Numerical modeling of wind waves in the Black Sea generated by atmospheric cyclones

V V Fomin

Department of Numerical Technologies and Mathematical Modeling, Marine Hydrophysical Institute RAS, 2 Kapitanskaya Str., Sevastopol, 299011, Russia

E-mail: fomin.dntmm@gmail.com

Abstract. The influence of the translation speed and intensity of atmospheric cyclones on surface wind waves in the Black Sea is investigated by using tightly-coupled model SWAN+ADCIRC. It is shown that the wave field has a spatial asymmetry, which depends on the velocity and intensity of the cyclone. The region of maximum waves is formed to the right of the direction of the cyclone motion. Speedier cyclones generate wind waves of lower height. The largest waves are generated at cyclonic translation speed of 7–9 m/s. This effect is due to the coincidence of the characteristic values of the group velocity of the dominant wind waves in the deep-water part of the Black Sea with the cyclone translation speed.

1. Introduction

Wind waves are among the main factors determining the safety of navigation, coastal zone dynamics that influence the coastal infrastructure, ecological processes and recreation potential. Severe storms are dangerous to vessels in open sea and coastal waters, storm waves can also cause severe damage along and on the coast. Therefore, the ability to predict wind waves is an important challenge and is of great value to many user communities. Recently, a large number of works dedicated to various aspects of mathematical modeling of the Black Sea wind waves has been published. The analysis of the storm climate in the western Black Sea on a continuous set of retrospective data covering the historical period of 63 years was performed in [1]. Numerical modeling of wind waves in the bays of the Crimean Peninsula was carried out in [2]. Assessments of interannual and seasonal wind waves parameter variability in the Black Sea were published in [3]. The performance of a wind-wave modeling system applied to the Black Sea basin was evaluated in [4]. In [5, 6], the results of numerical simulation of storm waves in the Black Sea using different wind forcing were presented. Spatiotemporal variability of the Black Sea wave climate for the last 37 years was investigated in [7].

The aim of this work is to study the sensitivity of wind wave fields in the Black Sea to changes in the characteristics of atmospheric cyclones. For the Black Sea, this problem has been studied very little. As is known [8], that atmospheric cyclones are capable of generating extreme wind waves. For specific basin, the intensity of wind waves is determined by the trajectory, intensity, and translation speed of atmospheric cyclones [9, 10].

2. Model description

The tightly-coupled model SWAN+ADCIRC [11] integrates two numerical models – Simulation Waves Nearshore (SWAN) [12, 13] and Advanced Circulation Model for Shelves Coasts and
Estuaries (ADCIRC) [14]. Both models are used to simulate the wind waves and storm surge in marine basins and lakes.

SWAN predicts the evolution in geographical space \((x,y)\) and time \(t\) of the wave action spectral density \(N(x,y,t,\theta,\sigma)\), where \(\theta\) is the wave direction and \(\sigma\) is the relative frequency, by means of the action balance equation

\[
\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}[(c_x + U)N] + \frac{\partial}{\partial y}[(c_y + V)N] + \frac{\partial}{\partial \theta} (c_\theta N) + \frac{\partial}{\partial \sigma} (c_\sigma N) = \frac{S}{\sigma},
\]

(1)

where \((c_x, c_y)\) are group velocity components; \((U, V)\) are ambient current velocity components; \(c_\theta\) and \(c_\sigma\) are propagation velocities in the \(\theta\) and \(\sigma\) spaces. In (1) \(S\) is the source which represents the effects of wind generation, dissipation and nonlinear wave-wave interactions. The choice of SWAN parameters are given by Booij et. al. [12].

The ADCIRC basic equations are defined as follows

\[
\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV = -g \frac{\partial}{\partial x} \left[ \eta + \frac{P_A}{g \rho_0} \right] + \tau_{xx} - \tau_{bx} + \frac{M_x}{H},
\]

(2)

\[
\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + fU = -g \frac{\partial}{\partial y} \left[ \eta + \frac{P_A}{g \rho_0} \right] + \tau_{yy} - \tau_{by} + \frac{M_y}{H},
\]

(3)

\[
\frac{\partial \eta}{\partial t} + \frac{\partial HU}{\partial x} + \frac{\partial HV}{\partial y} = 0,
\]

(4)

where \((U, V)\) are current velocity components; \(\eta\) is the sea level; \(f\) is the Coriolis parameter; \(g\) is the acceleration of free fall; \(P_A\) is the atmospheric pressure; \(\rho_0\) is the water reference density; \(H = h + \eta\) is the total water depth; \(h\) is the unperturbed depth of water; \(M_x, M_y\) are the horizontal eddy-viscosity terms; \((\tau_{xx}, \tau_{yy})\) are surface stresses; \((\tau_{bx}, \tau_{by})\) are bottom stresses components. The following notations are used in (2)–(4):

\[
\tau_{xx} = \rho_0 C_a W_x \sqrt{W_x^2 + W_y^2} + \tau_{wx}, \quad \tau_{yy} = \rho_0 C_a W_y \sqrt{W_x^2 + W_y^2} + \tau_{wy},
\]

(5)

\[
\tau_{bx} = \rho_0 C_d U \sqrt{U^2 + V^2}, \quad \tau_{by} = \rho_0 C_d V \sqrt{U^2 + V^2},
\]

(6)

where \((\tau_{wx}, \tau_{wy})\) are wave stresses components; \(\rho_0\) is the air density; \((W_x, W_y)\) are wind velocity components; \(C_a\) is the surface stress coefficient; \(C_d\) is the bottom stress coefficient. In (5), (6) the stress coefficients are given by: \(C_a = (0.75 + 0.067 \sqrt{W_x^2 + W_y^2}) 10^{-3}\), \(C_d = gn^2 / H^{1/3}\), where \(n = 0.025\) is Manning’s roughness.

SWAN computes wave fields by using of wind speed from an atmospheric model, as well as sea level and currents from ADCIRC. In its turn, in ADCIRC wave stresses obtained from SWAN is used. SWAN and ADCIRC are executed sequentially on the same unstructured grid and use the same set of computational cores. Both models use Message Passing Interface (MPI), which allows the use of parallel computing.

3. Results and discussion

In numerical experiments the finite element mesh consisted of 157,868 nodes and included the Black Sea and Sea of Azov. The size of triangular elements edges varies from 60 to 4000 m. Integration time steps in ADCIRC and SWAN were 3 s and 600 s respectively. The angular resolution in SWAN was set to 10°. A grid with 40 nodes was used for frequency coordinate in the range of 0.03–1 Hz.

The atmospheric pressure and wind speed components in the cyclone were set by the analytical model of a symmetric vortex proposed by Holland [15]:
where $r = \sqrt{r_x^2 + r_y^2}$ is the distance from the center of the cyclone $(x_c, y_c)$; $r_x = x - x_c$; $r_y = y - y_c$;

$P_C$ is the central low atmospheric pressure; $\Delta P = P_N - P_C$ is the atmospheric pressure anomaly; $P_N = 1000$ mb is the ambient atmospheric pressure; $W_g$ is the gradient wind speed; $R = 75$ km is the radius of the maximum wind speed; $B = 2.5$ is the scaling parameter; $\mu = 0.8$ is the reduced factor; $\alpha = 110^\circ$ is the included angle of the wind speed.

Trajectory of motion of the cyclone center was determined as follows: $x_c = x_0 + C t$; $y_c = y_0$,

where $x_0 = 25^\circ$E and $y_0 = 43.5^\circ$N are the coordinates of the cyclone center for $t = 0$; $C$ is the cyclone translation speed. The anomaly of atmospheric pressure $\Delta P$, which determines the intensity of wind waves, varied within 10–20 mb. The values of $C$ varied from 2 to 14 m/s.

Let's consider the effect of the cyclone translation speed on the spatial structure of the wave fields in the Black Sea. The distributions of the significant wave height (SWH) and the mean wave direction for the three characteristic values of $C$ are shown in figures 1–3. Here the moments of time are chosen so that the geographical location of the cyclones is the same. It follows that a cyclone with a symmetrical wind distribution generates a wave field with a radial asymmetry caused by the cyclone's translational motion. The region of maximum wave heights is formed in the southern part of the cyclone (to the right in relation to the direction of the cyclone) and its configuration is determined by the value of $C$.

![Figure 1](image.png)

**Figure 1.** The distribution of significant wave height and mean wave direction for $C = 3.5$ m/s, $\Delta P = 15$ mb and $t = 60$ h.
Figure 2. The distribution of significant wave height and mean wave direction for $C = 7 \text{ m/s}$, $\Delta P = 15 \text{ mb}$ and $t = 30 \text{ h}$.

Figure 3. The distribution of significant wave height and mean wave direction for $C = 14 \text{ m/s}$, $\Delta P = 15 \text{ mb}$ and $t = 15 \text{ h}$. 
At $C = 3.5$ m/s, the asymmetry of the wave field is small (figure 1). In the eye region of the cyclone, the area of the wave height minimums with values of $\text{SWH} \sim 2$ m is well traced. In turn, at $C = 7$ m/s, such a region of minimums does not arise (figure 2), and the region of maximums in the southern part of the cyclone becomes more localized and the wave height in it increases by $\sim 10\%$. At $C = 14$ m/s, the intensity of the wave field decreases noticeably, and its asymmetry increases (figure 3). This finds itself in the shift of the region of SWH maximums in the direction opposite to the direction of the cyclone. In all three cases, the mean wave direction does not coincide with the direction of the wind in the cyclone, which is especially noticeable at $C = 14$ m/s.

Calculations show that with an increase in the cyclone translation speed from 2 to 9 m/s, the wave heights also increase monotonically. On the contrary, when the cyclone translation speed exceeds 9 m/s, the wave heights begin to decrease monotonically. To illustrate this effect, figure 4 shows the dependence of the maximum SWH on the cyclone translation speed. Hence, it is clear that at a cyclone velocity of 7–9 m/s, the height of wind waves in the Black Sea will be the highest. This result is valid for the case when the cyclone moves over the deep sea part of the Black Sea.

The presence of a maximum of SWH can be explained by the resonant mechanism of wind wave generation by a moving cyclone [8]. The wind speed in the cyclone affects both the height of the generated waves and their period. In turn, the wave period determines the group velocity of the waves $C_g$ (the velocity with which the energy of the dominant waves propagates). The higher the wind speed, the higher the $C_g$ value. At $C_g \sim C$, the waves propagate at the same velocity as the cyclone. Remaining under the influence of strong wind for a long period of time, the waves will receive maximum energy from the wind. If $C < C_g$, then the waves will propagate ahead of the cyclone. Otherwise, if $C > C_g$, then the waves will lag behind the cyclone.

Let's consider the effect of atmospheric pressure anomaly (cyclone intensity) on wind waves. In figure 5 for $C = 8$ m/s and three values of $\Delta P$, the time dependence of the dimensionless quantity $S/S_0$ is shown, where $S$ is the part of the sea surface area for which the condition SWH $\geq 3.5$ m is satisfied; $S_0 = 2\pi R^2 = 35.3$ km$^2$ is the characteristic scale of the area. Curve 1 corresponds to $\Delta P = 10$ mb (maximum wind velocity, MWV = 18.7 m/s); curve 2 corresponds to $\Delta P = 15$ mb (MWV = 23.4 m/s) and curve 3 corresponds to $\Delta P = 20$ mb (MWV = 27.5 m/s). As can be seen, with increasing atmospheric pressure drop, the intensity of the storm increases. The maximum values of $S/S_0$ and SWH are respectively equal to: 0.54 (4.75 m); 3.57 (7.32 m); 5.73 (9.64 m).

**Figure 4.** Maximum SWH values of waves generated by cyclones moving with different cyclone translation speeds for $0 < t < 4$ days and $\Delta P = 15$ mb.

**Figure 5.** The area of intense waves $S/S_0$ as a function of time for different pressure anomalies $\Delta P$ and $C = 8$ m/s.
4. Conclusion
Mathematical modeling of wind waves in the Black Sea, generated by atmospheric cyclones with an asymmetric structure, is performed. The calculations were performed on the basis of the numerical model SWAN+ADCIRC using an unstructured calculation grid. An analysis of the results of numerical experiments showed that the wave field has a spatial asymmetry, the nature of which is determined by the translation speed and the intensity of the cyclone. The region of maximum wave heights is formed in the southern part of the cyclone (to the right in relation to the direction of the cyclone). Speedier cyclones generate wind waves of lower height. The highest values of wave heights are achieved at cyclonic velocities of 7–9 m/s. This effect is due to the coincidence of the characteristic values of the group velocity of the dominant wind waves in the deep-water part of the Black Sea with the cyclone translation speed.

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