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Numerical Estimation of the Black Sea Circulation near the Continental Slope Using SKIRON and ERA5 Atmospheric Forcing †

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Abstract: Assessment of the state of sea waters and complex studies of the marine environment in various ocean basins are often based on hydrophysical fields (currents, temperature, salinity, etc.) obtained using numerical modeling. The regular fields of currents are of particular importance for assessing the transport of impurities in sea waters at different depths, including pollutants of various origins. The results of hydrophysical field modeling, in turn, depend on the conditions set at the boundaries of the basin. So, the correct setting of atmospheric conditions changing most rapidly is extremely important for the reconstruction of marine dynamics. This paper presents model estimates of the Black Sea circulation obtained using two different datasets SKIRON and ERA5 as atmospheric forcing. Numerical experiments are carried out based on eddy-resolving MHI-model for 2016. ARGO floats and R/V Cruises data are used to validate the simulation results. It is found that temperature and salinity RMSE between the model and measurement data are decreased under ERA5 forcing. Near the northeastern continental slope, a change in the direction of the alongshore subpycnocline current which is detected in the ARGO float trajectory is modeled using ERA5 rather than SKIRON. Therefore, for a more accurate reconstruction of the Black Sea circulation, it is recommended to use ERA5 atmospheric forcing.

Keywords: Black Sea circulation; modeling; forcing; measurement data

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1. Introduction

The circulation in the ocean upper layer, which is in direct contact with the atmosphere, is obviously related to the distribution of meteorological parameters [1–3]. At the same time, influence of atmospheric forcing on the structure of deepwater circulation is not so clear. For the Black Sea, this problem is complicated by the presence of a strong vertical density gradient (permanent pycnocline) at 50–100 m horizons which blocks seawater vertical exchange [3].

Regional features of density stratification often arise near the Black Sea continental slope due to the processes of mixing and lowering of surface waters along the slope into the deep sea layers [3,4]. The formation of density anomalies here can be caused by both external forcing at the boundaries of the basin (including wind, river runoff, etc.), the sinking of denser waters down the continental slope, and the transfer of water with thermohaline characteristics that differ from the background ones by eddies [4,5]. These processes are especially important in the northeastern part of the basin due to the narrow and steep continental slope in this region. The seawater density anomalies formed near the slope can lead to transformation of the velocity field at deep horizons [5]. Thus, the generation of unsteady deepwater undercurrents is found out there [6].

Below the permanent pycnocline, the Black Sea waters become warmer and more saline towards the bottom [2]. At the same time, anticyclones can form near the shelf edge, and then can move along the slope [4,5,7]. In the centers of the anticyclones colder and less saline subpycnocline waters deepen, and their movement contributes to the transfer of thermohaline anomalies and corresponding perturbations of dynamical fields. Such complicated dynamics near the continental slope requires detailed and accurate reconstruction of all hydrophysical characteristics, which is possible only if boundary conditions are correctly specified.

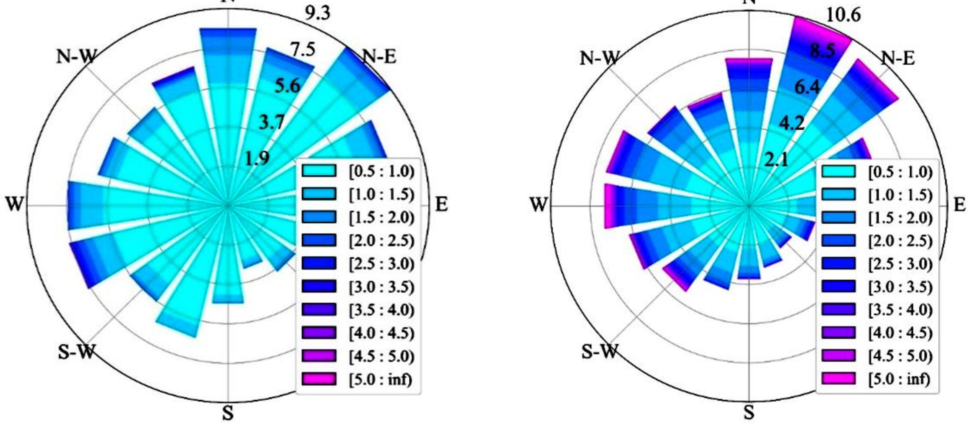
2. Materials and Methods

The Black Sea circulation is reconstructed by an eddy-resolving model of Marine Hydrophysical Institute (MHI-model) [8]. The model is based on the Navier-Stokes equations in Boussinesq and hydrostatic approximations. Vertical turbulent mixing is described by the Mellor-Yamada closure model 2.5, and horizontal mixing is described using a bilaplacian operator with constant coefficients. The model circulation is driven by the atmospheric forcing including wind stress, heat fluxes, precipitation, and evaporation on the sea surface. The climatological Black Sea rivers runoff and exchange through the straits are considered. Data assimilation (except for the satellite sea surface temperature data) is not used in the discussed numerical experiments. The MHI-model is implemented on C-grid with resolution of (1/48)° longitude, (1/66)° latitude, and 27 z-levels vertically. The model description in detail is presented in [8].

Basin bathymetry is built from EMODnet data [9]. The initial data are obtained from the Black Sea Physical Reanalysis CMEMS [10]. All initial and input fields are linearly interpolated in the MHI-model grid nodes.

In this work, two numerical simulations with identical model setup but different atmospheric forcing are carried out for the period of 2016. In the first one (SKIRON-experiment), the forcing includes 2-h data on wind velocity, thermal, latent, sensible, and solar heat fluxes, evaporation, precipitation provided by the SKIRON/Dust modeling system (Greece) with a spatial resolution of 0.1° [11]. In the second one (ERA5-experiment) the forcing is free-available hourly data of reanalysis supported by European Centre for Medium-Range Weather Forecasts for the global climate with a resolution of 0.25° [12].

Comparative analysis of the SKIRON and ERA5 data showed a significant difference in wind forcing in the Black Sea region. As can be seen in Figure 1, the ERA5 wind stress is stronger than SKIRON one by about 25–30%, and repeatability of NN-E and N-E wind directions (forming surface cyclonic circulation of the Black Sea) is higher. The remaining fluxes in ERA5 and SKIRON are close to each other with some excess (15–20%) of ERA5 data on total heat flux during the year and mass flux (precipitation minus evaporation) in autumn and winter.



(**a**) (**b**)

Figure 1. Histograms of the annual mean repeatability of the area-averaged wind directions (digits, %) and wind stress magnitudes (color, 10^{-5} N/cm^2) for the Black Sea area in 2016: (**a**) by SKIRON; (**b**) by ERA5. Data are calculated from the wind velocity at a height of 10 m.

3. Results

Daily data on sea surface height and three-dimensional fields of seawater temperature, salinity and current velocity for 2016 are obtained in two numerical experiments described above. The next stages of the study are the comparison of the simulation results with observational data (validation) and analysis of deepwater circulation with a focus on the continental slope region, where the most interesting features of the currents are observed. In the northeastern part of the sea, so-called undercurrents (opposite to the Black Sea surface basin-scale cyclonic gyre—the Rim Current [1–3]) are detected at a depth of 200 m for the period 9 June 2016–14 October 2016 according to ARGO data.

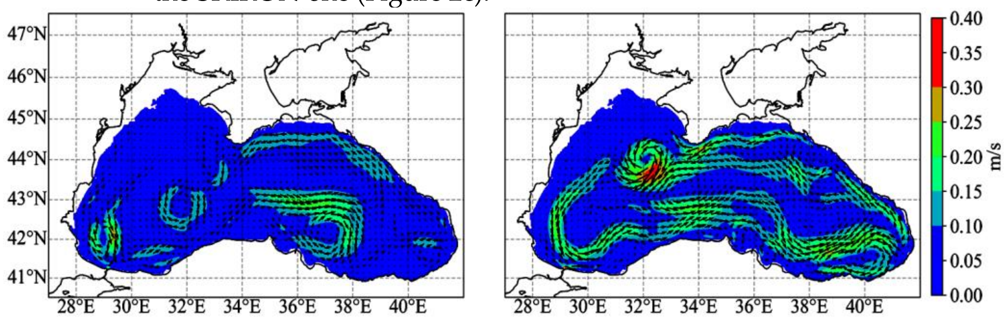
Validation of the model fields is performed based on temperature and salinity measurement data obtained by ARGO profiling floats [13] and R/V «Professor Vodyanitsky» Cruises 87, 89, 91 [14] in 2016. Validation methodology is described in [8] (Section 2.2). Root mean square errors RMSE between model and in-situ data for both experiments are presented in Table 1. It is obtained that the temperature RMSE in the upper layer (0–300 m) decreases in the ERA5-experiment compared to the SKIRON-experiment. The best decreasing of temperature error is observed at a depth of 0–30 m. The model salinity in the ERA5-experiment is more correct at a depth of 30–300 m. So, the permanent pycnocline and seasonal thermocline layers in the ERA5-experiment are closure to measurement data.

Table 1. The temperature and salinity RMSE between simulations and in-situ.

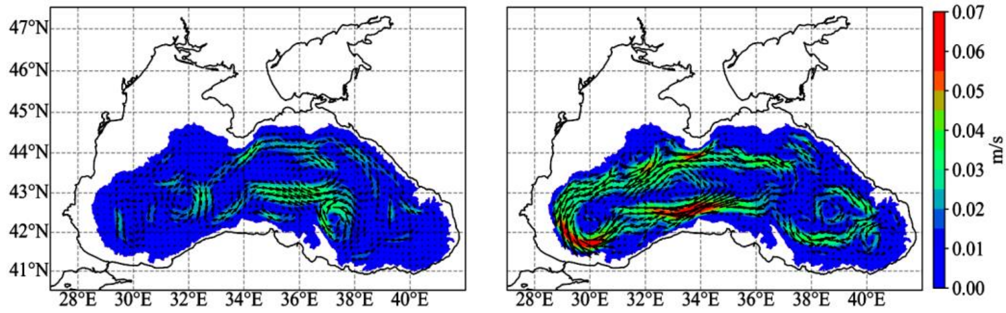
Depth, m	Temperature, °C		Salinity, psu	
	SKIRON	ERA5	SKIRON	ERA5
0–5	1.175	0.625	0.224	0.258
5–30	2.390	1.706	0.188	0.212
30–100	0.623	0.489	0.454	0.384
100–300	0.199	0.154	0.423	0.312
300–800	0.036	0.055	0.072	0.084
800–1500	0.030	0.027	0.055	0.075

A difference between the simulation results is primarily found in the velocity fields due to the strong influence of the wind on the Black Sea dynamics [1,2]. The increasing wind velocity in ERA5 (Figure 1b) leads to a more typical structure of the Rim Current at the end of 2016, when the basin-scale cyclonic gyre propagates above continental slope (Figure 2b). The Rim Current is not regenerated in winter, and mesoscale eddies are developed in the central sea part in the SKIRON-experiment (Figure 2a) due to insufficiency of kinetic energy inflow from the wind [8].

The model circulation in the upper layer is generally cyclonic for both experiments. At the same time, the most significant difference of the current velocity fields is detected below the permanent pycnocline core. Thus, at deepwater horizons in the ERA5-experiment (Figure 2d) the current field is more intense, and maximal velocity is higher than in the SKIRON one (Figure 2c).



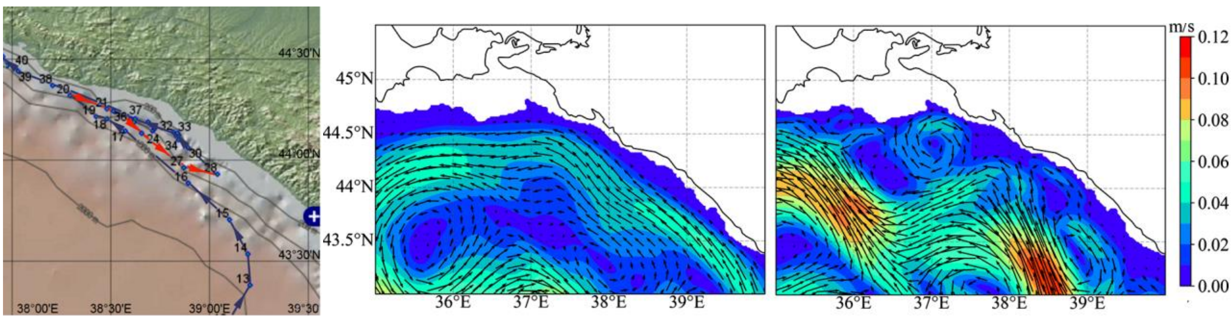
(**a**) (**b**)



(**c**) (**d**)

Figure 2. Monthly-mean current fields in December 2016 at depth of 50 m (**a**,**b**) and at depth of 500 m (**c**,**d**) according to the SKIRON-experiment (**a**,**c**) and the ERA5-experiment (**b**,**d**).

Analysis of ARGO float ID6901833 trajectory data [13] revealed the change in the direction of the alongshore subpycnocline current from the northwestern (cyclonic) to the northeastern (anticyclonic) near the northeastern continental slope. Thus, in 6 September–14 October, 2016 the float drifted anticyclonicaly at its parking depth of 200 m (Figure 3a, red arrows). Such behavior of the alongshore current is not modeled in the SKIRON-experiment (Figure 3b), but is clearly reconstructed in the ERA5-experiment (Figure 3c). Averaged over the period of anticyclonical movement of the float, the model velocity of the undercurrent riches 0.03–0.05 m/s with instant value up to 0.08 m/s. The undercurrent generation near the Black Sea continental slope is probably associated with intense mesoscale variability under the permanent pycnocline in the ERA5-experiment (Figure 3c). Thus, some eddies are observed along the continental slope here. The undercurrents that form near the Black Sea northeastern slope seem to be of an anticyclonic nature, similar to the undercurrents formed by anticyclones in the western part of the Bay of Bengal [15].



(**a**) (**b**) (**c**)

Figure 3. (**a**) ARGO float ID6901833 trajectory at parking depth of 200 m. Model current velocity at 200 m time-averaged for 6 September–14 October 2016 by the SKIRON-experiment (**b**) and the ERA5-experiment (**c**). Blue arrows illustrate the northwestern alongshore current, red arrows correspond to the southeastern current (undercurrent). Purple lines indicate to position of zonal cross-section along 44° N.

The structure of the circulation is inextricably linked with the spatiotemporal variability of seawater thermohaline characteristics [3,7]. The model temperature and salinity fields on zonal cross-section along 44°N averaged over the period of undercurrent existing are shown in Figure 4. As seen in temperature fields (Figure 4a,b), the upper mixed layer reaches a depth of 20–25 m in both experiments, but in the ERA5-experiment its thickness is larger near the eastern coast (up to 25–30 m) and its temperature is higher here. The mesoscale anticyclones shown in Figure 3c lead to the deepening of isotherms and isohalines near the eastern coast and the formation of undercurrent along the slope. There is a downward deflection of the isotherms at zone of 38.3–39.0° N in Figure 4b that corresponds to the anticyclonic current. A similar deflection is also visible in the salinity field (Figure 4d). So, the distribution of temperature and salinity in the ERA5-experiment is consistent with the anticyclonic current near the continental slope detected in the ARGO float ID6901833 data [13].

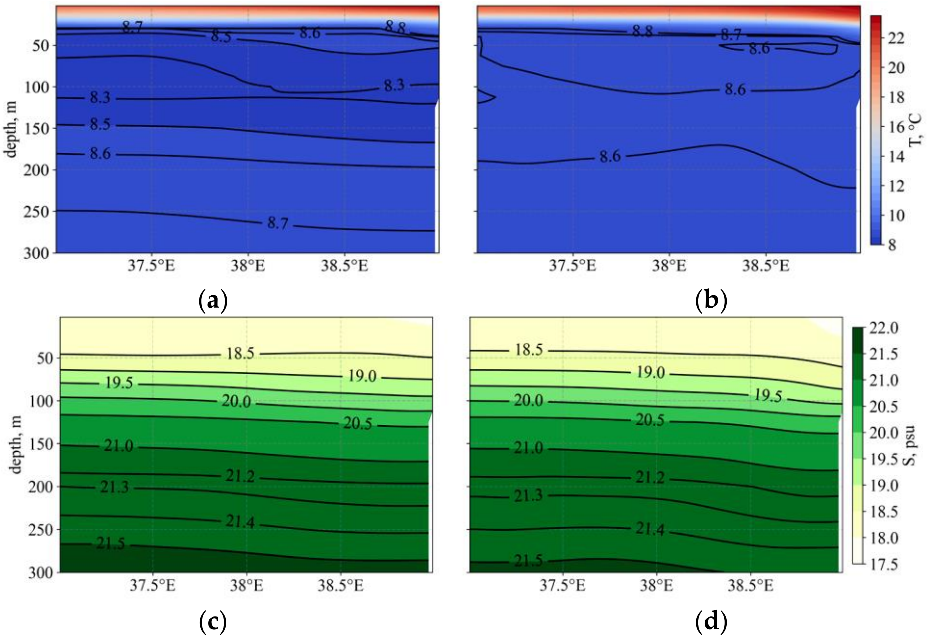


Figure 4. Zonal cross-section along 44° N of the model temperature (**a**,**b**) and salinity (**c**,**d**) fields time-averaged for 6 September–14 October 2016 by the SKIRON-experiment (**a**,**c**) and the ERA5-experiment (**b**,**d**).

4. Conclusions

The important result of the study is that atmospheric fluxes can affect the circulation of both the surface and deepwater layers of the Black Sea, and the choice of atmospheric forcing data can be decisive for the correct modeling of hydrophysical fields in the entire basin. The numerical analysis allows finding out that as well as the circulation in the upper sea layer, the deepwater dynamics depends on the characteristics of the atmosphere with a significant influence of wind forcing. Despite strong density stratification and difficult vertical exchange with deep layers, the atmospheric forcing also affects the circulation at a horizon of 200 m and deeper. Thus, mesoscale features of the model dynamics near the continental slope, such as subpycnocline undercurrents detected from the ARGO observations in the northeastern part of the sea, appear only when using ERA5 forcing. Also, the Black Sea thermohaline structure is more accurately reconstructed under ERA5 forcing that is confirmed by TS-measurement data. It is probably associated with more intense atmospheric fluxes in ERA5 compared SKIRON. Thus, for more accurate modeling of the Black Sea circulation and its subsequent application for complex studies, from two widely used meteorological datasets, it is recommended to use ERA5 data as atmospheric forcing, rather than SKIRON.

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Conflicts of Interest: The authors declare no conflict of interest.

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