstein, "Universality of the Modelled Small-Scale Response of the Upper Tropical Ocean to Squall Wind Forcing," J. Phys. Oceanogr. **29**, 519 (1999).
19. C. Schrum, J. Staneva, and E. Stanev, *Black Sea Surface Climatological Data for the Period 1979–1993. A Study Based on the ECMWF Atmospheric Re-Analysis* (Institut fur Meereskunde, Hamburg, 2001).
20. H. I. Sur, E. Ozsoy, and R. Ibrayev, "Satellite-Derived Flow Characteristics of the Caspian Sea," in *Satellites, Oceanography, and Society* (Elsevier Science, 2000), pp. 289–297.
21. D. Trukhchev, A. Kosarev, D. Ivanova, and V. Tuzhilkin, "Numerical Analysis of the General Circulation in the Caspian Sea," Comptes Rendus de l'Academie Bulgare des Sciences, Sofia **48** (10), 35 (1995).
22. J. Willebrand, B. Barnier, C. Böning, *et al.*, "Circulation Characteristics in Three Eddy-Permitting Models of the North Atlantic," Progr. Oceanogr. **48** (2–3), 123 (2001).