Journal of Shipping and Ocean Engineering 7 (2017) 35-42
doi 10.17265/2159-5879/2017.01.006

Long-Term Evolution of the Black Sea Dynamics Derived from Modeling

Viktor Dorofeyev and Larisa Sukhikh
Marine Hydrophysical Institute of the Russian Academy of Science

Abstract: Long-term evolution of the Black Sea dynamics (1980-2020) is reconstructed by means of numerical simulation. The model of the Black Sea circulation is z-coordinate model with 4.8 km horizontal space resolution and 40 levels in vertical direction. Mixing processes in the upper layer are parameterized with the Mellor-Yamada turbulent model. As for the boundary conditions on the sea surface, we used atmospheric forcing functions for the Black Sea region provided by CMCC using regional climate model COSMO-CLM. These data have a spatial resolution of 14km and a daily temporal resolution. To evaluate the quality of the Black Sea circulation dynamics, derived from simulation, the modeling results are compared with results of the Black Sea physical reanalysis. This reanalysis was performed by assimilating the temperature and salinity profiles from hydrographic surveys conducted during 1971-1993.

Key words: Numerical modeling, the Black Sea, ocean currents, seasonal variation.

1. Introduction

Influence of climatic changes on marine ecosystems is an important problem for modern oceanography. That is why it warrants considerable attention. An example of a highly stressed marine ecosystem is the Black Sea. The Black Sea is one of the largest enclosed basins in the world with a simple coastal line and maximum depth of about 2 km. It is connected to the Marmara Sea by the shallow Bosphorus Strait. The Black Sea marine ecosystem underwent considerable changes in the sixties-eighties [1]. These changes severely altered biomass, taxonomic composition and the community structure of plankton groups. A classical phytoplankton annual cycle with the main maximum biomass in spring and autumn was modified by an additional bloom in the summer which became the most pronounced. These changes were also accompanied by modifications in the vertical geochemical structure [2]. In addition to nutrient load factors influencing these variations, climate changes can be attributed as well. Climate changes have a strong impact on ecosystem health, particularly in such semi-enclosed seas such as the Black Sea. Due to its small size and near isolation the Black Sea has smaller thermal inertia compared to large oceans. As a result, it is more sensitive to variability of atmosphere-ocean interactions. Climate changes were dominant factors in launching some risk processes (such as warming seawaters and its impact on the marine ecosystem). The concern is to understand how the Black Sea ecosystem will react to these changes. Moreover, the first step to understand the observed changes in the Black Sea ecosystem is the evaluation of the environmental status of the basin, under current and scenario conditions. The present work points to simulate the long-term variability of the Black Sea dynamics (hindcast and future scenario) as a basis for modeling the low trophic level marine ecosystem.

2. Methodology of Simulation

The model of the Black Sea circulation is a z-coordinate model based on the traditional primitive equations [3]. The simulation was carried out with horizontally uniform grid and 40 vertical levels

Corresponding author: Viktor Dorofeyev, Ph.D., senior scientist, research fields: ocean dynamics, modeling of circulation and marine ecosystem, data assimilation.

compressed to the sea surface. Horizontal space resolution is 4.8 km. This spatial resolution permits to resolve inter-annual, seasonal and mesoscale variability of the Black Sea (Rossby radii for the first baroclinic mode is about 25 km). To describe the vertical mixing processes in the upper layer more carefully we also used Mellor-Yamada turbulent model [4] coupled with the circulation model. The coefficients of vertical turbulent viscosity and diffusion where computed using turbulent energy and length scale, were defined by solving evolution equations.

The boundary conditions on the lateral boundaries set to zero temperature, salinity and momentum fluxes except rivers estuaries and straits. These parts of the boundary are taken into account the river discharge and the water exchange with the Sea of Azov through the Kerch strait and with the Marmara Sea through the Bosporus, where water leaves the Black Sea in the upper layer (upper Bosporus current) and flows to the Black Sea in the lower layer (deep Bosporus current). The values of the rivers' discharges were defined as climatic monthly mean. Due to the lack of information on inter-annual variability of the deep Bosporus inflow, its discharge was estimated based on the assumption that the volume of the Black Sea water is preserved during a year, i.e. as a residual of the annual rivers' inflow, water discharge through the Kerch Strait, precipitations, evaporations and the upper Bosporus outflow.

One of the key parameters for sea dynamics modeling is an atmospheric forcing. In this work, we used atmospheric forcing functions for the Black Sea region provided in the CMCC (Euro-Mediterranean Center on Climate Change) using regional climate model COSMO-CLM [5] with 14 km horizontal resolution. It was downloaded from FTP server in the frame of PERSEUS project (Deliverable Nr. 4.2) and interpolated on the grid of the Black sea circulation model. The next parameters were used as boundary conditions on the sea surface: total precipitation (accumulated over 6 hours); accumulated flux of surface moisture; sensible heat flux; latent heat flux; zonal wind in 10 m; meridional wind in 10 m; surface albedo (shortwave radiation); average solar radiation budget; average thermal radiation budget.

3. The Main Numerical Experiment

Using the Black Sea circulation model, briefly described above, we obtained hydrodynamic fields for four decades (1980-2020). To evaluate its quality we compared them with results of the Black Sea physical reanalysis [6]. It was performed for a twenty-three year time interval from (1971-1993) by assimilating the temperature and salinity profiles into the circulation model. This interval was chosen because it was the richest with hydrological data. During this period, three to ten monthly hydrographic surveys were conducted with irregular coverage both in space and in time. The mutual time period for two data sets (reanalysis and our modeling results) is 1980-1993 years.

Fig. 1 represents an evolution of basin averaged annual-mean sea surface temperature based on reanalysis results (solid line) and the results of our modeling (dotted line). Straight lines denote linear trends. SST (sea surface temperature) derived from modeling is in general higher than from reanalysis data set by 0.4 °C. So the model results overestimate surface temperature, but the tendencies of temperature reduction are similar in both cases. Variability in the upper layer can be illustrated with time diagram (Fig. 2), where represented basin-averaged temperature as a function of depth and time.

This figure demonstrates the main processes forming thermal structure of Black Sea waters. The main signal is season changes during the annual cycle. The seasonal thermocline is formed at the 10-40 m depth during a spring-summer heating. The prominent feature of the Black Sea is the CIL (Cold Intermediate Layer). Its upper and lower boundaries are identified by 8 °C isotherm. In the figure this water mass is marked as a dark domain. In addition to strong seasonal variability, inter-annual changes in water temperature

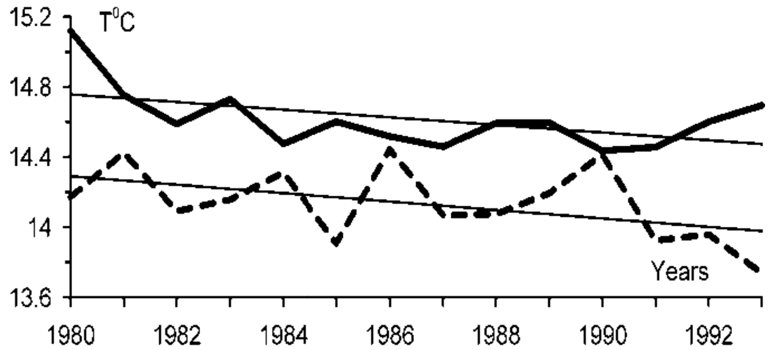

Fig. 1 Basin averaged annual-mean sea surface temperature (reanalysis—solid line, modeling—dotted line). Straight lines denote linear trends.

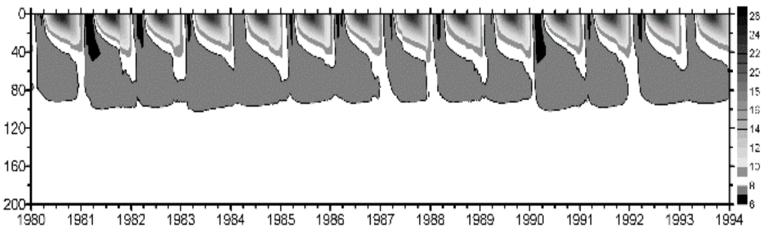

Fig. 2 Distribution of basin-averaged temperature within upper 200 m layer column (results of modeling).

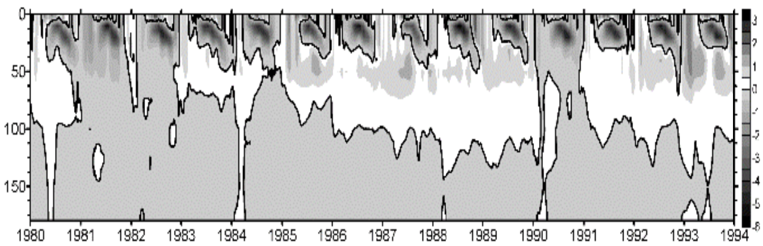

Fig. 3 Distribution of basin-averaged differences between modeling temperature and reanalysis. Solid line marks zero isoline.

are also well pronounced. It can clearly be seen in variations of the CIL thickness and lower boundary of the thermocline.

Fig. 3 demonstrates difference in temperature between results of modeling and reanalysis. The most significant deviation can be observed at the depth of about 20 m, where model values of temperature are smaller than reanalysis one during spring-summer season. In the lower layer (40-100 m), the modeling temperature is higher except for years 1981, 1982 and 1990, so the CIL in our results contains warmer water than in the reanalysis case.

The reason for such significant temperature deviation in the subsurface layer can be clarified if we look in Fig. 4, which represents mean seasonal temperature profiles. In spring and summer seasons seasonal thermocline in our results a little bit higher than in reanalysis. However, due to a great temperature gradient this small difference in thermocline position leads to large error in temperature value on these horizons.

Another factor forming the thermohaline structure of the Black Sea is salinity. Deviation of salinity from numerical modeling and from reanalysis is demonstrated in Fig. 5. In the upper layer (approximately 75 m), salinity from modeling is higher than reanalysis data, but in lower layer salinity values are underestimated in modeling results.

Therefore, comparison with reanalysis data shows a quite good capacity of the circulation model in simulating the main thermohaline features of Black Sea. The seasonal cycles of temperature and salinity are well captured. The main deviations in temperature are observed in narrow subsurface layer of seasonal

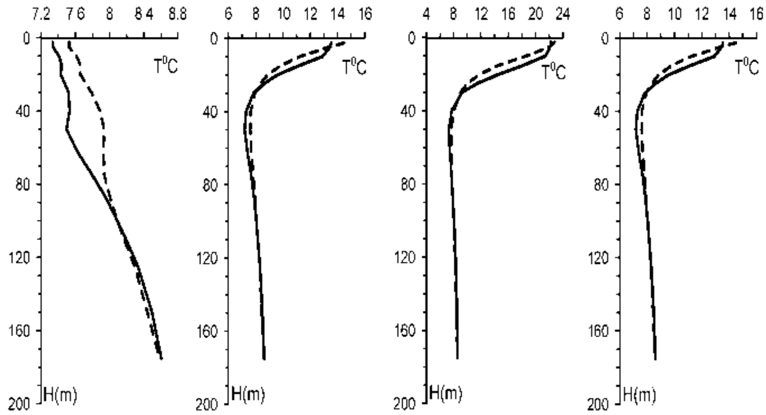

Fig. 4 Season-mean temperature profiles averaged over 14 years for winter, spring, summer and autumn (from left to right). Solid line—reanalysis results, dotted line corresponds to numerical simulation.

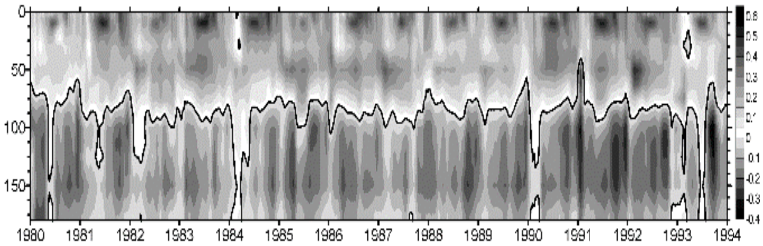

Fig. 5 Distribution of basin-averaged differences between modeling salinity and reanalysis. Solid line marks zero isoline.

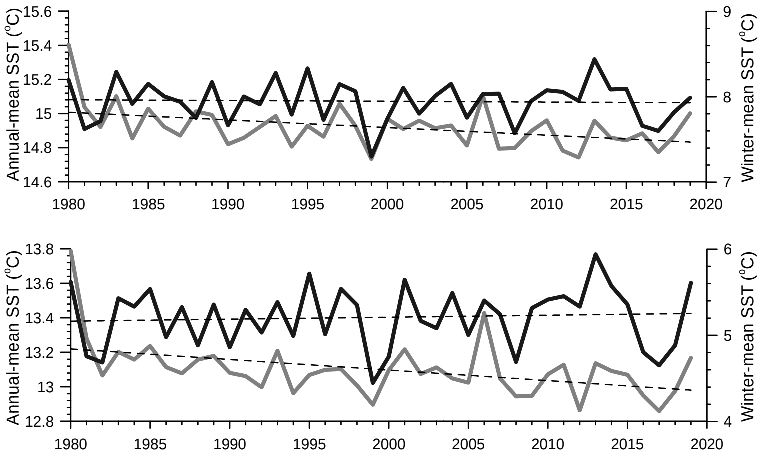

Fig. 6 Basin averaged annual (grey line) and winter (black line) mean sea surface temperature (°C). Straight lines denote linear trends. Upper panel corresponds to deep part of the basin, lower one to northwestern shelf.

thermocline. Model salinity in the surface layer is overestimated in comparison with reanalysis. That can be caused by not very careful description of the river runoff in the model.

Now let us consider results of modeling in more detail. Long-term evolution of the mean sea surface temperature is represented in Fig. 6. Graphs in the upper panel correspond to deep part of the basin, in the lower one—north-western shelf. In general, water temperature in the deep part of the basin is higher than on the shelf. In both cases annually averaged surface temperature tends to decrease, but winter averaged temperature has small positive linear trend in the shallow part of the Black Sea. In the deep part, this trend is negative as well as for annually averaged temperature, but its absolute value is remarkably smaller than for annual temperature. Such behavior means that seasonal oscillation amplitude of the surface temperature reduces.

As a subsurface signal of the temperature changes can be used variations of the cold intermediate layer characteristics. We chose annual mean thickness of the CIL and cold content. The last is defined as an integral between 8 °C isotherms minus CIL temperature ($\int_{h_1}^{h_2}(8-T)dz$). It characterizes not only the thickness of the CIL, but also its temperature value. Fig. 7 demonstrates evolution of these characteristics in time.

The mean CIL thickness varies from 45 to 65 meters in different years. The cold content also remarkably changes from year to year. Nevertheless, both these values tend to decrease during time period under consideration. This fact means that, in general, the upper layer of the Black Sea becomes warmer. That is in some contradiction with reduction of annually averaged sea surface temperature, observed in Fig. 6. It is known that CIL waters are renewed every winter due to penetrating convection over the basin area and cold water subduction from the shallow northwestern shelf. Fig. 8 shows the distribution of the surface sea temperature in winter season. This temperature map is obtained by averaging over all winter fields during 40 years. Surface temperature, lower than 8 °C, occupies approximately half area in the deep part of the Black Sea, moreover the value of this temperature is quite large (near boundary 8 °C). On the other hand, we can observe very cold waters on the northwestern shelf. Thus, we can conclude that the second mechanism of the CIL renewal prevails in our simulation. According to Fig. 6, the mean winter temperature on northwestern shelf tends to increase, that sources long-term reduction of the CIL thickness and cold content.

The next important hydrological parameter, characterizing thermohaline structure of seawaters is salinity. Fig. 9 demonstrates variability of the annually averaged mean SSS (sea surface salinity) separately for the deep part of the Black Sea and the northwestern shelf.

SSS inter-annual variability is well pronounced for both parts of the Black sea. The difference between the maximum value in 1985 and the minimum value in 2006 is equal to about 0.6 psu for northwestern shelf. For basin interior salinity, variation amplitude is smaller (approximately 0.25 psu). Strong minimum of surface salinity is observed in 2006. In general, the level of salinity on the northwestern shelf is noticeably lower than in the central deep part of the Black sea, due

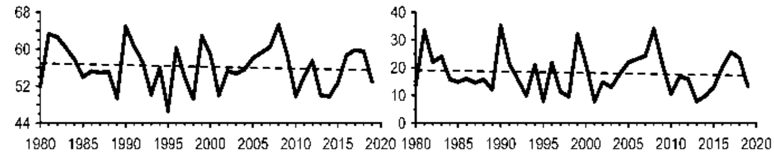

Fig. 7 Basin averaged annual mean thickness (m) (left panel) and cold content (m×°C) (right panel). Straight lines denote linear trends.

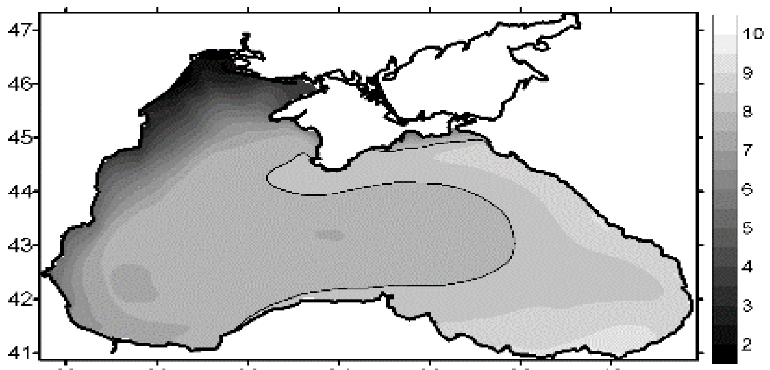

Fig. 8 Map of the winter surface temperature averaged over 40-year period. Solid line marks 8 °C isotherm.

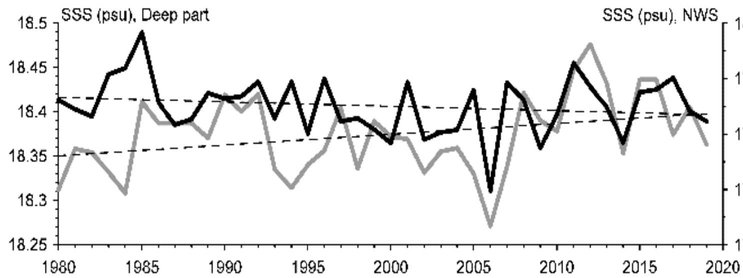

Fig. 9 Annually averaged mean sea surface salinity (psu) for deep part of the basin (grey line) and northwestern shelf (black line). Straight dotted lines denote linear trends.

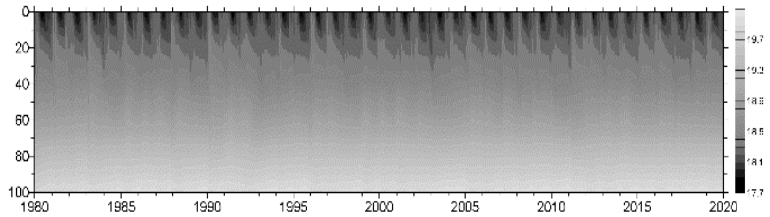

Fig. 10 Distribution of basin-averaged salinity within upper 100 m layer column (results of modeling).

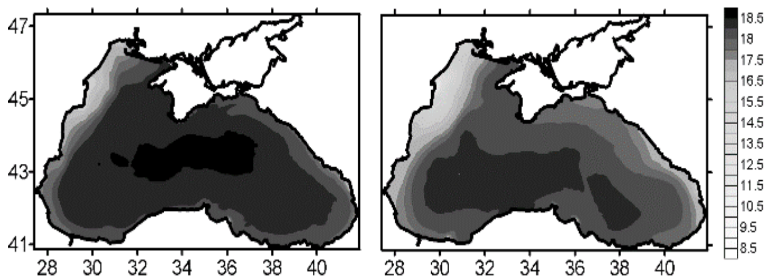

Fig. 11 Maps of climatic surface salinity distribution based on 40-year period. Left panel corresponds to February, right—June.

to Danube river runoff. Another essential distinction in SSS behavior of the two parts of the basin is different linear trends. In deep part, surface salinity tends to increase, but on northwestern shelf it decreases. Apart from inter-annual variability, seasonal changes in the upper 100 m layer can be observed in Fig. 10.

Analysis of the salinity distribution in the layer 0-100 m shows that a seasonal signal is traced clearly in the upper 40 meters. Minimum salinity is observed in June as a result of spring river flooding. Salinity of the surface waters grows after July until February when its maximum is observed. Space distribution of the sea surface salinity can be illustrated by Fig. 11. These are February and June climatic maps, when maximum and minimum SSS are observed during the annual cycle. These climatic fields were obtained on the basis of 40 year run. The saltiest water is in the center of the basin and the freshest near northwestern shelf caused by rivers runoff, particularly Danube.

Spatial distribution of the salinity in the Black Sea upper layers is presented in Fig. 12 as a zonal section along 43.4N latitude. It has a dome-like structure with deepening of isohalines towards the coast. The salinity highest gradient corresponds to the position of the Rim Current front.

The next important characteristics of sea dynamics is circulation. The winter circulation of the Black Sea is dominated by a two cyclonic gyre system in the western and eastern basins, encircled by a weakly meandering, organized and strong Rim Current jet. In summer time the upper layer circulation attains its most disorganized form, identified by a series of cyclonic eddies within the interior cell and accompanying larger coastal anticyclonic eddies around the periphery. Examples of the winter and summer circulation in the Black Sea upper layer are presented in Fig. 13.

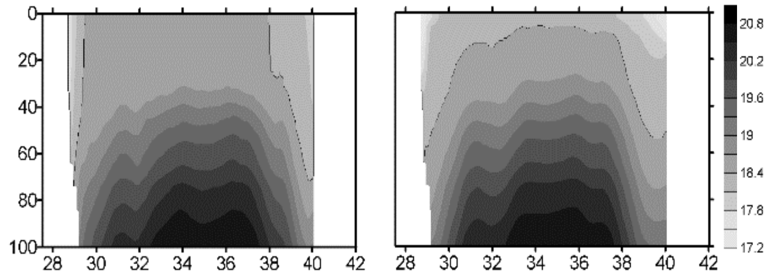

Fig. 12 Zonal sections along 43.4N of climatic salinity. Left panel corresponds to February, right—June.

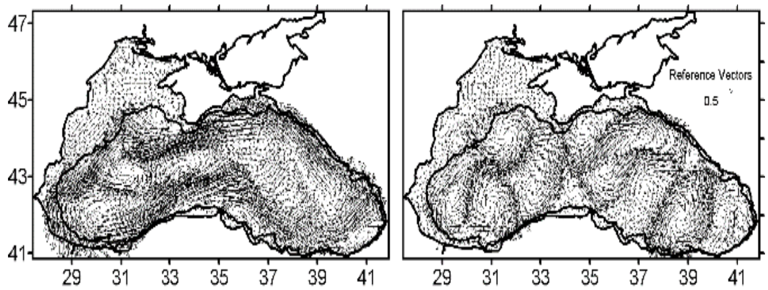

Fig. 13 Winter-mean (left panel) and summer-mean circulation in the upper 30 m layer of the Black Sea, derived from modeling.

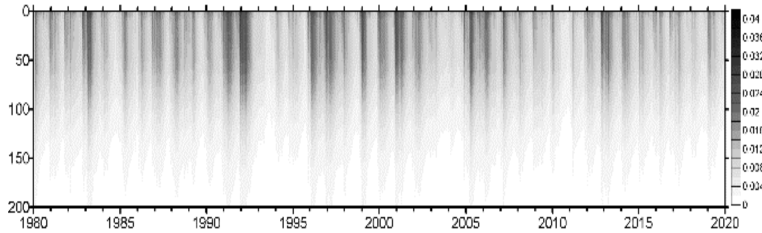

Fig. 14 Inter-annual and seasonal variability of the kinetic energy density (m2/s2) averaged over the basin area.

Seasonal and inter-annual variability of circulation intensity can be illustrated by Fig. 14, which presents density of currents kinetic energy in the upper 200 m layer. Seasonal signal is well pronounced. The highest intensity of the Black Sea circulation is observed in winter-early spring in season of strong storms on the Black Sea, when intense currents can reach a depth of 150 m, and the lowest one—in summer-early autumn. However, this picture differs from year to year. For example, the winter seasons of 1991 and 1992 demonstrate powerful circulation, but in the next three years, winter circulation is poor.

4. Summary

The long-term simulation of the Black Sea dynamics was fulfilled on the basis of circulation model, driven by COSMO-CLM atmospheric forcing. The modeling included as hindcast and future scenario as well. To investigate the quality of the results, we compare simulated hydrographic fields with reanalysis data (1980-1993). Comparison of these two data sets shows that the model sufficiently well describes the Black Sea thermohaline structure, its seasonal and inter-annual variability. However, there are some qualitative differences between results of modeling and reanalysis. In particular, surface water salinity is higher in the modeling results. Another difference is smaller amplitude of surface temperature seasonal variability in simulated fields. The results of modeling presented here are going to use for modeling the lower trophic level ecosystem of the Black Sea.

Acknowledgments

This study is a contribution to EU 7th Framework project PERSEUS (GA 287600) EC FP7/2011-2015.

References

[1] Oguz, T., and Gilbert, D. 2007. "Abrupt Transitions of the Top-Down Controlled Black Sea Pelagic Ecosystem during 1960-2000: Evidence for Regime Shifts under Strong Fishery Exploitation and Nutrient Enrichment Modulated by Climate Induced Variations." *Deep-Sea Res.* Part I 54: 220-42.

[2] Konovalov, S. K., and Murray, J. W. 2001. "Variations in the Chemistry of the Black Sea on a Time Scale of Decades (1960-1995)." *J Mar Sys.*31: 217-43.

[3] Korotaev, G. K., Oguz, T., Dorofeyev, V. L., Demyshev, S. G., Kubryakov, A. I., and Ratner, Yu. B. 2011. "Development of Black Sea Nowcasting and Forecasting System." *Ocean Sci*. 7: 1-21.

[4] Mellor, G. L., and Yamada, T. 1982. "Development of a Turbulence Closure Model for Geophysical Fluid Problems." *Rev. Geophys. Space Phys*. 20: 851-75.

[5] Rockel, B., and Geyer, B. 2008. "The Performance of the Regional Climate Model CLM in Different Climate Regions, Based on the Example of Precipitation." *MeteorologischeZeitschrift* 17 (4): 487-98.

[6] Knysh, V. V., Korotaev, G. K., Mizyuk, A. I., and Sarkisyan, A. S. 2012. "Assimilation of Hydrological Observation Data for Calculating Currents in Seas and Oceans." *Izvestiya, Atmospheric and Oceanic Physics* 48 (1): 57-73.