MEDCOAST 99 - EMECS 99 Joint Conference, Land-Ocean Interactions: Managing Coastal Ecosystems
9 - 13 November 1999; Antalya, Turkey, E. Özhan (Editor)

Three-dimensional Caspian Sea Circulation and Ice Model

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Abstract

A free surface three-dimensional primitive equation dynamical model coupled with ice thermodynamics and air-sea interaction sub-models are used for the study of seasonal variability of the Caspian Sea circulation. The formulation of boundary conditions includes momentum and buoyancy fluxes through the air-sea interface and the open lateral boundaries. General circulation of the sea is a complex combination of eddies in deep water regions and shelf currents. Our results support the hypothesis that the Volga River inflow plays an important role in driving the alongshore current in the southwestern direction from the source. The freezing ice and dense water formed in winter on the northern and eastern shelf regions and its subsequent sinking along the continental slope constitute the main driving mechanism for deep-water ventilation in the Caspian Sea. Predominantly west and southward winds over the Middle Caspian throughout the year constitute an additional mechanism of deep water ventilation, as they result in downwelling along the western coast and upwelling along the eastern coast, clearly indicated by a belt of cold water in summer.

Introduction

The Caspian Sea is the largest totally enclosed water body on Earth, constituting 44 % of the global volume of lacustrine waters. Its surface area varies within 380 - 403 x 10^9 m^2 as a function of sea level changes of about 2 m in recent years, and its volume is estimated to be 78 x 10^{12} m^3. It has an elongated geometry (1000 km in length and 200-300 km in width), where the Northern, Middle and Southern Caspian Basins constitute the main geographic divisions. The shallow Northern Caspian has maximum depths of 15-20 m, while the Middle Caspian and Southern Caspian have deep troughs with depths of 788 m and 1025 m respectively. Shelf areas with depth less than 100 m, mainly along the northern and eastern coasts, account for 62 % of the total area. The underwater extension of the Apsheron peninsula forms a sill with maximum depth of about 180 m separating the Middle and the Southern Caspian basins. The Southern Caspian basin contains two thirds and the Northern Caspian basin makes up 1% of the total volume of water (Kosarev and Yablonskaya 1994; Rodionov 1994).

The water budget of the landlocked Caspian Sea is extremely sensitive to climatic variability in the surrounding areas. With a large catchment area extending towards the Urals and Caucasia, the river runoff is the main component in the water budget (annual average ~3 x 10^{11} m^3 yr^{-1}, within a range of 2. - 4.5 x 10^{11} m^3 yr^{-1} during the period of record, Terziev et al. 1992). Annual precipitation is about one fifth of the runoff, while evaporation is of the same order as runoff. The runoff and evaporation individually correspond to about 1 m in units of sea level change per year; this is why the imbalances in water budget, originally depending on climate, but also modified strongly by water regulation schemes and other anthropogenic effects, have lead to patterns of interannual, interdecadal or longer term variations in sea level throughout the history of the Caspian Sea (Kosarev and Yablonskaya 1994; Rodionov 1994). During 1930-1977, the sea level has decreased to -29 m relative to the global mean sea level, following a period of high values of about -26 m in the beginning of the century up until the 1930's. From 1977 onwards, it has been rising and has reached the pre-1930's levels once again.

The elongated geometry and strong topography of the basin, acted upon by variable wind forcing and baroclinic effects result in spatially and temporally variable currents in the Caspian Sea. The general circulation has been described to be cyclonic, based on the investigations carried out from the end of the 19th century till the 1950's, using indirect methods of current measurement (floats, bottles or the dynamic method), and mostly relying on hydrodynamic arguments (see the reviews by Bondarenko 1993; Terziev et al. 1992). Especially standing out among these were the six instrumental surveys along the western coast of the Middle Caspian, carried out in 1935-37 (Stockman 1938), showing predominantly southward currents along the western coast of the Middle Caspian, modified by wind-driven drift currents. Observations showing southerly currents along the eastern coast of Middle Caspian in summer (Klevtsova 1967; Bondarenko 1993) contradict with the above description of the general circulation, but the scheme of cyclonic circulation is partially recovered if one considers the observations of northward currents 7-8 m below the southward drift currents at the surface along the eastern coast. It appears that the southward surface currents along the eastern coast are driven by winds with a prevailing northerly component in the eastern half of the Middle Caspian and Southern Caspian from spring till autumn. The circulation in the shallow Northern Caspian appears almost totally to be controlled by local winds (Bondarenko 1993; Terziev et al. 1992).

The gravitational sinking of dense waters formed by winter convection in the Northern Caspian and the northern part of the Middle Caspian drives ventilation of the deep waters of the Caspian Sea. In winter, the shallow waters of the north are cooled and acquire salinity through the formation of ice, before sinking to deep water (Kosarev 1975; Terziev et al. 1992). Complex factors such as the depth of water to be cooled, ice formation, fresh water runoff, and local meteorological conditions determine the amount and properties of dense water formed on the shelf.

The Caspian Sea differs from other inland seas, e.g. the Mediterranean and the Black seas, with respect to a well-defined and extensive region of upwelling. Seasonal upwelling consistently occurs along the eastern coast of the Middle Caspian, confirmed by warm season climatological temperature fields (see Kosarev and Tuzhilkin 1995) and satellite images.

In the past, modelling of the Caspian Sea circulation has been rather limited in scope, with shallow water models applied to the circulation in the Northern Caspian, as well as diagnostic models applied to the whole sea. The baroclinic diagnostic model of Sarkisyan et al. (1976) showed the importance of wind stress and the summertime deep thermal stratification in establishing the circulation. The space and time variability of the summer circulation in response to prevailing northwest and southeast winds was studied by Badalov and Rzheplinski (1989). The hydrodynamically adjusted seasonal, climatic circulation investigated by Trukhchev et al. (1995) and Tuzhilkin et al. (1997) showed persistent cyclonic and anticyclonic vortices respectively in the north-west and the south-east sectors of the Middle Caspian, and anticyclonic vortices in the north-west and the south-east of the Southern Caspian, to be the main elements of the circulation.

Considering the general lack of knowledge of the sea circulation, we aim to develop three-dimensional circulation model and to study variability of the sea currents on seasonal and annual time-scales.

Formulation of the Problem

Strong intra- and inter-annual variability of circulation patterns is a characteristic feature of the Caspian Sea, as shown by previous studies. Therefore there has been a strong need to simulate the Caspian Sea dynamics with intra- and inter-annual variability of atmospheric forcing and river run-off. The hindcast simulations were run for the period 1982-99, which are the years of dramatic Caspian mean sea level rise. All types of forcing used in the current study are based on monthly mean values. As an example, we will analyse intra-annual variability of the 1991 circulation.

Basic Equations and Boundary Conditions

We use a three-dimensional primitive equation ocean general circulation model developed in the Institute of Numerical Mathematics of the Russian Academy of Sciences, which employs Boussinesq and hydrostatic approximations. The basic equations of the model in spherical coordinates (λ - longitude, φ - latitude, z - depth) are the following:

$$u_t + (\mathbf{v}\cdot\nabla)u + wu_z - fv + a^{-1}u^2 tg\varphi = -(\rho_0 a\cos\varphi)^{-1}P_\lambda + (K_m u_z)_z + F_u \quad (1)$$

$$v_t + (\mathbf{v}\cdot\nabla)v + wv_z + fu + a^{-1}uvtg\varphi = -(\rho_0 a)^{-1}P_\varphi + (K_m v_z)_z + F_v \quad (2)$$

$$P_z = \rho g \quad (3)$$

$$\nabla\mathbf{v} + w_z = 0 \quad (4)$$

$$T_t + (\mathbf{v}\cdot\nabla)T + wT_z = \delta^{-1}(K_h T_z)_z + F_T \quad (5)$$

$$S_t + (\mathbf{v}\cdot\nabla)S + wS_z = \delta^{-1}(K_h S_z)_z + F_S \quad (6)$$

$$\rho = \rho(T,S) \quad (7)$$

where $\mathbf{v}=(u,v)$ is the horizontal velocity vector; w -the vertical velocity; T, S, ρ - temperature, salinity and density of sea water; ∇ - two-dimensional gradient operator; K_m , K_h - vertical turbulent viscosity and diffusion coefficients; a - Earth's radius; F_u , F_v, F_T , F_S - horizontal turbulent viscosity and diffusion terms defined as

$$F_\alpha = (a\cos\varphi)^{-2}(A_m\alpha_\lambda)_\lambda + a^{-2}\cos^{-1}\varphi(A_m\cos\varphi\alpha_\varphi)_\varphi \quad (8)$$

where a stands for u, v velocity components or T, S and A the horizontal diffusion (A_m) and diffusion (A_h) coefficients, $f = 2\Omega\sin\varphi$ the Coriolis parameter, with Ω representing the earth rotation angular velocity, and $\nabla\alpha = (a\cos\varphi)^{-1}[(u\alpha)_\lambda + (v\alpha\cos\varphi)_\varphi]$ - the two-dimensional gradient operator.

At the rigid lateral boundaries free slip condition, and zero heat and salt fluxes are imposed. At the liquid inflow boundaries approximating river mouths, normal velocity, temperature and salinity of river water are prescribed. At outflow boundary approximating outflow to Kara-Bogaz-Gol normal flow velocity is prescribed. At the bottom, friction and heat and salt isolation conditions are imposed.

The numerical procedure used for solving equations (1-7) is based on ocean dynamics model of Demin and Ibraev (1989) and Ibraev (1993).

Sea Ice Sub-model

A thermodynamical sea ice model of Schrum and Backhaus (1999) is used in the study.

The Model Region

The grid resolution of the model is $(1/12)^{0}$ in latitude and $(1/9)^{0}$ in longitude, which gives a grid size of about 10 km. There are 22 vertical model levels defined at depths of 1, 3, 7, 11, 15, 19, 25, 35, 50, 75, 100, 125, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900 m. The maximum depth is 950 m, and a minimum depth of 5 m occurs in the shelf region. The model bottom topography (Fig. 1) of the Caspian sea corresponding to mean sea level of -28 m realistically represents the flat Northern Caspian shelf, the steep topographic slopes of the Southern Caspian and the western part of the Middle Caspian. The Ogurchinskii Island near the eastern coast of the Southern Caspian, Seal Islands near eastern coast and Seal Island near western coast of the Northern Caspian are explicitly resolved.

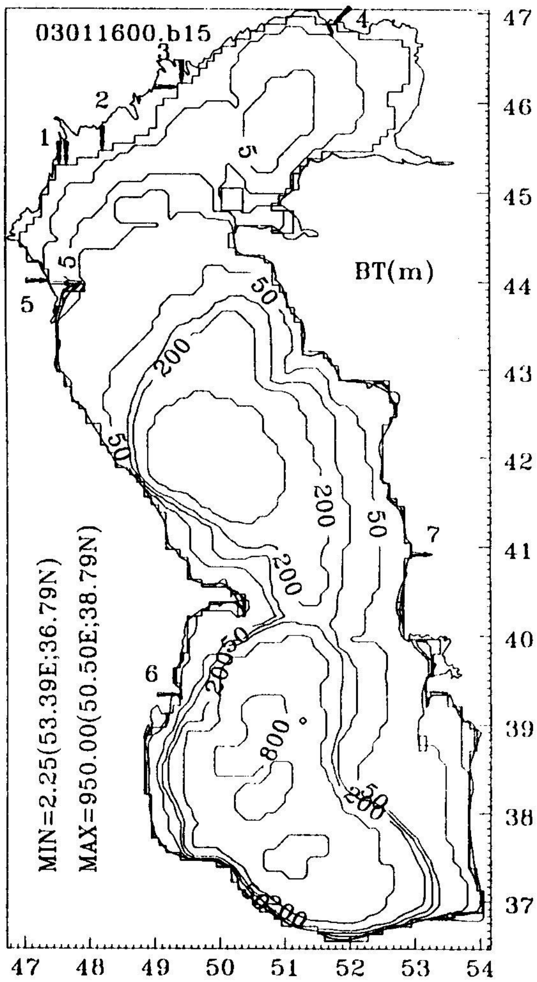

Fig. 1: Model bottom topography of the Caspian sea (depths are in meters). Arrows indicate open lateral boundaries, which include branches of Volga River mouth:

1 - Bakhtemir; 2 - Kamyzjak;
3 - Buzan, and 4 - r. Ural;
5 - r. Terek; 6 - r. Kura;
7 - outflow to Kara-Bogaz-Gol bay.

Atmospheric Forcing

For atmospheric forcing we use wind speed, air temperature, air dew point temperature data, precipitation, downward sort-wave solar and upward long-wave radiation fluxes of European Center for Medium-Range Weather Forecast re-analysis project. Heat fluxes at the sea surface are taken as a sum of incoming short-wave solar radiation, emitted long-wave radiation, and sensible and latent heat fluxes from air-sea interaction sub-model. Formulation of air-sea interaction sub-model which also output evaporation fluxes is based on a Monin-Obukhov approach (Launiainen and Vihma, 1990).

Lateral Water Fluxes

River run-off and evaporation are the main components of the water budget of the Caspian Sea, with a relatively smaller contribution of precipitation. All valuable sources/sinks with net annual flux greater than 10^{10} m^3 yr^{-1} are included in the model. They are Volga, Ural, Terek and Kura rivers and Kara-Bogaz-Gol bay (Fig. 1). Kara-Bogaz-Gol acts as an important sink in the water balance, as a result of the evaporative losses in this arid sub-basin. The most considerable inflow comes with Volga River, which accounts for about 80% of the total river runoff and therefore plays an important role in the salt balance and circulation of the sea. The vast Volga River delta, which has a number of branches, is approximated by three main branches, namely Bakhtemir, Kamyzjak and Buzan respectively from west to east. Altogether, there are 7 input/output ports where lateral fluxes are specified in the model. Volga River run-off and outflow to Kara-Bogaz-Gol Bay covers the same period as the atmospheric forcing. Run-off data of Ural, Terek and Kura rivers are averaged for the period 1966-1981 monthly mean water fluxes (Baidin and Kosarev 1986).

Seasonal Variability of the Sea Circulation

In response to the seasonal cycle of heat fluxes the sea surface temperature changes from a mean value of 9 deg. C in winter to 22.5 deg. C in summer. In winter (Fig. 2a), waters of the shelf regions are colder than the deep sea regions as a result of the lower heat capacity of the shallow waters. Gravitational sinking and downwelling transport of cold waters to the deeper layers are clearly seen in the vertical cross-sections. The average depth of the mixed layer is about 100-200 m, with a maximum along the eastern shelf slope. In summer, the sea surface temperature is almost uniform over the sea (Fig. 2b) except within the belt of upwelled cold waters along the eastern coast of the Middle Caspian Basin.

As a result of winter cooling, the Northern Basin and small areas close to the eastern coast of the Middle Basin are covered by ice (Fig. 2a). Though the seasonal cycle of the ice differs from one year to another, on the average the ice appears in the first half of December and in the beginning of February, when it covers almost whole Northern Basin. The maximum ice height of about 70 - 80 cm is reached in the middle of March when the area covered by ice starts to decrease.

Only slight differences occur in the sea surface salinity pattern in a yearly cycle. The minimum of salinity occurs close to the mouth of Volga River, but salinity increases sharply towards the boundary between the shallow Northern and deep Middle Basins. Depending on the river run-off and wind forcing, the salinity front in the Northern Basin can move in the south-north direction by up to 50 km. In all seasons a belt of brackish waters is clearly seen along the western coast of the Middle Basin. The outward transport of brackish water along the western coast and an anti-symmetry in precipitation - evaporation in the Southern Basin result in an increase of water salinity in the whole sea from west to east, see Fig. 3.

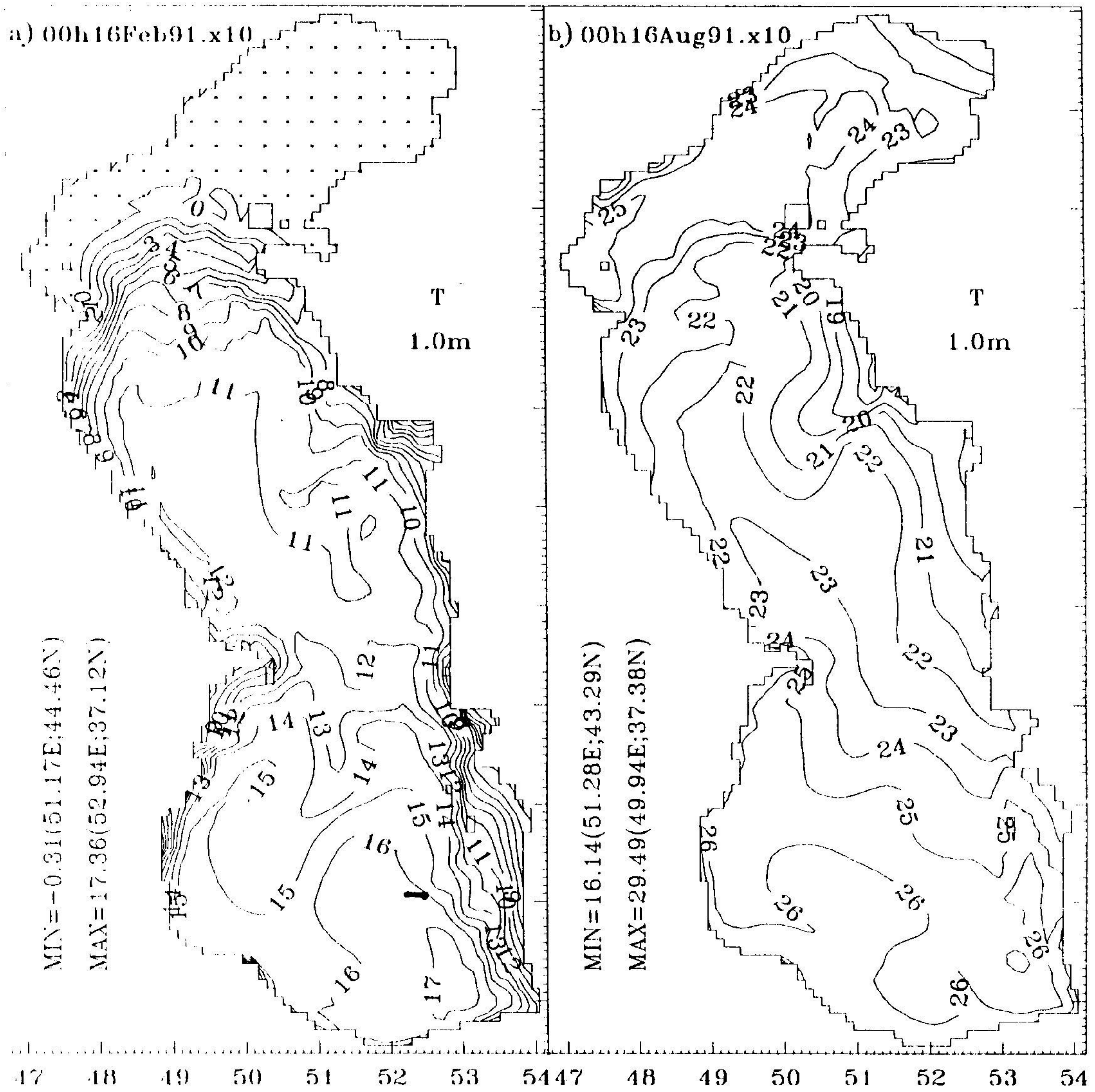

Fig. 2: Sea surface temperature in February (a) and August (b). Dotted areas are covered by ice.

As it is seen in Fig. 4, sea surface currents strongly vary in space and time. The most important permanent forcing is the run-off of the Volga river, which generates currents through its dynamical contribution (input of momentum) and through its buoyancy contribution (the inflow of fresh waters). Currents dynamically induced by the Volga River are about 5 - 10 cm s^{-1} at a distance of 100-150 km from the river mouth, the value of which is close to the moderate wind driven currents in Northern Caspian. Hydraulic pumping results in a sea level rise of about 14 cm close to Volga Delta. The Coriolis force turns the outflow to the south and southeast, yielding sea level rise along the northwestern coast of Northern Caspian.

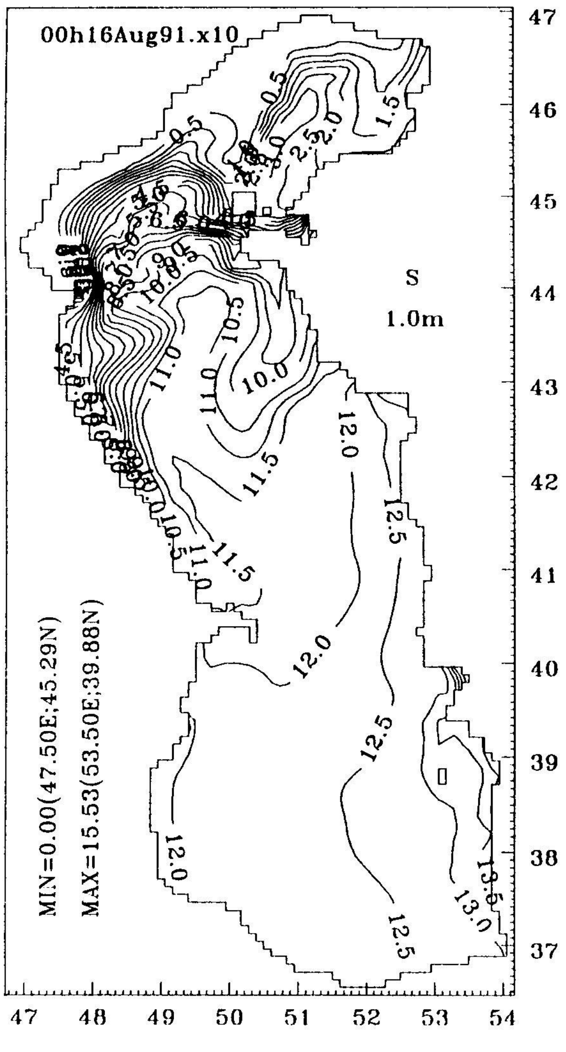

Fig. 3: Sea surface salinity in August.

A jet-like coastal current can be traced till the Apsheron peninsula. The effects on the circulation remains confined to the western Middle Caspian coast, where currents rapidly decrease with distance along the coast, becoming less than 1 cm s^{-1} at 42°N (Ibayev et al., unpublished manuscript). Input of fresh water makes the southward coastal current stronger (Fig. 4bc). In wintertime the southward coastal current competed with Ekman northward drift and anticyclonic eddy of the deep-water part of the Middle Caspian. In summer when the anticyclonic eddy on the sea surface is weaker the southward coastal current transports brackish water till Apsheron peninsula (Fig. 3). The most dynamically active region is the eastern part of the Middle Caspian Basin. Here, in winter, the shelf slope corresponds with the frontal zone between more denser cold shelf waters and warmer waters of the deep sea, yielding geostrophic currents directed to the south. But Ekman current forced by westward wind is directed to the north. Competition between baroclinic and drift currents results in highly unstable dynamics of that region, which is clearly seen as a chain of cyclonic eddies (Fig. 4a). In summer, when baroclinic forcing of the currents are weaker, the surface currents are mainly wind driven (Fig. 4c). Ekman drift in the eastern part of the Middle Caspian forced by southward wind gives an upwelling of sub-surface cold water along the eastern coast.

Conclusions

In this paper we have developed a coupled air - sea - ice model of a very specific area - an inland basin. In a view of the complex and unresolved problems of the Caspian Sea, such as the problems of inter-annual sea level variability, flooding of flat lands and deep-water ventilation processes, this study can be considered as one of the first steps in understanding the processes of the sea. Though the model experiment we presented in the paper covers inter- and intra-annual variability of the period 01.1982 - 12.1998, we concentrate on analysis of seasonal variability.

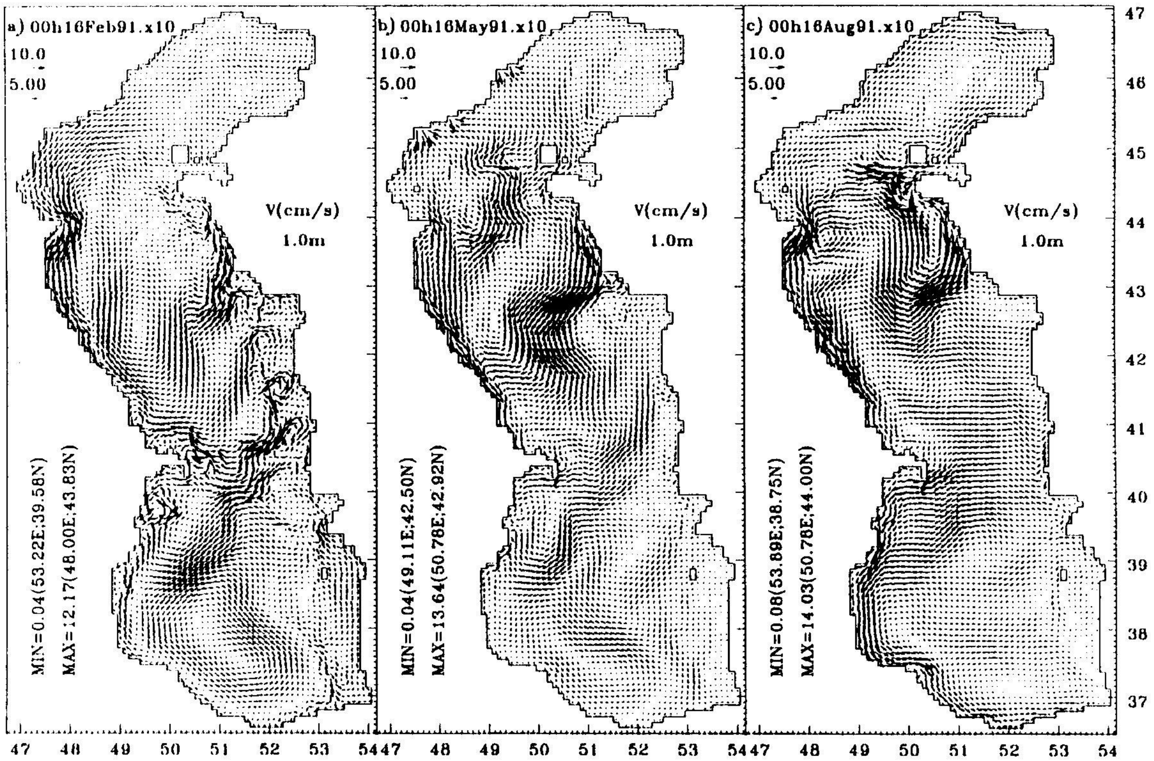

Fig. 4: Sea surface currents (cm/s) in February (a), May (b) and August (c).

Understanding of inter-annual variability of the Caspian mean sea level can not be done without better understanding of seasonal variability of the circulation, especially of the variability of sea surface temperature as one of the key elements in defining the variability of evaporation fluxes. The main purpose of this paper, i.e. the response of the Caspian Sea to seasonal variability of atmospheric and riverine forcing, addresses the issues by making use of eddy-resolving sea model, dynamics of the shelf currents, deep water ventilation processes. Model results are in good correlation with available data on the sea dynamics and are supported with diagnostic studies of mean climatic circulation of the sea (Ibrayev at al., submitted manuscript).

Acknowledgments

This research was sponsored by Russian Basic Research Foundation grant 99-05-64920 and by NATO Linkage Grant SA.12-2-02. We thank O. Gorelits from State Oceanographic Institute, Moscow for providing us with the run-off data for the Volga River.

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