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CASE STUDY

Analysis of current influence on the wind wave parameters in the Black Sea based on SWAN simulations

Aleksandra Rybalko[1] · **Stanislav Myslenkov**[1,2,3]

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Abstract
This study is dedicated to the assessment of the current influence on the wind wave height in the Black Sea based on numerical modeling. The research was carried out based on the SWAN wave model driven by NCEP/CFSv2 wind reanalysis. Current data from the Remote Sensing Department's archive of the Marine Hydrophysical Institute of RAS were used. It is shown that the average wave height mainly decreases when sea currents are considered. These changes are insignificant relative to the average values of wave heights. The greatest negative changes are typical for the western, central, and northeast parts of the Black Sea. Here, currents reduce the average annual wave heights down to – 7.5 cm. A slight increase in the average wave height is typical for the southern, southeast parts, and the northwest shelf of the sea. Currents have the greatest influence on the wave parameters during winter and the least during late spring and summer. The validation shows that currents increase the correlation coefficient when wave heights are > 2 m, but this increase is insignificant, over 0.05. In general, the quality of wave simulation in the Black Sea does not improve by supplementing currents in the model used in this study.

Keywords Current influence on waves · Wind waves · Black Sea · Wave model · SWAN

1 Introduction

High-quality hydrometeorological information on the Black Sea region is of high importance for developing various hydrotechnical structures and ensuring the safety of marine works as well as conducting environmental monitoring of marine and coastal ecosystems. Wind waves are among the most important hydrometeorological parameters for various groups of consumers. It is known that currents affect wind waves parameters. Although wind waves and circulation in the Black Sea are well researched, the question of the current influence on the wave parameters is little studied in the Black Sea. There is no research on within what limits can the currents change the wave height for the entire basin.

✉ Aleksandra Rybalko
ryb.aleksandra1@gmail.com

Stanislav Myslenkov
stasocean@gmail.com

1 Lomonosov Moscow State University, Moscow, Russia

2 Hydrometeorological Research Center of Russian Federation, Moscow, Russia

3 Shirshov Institute of Oceanology of RAS, Moscow, Russia

The question of the current influence on the wave parameters is well researched. The ratio of the wave number k and the phase velocity C in the absence of currents and in the presence of the flow with velocity U can be represented as

$$\mathrm{k(U + C) = k_o C_0}, \tag{1}$$

where the subscript 0 indicates the absence of currents.

Phase velocity change C/C_0 can be written as

$$\frac{C}{C_0} = \frac{1}{2}\left(1 + \sqrt{1 + \frac{4U}{C_0}}\right). \tag{2}$$

Changes in the wave amplitude a can be estimated by the equation, where the subscript 0 indicates the absence of currents

$$\frac{a}{a_0} = \frac{c_0}{\sqrt{c(c + 2U)}}. \tag{3}$$

In the case of a counter flow (U < 0) in (3), the wave height increases, and wavelength and wave velocity decrease. Co-direction of waves and currents increases the wave velocity and wavelength compared to their values in the absence of

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currents. In this case, the wave height should decrease (Bowden 1984).

Waves can be refracted if the angle of wave–current interaction is different from 0° and 180° or the surface velocity of a current varies transversely.

The history of studying the wave-current interaction is well described by Rusu and Soares (2011). The first studies devoted to theoretical aspects appeared in the early 1960s. However, the question of the influence of currents on wind waves in specific areas of the World Ocean has been little studied so far. The influence of currents on wind waves in the World Ocean is studied by various methods. The most widely used ones are by remote-sensing methods using aircraft (Liu et al. 1989, 1994; Romero et al. 2017) and by wave model simulations. Most studies using wave models consider relatively small water areas and use the third-generation SWAN wave model (Booij et al. 1999).

The impact of surface currents and sea level on the wave field parameters during St. Jude storm in the eastern Baltic Sea was described in (Viitak et al. 2016). It was shown that the surface current input improves the simulation results, especially in storm conditions. The surface currents produced changes in the significant wave height by lowering it by as much as 50 cm in deep water (> 20 m) and by increasing it up to 40 cm nearshore.

The effect of the wave–current interaction on waves in the semi-enclosed Gulf of Venice was investigated in (Benetazzo et al. 2013). The authors used the Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST) modeling system, which relies on the ROMS (Regional Ocean Modeling System), the wave model SWAN (Simulating WAves Nearshore), and the CSTMS (Community Sediment Transport Modeling System) routines. The analysis of the wave–current interaction was performed over the winter season with a particular focus on the waves generated by the local dominant winds. Different effects on the wave–current interaction were depicted due to the variable wind and ocean current direction, showing that within the northern Adriatic Sea, the ocean–wave interactions are strongly dependent on the wind forcing direction.

The impact of currents on waves in estuarine zones is actively studied (Liu and Xie 2009; Rusu et al. 2011; Dodet et al. 2013; Rusu 2010; Akan et al. 2017). A comparison of the obtained simulation results with the results of satellite observations/direct measurements showed that the accuracy of the wave height simulation is increasing when currents are taken into account. Rusu (2011) estimated the influence of currents on the parameters of wind waves in the Black Sea. He studied the area of the Danube Delta and analyzed the cases of most typical variants of the wind–wave conditions for the target area. The increase of the wave height by 12–55% was detected when adding currents data to the model. Longer model calculations (3 months) demonstrated

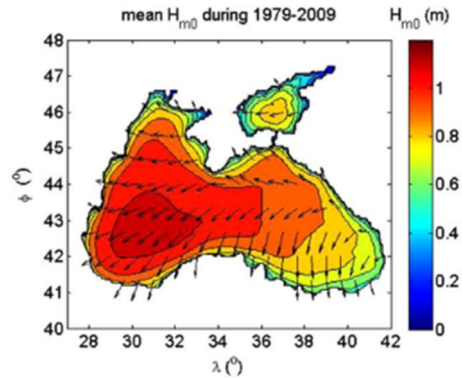

Fig. 1 Spatial distributions of mean significant wave height and averaged mean wave direction for the periods of 1979–2009 (Akpınar et al. 2016)

the increase of the wave height and the decrease of the wave period up to 28% and the wavelength up to 40%. The change in propagation directions for waves was approximately 20°. In addition, it was noted that currents can cause rogue waves in the target area. In general, the analysis of statistical parameters showed some improvements in the results of the SWAN model simulations for that area when the current field was inputted.

In the study (Causio et al. 2021), the authors claimed to have investigated wave–current interaction for the first time in the Black Sea, having implemented a coupled numerical system based on the ocean circulation model NEMO v4.0 and the third-generation wave model WAVEWATCH III v5.16. Coupling slightly improved the wave model performance when it was compared to the wave height satellite observations. The results indicate that the improvement was mainly related to the better representation of the effect of air–sea temperature differences on the wave growth, while the usage of the surface currents plays a minor role (Causio et al. 2021).

However, most authors (Kabatchenko et al. 2001; Rusu et al. 2006; Polonsky et al. 2011; Arkhipkin et al. 2014; Van Vledder and Akpınar 2015; Myslenkov et al. 2016) did not input the current field to the model to simulate wind waves in the Black Sea. The simulation in these works is of high quality: validation of model results obtained on the basis of reanalysis data and spectral wave models against direct measurement data shows the correlation coefficient of ~ 0.8–0.9 and root-mean-square error of ~ 0.3 m. The mean scatter index, which is calculated by dividing root-mean-square error by the average wave height of observed values, ranges from 40% (Akpınar et al. 2016) to 65% (Gippius and Myslenkov 2020).

The Black Sea belongs to relatively calm areas of the World Ocean (Fig. 1). The average values of SWH (significant wave height) exceed 1 m in the western part of the sea.

The southeastern part of the basin is characterized by the lowest SWH values. The mean direction of wave propagation in the southern and central parts of the sea is northeastern and northern with long-term averaging. The average wave direction in the northwestern part of the sea is eastern and the northeastern part of the sea is characterized by a southeastern average wave direction.

As for the spatial distribution of the average SWH in the Black Sea by seasons, the average SWH in the western part is higher than in the eastern one in all seasons (Fig. 2). Here and below, we mean by seasons the division into winter (December–February), spring (March–May), summer (June–August), and autumn (September–November). The most intense waves are observed in winter. The calmest sea is typically observed in summer. The average SWH values in winter exceed 1.5 m (Akpınar et al. 2016, Fig. 3) in the west part of the sea. The maximum SWH in winter are about 9–13 m (Akpınar et al. 2014; Polonsky et al. 2011). The lowest values of SWH during all seasons are typical for the southeast of the Black Sea.

Schema of the upper layer general circulation in the Black Sea is presented in Fig. 3.

The upper layer circulation pattern of the Black Sea can be divided into three major regions (Ivanov and Belokopytov 2013). The first one is a 40–80 km jet-stream current zone, which consists of the Rim Current and the western and eastern cyclonic gyres. The Rim Current propagates along the periphery of the sea and mainly corresponds to the zone above the continental slope. However, the Rim Current‘s jet can move away from the coast and cross the deep-water part. The velocity in the zone is on the average 20–25 cm/s during summer and about 40–50 cm/s during winter (Titov and Prokopov 2002; Ivanov and Belokopytov 2013). Speeds can reach values of 1–1.5 m/s (Ivanov and Belokopytov 2013). The second zone is characterized by coastal anticyclonic eddies with very variable flow, with currents speeds of up to 20–30 cm/s. The current regime is different in the open sea area (the third zone), where the velocity does not exceed 5–15 cm/s and decreases gradually from the periphery to the center (Ivanov and Belokopytov 2013).

The seasonal variability of the current fields is described in (Demyshev et al. 2022) using the example of 2011 and 2016 years. The Rim Current velocities and mesoscale eddies positioning areas show significant variability for the same seasons in different years (Demyshev et al. 2022).

The spatial distribution of average wind speeds by seasons for the Black Sea is characterized by maximum values in winter and minimum values in summer (Fig. 4). Average wind speeds are higher in the western half of the sea than in the eastern one in all seasons. In winter, average wind speeds reach 8 m/s in the northwestern part of the sea and are 4–6 m/s in the southeastern part. In summer, average wind speeds exceed 5 m/s only in small areas in the western part of the sea.

The purpose of our work is to study for the first time the scale, spatial, and temporal variability of the influence of sea currents on the wave height in the entire Black Sea during the period from 2013 to 2017 based on the results of numerical simulation using the SWAN wave model.

The paper is organized as follows: Sect. 2 introduces data and methods used in the study; Sect. 3 describes the results, which are discussed and summarized in Sects. 4 and 5, respectively. In turn, the Results section describes changes of wave height when adding currents with averaging of different temporal scales and includes the following subsections: (1) interannual variability of wave height, (2) seasonal variability of height differences, (3) average monthly height differences, and (4) quality assessment of model performance with currents added.

2 Materials and methods

2.1 Model setup and computational grid

In this study, the third-generation SWAN wind wave model was used. The main equation in the SWAN model is as follows: In the model, currents are taken into account as follows:

$$\frac{\partial N}{\partial t} + \nabla_{\vec{x}} \times \left[\left(\vec{c}_g + \vec{U}\right)N\right] + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma}, \quad (4)$$

where currents are taken into account by adding flow velocity to the group velocity; N is action density, $N = E/\sigma$ and E is energy density spectrum; $\vec{c}_g$ is a group velocity and $\vec{U}$ is ambient current, σ is the relative frequency and θ is the wave propagation direction, and S_{tot} stands for sources and sinks of wave energy.

The computation is performed on an original unstructured grid based on digitized nautical maps of the entire Black Sea and its coastal areas. These maps contain isolines corresponding to depths of 0, 5, 10, 20, 50, 100, 200, 300, 500, 1000, 1500 and 2000 m (Fig. 5).

After digitizing the maps, we obtained a grid containing 42,284 nodes and 77,036 elements. This grid has been tested in previous studies (e.g., Gippius and Myslenkov 2020). The distance between the grid points varies from 5 to 10 km in the deep-water regions, till 25 m in coastal areas (Fig. 6). The order of magnitude of the spatial step values in the deep-water part corresponds to that in similar works on wind waves in the Black Sea (e.g., Akpınar et al. 2016).

SWAN model offers the user to choose between various source terms, and the influence of the model settings for the Black Sea is a topical issue and is studied in various works (Rusu et al. 2014; Akpınar et al. 2012). Yet, our study is

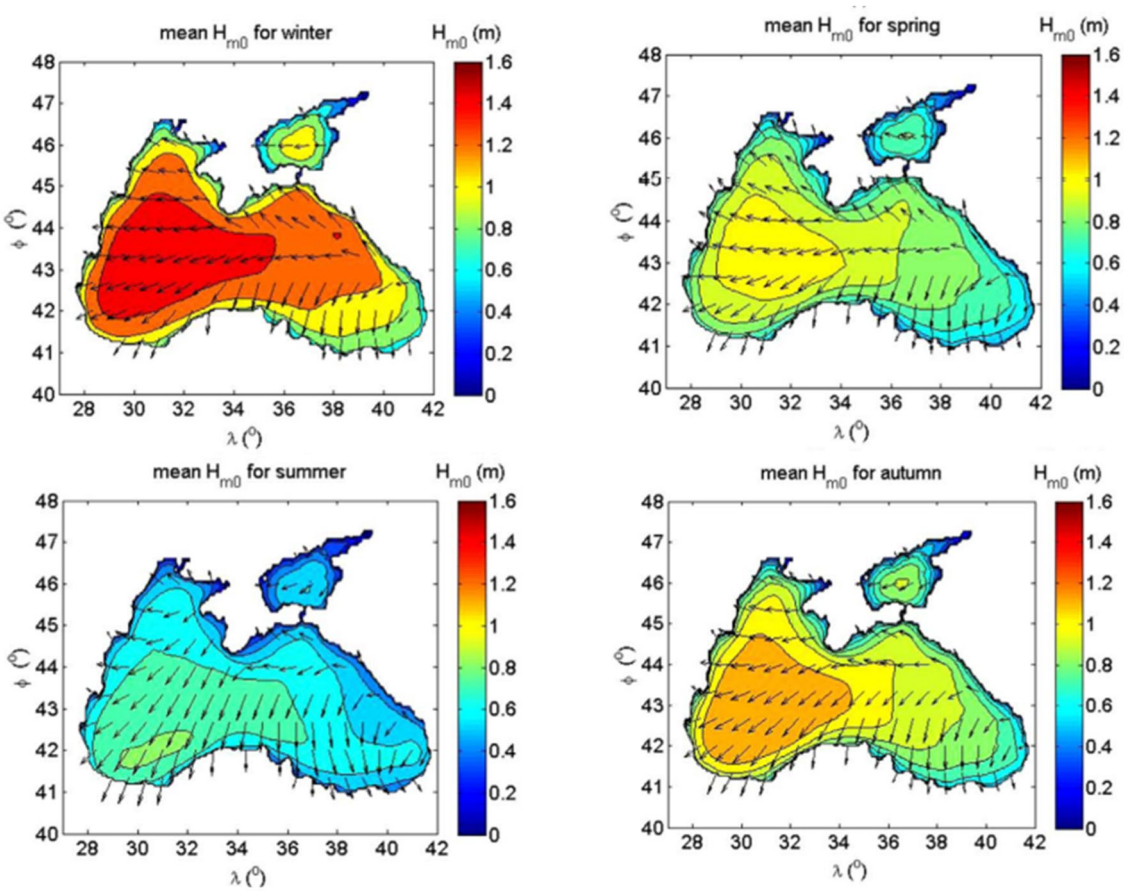

Fig. 2 Spatial distributions of mean significant wave height and averaged mean wave direction for the period 1979–2009. Winter: December–January–February, spring: March–April–May, summer: June–July–August, and autumn: September–October–November (Akpınar et al. 2016)

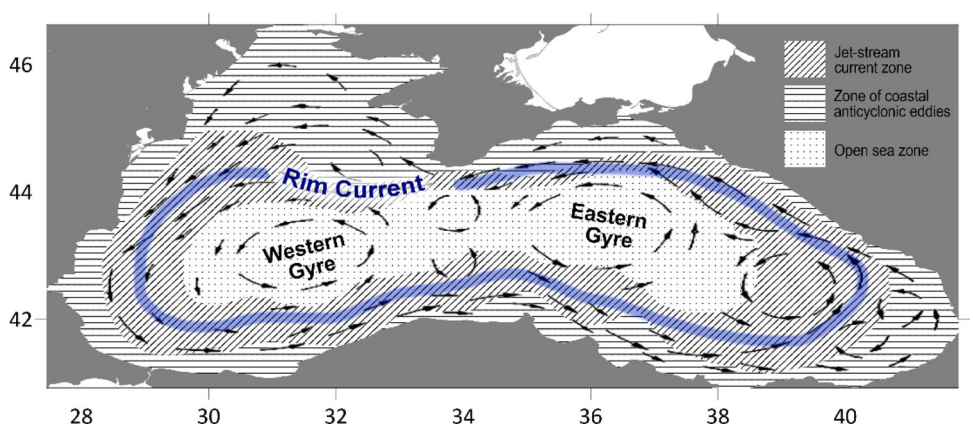

Fig. 3 Approximate division of the Black Sea into regions according to the regime of the upper layer circulation (Ivanov and Belokopytov 2013) based on the scheme by Bogatko et al. (1979)

focused on the sensitivity of the model to current adding, so the default settings recommended by its authors and previously used in several works (e.g., Arkhipkin et al. 2014; Medvedeva et al. 2015) were chosen. The spectral directional resolution of the SWAN simulation was set to 5°. In frequency-space, there were 38 logarithmically distributed discrete frequencies between 0.03 and 1 Hz. GEN3 mode was applied. Exponential wave growth was parametrized according to Komen et al. (1984). Bottom friction was described according to the JONSWAP formulation (Hasselmann et al. 1973). The processes of refraction and diffraction, white-capping, quadruplets, triad wave interactions, and bottom friction were considered. The timestep of the computations was 20 min, whereas the results were recorded to output

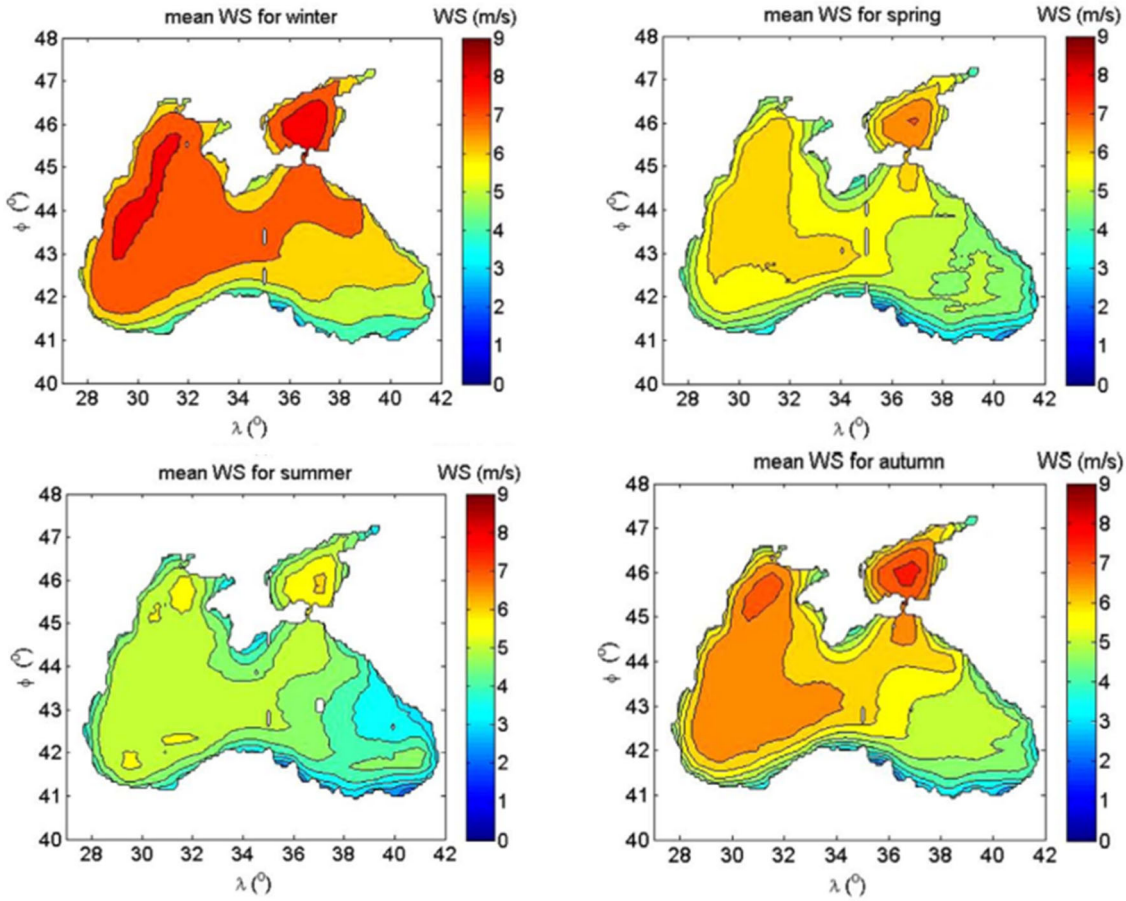

Fig. 4 Averaged seasonal mean WS for the period 1979–2009. Winter: December–January–February, spring: March–April–May, summer: June–July–August, and autumn: September–October–November (Akpınar et al. 2016)

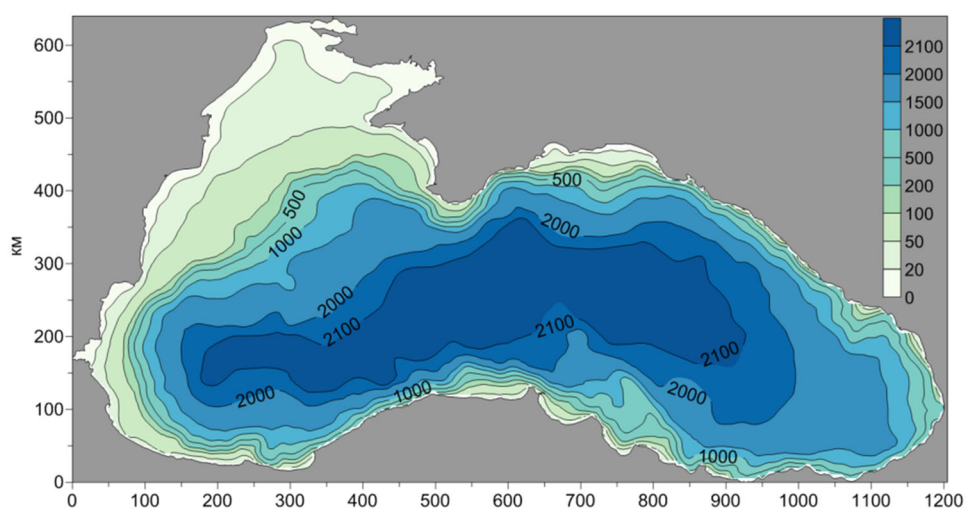

Fig. 5 Bathymetry map of the Black Sea (Myslenkov 2017)

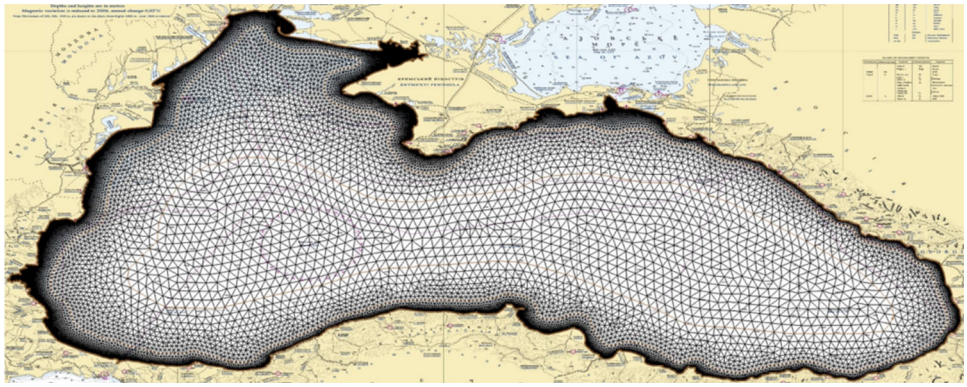

Fig. 6 The unstructured computational grid (Gippius and Myslenkov 2020)

files every 3 h. The computations were performed continuously for every year. A more detailed description of the model setup, computational grid, and model validation is given in (Myslenkov et al. 2016; Gippius and Myslenkov 2020). The quality assessment for this implementation of SWAN is the following: the average monthly bias is between 0 and 0.2 m and the correlation coefficient is between 0.8 and 0.9 (Gippius and Myslenkov 2020). The computational accuracy for this implementation is quite high, from 95 to 99% of the wave height, since six iterations were set during the calculations.

2.2 Wind and current data

The numerical experiment was forced with a 10 m wind field from the NCEP/CFSv2 reanalysis (Saha et al. 2014). The timestep of this data is 1 h; a spatial resolution is ~ 0.2° in both latitudinal and longitudinal directions (https://cfs.ncep.noaa.gov).

The input of surface currents was obtained from the Remote Sensing Department's archive of the Marine Hydrophysical Institute of RAS (Stanichny et al. 2016; http://dvs.net.ru). Arrays of total geostrophic velocities of currents in the Black Sea basin are retrieved by summing the geostrophic component restored from the altimetry data (Le Traon 2001; Pascual 2006; Kubryakov and Stanichny 2011) and drift component estimated from NCEP wind fields (GFS 0.25°). The spatial resolution of the resulting current fields is 0.125°, and the timestep is 6 h. An assessment of the current fields' quality based on comparison with drifter data is given in Kubryakov and Stanichny (2013). For most (33 out of 52 drifters) of the measurements, the correlation coefficient exceeds 0.7 for the zonal component and 0.6 for the meridional component. The root-mean-square deviation is 0.086 m/s.

2.3 Spatial analysis

To assess the influence of currents on the wave parameters in the Black Sea, two numerical experiments with SWAN model were carried out using different dynamical forcings. The model settings and the wind input data were set to be identical. Current fields were included as the input data in the first of numerical experiment (let us call this experiment version "current setup", CS), while the second reference experiment was carried out using only wind as an input data ("reference setup", RS). As a result, two data arrays were obtained: the entire Black Sea wind waves parameters from 2013 to October 2017 with a 3 h time step.

The value of the significant wave height from RS subtracted from an equivalent value from CS. Then, the average annual, monthly, and seasonal differences were calculated.

The Black Sea was divided into 29 sectors (Fig. 7) for the subsequent analysis. The longitude spacing is 2° and the latitude spacing is 1°. By choosing this scale of division, we tried to achieve sufficient generalization for the convenience of the analysis and comparison of the studied statistical parameters but at the same time not to lose local features.

For each sector, two statistical parameters were calculated

$$\text{arithmetic mean (Mean)} = \frac{\sum_{i=1}^{n} Dif_i}{n}; \tag{5}$$

standard deviation (SD) of the differences

$$= \sqrt{\frac{\sum \left(Dif_i - \overline{Dif}\right)^2}{n}}; \tag{6}$$

where n is number of data points; Dif means difference and is calculated as $Dif_i = CSvalue - RSvalue$; $\overline{Dif}$ means the average difference.

These parameters for each sector were calculated for monthly, annual, and seasonal average differences.

For convenience and simplification in describing the spatial distribution of differences, we propose to divide the Black Sea into seven notional regions, the boundaries of which are shown in Fig. 7.

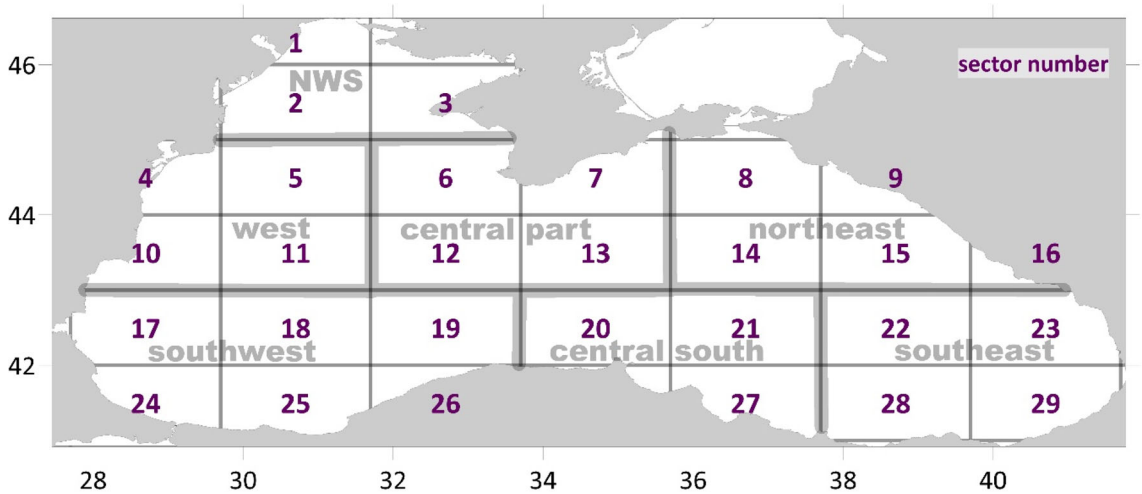

Fig. 7 Sector and region partition of the Black Sea. NWS stands for Northwestern Shelf

2.4 Model validation

To perform the validation, the results of remote satellite observations were used as it is the only method that provides sufficient territory coverage for the entire Black Sea. It should be noted that comparing the wave heights from the model with altimeter data is a standard approach for assessing the quality of the model (Van Vledder and Akpınar 2015; Myslenkov and Chernyshova 2016; Gippius and Myslenkov 2020; Rusu et al. 2014). In papers where model data were compared with both data from buoys and satellites (e.g., Rusu et al. 2014), the model demonstrates errors of the same magnitude, which indirectly indicates the acceptable quality of the satellites.

Data of the AltiKa altimeter installed on the SARAL satellite (Steunou et al. 2015) were used. The data quality of this altimeter is assessed in (Janssen et al. 2007; Kumar et al. 2015; Jayaram et al. 2016; Hithin et al. 2015). Jayaram et al. (2016) compared data on wave height from the AltiKa altimeter with buoys, and concluded that for the wave heights, the standard deviation is 0.21 m and the bias is 0.04 m. Altimeter data on the significant wave height have an approx. 7 km spatial resolution and are available via the Radar Altimeter Database System (http://rads.tudelft.nl/rads/rads.shtml). Data corresponding to the period from 2013 till 2016 were used for validation. Following data were rejected from the validation process:

- values with standard deviation of the altimeter significant wave height exceeding 0.4 m;
- values with significant wave height lower than 0.3 m;
- values with a distance to the shore closer than 10 km to avoid any coastal effect that could degrade the quality of the satellite observations (Van Vledder and Akpınar 2015)

Significant wave heights from the altimeter were compared to modeling results from the reference setup experiment located not more than 8 km and 1 h from the place and time the satellite observation was made. The following statistical parameters were calculated:

The bias

$$bias = \frac{1}{n}\sum_{i=1}^{n}\left(SWH_{mod_i} - SWH_{sat_i}\right). \tag{7}$$

The mean absolute error (MAE)

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|SWH_{mod_i} - SWH_{sat_i}\right|. \tag{8}$$

The root-mean-square error (RMSE)

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(SWH_{modi} - SWH_{sat_i})^2}. \tag{9}$$

The correlation coefficient (R)

$$R = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{SWH_{mod_i} - \overline{SWH_{mod}}}{\sigma SWH_{mod}}\right) \times \left(\frac{SWH_{sat_i} - \overline{SWH_{sat}}}{\sigma SWH_{sat}}\right), \tag{10}$$

where SWH_{mod_i} is the modeled significant wave height value, SWH_{sat_i} is the measured significant wave height values, and σSWH_{mod}, and σSWH_{sat} are their standard deviations.

The obtained values are presented in Table 1.

Table 1 Values of studied statistical parameters

Period	Bias, m	MAE, m	RMSE, m	*R*
2013	– 0.064	0.193	0.251	0.922
2014	– 0.041	0.193	0.257	0.894
2015	– 0.072	0.204	0.289	0.911
2016	– 0.078	0.238	0.315	0.886
The entire research period	– 0.066	0.209	0.283	0.903

The obtained values of the correlation coefficient demonstrate that it is high during the whole studied period: around 0.9 for the entire period and between 0.886 and 0.922 for single years. The values of bias are minimal in 2014 and range from – 0.041 to – 0.078 m. Bias is – 0.066 m for the entire research period. MAE and RMSE range from 0.193 to 0.238 m and from 0.251 to 0.315 m, respectively. It seems that as the variance of values is small and the correlation coefficient is high, the SWAN model settings can be considered reliable.

3 Results

3.1 Interannual variability of wave height

To determine the interannual effect of circulation on the SWH, the average annual values of the SWH by CS and RS experiments for different years from 2013 to 2016 were compared. Positive differences mean an increase of the SWH when currents are taken into account, and negative differences mean, on the contrary, an SWH decrease. The results for 2017 were not considered in the interannual analysis as there are no results for November and December that year. The resulting average annual differences were averaged over each sector (Mean). The standard deviation of the mean differences (SD) was also calculated for each sector.

A spatial distribution analysis of the average annual differences of SWH (Fig. 8) shows that the average annual SWH decreases in most parts of the Black Sea when the current fields are included in the model. Despite significant interannual differences, the general features of the spatial distribution of the current influence on the average annual SWH can be distinguished. Negative differences are typical for the western and the central parts of the sea, and in the northeast of the Black in all studied years. This means that in these areas, the average SWH is reduced by adding currents to the model. The largest negative average annual differences are observed in 2015 and 2016 and reach – 5.85 cm. In general, 2013 and 2014 are characterized by lower differences. In these years, significant areas are observed where there are non-negative differences. These areas include the Northwestern Shelf, the southwest, the central south, and the southeastern part of the sea. Currents increase the average annual SWH up to 3–4 cm here in 2013. The sector-averaged values (Mean) are negative for all the years in most parts of the sea. The exception is the southwestern part of the sea, where in 2013 and 2014, the bigger positive value of the Mean reaches 1.17 cm. The spread of difference values (SD) is in general higher along the periphery of the sea in the jet-stream current zone, where the Rim Current passes. The lowest spread of values (SD) relative to Mean values is observed in the central part of the sea.

Thus, with regard to interannual variability, the deep-water areas of the central part of the Black Sea have negative differences in all years, that is, the SWH decreases as a result of taking currents into account. The same is true for the west. In the southern part of the sea, the average annual SWH differences may be positive or negative, and the biggest spread of values is noted in the southwestern part.

The change in the average annual SWH in percentage is shown in Fig. 9 using the example of 2014. These changes range from – 6 to + 3%.

Thus, there is a significant interannual variability. The average annual differences are small and more often negative. Initially, we expected to see a strong and well-expressed influence of currents on waves where a stream of the Rim Current flows. However, this is not observed in Fig. 8. In our opinion, this can be explained by several factors. First of all, studies demonstrate strong variability and instability of the Rim Current (e.g., Demyshev et al. 2022; Kubryakov and Stanichny 2015) which leads to the fact that its influence on the average annual SWH differences is poorly expressed. Second, the variability of wave directions leads to the fact that wave interaction with a relatively stable direction of the Rim Current is weakly expressed during averaging. In addition, sufficiently strong wind, which is capable of generating waves, causes a drift current (Wu 1975; Kenyon 1970). The paper (Arkhipkin et al. 2013) demonstrates the results of modeling currents in the Black Sea without taking into account the drift component. When averaged over the seasons, the velocities outside the Rim Current are small (Fig. 3, Arkhipkin et al. 2013). Thus, except for the Rim Current area, drift currents should prevail over other currents. Therefore, waves and currents are on average more often co-directed, which reduces the wave height.

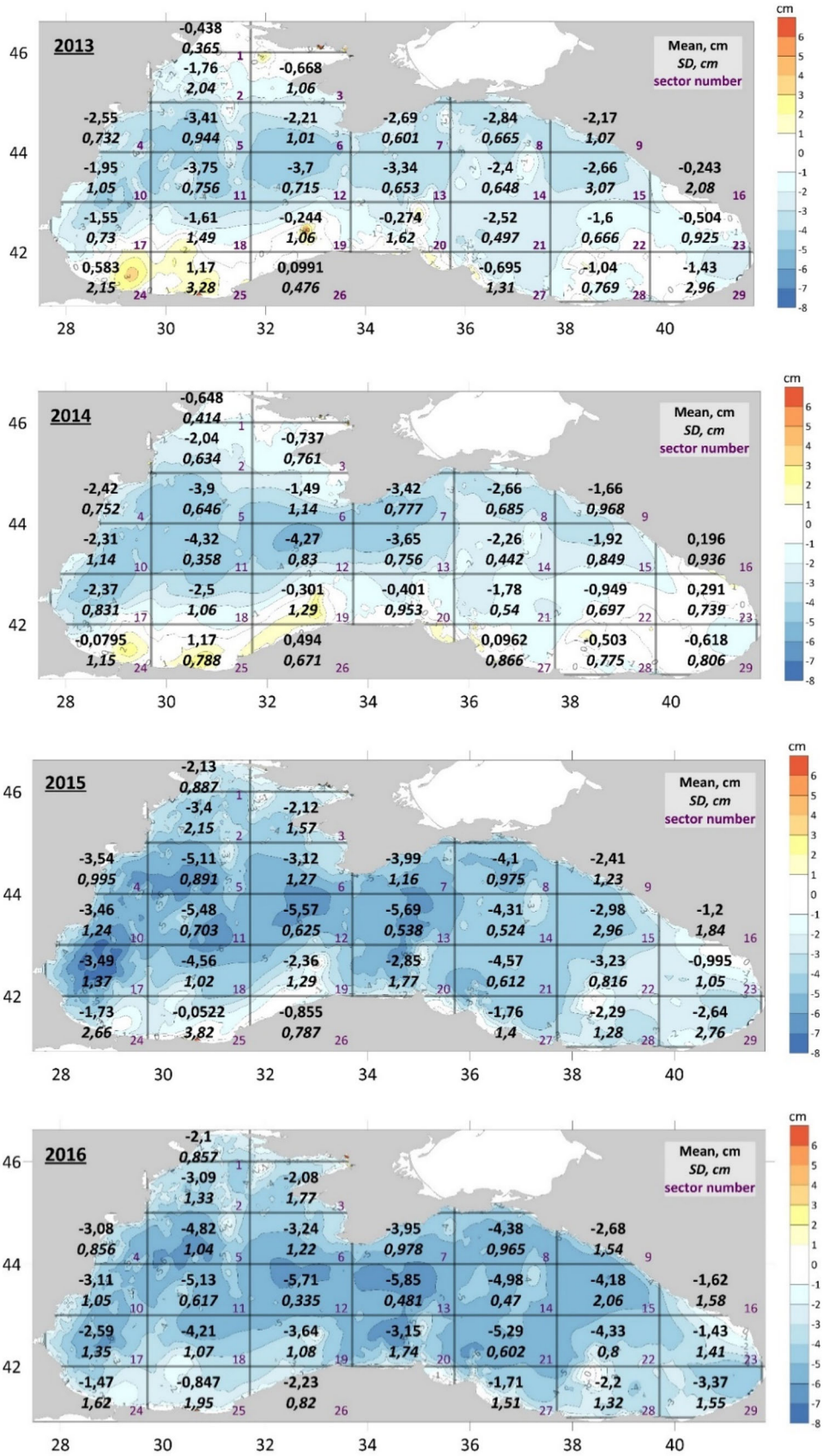

Fig. 8 Average annual SWH difference (cm) in 2013–2016

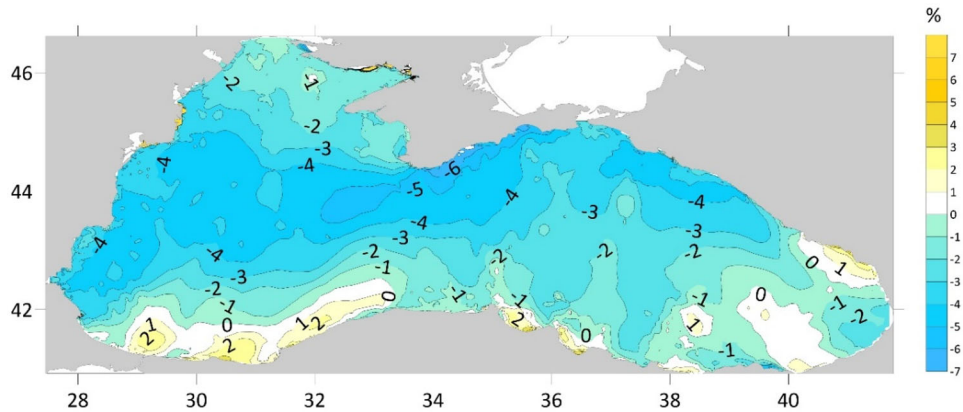

Fig. 9 Percentage change in the average SWH in 2014

3.2 Seasonal variability of height differences

The seasonal SWH differences were calculated by analogy with the annual average. For each season in the period from 2013 to 2017, the average differences were calculated, and then averaged over sectors (Mean value), and the standard deviation of the differences for the sectors was calculated (SD value). Figure 10 and 11 show the seasonally averaged SWH differences in 2013 and 2015.

The average SWH decreases in most parts of the sea in winter during all years studied when currents are supplemented to the model. The average SWH decreases most significantly in the western and central parts of the sea when currents are taken into account. Here, in the central deep-water part, the standard deviation is especially low, ≤ 1 cm in all studied years, while the Mean is from -9.31 cm to -3.51 cm. The northeast is one more zone where the SWH noticeably decreases by supplementing currents. This part is characterized by high SD values in winter.

Positive differences are observed in the southwest and central south of the sea in 2013 and 2014. In 2013, the Mean here reaches up to 1.1 cm with a standard deviation of 2.25 cm. In 2014, Mean values are lower and reach 0.272 at SD 1.28.

In general, SD increases by moving from the central deep-water part to the coastal zones, while the absolute value of the Mean decreases.

In spring, the decrease in average height across the sea is less. The pattern is preserved when the highest negative differences are observed in the deep-water part in the central and western parts of the sea. Average negative differences are < -5 cm in 2015 there. There are some areas with a positive average difference in the southwest, the central south, and the southeast of the sea. The maximum Mean value here reaches 1.89 cm. The same area is characterized by the highest SD values in the spring season.

The summer season is characterized by the lowest Mean values. The biggest negative Mean is < -4 cm in the central part in 2017. The Positive Mean value reaches 1.41 cm in the southwestern part in 2014. The order of magnitude of the standard deviation does not change much from season to season. It tends to increase from the central part to the sea's periphery.

In autumn, positive Mean values are observed in 2013 and 2014. The biggest positive Mean value reaches 1.6 cm again in the southwest in 2013. The biggest negative Mean values, as in other seasons, are found in the western and central parts. The western half of the sea is characterized by a more significant decrease in wave height than the eastern one in all studied years, except in 2013.

Although the interannual differences are large, it can still be claimed that the greatest differences in SWH are observed in winter, and the smallest ones are in summer. This corresponds to a seasonal increase in storm activity and the intensity of currents in the Black Sea. The wave heights reach their maximum in winter, and the average height of significant waves for some areas exceeds 1.4 m (Akpınar et al. 2016). The Rim Current as the main element of the circulation is also most intense in the cold season, and the flow velocity is 35–40 cm/s (up to 80 cm/s) in winter (Titov and Prokopov 2002). The Rim Current's jet is the least intense during summer, and the speed values are in the range of 10–25 cm/s. The wave heights are also minimal in summer; the average height does not exceed 0.8 m (Akpınar et al. 2016). The seasonal variation of the differences repeats these features.

3.3 Average monthly height differences

In addition to the annual and seasonal averages, the differences, sector mean (Mean), and the standard deviation of sector differences (SD) were analyzed for each month over the study period. Examples of average monthly differences for 2014 and 2016 are shown in Figs. 12 and 13.

All monthly mean difference values are from – 15 to 10 cm. The largest negative values are observed in the western half of the sea near the Bulgarian coast in February 2015. The biggest positive one is found in the southeastern part of

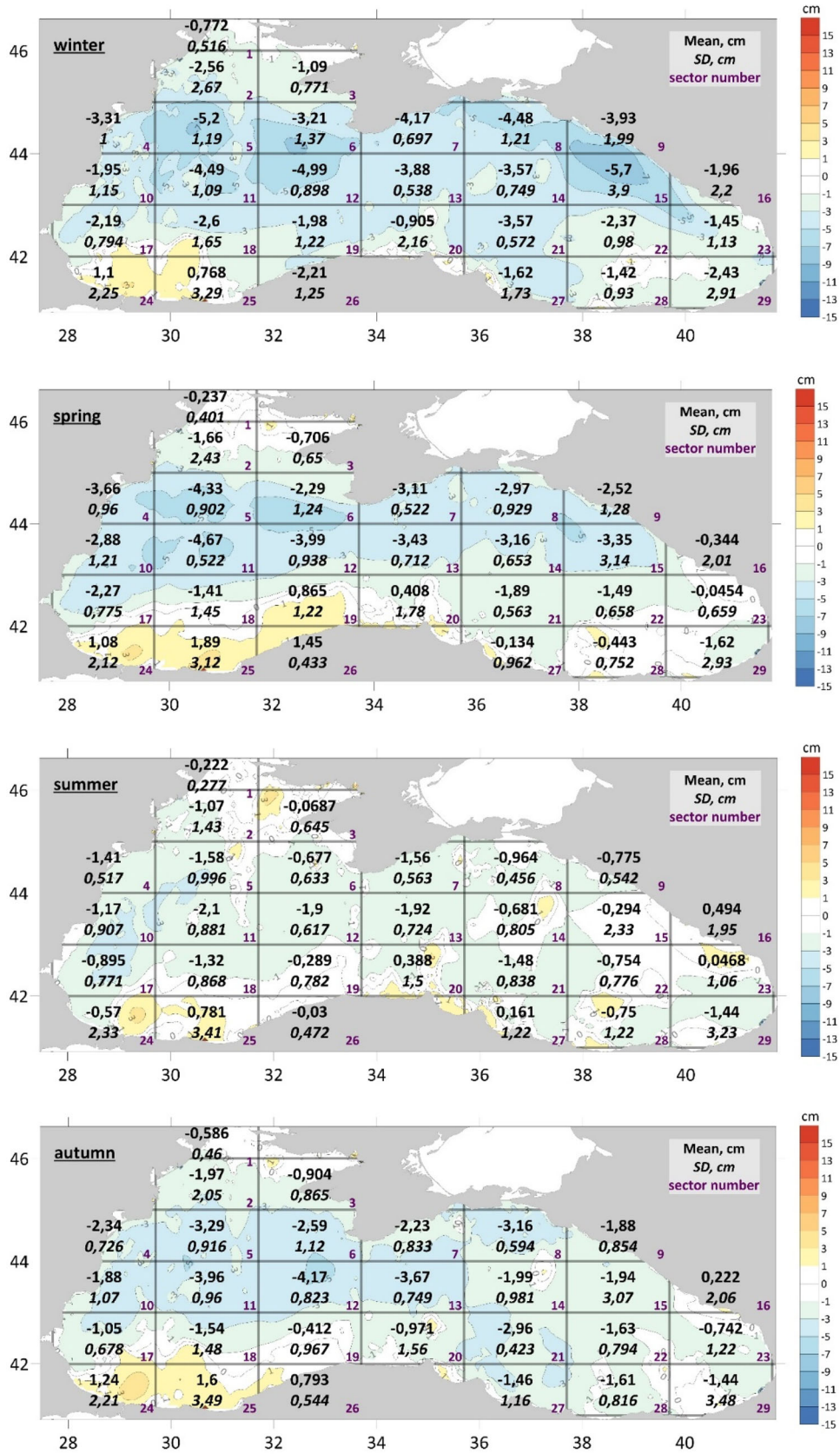

Fig. 10 Seasonally averaged difference in 2013

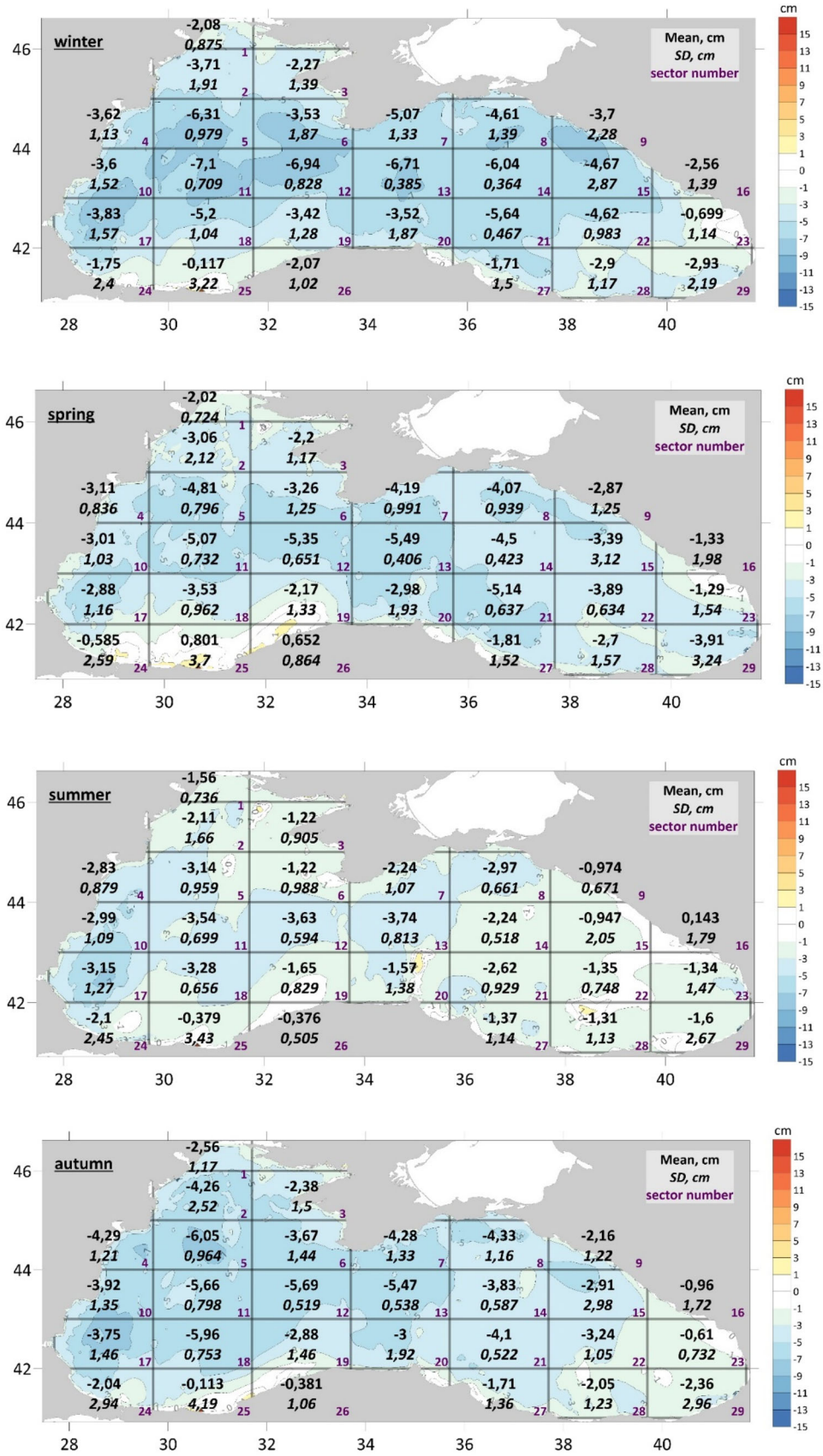

Fig. 11 Seasonally averaged difference in 2015

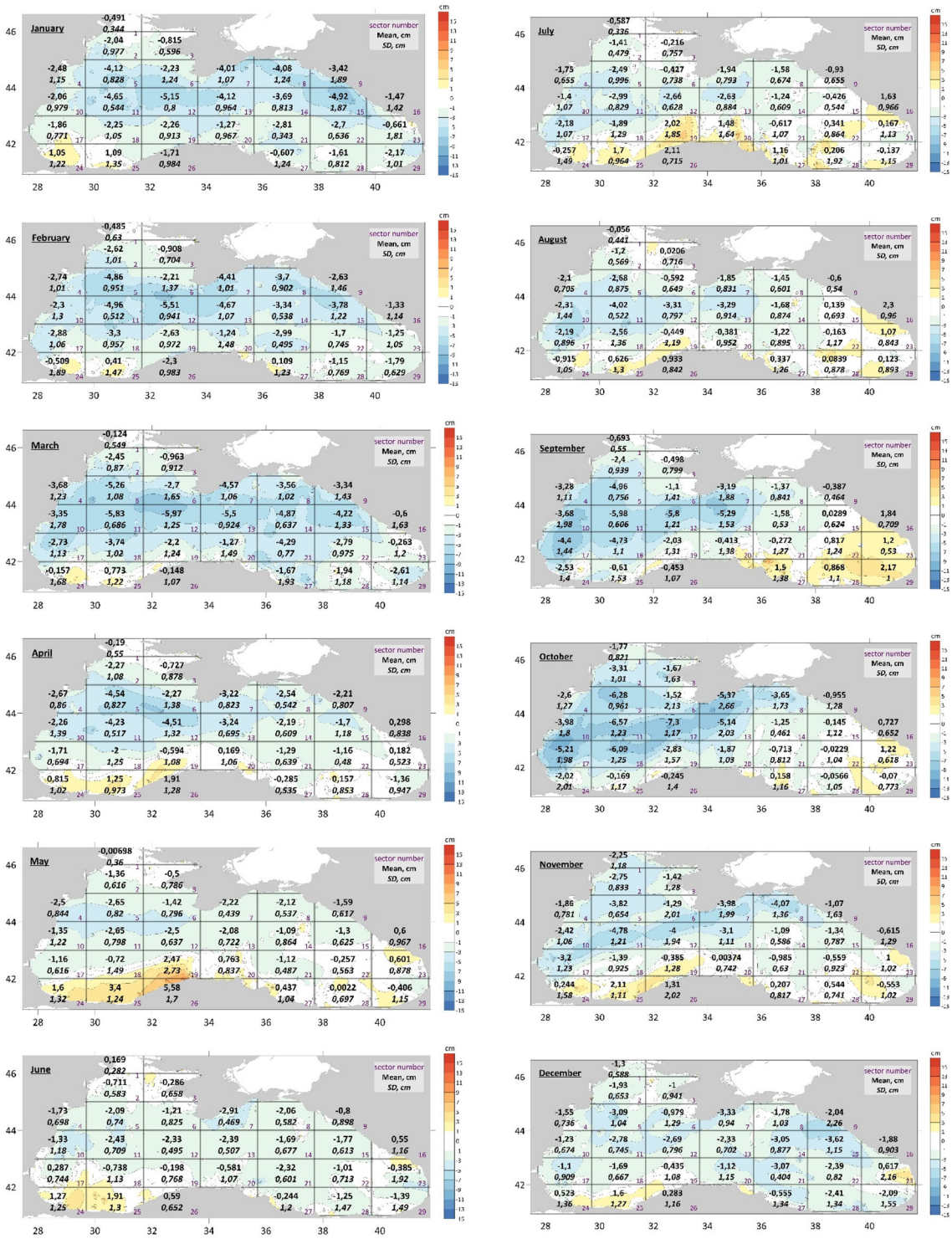

Fig. 12 Average monthly wave height difference in 2014

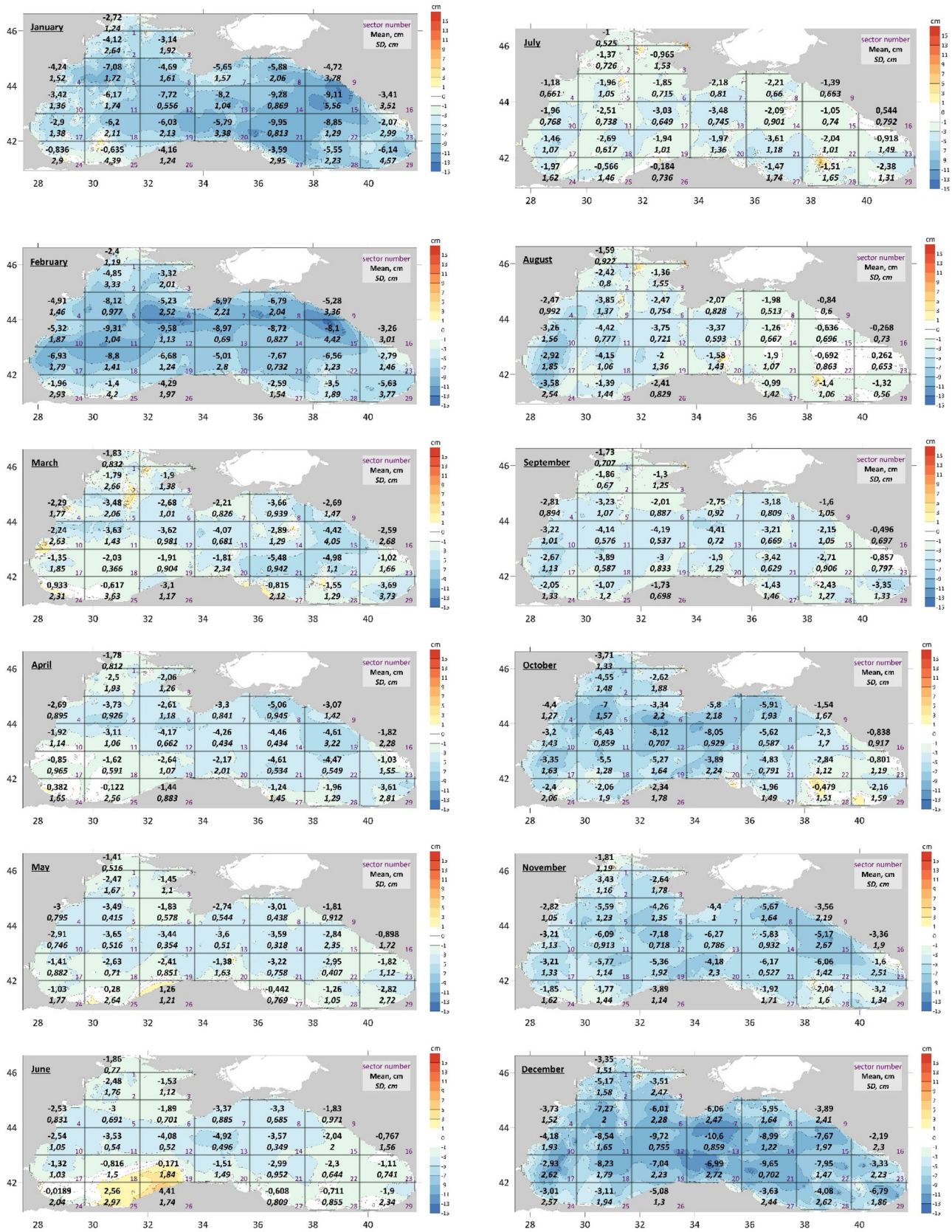

Fig. 13 Average monthly wave height difference in 2016

the sea in August 2017. Negative differences predominate, that is, the mean monthly SWH decreases when currents are supplemented to the model.

As noted in the analysis of the differences' seasonal variability, the winter months are characterized by the predominance of the highest negative values in most parts of the sea. The most insignificant negative differences of all the winter months are observed in December. Negative differences reach their picks in January and February.

In January 2013 and 2014, the differences are from – 5 to – 1 cm in most parts of the sea. Positive differences are observed in the southwest and central south in 2013. At the same time, positive Mean values are observed in the southwestern part and are < 1 cm. There are no positive Mean values in 2015, 2016, and 2017 during that month. In January, negative Means reach their peaks in the northeast are < – 9 cm. The spatial distribution and the order of magnitude of the differences in February are similar to the January values for each of the analyzed years. The highest negative differences are found in 2015.

In March, the negative values of the differences are lower. The largest negative value of the Mean is – 8.05 cm in the west in 2015. The highest positive Mean values are found in the coastal zone of the southwestern in 2013, while SD values are also high and exceed the Mean values. There is also a positive Mean value (0.933 cm) here in March 2016 at SD 2.31 cm. In April 2013 and 2014, the southern part of the sea is occupied by differences with positive values or values close to 0. Positive Mean is observed in the southwest, central south, and southeast of the sea in 2013 and 2014. Positive Means are also detected in the southwest in 2015 and 2017. In May 2013, a positive Mean value was detected on the northwestern shelf of the Black Sea. The positive differences exceed 10 cm in the southwestern part. Here, the highest positive value of the Mean this month is 5.58 cm with SD of 1.7 in 2014. In June and July, non-negative differences are observed in most parts of the sea. The greatest negative Mean is – 4.77 cm and is observed in the deep-water central part in 2016 and 2017. August and September retain the features of June and July, but the negative differences increase. September 2014 is characterized by a large area of positive differences in the southern part of the northeast and all southern parts of the sea. Positive Means reach 2.17 cm. In October 2013, differences are positive or close to 0 in most parts of the sea. Positive Means are found only in the coastal area of the southwestern part. Also here, there are positive Means in 2017. All Means are negative over the whole sea in 2015 and 2016. November is similar to October in all years.

The observed intra-annual differences are comparable to the interannual ones. The absolute differences are minor even during colder months.

3.4 Quality assessment of model performance with currents added

In addition, it is important to assess whether accounting for currents improves the simulation results. For this purpose, significant wave heights from the CS and RS model experiment versions were compared to the altimeter results. Four statistical parameters (bias, mean absolute error, root-mean-square error, and correlation coefficient) were calculated for the entire research period from March 5, 2013, to December 31, 2016, and for each year separately for CS and RS experiment versions. The obtained values are presented in Table 2.

The difference between the metrics values is quite insignificant. Nevertheless, the RS experiment shows slightly better results for all metrics. The correlation coefficient between the RS and CS wave heights and satellite measurements for the entire research period is around 0.9. The values of bias, MAE, and RMSE are minimal for both CS and RS in 2014. The correlation coefficients for both experiments reached the maximum values in 2013: 0.917 for CS and 0.922 for RS. That is to say, adding currents to the model worsens the result; however, these values are very close, so we cannot draw unambiguous conclusions. This may indicate a minimal influence of currents.

In addition, statistical parameters were calculated for SWH of more than 2 m. Waves with this height represent the ~ 90th percentile, which is of interest to shipping and the operation of coastal infrastructure. The results are presented in Table 3. The waves are well developed, and white caps are everywhere.

First of all, we note that the model reproduces the SWH worse when SWH are more than 2 m. This was observed in previous studies, and is explained by the fact that the reanalysis error increases at high wind speeds (Fig. 12, Myslenkov and Chernyshova 2016) and the quality of the wind fields is reflected in the quality of the wave simulation. The obtained values demonstrate that during strong waves (SWH > 2 m), there is a more significant difference in the values of bias and MAE and RMSE. The greatest differences are achieved in 2015 and 2016. RS experiment demonstrates the better values of bias, MAE, and RMSE. However, the value of the correlation coefficient for the CS experiment exceeds the same values for the RS experiment in 2014 and 2016, as well as for the entire study period. This indicates that supplementing currents in stormy conditions can improve the correlation coefficient, but the increase is insignificant.

Therefore, it turns out that although adding currents and therefore more realism should have improved the results, we see the opposite. A possible explanation will be given in the Discussion section.

Table 3 Values of studied statistical parameters for CS and RS for wave heights for more than 2 m

		Bias, m	MAE, m	RMSE, m	R, m
2013	CS	– 0.154	0.372	0.459	0.703
	RS	– 0.063	0.347	0.437	0.712
2014	CS	– 0.204	0.335	0.419	0.761
	RS	– 0.105	0.309	0.389	0.759
2015	CS	– 0.379	0.426	0.536	0.710
	RS	– 0.238	0.338	0.462	0.710
2016	CS	– 0.361	0.460	0.556	0.755
	RS	– 0.236	0.397	0.506	0.752
The entire research period	CS	– 0.287	0.402	0.493	0.778
	RS	– 0.187	0.351	0.463	0.726

Table 2 Values of studied statistical parameters for CS and RS

		Bias, m	MAE. m	RMSE. m	*R*
2013	CS	– 0.085	0.199	0.258	0.917
	RS	– 0.064	0.193	0.251	0.922
2014	CS	– 0.066	0.198	0.263	0.888
	RS	– 0.041	0.193	0.257	0.894
2015	CS	– 0.118	0.221	0.304	0.907
	RS	– 0.072	0.204	0.289	0.911
2016	CS	– 0.123	0.250	0.326	0.885
	RS	– 0.078	0.238	0.315	0.886
The entire research period	CS	– 0.102	0.220	0.293	0.899
	RS	– 0.066	0.209	0.283	0.903

4 Discussion

The results obtained during the study demonstrate minor influence of currents on the wave height in the Black Sea. The values of the differences at the nodes range from—15 cm to 10 cm with averaging in time for more than a month. The largest values of the differences correspond to 6–10% of the average monthly wave heights. On average, the height changes by 2–4% depending on the season and location when supplementing currents to the model.

Negative differences prevail in most parts of the sea in all the studied years. The influence of currents is noticeable mainly when the wave height is more than 1 m, while the wind speed is 7–10 m/s. The wind, which is capable of generating waves, also generates drift currents, which are co-directed with the waves. The Rim Current is poorly distinguished on the maps of differences averaged over a year or a season, since the jet is quite variable and statistically blurs over space during averaging. At the same time, drift currents in the near-surface layer almost always occur in the presence of wind, so statistically, the currents and waves are co-directed on the maps even in the jet.

This reasoning is indirectly confirmed by the results obtained. In the central and western parts of the sea, the average direction of waves and currents approximately coincides, which leads to the largest negative differences in the basin. Near Bosphorus strait, the Rim Current jet changes direction to southeastern up to Cape Sinop, while the average direction of the waves is against the current. This leads to a certain increase in the SWH height due to wind–current interaction, and this area is the zone of the biggest positive or at least the smallest negative differences. Another zone where waves and currents have opposite mean directions is the coastal area near Batumi. Here, the Rim Current jet turns along the coastline and flows to the north–northwest. In addition, this is the location of a large anticyclone Batumi eddy (Kubryakov and Stanichny 2015). The Rim Current jet and the average wave direction again coincide near the northeastern coast. In the rest of the regions, apparently, with annual averaging drift currents co-directed with waves predominate.

This study was carried out using a spectral wave model, similar to earlier studies for other areas of the World Ocean (discussed in the Introduction section), which allows a comparison of results. Indeed, attention is drawn to the fact that in the studies considered in the literature review, taking

into account currents improves the SWH modeling accuracy, while we obtain the opposite result. In our opinion, this is interesting and requires further study. The model validation of both experiments shows that the quality of the results does not improve by supplementing currents. Currents increase the correlation coefficient when SWH > 2 m, but this increase is insignificant and just over 0.05. At the same time, RMSE also increases. It may be undesirable to implement currents when modeling wind waves in the entire Black Sea basin.

However, the results obtained can be criticized. We want to emphasize that the effect of currents on waves in the Black Sea cannot be unambiguously assessed only based on the conducted study. First of all, it is difficult to assess the quality of the current fields due to the small amount of field data. The paper (Kubryakov and Stanichny 2013) shows that the correlation coefficient of current field calculations exceeds 0.7 for the zonal component and 0.6 for the meridional component compared to drifter measurements. Second, in our study, only simulation data (wind, waves, and currents) are used, which inevitably entails some simulation errors. In addition, the simulation results were compared with satellite altimetry data, but there is no information about whether the quality of satellite data changes in the presence of strong currents. It is not known whether the effect of currents is taken into account in the altimeter data‘s processing algorithm, which makes it difficult to assess the quality of satellite data in relation to the purpose of the study.

However, previous studies (e.g., Gippius and Myslenkov 2020) demonstrate a relatively high quality of wave modeling in the Black Sea. In addition, the current fields used in this study demonstrate a plausible order of magnitude for velocities. The general structure of the current field has visible contours of the Rim Current and the correct seasonal pattern. This suggests the relevance of the results of the relative influence of currents on wind waves in the Black Sea. The results should be confirmed based on direct current and wave measurements.

In our opinion, the question of whether currents should be added as the model input data for the Black Sea and other areas of the World Ocean does not have an obvious answer. A priori application of the available currents data for wave models is incorrect. It seems that there are areas for which current accounting is more effective. The criterion for such potential efficiency may be the presence of strong tidal currents that are better predictable. Currents with a velocity of more than 1 m/s can also significantly affect the result of wave simulating (e.g., Wang et al. 2020; de León and Soares 2021). However, the results of the study show that it is necessary to assess the quality of the result of wave models before using the flow fields as additional input data for practical needs.

5 Conclusions

The influence of sea currents on the wave height in the Black Sea was studied based on SWAN simulations driven by NCEP/CFSv2 winds and the total surface currents obtained from combination of the wind and altimetry data from the Remote Sensing Department, MHI (Kubryakov and Stanichny 2013) as the model input. The entire Black Sea wind wave parameters were obtained from 2013 to October 2017. The monthly and annual average SWH mainly decreases due to the inclusion of current fields in the model. A possible explanation is that waves and currents are co-directed when averaged in time for more than a month.

The influence of the current field on the average values of the wind wave parameters has the following spatial features:

- Surface currents reduce the average values of heights during the whole study period along the entire central part of the sea (from 43° to 46° N) except for the eastern part apparently due to the co-direction of waves and currents during long-term averaging.
- The greatest values of the differences between CS and RS are typical for the western, central deep-water, and northeastern parts of the Black Sea.
- The wave height increases in the south of the sea and in its eastern part. Less often positive differences are detected on the northwestern shelf. However, the positive contribution is minor.

The mean annual SWH can decrease down to –7.5 cm and increase up to 5.5 m. Currents have the greatest influence on the wave parameters during the winter months and the least during late spring and summer.

The spread of mean values (standard deviation) in the central part of the sea is characterized by minimum values. The standard deviation increases and exceeds the average value in the area of the Rim Current jet at the periphery of the sea. The standard deviation values decrease on the northwest shelf.

Based on the results, we can suggest that as the influence of currents on the SWH in the Black Sea is insignificant and the errors in modeled current fields are usually large, so it is not necessary to take currents into account while simulating waves in the whole Black Sea. However, the decision on whether to add currents to the model for certain parts of the Black Sea should be made based on preliminary study and the quality simulation assessment. In addition, the use of direct wave and current measurements will be beneficial for further research.

Author contributions The concept of the study was jointly developed by AR and SM. AR did numerical simulations, analysis, visualization, and manuscript writing. SM did numerical simulations and manuscript writing. All authors have read and agreed to the published version of the manuscript.

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Declarations

Conflict of interest The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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