ГЕОГРАФИЯ

IMPACT OF CLIMATIC CHANGES ON THE PHYSICAL STATE OF THE CASPIAN SEA IN REGULATING THE PRIMARY PRODUCTION

R.M.Mammadov[1], R.A.Ibrayev[2], Ch.N.K.Moors[3], M.A.Salmanov[4]

1 – *Institute of Geography ANAS*

2 – *Institute of Numerical Mathematics, RAS*

3 – *Rosenstiel School of Marine and Atmospheric Science University of Miami*

4 – *Institute of Microbiology ANAS*

ramiz.mamedov@geo.ab.az

The main goal of the study is to understand the role of climatic changes of the physical state of the sea in regulating the primary production. The methodology of the project made combined use of modeling and observations as tools to diagnose and understand the interactions between physical and ecological states of the Caspian Sea. The most important result of the study is development of the coupled 3-dimensional physical-biochemical (ecosystem) model of the Caspian Sea. The ecosystem model was used for understanding seasonal dynamics of low-trophic biochemical cycles of the Caspian Sea.

Introduction

The Caspian Sea is fundamentally a unique reservoir of relic flora and fauna, which are mostly endemic (Dumont, 1998). It has rich food resources for the riparian countries as well as the world markets. Caviar and sturgeon, as well as kilka, are among the economically important food resources seriously affected by the environmental crisis in the Caspian Sea. Compared to other European seas, the Caspian Sea is a highly productive water basin as is seen from estimates of annual mean primary productivity ($gC*m^{-2}*day^{-1}$): Mediterranean Sea – 0.235; Black Sea – 0.58; Azov Sea – 0.97; Caspian Sea – 1.3 (Zaika, 2000; Salmanov, 1999).

At the top of the Caspian Sea trophic chain there are sturgeon, sevryuga, beluga fishes and Caspian seals. These fish species, which are living fossils, are now on the verge of extinction due to the reduction of reproduction grounds, overfishing and water pollution by pesticides, heavy metals and oil products. In recent years, sturgeon landings have decreased dramatically: from 30,000 tons in 1985 to only 5,672 tons in 1995. At its peak, the Caspian supplied more than 80% of the world's sturgeon stock.

Ecological deterioration has started in regions of great economical value such as near the Volga river delta and the adjoining North Caspian Sea (Kosarev, Yablonskaya, 1994). On top of these changes, the recent increase in invasive species, in particular of *Mnemiopsis*, having been introduced from the Black Sea via the Volga-Don canal, is causing great concern, because of its effect on the biodiversity of the sea and its fisheries yield (CEP, 2002). In addition to these immediate environmental signals, there is a longer term threat, which may lead to rather rapid, precipitous collapse of the ecosystem: the threat of eutrophication in an enclosed sea, as has been recently experienced in the neighboring Black Sea (Ozsoy, 2001).

During the last 30 years, important shifts in the biochemical cycles of the Sea have been determined. The anthropogenic eutrophication is in progress; this process has been detected in various phenomena: (i) the areas of maximum bacteria plankton production have shifted from shallow water (25-30 m) to deepwater (50-100 m) regions; (ii) in deepwater areas, biological consumption of the dissolved oxygen has intensified;, furthermore, anaerobic processes are in progress in the benthic layers and deposits. Due to the reduction of fodder stock, in the western coast of South Caspian sub-basin, trophic links of the commercial units have been broken (Salmanov, 1999).

Long-term observations of biochemical parameters at different parts of the Sea clearly show a positive trend in plankton production (PP), **Figure 1**. The same tendency is observed in other regions of the Sea. On the other hand, the dynamics of primary production in the extremely polluted Baku bay (**Figure 1**, curve 6) has been depressed, due to excessive pollution of the bay by oil products.

As an example of dramatic changes in low level trophic dynamics, an Anomalous Algal Bloom (AAB) occurred in the Southern Caspian in 2005 with an affected area of 20,000 km^2, **Figure 2**. The unprecedented bloom developed in the beginning of the second decade of August and existed until the end of September.

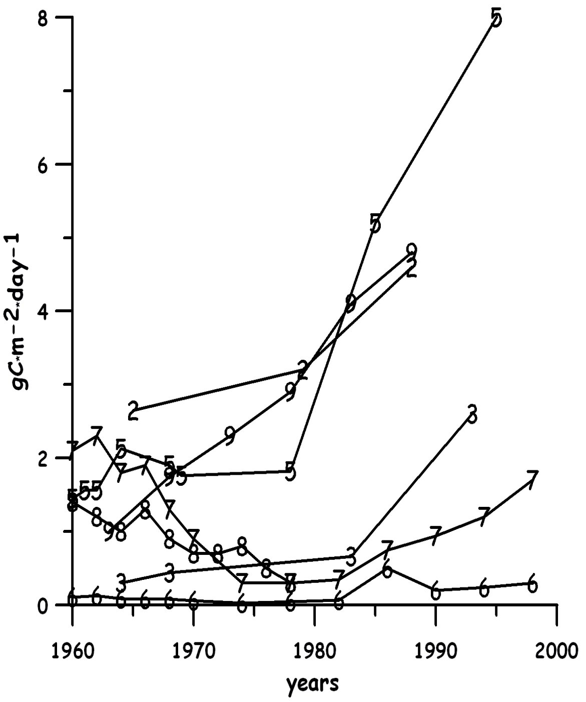

Figure 1. Change of phytoplankton production at the different locations of the Caspian Sea: 2 – yearly mean PP at Derbent (western coast of Middle Caspian sub-basin); 3 – spring-summer PP at Peschannyi cape (eastern coast of Middle Caspian sub-basin); 5 – June PP at western coast of South Caspian sub-basin; 6 – June-July PP at Baku bay (station 2); 7 – June-July PP at Baku bay outlet (station 17); 8 – summer PP at Baku archipelago; 9 – summer PP at North Caspian sub-basin. Data after *Salmanov, 1999.*

The development process was very fast – the phenomenon was first registered in the satellite image on August 12 and reached its maximum on September 1. Analysis of the satellite images for the same season in the previous five years confirmed that a phenomenon of such scale has never occurred before. (*CEP, http://www.caspianenvironment.org/newsite/ Caspian-AAB.htm*)

At the same time, the period from late 70s until the present is characterized by a decrease in oxygen concentration in all parts of the Sea. Anthropogenic eutrophication, presence of sufficient concentration of sulfate – sulfide and an increase in biological consumption of oxygen create real conditions for development of anaerobic processes and hydrogen sulfide increases. In the deepwater part of the Middle Caspian sub-basin, at a depth of 700-750 m, total oxygen has been reduced by 40-45% during 1984-99. In the Southern Caspian sub-basin, at a depth of 995 m, the 1.6-2.0 mg/l oxygen available in 70s had disappeared by 1995.

Anthropogenic eutrophication being an important phenomenon is not the only factor in ecological changes of the Caspian Sea. The physical state of the Sea in the past 30 years has also undergone dramatic changes. The less obvious and poorly understood climatic mechanism that affects the Caspian Sea is the observed changes in the ventilation of its deep waters, which in turn determines its biochemical regime.

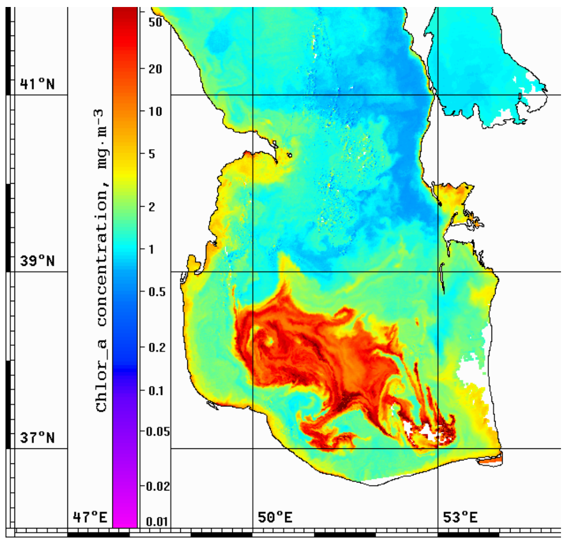

Figure 2. Chlorophyll-a concentration maps for September 01, 2005

The Caspian Sea is an isolated, complex realm influenced by large rivers, heterogeneous precipitation and evaporation, and atmosphere-ocean-land interactions in a region of rapid transition between the sea, deserts, flat lands, and high mountains. It lies in a region of mid-latitude climatic variability. Its surface level is below the level of the World Ocean and it links a large watershed area with such different rivers as the Volga, Ural, Kura, and Terek, as well as several small rivers in Iran. With such a low sea level, its evaporation is the greatest in all internal lakes on Earth. An immediate consequence of climatic variability is the observed abrupt changes in sea level, which have a major influence on the stability of the Caspian Sea and the surrounding lands. Most recently, the sea level has abruptly started to rise by more than 2.6 m in the period 1977-96, following an earlier rapid drop in the 1930's, and the subsequent gradual lowering in the following 30 years. The rapid sea level rise has led to great socio-economic losses in the region, as it has occurred numerous times in history (Mammadov, 2001; Radionov, 1994). On the other hand, it is known that the change in sea level has a large anthropogenic component related to water retention schemes (Kosarev, Yablonskaya, 1994).

The latest increase in sea level occurred as a result of a significant change in the climate of the Caspian Sea basin (Mammadov, 2001). Beginning in 1978, a change in the general circulation of the atmosphere occurred, the number of cyclones in the Atlantic and Western Europe increased with a simultaneous increase of their water capacity by 35% and 18%, respectively. As a result of the appearance of these climatic conditions, evaporation from the surface of the sea reached *948* km^3*/yr* with a simultaneous increase in precipitation over the surface of the sea (up to *22.5cm/yr*). The development of this state of affairs tipped the balance towards a positive net gain. The last sea level rise during the 1978-1995 period flooded about *400* km^2 in territories of the Azerbaijan coastal zone and resulted in economic losses of 2 billion USA dollars (Mammadov, Hadiyev, 1998; Mammadov, 2001).

Sea level changes appear to have important consequences on the vertical circulation. For example, there is evidence for the presence of hydrogen sulfide near the bottom of the Middle Caspian sub-basin prior to 1930 when the sea level was higher than the last epoch of low sea level in the 1930-77 period. A number of studies suggest that the ventilation of deep waters sensitively depend on the sea level (Kosarev, Yablonskaya, 1994). Denser water is expected to be formed in the shelf area during periods of lower sea level, consequently increasing the degree of ventilation of deep waters. With increased sea level since 1977, conditions conducive to hydrogen sulfide formation, similar to those prior to 1930's, could be approached once again in the near future. Such changes have disastrous consequences for the ecosystem, leading to adverse changes under conditions of environmental stress. Though there have been very few recent oceanographic surveys in the Caspian Sea, observations show a notable decrease in deep oxygen content (see below).

Recent hydrological data analyses support the idea that the intensity of vertical ventilation depends on sea level changes, and they show dramatic changes in the vertical stratification of the thermohaline fields before and after the sea level minimum period in 1977 (Kosarev et al., 2004).

Goals and methodology of study

The main goal of the study is to understand the role of climatic changes on the physical state of the sea in regulating the primary production.

One of the main aims of the NATO Science for Peace Programme project SFP–981063 'Multi-disciplinary Analysis of the Caspian Sea Ecosystem' (MACE) project was the study of physical processes connected with regional climate change.

Model hindcasts were used to identify key physical processes of change and their climatic controls, such as periods of intensive convection depending on air-sea interaction and water budgets. The Model of Enclosed Sea Hydrodynamics (MESH), 2001), which includes 3-D PE OGCM with a free surface condition, an air-sea interaction model and a sea ice thermodynamic model, was shown to be able to simulate the Caspian Sea intra-annual variability of the three-dimensional circulation and of the water budget and hence of sea level. The accuracy is sensitive to uncertainties in the model physics (Ibrayev et al., 2002). The model also has shown the critical importance of simulated sea surface temperature in producing reasonable air-sea fluxes, e.g. of evaporation and consequently the water budget of the Sea. The sigma-z version of MESH (s-z MESH) was developed to make it possible to simulate large (up to 5 m) inter-annual variations of mean sea level.

The methodology of the study makes combined use of modeling and observations as tools to diagnose and understand the interactions between physical and ecological states of the Caspian Sea. The following tasks encompass the logical steps of the project methodology, and was conducted step-by-step.

Study of seasonal variability of the Caspian Sea low-trophic food web. This task is aimed at studying the characteristics of seasonal and spatial variability of biochemical processes of the Sea. The 3-D physical-biochemical models of low-trophic food web for the Caspian Sea were developed. The study was concentrate on simulations and analyses of primary productivity seasonal cycle for a ‘normal’ year prior to 1977, when the sea level was at a low level, and preceding the invasion of *Mnemiopsis.*

The physical models, which were used in the project are the 3-D PE OGCM Princeton Ocean Model (POM) (used by the USA Team) and s-z Model of Enclosed Sea Hydrodynamics (s-z MESH) (see above). POM has a coupled biochemical sub-model. S-z MESH was coupled with the ecological module of ECOSMO (ECOSystem MOdel) (Schrum et al., 2006). The biological module of ECOSMO is based on lower trophic level interactions between two phyto- and two zooplankton components. The dynamics of the different phytoplankton components is governed by the availability of the macro nutrients: nitrogen, phosphate and silicate as well as light. Zooplankton production is simulated based on the consumption of the different phytoplankton groups and detritus. For simulation of primary production under different nutrient limiting conditions occurring in the different parts of the Caspian Sea (Salmanov, 1999), the ecosystem module of ECOSMO is quite good, because it includes all three nutrients as limiting factors. ECOSMO includes interactions between 12 state variables. The basis of the model are three nutrient cycles: the nitrogen cycle, the phosphorus cycle and the silica cycle, covering the main macro nutrients limiting phytoplankton production in shelf seas.

Spatial resolution of the coupled models was 9 km horizontally and 21 vertical levels. The resolution, which is not fine enough to simulate some local dynamic features, but still is good enough to reproduce main features of the Sea circulation and was used at the next step, where it is planned to run the model for 40 years.

Analysis of observed data of bio-chemical constituents of the Sea

The data arrays, which are available in the Institute of Geography and the Institute of Microbiology of the Azerbaijan National Academy of Sciences, were used for validation of the models. Data include time series of physical (sea level, temperature, salinity, currents and meteorological variables from coastal stations) and biochemical (concentration of phyto-, zoo- and bacteria- planktons, of nitrogen, phosphate, silicate and their various forms) variables. The analyzed data was also used for defining initial and boundary conditions in the model.

Validation of coupled ecosystem models is critical for assessing their ability to capture the dynamics of the ecosystem they are designed to study. A first step in this validation process is a comparison of simulation outputs with existing climatic data as well as other simulation estimates. One-dimensional version of coupled physical-biochemical model was tested in regimes with different limiting nutrients (nitrogen, phosphate and silicate) and in different physical conditions (shallow brackish water of the North Caspian sub-basin, deep sea of South Caspian sub-basin). For the deep-sea regions of the South Caspian sub-basin the dynamics of biochemical cycles, i.e. primary production, phytoplankton biomass and nutrient dynamics shows patterns close to what has been studied in other seas, like North and Black, see **Figure 3**.

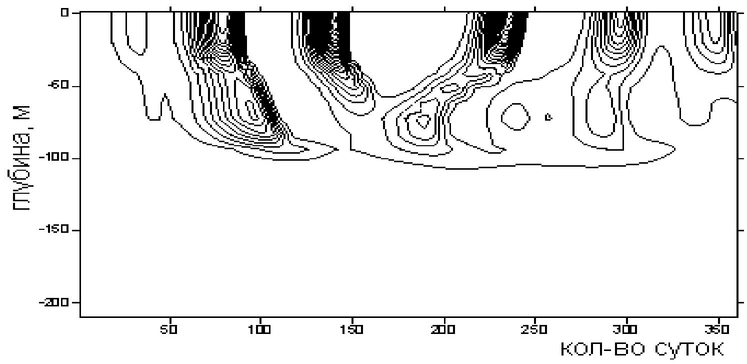

Figure 3. Phytoplankton dynamics (time – abscissas, depth - ordinates) under solar radiation.

The spatial structure of predicted primary production (**Figure 4**) illustrates the regional differences in ecosystem dynamics. Primary production in the Northern Caspian sub-basin is the highest through out the year. In this shallow region mixing processes, nutrients input from Volga and Ural rivers make nutrients available during the year. The high primary production along the coastal belt of Middle and South sub-basins show hydrodynamical control of biochemical cycles, when highly nutrified waters of the North sub-basin are transported by coastal southward currents, the well known feature of the Sea circulation. In our simulation for 1982, the Caspian Sea depth-integrated annual primary production was predicted to vary between 20-140 gC m^{-2} yr^{-1} with the lowest production occurring in the central parts of the Sea and the highest values in the coastal areas e.g. Northern sub-basin, western coast and Turkmen shelf. A comparison of our results with field observations (as reviewed in Kosarev, Yablonskaya, 1994) show similar magnitudes.

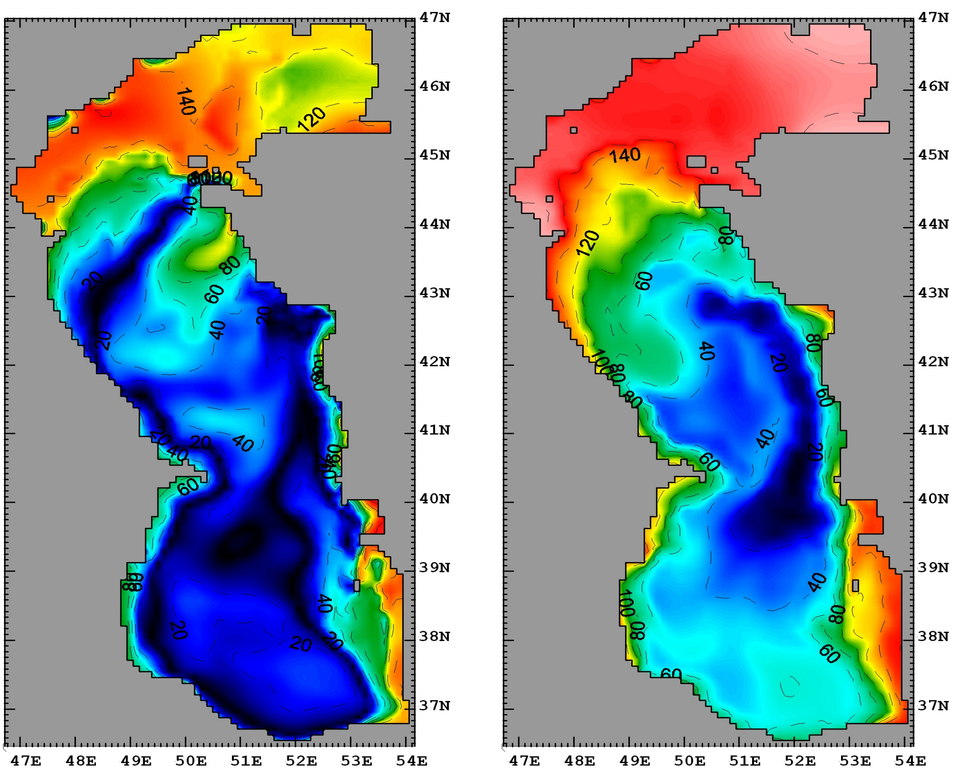

Figure 4. Model simulated monthly averaged primary production for December (left) and June (right) [gC m^{-2} yr^{-1}].

For 1982, the simulated temporal development of total phytoplankton biomass over the entire deep-sea regions of the Caspian Sea are presented in **Figure 5**. A spring phytoplankton bloom commences at the end of February and reaches its maximum with values up to 4 mgC m^{-2} day^{-1} in the beginning of March. This first phytoplankton maximum consists mainly of diatoms, with low flagellate biomass. Diatoms remain being the dominant phytoplankton group until silicate limitation is reached and diatoms biomass starts to decrease. The following second peak of phytoplankton biomass occurring in August is then based mainly on flagellates. During summer phytoplankton biomass ranges from 1,0 to 1,5 mgC m^{-2} day^{-1} dominated by flagellates biomass. In the fall, flagellates biomass shows a rapid decrease in October and November with a small fall bloom of diatoms. Significant phytoplankton biomass was predicted to occur until end of November. For mesozooplankton biomass two peaks occur in April and September. Microzooplankton biomass is relatively low during the entire season, partially in response to grazing by mesozooplankton.

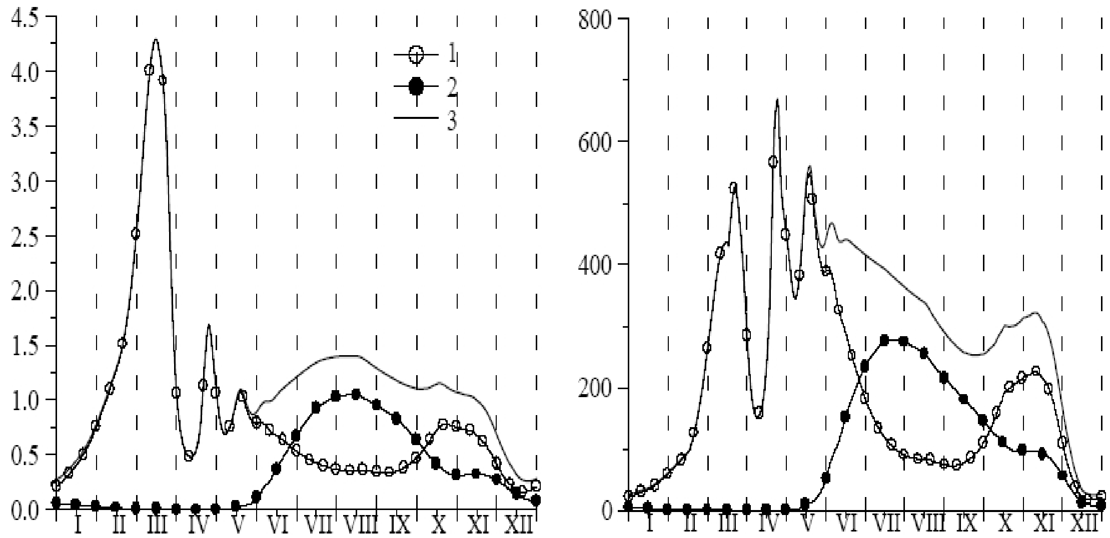

Figure 5. Annual cycle of phytoplankton biomass (mgC m^{-2}) (left) and of primary production (mgC m^{-2} day^{-1}) (right) in upper 100 m of deep-sea region of the Caspian Sea. 1 – phytoplankton diatoms; 2 – flagellates ; 3 – total phytoplankton.

This study was carrying out by grant support ANSF and CRDF Bilateral Grants Program (award number: AZG1-3109-BA-08), which we would like to express our sincere thanks.

REFERENCES

CEP. 2002. Transboundary diagnostic analysis for the Caspian Sea. *Caspian environment programme,* 1, 2 and 3, Baku, 36; 132; 163.

DUMONT, H. J. 1998. The Caspian Lake: History, Biota, Structure and Function. *Limnol. Oceanogr.,* 43, 44-52.

IBRAYEV, R. A., ÖZSOY, E., SCHRUM, C. 2002. Seasonal variability of the Caspian Sea circulation and sea level: analysis of model results and observed data. *Caspian Floating University Research Bulletin, 3,* CaspNIRKH Publ., Astrakhan, Russia, 8-19.

KOSAREV, A.N., TUZHILKIN, V.S., KOSTIANOY, A.G. 2004. Main features of the Caspian Sea hydrology. In: *Dying and Dead Seas*. Kluver Academic Publishers, Dordrecht, 159-184.

KOSAREV, A.N., YABLONSKAYA, E.A. 1994. The Caspian Sea. Backhuys Publishers. Haague. 259.

MAMMADOV, R. M. 1996. Long-Term prognosis of the Caspian Sea level. In Regional workshop on *Integrated coastal zone management*, Chabahar-I.R.Iran, 24-29 February, 79-84.

MAMMADOV, R. M. 2001. Caspian Sea level and ecological problems. *International Symposium on the Problems of the Regional Seas*. Istanbul.Turkey, 1-11.

MAMMADOV, R. M., HADİYEV, Y. K. 1998. Impact of climate anomalies on the level of Caspian Sea. Second Int. Conference on *Climate and Water,* Espoo, Finland, 17-20 August, 972-980.

ÖZSOY, E. 2001. A Review of Caspian Sea environment, climate variability and air-sea interaction. Planetary emergencies meeting *Workshop on Environmental Pollution in the Caspian Sea.* Erice, Italy.

RADIONOV, S. N. 1994. Global and regional climate interaction: the Caspian Sea experience. *Ser. Water and Technology Library,* 11, Kluwer Academic Publishers, 241.

SALMANOV, M.A. 1999. Ecology and biological productivity of the Caspian Sea. Ismail Publ. Baku. 400.

SCHRUM, C., ALEKSEEVA, I. St., JOHN, M.A. 2006. Development of a coupled physical-biological ecosystem model ECOSMO. Part I: Model description and validation for the North Sea. *Journal of Marine Systems,* 61, 79-99.

ZAIKA, V.E. 2000. Marine biodiversity of the Black Sea and Eastern Mediterranean. *Ecologiya moray*, 51, 59-62.