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Original paper

Assessment of SKIRON and ERA5 Atmospheric Forcing for the Reconstruction of the Black Sea Circulation Based on Hydrophysical Modeling Results

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Abstract

A modeling of the Black Sea circulation for 2016 was carried out with different sets of atmospheric forcing data to determine the optimal atmospheric forcing for retrospective analysis of hydrophysical fields. An eddy-resolving z-model of Marine Hydrophysical Institute with a resolution of 1.6 km was used for the calculations. Differences in the circulation structure for the two experiments were revealed. It was shown that in the SKIRON experiment compared to ERA5, the cyclonic circulation of the Black Sea was weakened, the isopycnic surfaces were aligned, and the cold intermediate layer was not determined by the 8°C isotherm due to the underestimation of the solar radiation flux and weakening of the wind influence. A comparison of the model thermohaline characteristics calculated using ERA5 and SKIRON atmospheric forcings and measurement data of temperature and salinity obtained by ARGO profiling floats and onboard equipment in 87, 89, 91 cruises of R/V *Professor Vodyanitsky* was carried out. According to the validation results, it was obtained that in the upper 300-meter layer, for all measurement stations the mean RMSE of temperature and salinity in the ERA5 experiment were 28 and 17% lower, respectively, than the RMSE calculated from the SKIRON data.

Keywords: Black Sea, modeling, temperature, salinity, current velocity, *in situ* data, forcing, *ERA5, SKIRON*

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Оценка применимости атмосферных форсингов *SKIRON* и *ERA*5 для реконструкции циркуляции Черного моря на основе результатов моделирования гидрофизических полей

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Аннотация
Проведено моделирование циркуляции Черного моря в 2016 г. с разными наборами данных об атмосферном воздействии с целью определения оптимального атмосферного форсинга для проведения ретроспективного анализа гидрофизических полей. Для расчетов использована вихреразрешающая *z*-модель Морского гидрофизического института с разрешением 1.6 км. По результатам двух экспериментов выявлены различия в структуре циркуляции. Показано, что вследствие заниженного потока коротковолновой радиации и слабого ветрового воздействия по данным *SKIRON*, по сравнению с *ERA*5, циклоническая циркуляция Черного моря ослабевает, изопикнические поверхности выравниваются, а холодный промежуточный слой не определяется по изотерме 8 °C. Выполнено сопоставление модельных термохалинных характеристик, рассчитанных при использовании атмосферных форсингов *ERA*5 и *SKIRON*, с данными натурных наблюдений за температурой и соленостью, полученными буями-профилометрами *ARGO* и судовым оборудованием в 87, 89, 91-м рейсах НИС «Профессор Водяницкий». По результатам валидации получено, что в верхнем 300-метровом слое средние по всем станциям измерений среднеквадратические отклонения температуры и солености в эксперименте *ERA*5 меньше на 28 и 17 % соответственно, чем среднеквадратические отклонения, рассчитанные по данным эксперимента *SKIRON*.

Ключевые слова: Черное море, моделирование, температура, соленость, скорость течений, натурные наблюдения, форсинг, *ERA*5, *SKIRON*

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Introduction

The Black Sea is a semi-enclosed basin connected to the World Ocean by a narrow shallow strait with a double-layer current. According to the type of vertical structure of currents in the Bosphorus Strait, the Black Sea belongs to the estuarine type of basins with outflow of more fresh water in the upper layer and inflow of more saline water in the lower one. Due to the fact that water exchange with the World Ocean is limited in such seas, their circulation pattern depends significantly on atmospheric conditions.

Based on comparative numerical analyses of the energy budget of semi-enclosed seas such as the Mediterranean, Red, Black and Baltic seas, it is shown in [1] that the basin circulation is significantly influenced by buoyancy fluxes through the straits in addition to the wind work. The authors attribute qualitative aspects of the variability of currents in basins to differences between the relative contributions of the wind work and buoyancy work to the energy budget. Based on numerical modeling of the Caspian Sea water dynamics, it is shown in [2] that the level rise in the 1980–1990s was caused by changes in the volume of river runoff and atmospheric conditions over the basin. Correct reproduction of the water balance determined by atmospheric forcing helped to reproduce a sharp increase in the level (up to 2.5 m) in the Caspian Sea. In [3], the results of extreme surges modeling in the Sea of Azov are presented. It is shown that when using high-resolution WRF atmospheric data (10 km resolution), the accuracy of storm surge reproduction is higher than in the data calculated using ERA-Interim forcing (0.75° resolution). In [4], based on the results of numerical experiments, the effect of such atmospheric data as wind and thermohaline forcing on the Black Sea circulation is investigated and it is shown that the mean annual cyclonic vorticity of the wind field and the seasonal variability of the heat flux from the atmosphere support the large-scale cyclonic circulation in the basin. It is shown in [5] that changes in the intensity of the wind influence over the Black Sea lead to significant differences in the structure of current velocity field: if cyclonic vorticity of the wind field prevails over the sea, the velocity field is dominated by large-scale circulation; if the wind influence is weakened, an eddy circulation regime with predominance of mesoscale structures is formed.

In [1–5] above, the importance of atmospheric forcing in numerical analyses of the dynamics of enclosed and semi-enclosed seas is demonstrated. Therefore, the selection of external forcing data, especially wind stress, should be carefully controlled for retrospective analysis of the circulation of such seas. Despite the large number of high quality reanalyses of the Black Sea (see, e.g., [6, 7] and data set [1)]), in addition to thermohaline and hydrodynamic arrays, we also intend to calculate the circulation energy characteristics, which are not provided by the reanalyses known to us, in order to study the mechanisms of the observed trends in the variability of hydrophysical fields.

The aim of this paper is to validate the Black Sea circulation modeling results obtained by using different atmospheric datasets and to select the atmospheric forcing for the retrospective analysis of the Black Sea hydrophysical fields.

Numerical model

An eddy-resolving z-model of Marine Hydrophysical Institute (MHI model) was used to reconstruct the Black Sea circulation [8]. The model is based on full system of ocean thermohydrodynamics equations in the Boussinesq approximation, hydrostatics and incompressibility of seawater. The equation of state is represented

[1)] Lima, L., Masina, S., Ciliberti, S. A., Peneva, E. L., Cretí, S., Stefanizzi, L., Lecci, R., Palermo, F., Coppini, G. [et al.], 2020. *Black Sea Physical Reanalysis (CMEMS BS-Currents) (Version 1): Data set.* Copernicus Monitoring Environment Marine Service (CMEMS). https://doi.org/10.25423/CMCC/BLKSEA_MULTIYEAR_PHY_007_004 by a nonlinear dependence of density on temperature and salinity. The sea level is calculated from the equation obtained by fulfilling the linearized kinematic condition on the free surface, the vertical velocity is calculated from the continuity equation. In the context of solid lateral boundaries, the conditions of equality to zero of the normal velocity and the normal derivative of the tangential velocity are set for the components of the velocity vector; for temperature and salinity, the equality to zero of the normal derivatives is set. A no-slip condition and zero normal heat and salt fluxes are placed on the bottom. The model takes into account river runoff and water exchange through the straits, with Dirichlet conditions imposed on the liquid parts of the boundary. Wind stress, heat fluxes from the atmosphere, precipitation and evaporation are given as boundary conditions on the free surface. In addition, sea surface temperature is assimilated on the free surface when data are available. Vertical turbulent mixing is described using the Mellor–Yamada closure model [9], while horizontal viscosity and diffusion are described by the Laplace operator with constant coefficients. The sea level, temperature and salinity, horizontal components of the velocity vector are set at the initial moment of time. The model equations, boundary conditions and coefficients used are described in detail in [8].

The MHI model was implemented on grid C [10] with a resolution of 1.6 km in horizontal coordinates, which is sufficient to reproduce the mesoscale circulation features in both abyssal and coastal zones of the Black Sea [11], as it is smaller than the barotropic Rossby radius of deformation, which averages 15–17 km, and the baroclinic radius, which reaches 5 km in the coastal zone. According to [12], the term “mesoscale” will be used in this paper to denote eddy structures with sizes of 30–150 km. Vertically, 27 z-horizons were set with spacing from 2.5 m near the surface to 200 m in deep layers. Basin bathymetry was constructed from EMODnet [2)] data at a resolution of $(1/8)'$.

Numerical experiments and atmospheric forcing

Two numerical experiments were performed for 2016 with the same model settings but different atmospheric forcing. The initial fields for the experiments were the same and they were constructed from CMEMS reanalysis data for the Black Sea [1)]. Data from the Copernicus system [3)] were taken to set the sea surface temperature. Temperature, salinity and water discharge in rivers and straits correspond to monthly mean climatic values from atlas [13]. The first experiment (hereinafter referred to as the ERA5 experiment) used hourly data from the ERA5 reanalysis [4)] provided

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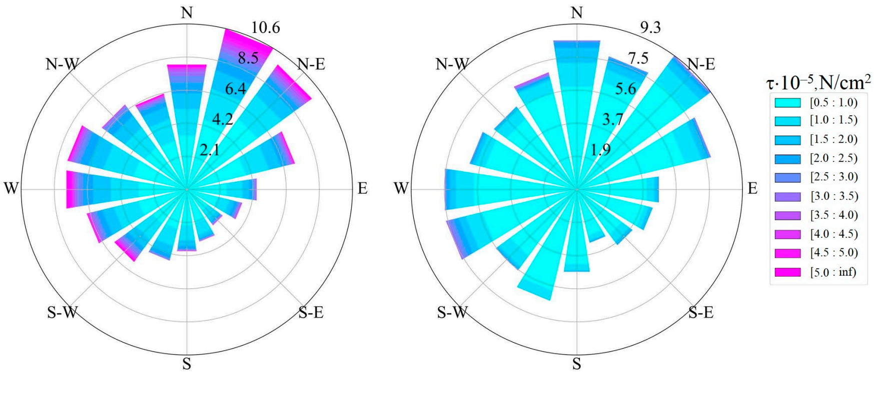
[2)] European Commission. *European Marine Observation and Data Network (EMODnet).* [online] Available at: https://www.emodnet-bathymetry.eu [Accessed: 3 March 2025].

[3)] CMEMS. *Black Sea - High Resolution and Ultra High Resolution L3S Sea Surface Temperature: Product ID.* SST_BS_SST_L3S_NRT_OBSERVATIONS_010_013E.U/CMEMS; Copernicus Marine Data Store. https://doi.org/10.48670/moi-00158

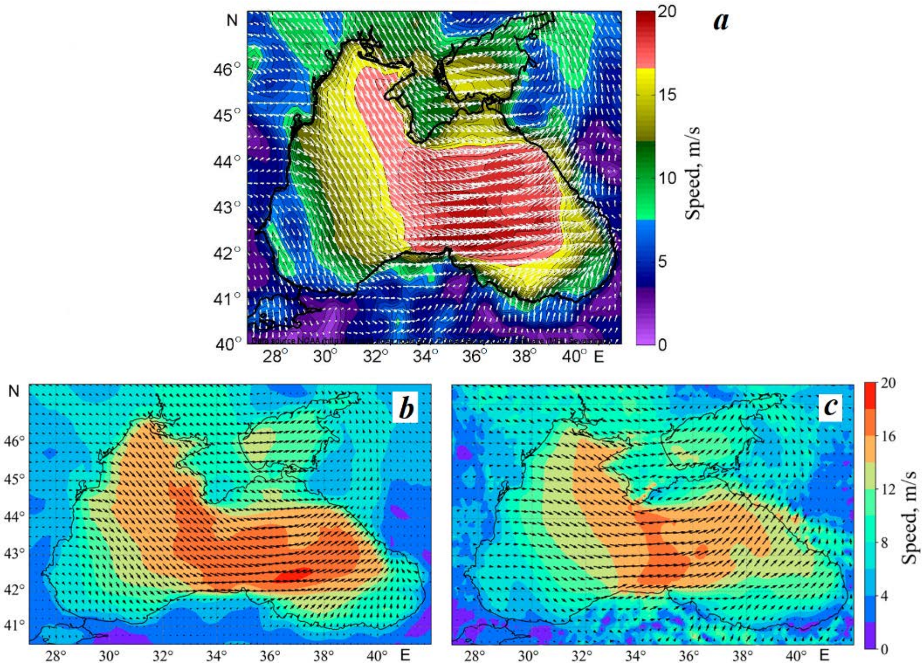
[4)] Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R. [et al.], 2023. *ERA5 Hourly Data on Single Levels from 1959 to Present:* Data Set. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.adbb2d47 by the European Centre for Medium-Range Weather Forecasts for global climate, with a resolution of 0.25°. In the second experiment (hereinafter referred to as the SKIRON experiment), the atmospheric forcing included two-hourly data obtained by the SKIRON/Dust modeling system (Greece) with a spatial resolution of 0.1° [14].

Comparative analysis of SKIRON and ERA5 data showed a significant difference in wind forcing over the Black Sea region. The tangential wind stresses were calculated using an aerodynamic formula similar to [15] based on wind speed data at 10 m height. As can be seen from Fig. 1, for both forcings, strong winds over the Black Sea most often (about 10%) have a direction between northerly and northeasterly, which is consistent with climatic estimates [15]. This structure of wind fields favours the formation of cyclonic circulation of waters [5)] in the upper active layer [16]. However, the maximum values of wind stress differ almost by a factor of 1.4 and reach $5 \cdot 10^{-5}$ N/cm^2 according to ERA5 and $3.5 \cdot 10^{-5}$ N/cm^2 according to SKIRON, corresponding to wind speeds of about 23 and 18 m/s, respectively. Comparison with available observations shows that the wind speed from ERA5 data is closer to reality. In confirmation of the above, Fig. 2 presents the wind fields on 3 December 2016 plotted using ERA5 and SKIRON forcing data and obtained at the Remote Sensing Department of Marine Hydrophysical Institute from satellite data (available at: http://dvs.net.ru/mp/data/main_ru.shtml). It can be seen that the high wind speed areas in ERA5 (Fig. 2, *b*) are more representative.

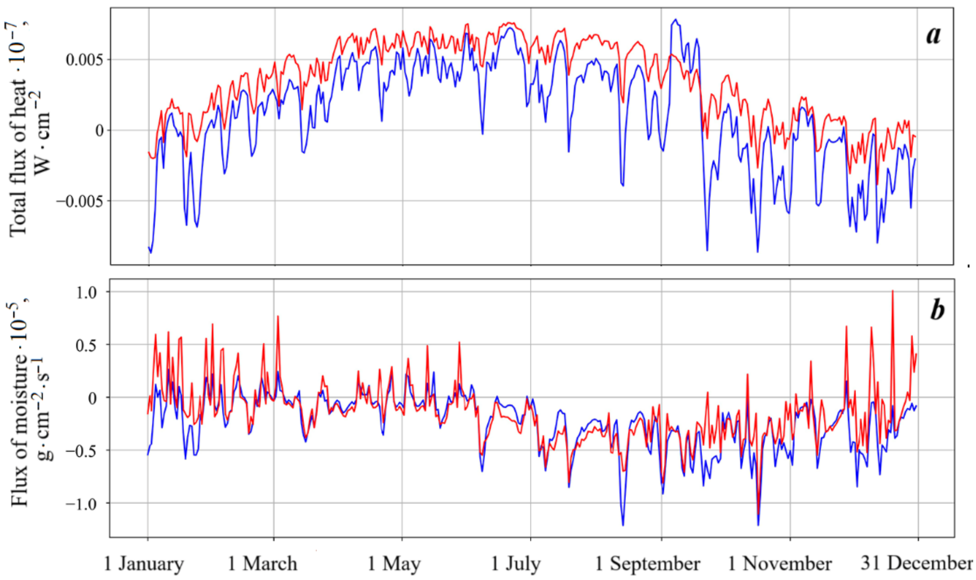


F i g. 1. Histograms of repeatability, %, of the wind directions and the wind stress values τ for the Black Sea in 2016: *a* – ERA5; *b* – SKIRON. The data are calculated from wind speed at a height of 10 m

[5)] Blatov, A.S., Bulgakov, N.P., Ivanov, V.A., Kosarev, A.N. and Tuljulkin, V.S., 1984. *Variability of the Black Sea Hydrophysical Fields*. Leningrad: Gidrometeoizdat, 240 p. (in Russian).



F i g . 2 . Examples of presentation of the wind fields on 3 December 2016: *a* – from satellite data (http://dvs.net.ru/mp/data/vel/jpg/wind/wind_nomads_2016120306.jpg); *b* – from ERA5 data; *c* – from SKIRON data

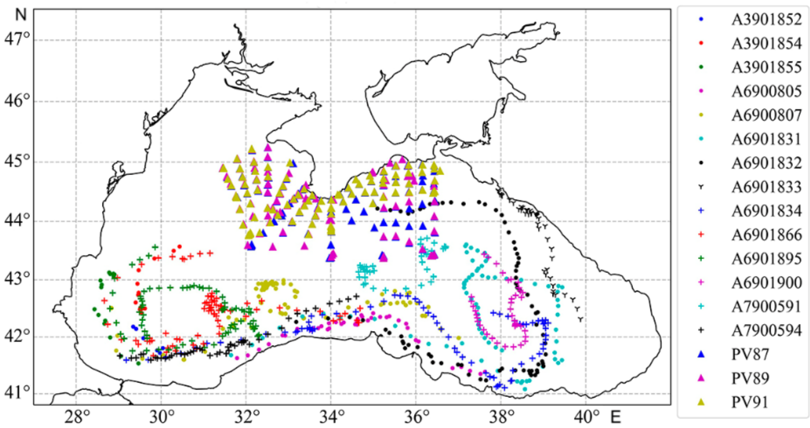


F i g . 3 . Total fluxes of heat (*a*) and moisture (*b*) in 2016 according to ERA5 (red lines) and SKIRON (blue lines)

The temporal variability of other fluxes from the ERA5 and SKIRON forcing data is qualitatively similar. For area averages, the total heat flux (sensible and latent heat, thermal and solar radiation) during the year is 15–20% higher according to the ERA5 data (Fig. 3, *a*). For the moisture flux (precipitation minus evaporation), an increase in precipitation is observed in winter and autumn according to ERA5 (Fig. 3, *b*).

Results of modeling and validation

As a result of numerical experiments, daily temperature, salinity and current velocity fields as well as sea level data were obtained for the entire study period. To validate the results, we calculated the root mean square errors (RMSE) of the model temperature and salinity from the *in situ* data obtained by ARGO profiling floats[6)] and onboard equipment in 87, 89 and 91 cruises of R/V *Professor Vodyanitsky* [17] in 2016 provided by the Oceanographic Database of Marine Hydrophysical Institute [18] (Fig. 4, Table 1). The data array contained more than 200 thousand measurements obtained both in the coastal zone and in the deep sea. As can be seen from Fig. 4 and Table 1, the coasts of Crimea, Turkey and the central deep sea are well provided with observation data in the cold and warm seasons. For the North Caucasus coast, the data from two ARGO floats are available for autumn and winter 2016. No data are reported for the northwestern shelf and the area of the Batumi anticyclone.



F i g . 4 . Map of location the temperature and salinity measurement stations conducted by ARGO floats and R/V *Professor Vodyanitsky* in 2016

[6)] IFREMER. *Coriolis Operational Oceanography*. [online] Available at: https://www.coriolis.eu.org/Data-Products/Data-selection [Accessed: 3 March 2025].

T a b l e 1 . Information about temperature and salinity measurements in 2016

Identifier of float A / cruise PV	Date of stations	Number of stations	Number of measure-ments	Maximum pro-file depth, m
A3901852	6–28 December	6	624	1507
A3901854	2 November – 29 December	13	1507	1509
A3901855	22 October – 28 December	15	1461	1356
A6900805	2 January – 12 November	39	2354	1500
A6900807	2 January – 31 December	137	189737	991
A6901831	5 January – 30 December	74	7126	1513
A6901832	2 January – 27 December	73	6579	1520
A6901833	2 June – 29 December	42	3614	1517
A6901834	5 January – 30 December	74	6746	1505
A6901866	2 January – 28 December	74	96639	987
A6901895	2 January – 27 December	73	8321	723
A6901900	4 January – 22 July	41	10777	978
A7900591	11 January – 27 December	38	36836	1012
A7900594	3 January – 25 August	48	18307	1974
PV87	30 June – 18 July	124	108681	2180
PV89	30 September – 9 October	104	60741	2185
PV91	16 November – 3 December	107	48945	2068

For data obtained from each float, in each cruise and for each model, at the points closest to the measurement stations on the corresponding date, vertical averaging of profiles in six layers characterised by specific thermohaline conditions [5)] was carried out: upper layer (0–5 m), seasonal thermocline layer (5–30 m), cold intermediate layer (30–100 m), permanent halocline layer (100–300 m), two deep water layers (300–800 m and 800–1500 m). Then, along the tracks, the series of temperature and salinity deviations from the measured data were calculated and the RMSE were obtained. Analysis of the RMSE tables for all tracks (not presented in the paper) showed that the trend of the RMSE changes in the indicated layers was preserved for all data. The largest deviations from the observational data were obtained for the summer season temperature fields in the thermocline, and for the salinity fields in the halocline. Below a depth of 300 m, the RMSE values are small and close in two experiments, the difference between them does not exceed 0.025 °C and 0.036‰ for temperature and salinity, respectively. Table 2 further summarises the RMSE of temperature and salinity averaged over all tracks by the results of both experiments in the upper 300 m layer.

As can be seen from Table 2, in the whole layer, the values of temperature reproduction errors are smaller in the ERA5 experiment than in SKIRON. The highest RMSE of temperature in both experiments were found in the 5–30 m layer, with the RMSE values in the ERA5 experiment being 28% lower than in SKIRON. For salinity, the difference between the RMSE values in the 0–30 m layer is small, about 0.03‰, and in the halocline layer, the RMSE of salinity in the ERA5 experiment is about 17% less than in the SKIRON experiment.

Thus, the thermohaline characteristics in the layers of the permanent halocline and seasonal thermocline in the ERA5 experiment are closer to the measurement data than in the SKIRON experiment. The seasonal thermocline formation is primarily due to the warming of the upper water layer, hence, the increased heat flux in the ERA5 data (see Fig. 3, *a*) gives more realistic temperature fields. The error decrease in the halocline layer in the ERA5 experiment can be related both to the increase in the precipitation flux in autumn and winter (see Fig. 3, *b*) and to the change in the current field structure. The latter statement will be verified below by a comparative analysis of the current velocity and salinity fields in two experiments.

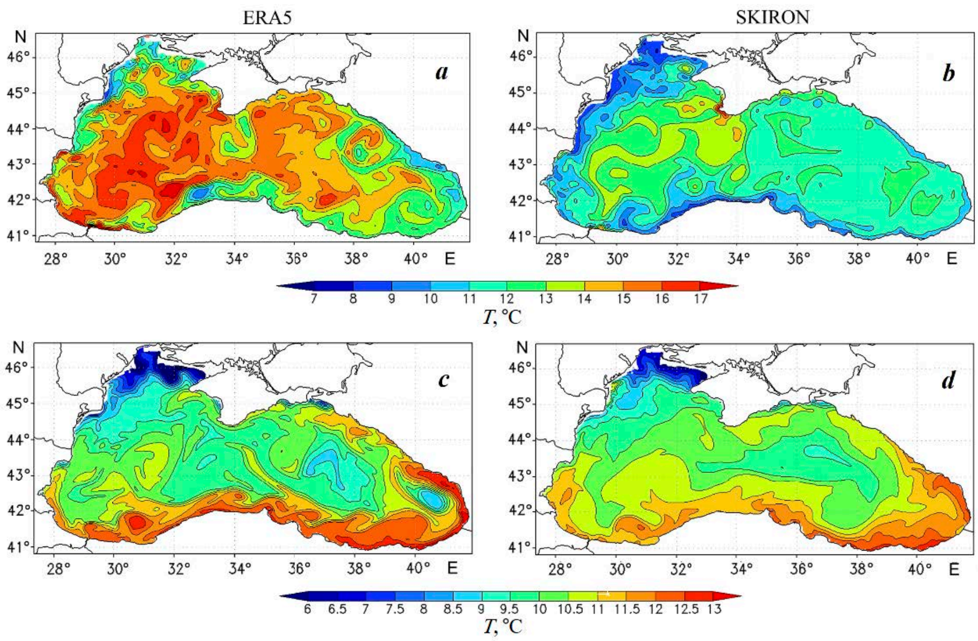
T a b l e 2. RMSE of temperature and salinity by the results of the ERA5 and SKIRON experiments

Layer, m	Temperature RMSE, °C		Salinity RMSE, ‰	
	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

To analyse the differences between the experimental results, the spatial distributions of the fields of currents, temperature and salinity at different horizons during the year were compared. It was obtained that calculations with SKIRON data showed smoother fields of all considered thermohydrodynamic characteristics in the upper 20 m layer than in calculations with ERA5 forcing.

Let us consider in detail the peculiarities of the model temperature fields. From January to the end of April in the ERA5 experiment, the water temperature in the surface layer in the area of the northwestern shelf was 3–4 °C lower than in the second experiment. For the basin as a whole, this difference was 1–2 °C at the 5 m horizon, 0.5–1 °C at the 20 m horizon. From the third ten-day period of April, water began to warm up faster at both horizons in the first experiment than in the second one. According to the literature data [5)], as a result of the spring and summer warming, a thermocline layer is formed in the Black Sea, with a depth of the vertical gradient summer maximum of 15–20 m [19]. According to the validation (Table 2), the maximum RMSE of temperature were revealed in the 5–30 m layer by the results of both experiments.

Fig. 5 shows temperature distributions at the 20 m horizon on 15 June and 15 December calculated in two experiments. It can be seen that in June, the difference between temperature values from ERA5 and SKIRON data for the western part of the basin averaged 3–4 °C, for the eastern part – up to 3 °C (Fig. 5, *a*, *b*).



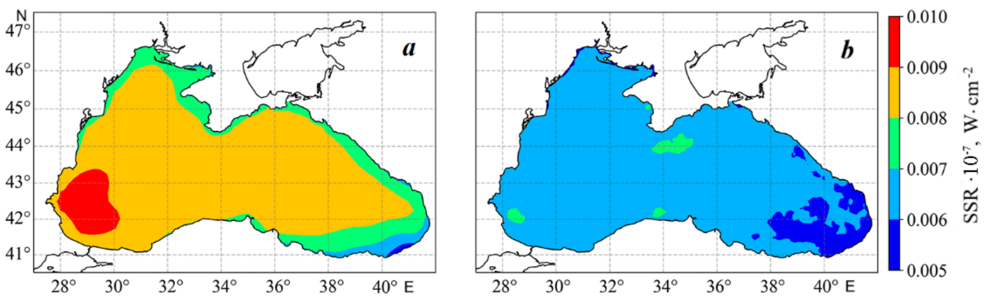
F i g . 5 . Temperature fields at the 20 m horizon on 15 June 2016 (*a*, *b*) and 15 December 2016 (*c*, *d*) obtained by using atmospheric forcings ERA5 (*a*, *c*) and SKIRON (*b*, *d*)

It should also be noted that for each experiment, the largest temperature difference of 3–5 °C between the western and eastern parts of the basin was observed in the zones of eddy activity.

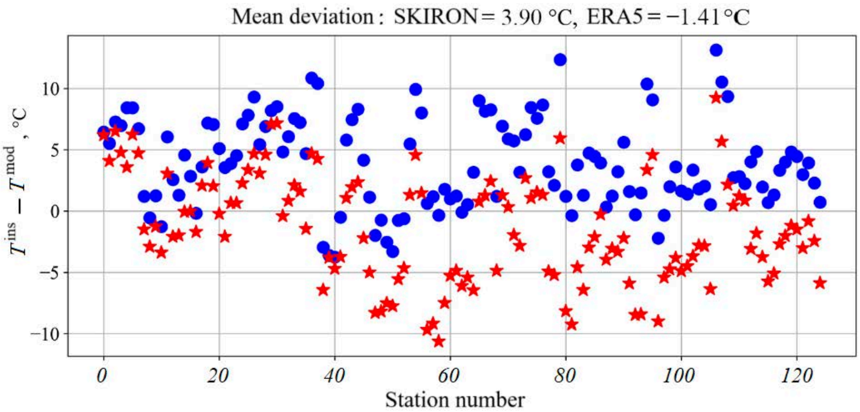
In the ERA5 experiment, the eastern part warmed to almost the same temperature values (20–24 °C) as the western part by September. For the SKIRON experiment, the temperature difference at 20 m horizon between the western (22.5–24 °C) and eastern (12.5–15.5 °C) parts of the basin was about 10 °C by mid-September. Since late October, the temperature fields in two experiments differed insignificantly (0.5–1 °C) across all the horizon, except for the southeastern region of the sea, where, according to the ERA5 experiment, the temperature was 3–4 °C lower due to the effect of a cyclonic mesoscale eddy (Fig. 5, *c*).

For the summer period, the heat fluxes from the atmosphere were analysed and the reconstructed temperature was compared with the data obtained in 87th cruise of R/V *Professor Vodyanitsky* (30 June – 18 July 2016). It was found that the difference in the heating intensity of the upper water layer in two calculations (Fig. 5, *a*, *b*) was related to differences in the magnitude of the solar radiation flux. Thus, the monthly solar radiation flux at the sea surface for June 2016 was 249.51 and 187.43 W/m^2 according to ERA5 and SKIRON data, respectively. The spatial distribution of the flux (Fig. 6) is also consistent with the non-uniformity of the temperature distribution in the western and eastern parts of the sea: for both forcings, the solar radiation flux in the western part is higher than in the eastern one.

Estimates of deviations from the direct measurement data make it possible to determine which of two experiments gives results closer to the actual observed temperature. Fig. 7 shows the difference between the measured and calculated temperature at the 15 m horizon at the stations of 87th summer cruise of R/V *Professor Vodyanitsky* (see Fig. 4). It can be seen that the temperature deviations in the ERA5 experiment were lower than in the SKIRON experiment: the mean difference over all stations was almost twice as small in absolute value (Fig. 7) and the RMSE in the 5–30 m layer was 2.83 °C according to ERA5 data versus 3.65 °C according to SKIRON data.



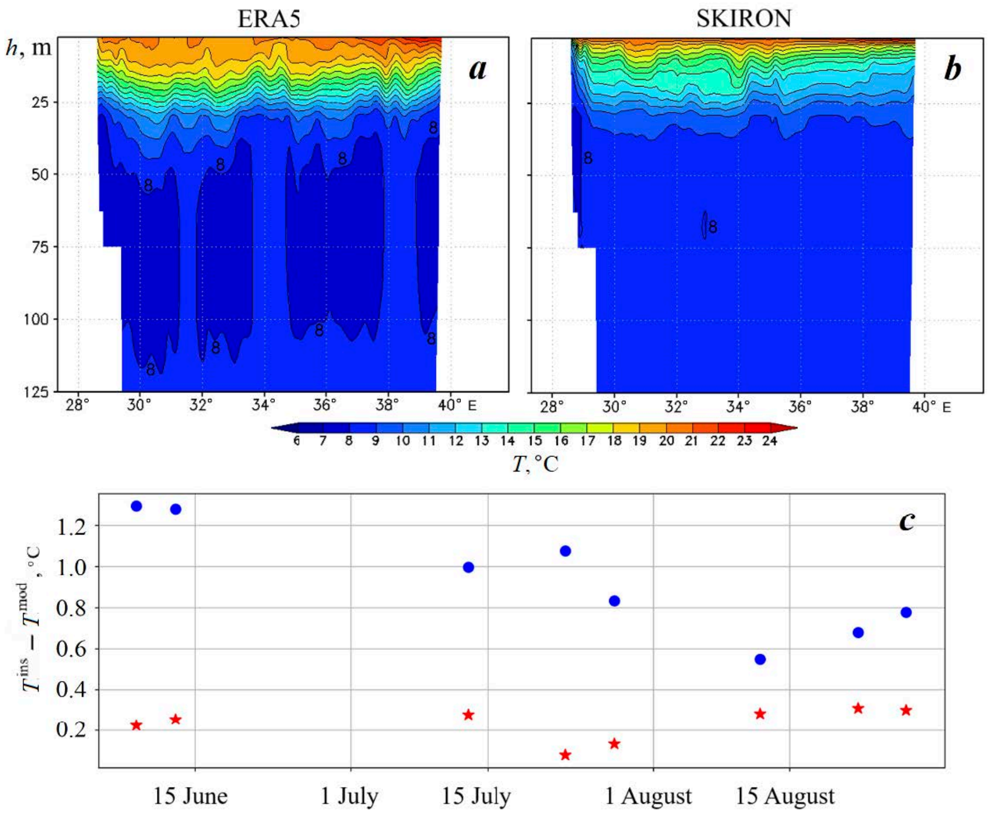
F i g . 6 . Monthly-mean solar radiation fields for June 2016 according to ERA5 (*a*) and SKIRON (*b*) data



F i g . 7 . Temperature deviation between the measurement data of 87th cruise of R/V *Professor Vodyanitsky* and the results of numerical experiments ERA5 (stars) and SKIRON (circles) at the 15 m horizon

It is known that the main contribution to the heat balance over the Black Sea comes from solar radiation (with a maximum in June) [19]. It should be expected that the differences in the magnitude of the total heat flux in the spring and summer season according to the ERA5 data observed in Fig. 3, *a*, will also be determined by this component of the balance. Fig. 6 confirms that the solar radiation from ERA5 is higher. Since the setup of the numerical experiments was identical, and only the atmospheric fluxes at the free surface differed, it can be argued that the underestimated solar radiation fluxes in the SKIRON forcing compared to ERA5 lead to significant temperature underestimation in the upper sea layer.

Analysis of the temperature distribution on a zonal section along 43.5°N showed that the temperature fields in the autumn and winter period were more homogeneous in the SKIRON experiment than in ERA5. In addition, calculations using SKIRON data showed that the water temperature in the upper mixed layer was about 0.5–1.0 °C higher in the first half of the year than using ERA5 data. Spring water warming in the SKIRON experiment started earlier than in the ERA5 experiment, but from the end of April the process intensified in the ERA5 experiment and the water started to warm faster than in the SKIRON experiment. Fig. 8, *a* shows that in the ERA5 experiment, the formation of a cold intermediate layer determined by the 8 °C isotherm is clearly observed, whereas in the SKIRON experiment, it is almost undetermined by the 8 °C isotherm (Fig. 8, *b*). Comparison of the model temperature with data from ARGO profiling float 6901831 (the trajectory of the float in the summer of 2016 was in the vicinity of 43°N – see Fig. 4) showed that the results of the ERA5 experiment were closer to the observational data, since the deviation of the model temperature from the observational data in the ERA5 experiment was 0.3–1 °C smaller than in SKIRON (Fig. 8, *c*). The vertical location of temperature isolines



F i g . 8 . Zonal sections of temperature fields along 43.5° N for 15 June 2016 obtained by using atmospheric forcing ERA5 (*a*) and SKIRON (*b*). Temperature deviation between the measurement data of ARGO profiler float no. 6901831 and the modeling results of numerical experiments ERA5 (stars) and SKIRON (circles) (*c*) at the 75 m horizon

in the 50–110 m layer in Fig. 8 indicates the presence of frontal zones preventing horizontal mixing which can be stipulated by eddy dynamics in the central deep sea.

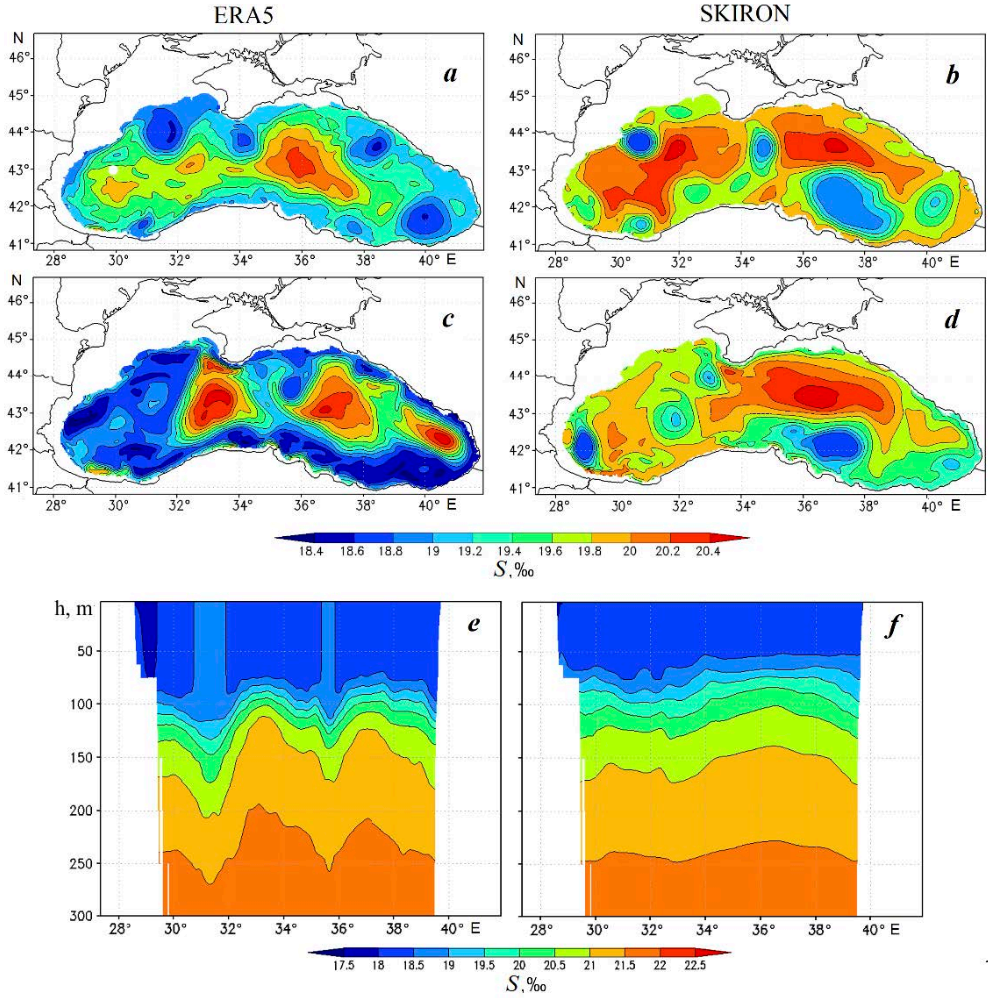
Salinity fields at horizons up to 20 m obtained from the results of two numerical experiments are quantitatively and qualitatively similar in the autumn and winter period (January–February and October–December), while differences appear from March to October. Thus, according to the results of calculations using ERA5 data, it was obtained that during this period at the 20 m horizon in the areas of the Danube, Dnieper and Dniester river mouths, quite extensive zones of waters with salinity below 16‰ were observed, whereas in the second experiment the salinity was higher than 16.75‰. In addition, during this period at the mentioned horizon, more saline waters occupied a larger area according to the results of calculations using SKIRON data. Analysis of the sea surface moisture flux (precipitation minus evaporation) showed that during the spring and summer seasons, the forcing data were close (Fig. 3, *b*) and heat and mass fluxes in the mouths of rivers and in the straits were the same in both experiments. Consequently, change in stratification due to heating leads to rearrangement of velocity field and then salinity field as a result of advective transport. Therefore, we assume that differences in the spatial distribution of salinity field are related to the structure of current field.

Below the 30 m horizon, salinity fields differ more significantly throughout the entire calculation period. As can be seen from Table 2, the greatest difference between calculations is observed in the permanent halocline layer. Fig. 9 demonstrates salinity fields at the 100 m horizon in June and December 2016. It was obtained that in the SKIRON experiment, salinity in the continental slope zone was about 0.5‰ higher in summer (Fig. 9, *b*) and 1‰ higher in winter (Fig. 9, *d*) than in the ERA5 experiment. Salinity values are close in the zones of action of mesoscale eddies. By the end of the year, the salinity difference between the deep sea and the near-slope zone in the ERA5 experiment is larger (Fig. 9, *e*) than in the SKIRON experiment (Fig. 9, *f*), which indicates indirectly the intensification of the Rim Current and formation of the salinity field dome-shaped structure with higher values in the centre of the basin and lower ones in the periphery.

Comparison of model data and along-track measurements of salinity by ARGO floats at horizons in the constant halocline layer showed that the ERA5 data reproduced salinity more accurately. This is confirmed by the analysis of mean and root mean square deviations of salinity. Table 3 shows the RMSE of salinity from measurement data in the 100-300 m layer for some ARGO floats operating in deep water (Fig. 4). For most floats, the RMSE of salinity is smaller when using ERA5 forcing.

Fig. 10 demonstrates deviation between measured and calculated salinity values at 100 m horizon. It can be seen that in May–August, the RMSE of salinity in the ERA5 experiment is two to three times smaller than in the SKIRON experiment, and the annual mean deviation is about 20% smaller.

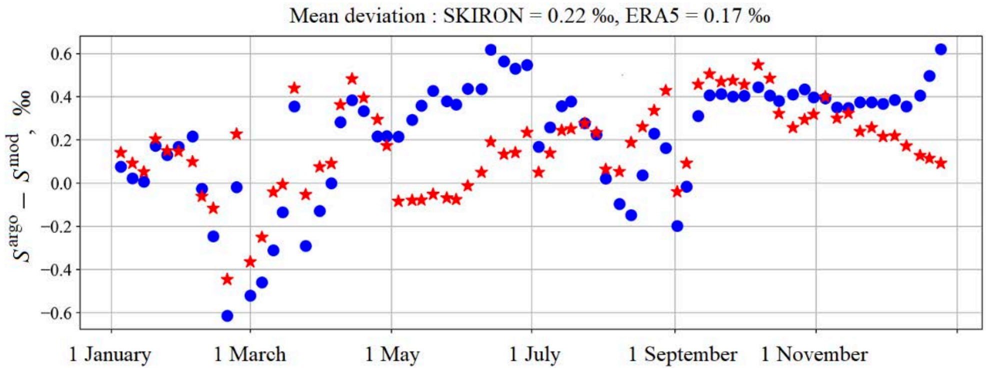
As shown by the analysis, the differences in the spatial distribution of salinity have little to do with the difference in the moisture flux from the atmosphere in two experiments and appear to be determined by a change in the velocity field structure. In the upper 20 m layer, current velocities and eddies from January to the end of April 2016 in the SKIRON experiment were less intense, especially in the area of the Anatolian Coast and Crimea. In January–April, the maximum velocities in the indicated areas according to the ERA5 experiment were 1.5 times greater than the values from the SKIRON data (at the 20 m horizon, 55–60 and 30–35 cm/s, respectively), with current directions remaining unchanged. In the second half of the year, the Rim Current is not formed as a single gyre in the SKIRON experiment, therefore a significant difference in the localisation of the currents is observed, especially in the area of formation of the Sevastopol anticyclone and also in the area of the Anatolian Coast. In July–October, maximum velocity values in the area of



F i g . 9 . Salinity fields on 15 June 2016 (*a*, *b*) and 15 December 2016 (*c*, *d*) at the 100 m horizon and zonal section of the salinity field along 43°N for 15 December 2016 (*e*, *f*), obtained by using atmospheric forcing ERA5 (*a*, *c*, *e*) and SKIRON (*b*, *d*, *f*)

T a b l e 3 . RMSE salinity, calculated in the ERA5 and SKIRON experiments, from ARGO data at a depth of 100–300 m

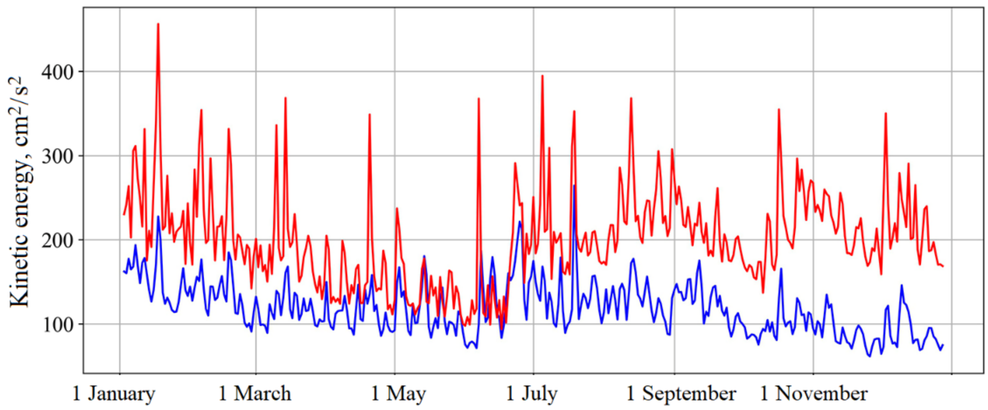
Forcing	Float identifier					
	6900805	6900807	6901832	6901834	7900591	7900594
ERA5	0.267	0.271	0.291	0.266	0.334	0.187
SKIRON	0.241	0.487	0.368	0.45	0.511	0.25



F i g . 1 0 . The salinity deviation between the measurement data of ARGO profiler float 6901834 and the results of numerical experiments ERA5 and SKIRON at the 100 m horizon

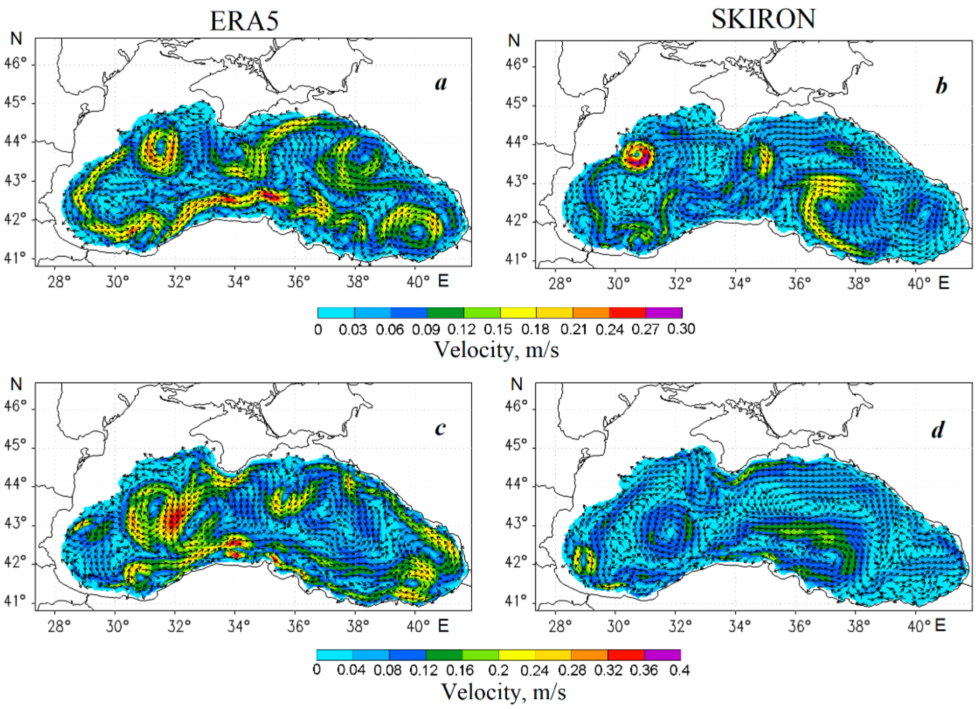
the Sevastopol anticyclone became different by two to three times (55–60 cm/s for ERA5 and 20–25 cm/s for SKIRON at the 20 m horizon). And the current directed to the east near the coast of Turkey was not observed in the SKIRON experiment.

Fig. 11 shows time variability of mean current kinetic energy at the first z-level of the model grid in two experiments. Since the equations of motion include wind tangential stresses as boundary conditions at this level, the energy change of the currents here depends directly on the wind. According to Fig. 1, the wind over the Black Sea was more intense from ERA5 forcing data than from SKIRON data,



F i g . 1 1 . Time variability of mean current kinetic energy in the upper model horizon according to data of ERA5 (red line) and SKIRON (blue line) experiments which led to an increase in the velocity of surface currents. The curves in Fig. 11 confirm current velocity increase at the upper horizon in the ERA5 experiment and increasing difference between experiments in the second half of the year.

The change in the currents structure at the upper horizons was also reflected in the intensity of the Rim Current and mesoscale eddies in the deep layers. Fig. 12 shows model current velocity fields at the 100 m horizon in June and December 2016. It can be seen that the orbital velocities at the periphery of the mesoscale eddies reach 25–30 cm/s in two experiments in June (Fig. 12, *a*, *b*) and the Rim Current intensity (velocity in the core and current width) is higher according to the data of the ERA5 experiment. The ERA5 experiment shows clearly Sevastopol and Batumi anticyclones with velocities up to 36 and 28 cm/s, respectively, in the current field in December, when a chain of mesoscale anticyclones is also observed near the Anatolian Coast (Fig. 12, *c*). In the second experiment at a horizon of 100 m in winter, the number and intensity of mesoscale anticyclones at the periphery of the Rim Current are significantly lower, and the Rim Current velocity averages about 10 cm/s.



F i g . 1 2 . Current velocity fields obtained by using atmospheric forcing ERA5 (*a*, *c*) and SKIRON (*b*, *d*) at the 100 m horizon on 15 June 2016 (*a*, *b*) and 15 December 2016 (*c*, *d*)

Comparison of the current fields (Fig. 12) with the salinity fields (see Fig. 9) at the 100 m horizon confirms that the increase in the salinity gradient between the deep water and near-slope zones in the ERA5 experiment in winter is caused by more intense cyclonic circulation of waters and evolution of mesoscale anticyclones at the periphery of the Rim Current.

Conclusion

Two numerical experiments on the reconstruction of the Black Sea circulation for 2016 using the ERA5 and SKIRON atmospheric forcings were carried out. The results of temperature and salinity modeling were validated on the basis of contact measurements made by ARGO profiling floats and in the cruises of R/V *Professor Vodyanitsky*. The comparative analysis of hydrophysical fields obtained in two experiments was performed.

Validation of the model temperature and salinity fields showed that the thermohaline structure of the Black Sea waters was more accurately reconstructed using the ERA5 atmospheric forcing. For this experiment, the RMSE of temperature in the 5–30 m layer decreased by 28% and the RMSE of salinity in the 30–100 m layer decreased by about 17%.

Hydrophysical fields of the Black Sea for 2016, calculated using ERA5 data differ from those calculated from SKIRON data by the increase in the temperature of the upper 20 m layer in the spring and summer season, formation of the cold intermediate layer, increase in the horizontal salinity gradient between the periphery and the central part of the basin in the permanent halocline layer, intensification of the Rim Current and coastal mesoscale anticyclones (Sevastopol, Batumi anticyclones, Anatolian coastal eddies) in the upper 300 m layer.

When comparing the forcing data for 2016, it was obtained that ERA5 had higher wind intensity throughout the year and higher solar radiation intensity during the warm period of the year. According to the SKIRON experiment results, insufficient wind energy and underestimated heat flux lead to weakening of the Black Sea cyclonic circulation, alignment of isopycnic surfaces and temperature decrease in the 50–150 m layer. Thus, it is reasonable to use the ERA5 atmospheric reanalysis for retrospective analysis of the Black Sea hydrophysical fields.

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Nadezhda A. Miklashevskaya – processing and description of the study results, qualitative and quantitative analysis of the results, data visualisation and their presentation in the text, preparation of the article text

All the authors have read and approved the final manuscript.