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Modeling of Wind Waves in the Bays of South-West Part of the Crimea Peninsula

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Abstract

Numerical simulation of wind waves in the bays of south-west part of the Crimea Peninsula is carried out with high space resolution. Particular attention is paid to the local characteristics of wind waves in the Sevastopol Bay. The parallel version of wind wave spectral model SWAN is implemented. The steady state waves caused by wind of different directions are considered. It is obtained that the most intensive waves near the Crimea south-west coast and in the Sevastopol Bay are generated by west wind; the less intensive ones are caused by east wind. Evolution of wave heights, velocities and lengths on different stages of storm on 11 November 2007 are studied. The areas of coast which are subjected mostly by storm waves are determined.

Keywords: Computing cluster, SWAN, the Sevastopol Bay.

Introduction

Bays of the Crimea south-west coast (Figure 1) are intensively used both for economic and military purposes. The commercial, passenger and fishery ports, shipyards are placed here as well as navies of Russia and Ukraine. Not infrequently do the storm waves break functioning of maritime economic complexes; they cause underflooding or sometimes collapse of shores, destruction of coastal buildings, significant material damage and human losses (Dotsenko, 2000). So the investigation of wave conditions of the Crimea south-west region has the top-priority scientific and applied interest.

The Sevastopol Bay is the largest bay of the Crimea south-west coast. It stretches out in zonal direction from the west to the east for 7.5 km. The maximal width of the bay is approximately 1 km. Depth decreases from 20 m in the west to 4-5 m in the east. The bay has indented coastline due to the presence of small bays and capes (Figure 2). The mouth of the Sevastopol Bay is bounded by two piers, the distance between which equals 550 m.

Till now there haven't been any theoretical investigations in which wave local peculiarities in the Crimea bays would be resolved and the realistic conditions on their boundaries would be accounted for. In the present work the space distribution of wind wave parameters along the south-west coast of the Crimea Peninsula in case of winds with different directions is studied by using the method of computer simulation. Particular attention is paid to the local characteristics of wind waves in the Sevastopol Bay. The characteristics of extreme waves in the bay during devastating storm on 11 November 2007 were considered. Evolution of the storm occurred the following way. At night on 10 November 2007 the Mediterranean cyclone left the Balkan region and with the velocity of 70 km/h started to move towards the Crimea. At the beginning on 11 November above the Crimea region the south-east wind increased to 10-15 m/s and by 9 a.m. reached 20-25 m/s changing direction to south-west. Wind velocity in blasts reached 32 m/s. On 12-13 November the cyclone center was moving from the Crimea Peninsula to the north and the wind above the Black Sea water area didn't exceed 7-12 m/s. As a result of the storm the part of a quay between the Artyleriis'ka Bay and Pivdenna Bay (Figure 2) was destroyed, a boat was submerged in the Artyleriis'ka Bay, and some warships were damaged.

Mathematical Model

Characteristics of wind waves (significant wave height, wave direction, length and period) are

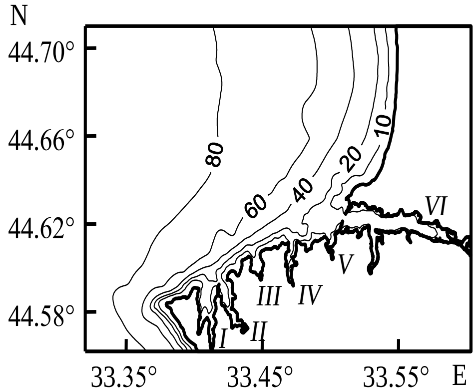

Figure 1. Bathymetry of the Crimea south-west coastal zone (m). Bays: I – Kozacha, II – Komysheva, III – Kruhla, IV – Strilets'ka, V – Karantinna, VI – Sevastopol.

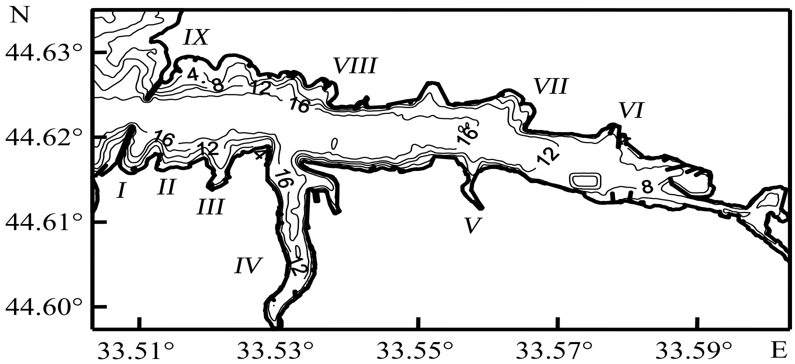

Figure 2. Bathymetry of the Sevastopol Bay (m). Bays: I–Martynova, II–Oleksandrivs'ka, III–Artyleriis'ka, IV–Pivdenna, V–Kilen, VI–Sukharna, VII–Hollandiia, VIII–Pivnichna, IX–Kostiantynivs'ka.

obtained by using the spectral wave model SWAN (SWAN technical documentation, 2007; Booij *et al.*, 1999; Ris *et al.*, 1999). This is the most widely used computer model for wave simulations in the near-shore region. SWAN accounts for all relevant processes of wave propagation, generation by wind, nonlinear interactions between the waves and decay. Compared to the deep-water wave models, SWAN includes depth-induced wave breaking and triad wave-wave interactions that may be important for near shore wave prediction. Diffraction is accommodated in an approximate manner in the model. SWAN is based on the wave energy balance equation in spectral form

$$\frac{\partial N}{\partial t}+\frac{\partial(c_{gx}N)}{\partial x}+\frac{\partial(c_{gy}N)}{\partial y}+\frac{\partial(c_{\omega}N)}{\partial \omega}+\frac{\partial(c_{\varphi}N)}{\partial \varphi}=\frac{S}{\omega}, \quad (1)$$

where $N=E(t, x, y, \omega, \varphi)/\omega$ is the action density; $E(t, x, y, \omega, \varphi)$ is the energy density spectrum; x, y are the horizontal coordinates; t is the time; g is the gravitational acceleration;

$$c_g=\frac{1}{2}\sqrt{\frac{g}{k}\tanh(kH)}\left(1+\frac{2kH}{\sinh(2kH)}\right);$$

$$\{c_{gx},c_{gy}\}=c_g\left\{\frac{k_x}{k},\frac{k_y}{k}\right\};$$

$k=\{k_x,k_y\}$ is the wave vector; $k=\sqrt{k_x^2+k_y^2}$; H is the water depth; $\omega=\sqrt{gk\tanh(kH)}$ is the wave frequency; φ is the wave propagation direction;

$$c_{\omega}=\frac{\partial\omega}{\partial H}\frac{\partial H}{\partial t};\ c_{\varphi}=-\frac{1}{k}\frac{\partial\omega}{\partial H}\frac{\partial H}{\partial m};$$

m is a coordinate perpendicular to the wave propagation direction φ;

$S=S_{in}+S_{nl}+S_{wc}+S_{bf}+S_{dib}$ is the source/sink term; S_{in} is the energy transfer from wind to waves; S_{nl} is the nonlinear transfer of wave energy through three-wave and four-wave interactions; S_{wc}, S_{bf}, S_{idib} are the wave decay due to whitecapping, bottom friction and depth-induced wave breaking correspondingly.

For the terms describing wind input, whitecapping and bottom friction SWAN provides optional choice of physical approximations. In the present work the third-generation mode of model was used with Komen *et al*. (1984) formulation for exponential wave growth due to the wind and whitecapping. According to Moeini and Etemad-Shahidi (2007) the use of Komen's formulation for the wind input leads to the most accurate prediction of wave heights.

At the JERICHO (Joint Evaluation of Remote sensing Information for Coastal defence and Harbour Organisations) project (Wolf *et al*., 2000) for the three near-shore zones with local morphological peculiarities the verification of SWAN model was carried out on the basis of satellite altimeter data by using different bottom friction formulations. The best coincidence of results of numerical simulations with the observation data was obtained when the Grant – Madsen (Madsen *et al*., 1988) approximation for the bottom friction was used. So this approximation was chosen for the present study.

In SWAN for the depth-induced wave breaking the model of Battjes and Janssen (1978) is applied. To calculate four-wave and three-wave interactions approximations of Hasselmann *et al*. (1985) and Eldeberky (1996) were implemented correspondingly.

To validate the results of SWAN model with the chosen physics test calculations for region of location of the gas platform "Golitsyno – 4" on the north-west shelf of the Black Sea was carried out (Polonsky *et al*., 2011). Marine Hydrophysical Institute of the NAS of Ukraine obtained series of wind parameters and level oscillations during 1998-1999 on the platform. The results of wave height simulation for the same period were compared with the in-situ data and showed quite a good coincidence.

On the rigid side boundaries the condition $E = 0$ is used. By the angular variable the periodicity condition is used $E(\varphi = 0) = E(\varphi = 2\pi)$ and by the frequency variable the following one is used $E(\omega_{\min}) = E(\omega_{\max}) = 0$.

By using of the solution of equation (1) the following wave characteristics can be obtained: the significant wave height

$$H_s = 4\sqrt{\int_0^{\infty}\int_0^{2\pi} E(\omega, \varphi)\, d\omega d\varphi}, \quad (2)$$

the mean wave direction

$$\varphi = \arctan\left[\int_0^{\infty}\int_0^{2\pi} \sin\varphi\, E(\omega, \varphi)\, d\omega d\varphi \Big/ \int_0^{\infty}\int_0^{2\pi} \cos\varphi\, E(\omega, \varphi)\, d\omega d\varphi\right], \quad (3)$$

the mean wavelength

$$\lambda = 2\pi\left[\int_0^{\infty}\int_0^{2\pi} E(\omega, \varphi)\, d\omega d\varphi \Big/ \int_0^{\infty}\int_0^{2\pi} k E(\omega, \varphi)\, d\omega d\varphi\right], \quad (4)$$

and the mean absolute wave period

$$T = 2\pi\left[\int_0^{\infty}\int_0^{2\pi} \omega E(\omega, \varphi)\, d\omega d\varphi \Big/ \int_0^{\infty}\int_0^{2\pi} E(\omega, \varphi)\, d\omega d\varphi\right]^{-1}. \quad (5)$$

The model was installed onto the computing cluster of Marine Hydrophysical Institute of the NAS of Ukraine. To do this parallel version of SWAN model built on the MPI technology for computers with distributed memory was used (MPI Documents, 2009).

To refine the space resolution of the model the calculations of wave fields were carried out on four nested grids. These grids cover the Black Sea and the Sea of Azov basin, the Crimea west coastal zone, the Crimea south-west coastal zone (Figure 1), and the Sevastopol Bay (Figure 2) with space resolution of 4.6×4.5 km, 211×197 m, 49×48 m, and 10×11 m correspondingly. When calculating wave characteristics in the Sevastopol Bay the effect of diffraction was taken into account. Angular resolution while determining wave spectrum equals 10°. Throughout the frequency coordinate the grids with 32 nodes in frequency range 0.04–2 Hz in case of stationary wind and with 70 nodes in frequency range 0.01–5 Hz in case of non-stationary wind were used.

Results and Discussion

According to the observations on the marine hydrometeorological station "Sevastopol", the winds of four main directions (north, south, east and west) as well as north-east one are the most frequent during the year above the Sevastopol Bay. The east (23.1%) and south (19.6%) winds dominate among them, but the velocity of the east wind is minimal. As to the strong winds, the south one is most frequent (1%).

Let's consider the steady state waves caused by stationary and space homogeneous wind of four main directions. In numerical calculations the wind velocity equals 10 m/s. This value is close to the maximum of monthly mean velocity for the Crimea south-west coast.

The most intensive waves near the Crimea south-west coast are caused by west wind (Figure 3a) due to the longest fetch in this case. Significant wave height reaches 1.7 m in the open part of the water area and 1.3 m in the coastal zone. In case of east wind the fetch is shortest and as a result maximal wave height becomes more then two times smaller (up to 0.8 m) in comparison with the west wind effect. So the east wind causes the weakest waves (Figure 3b). In central part of the water area wave heights vary insignificantly in case of west wind and in case of east wind they are characterized by significant space variability. Maximal heights of waves generated by south and north winds are close to each other and equal 1.6 m and 1.4 m correspondingly (Figure 3c, 3d). But near the bay mouths the wave heights differ greatly due to the screen effect of Crimea Peninsula for the south wind.

Direction of wave propagation is determined by wind characteristics and by peculiar properties of coastline and bottom. Near the Crimea south-west coast direction of wave propagation coincides with

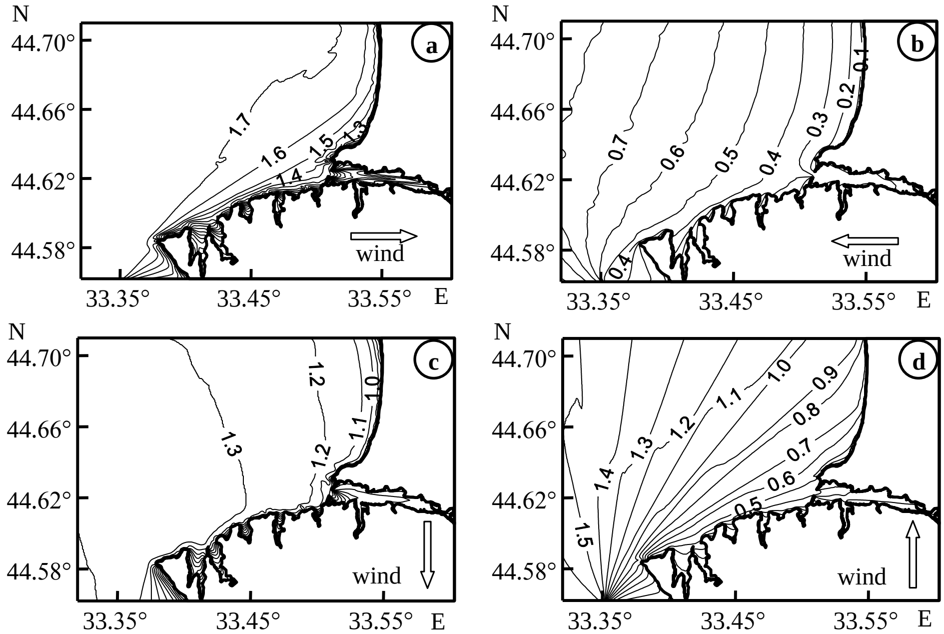

Figure 3. Significant wave heights (m) near the south-west coast of the Crimea in case of west (*a*), east (*b*), north (*c*) and south (*d*) winds.

the wind direction only in case of west wind (Figure 4a). In case of east wind due to refraction in the southern shallow region near shore the waves deflect to the south following the coastline shape (Figure 4b). In other parts of the water area waves follow the wind direction. Under the effect of north and south winds the wave deflection to the east shallow region appears almost everywhere (Figure 4c, 4d). But in case of south wind these deflection is more significant than in case of north one. Intensive penetration of waves into the Sevastopol Bay occurs under the effect of west wind. The other bays are more subjected by the waves generated by the north wind.

The longest waves (up to 26 m) are generated in the open part of the water area by west wind. In bays wave lengths vary from 6 to 16 m. In case of north wind far from the shore wave lengths are shorter (up to 20 m) and in the bays (with the exception of the Sevastopol Bay) they are longer (from 10 to 18 m) then in case of west wind. Maximal wave lengths generated by south wind have approximately the same values as in case of north one but the range of their variability is wider (from 4 to 20 m). East wind effect causes the shortest waves (from 2 to 10 m) among all considered wind directions.

Wave period space distributions are qualitatively similar to the wave length ones. The longest waves generated by west wind have the biggest periods of 4.6 s. In the bays the periods take on the values of 1-4 s for this wind. In case of north and south winds, maximal periods in the open part of the water area are 4 and 4.2 s correspondingly, and in the bays they lie in the ranges of 2-3.9 s and 1-2 s with the exception of the Sevastopol Bay. For the east wind periods are smallest and do not exceed 2.8 s.

Further we consider peculiarities of wind waves in the Sevastopol Bay. As in the open part of the Crimea south-west coastal zone the maximal waves are generated here by the west wind and minimal ones are caused by east wind. In case of west wind intensive waves penetrate along the bay axis up to the east boundary. But between the Artyleriis'ka Bay and the Pivdenna Bay and in the Pivnichna Bay there are local regions where intensive waves reach the south and north coasts correspondingly. Under the effect of north wind the maximal wave heights occur near the south-west coast of the Sevastopol Bay and under the effect of south wind they occur near the north-west coast.

Wave direction generally coincides with the wind one in the Sevastopol Bay in case of west and east winds. Deflection to the north and south occurs only near the north and south coasts of the bay correspondingly. In case of north and south winds wave direction deflects to the east on the whole bay water area due to the depth decreasing from the west to the east.

Wave lengths in the Sevastopol Bay are shorter then in the open part of the Crimea south-west coastal zone. In case of west wind significant variations of wave lengths occur alone the whole bay in zonal direction from 14 to 3 m. This corresponds to the wave period changing from 3.7 to 1.5 s. Under the effect of north wind wave lengths vary in the range from 10 to 3 m only near the mouth of the bay. In case of east and south winds wave lengths in the Sevastopol Bay lie in the range from 1 to 3 m and insignificantly vary in space. As to the wave periods, their values are between 0.8 and 1.6-1.9 s.

Now let's consider the results of simulation of

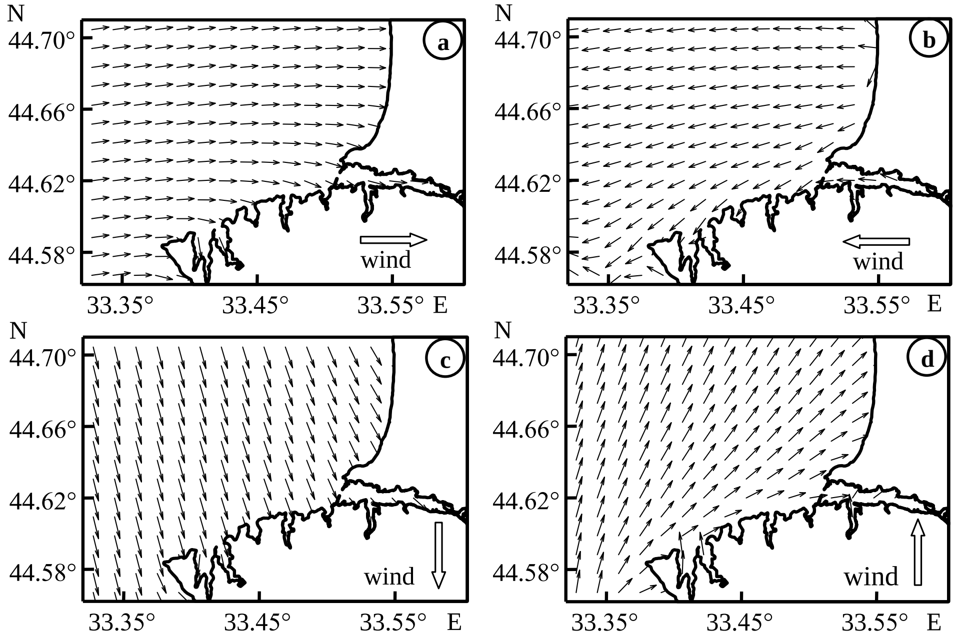

Figure 4. Wave direction near the south-west coast of the Crimea in case of west (*a*), east (*b*), north (*c*) and south (*d*) winds.

wave field evolution in the Sevastopol Bay on 10-11 November 2007. In numerical experiments wind velocity values obtained from the SKIRON regional prognostic model (National and Kapodistrian University of Athens, 2007) were used as atmospheric forcing. Wind field resolution was 10×10 km. Calculation was carried out from 5 November 2007 to provide adjustment of wave field with the wind condition at the moment of storm begin.

By the end of 10 November 2007 wave fields in the Sevastopol Bay were formed by the south-east wind, which predominated all the day. The wind velocity was increasing not monotonically from 6 m/s to 10 m/s. Space distribution of wave heights was characterized by the increase of their values from 0.1 m in the south-east to 0.28 m in the north-west of the bay with the maximal gradients near the south coast and minimal ones near the north coast. Wave direction coincided with the wind one in the most part of the bay. But near the south coast waves propagated predominately to the west. Wave length range was quite narrow from 0.5 m in the east to 1-1.5 m in the west. It corresponds to period variations from 0.8 s to 1.2-1.3 s.

After midnight on 11 November wind increasing with time became more intensive due to beginning of atmospheric cyclone moving above the Crimea Peninsula. At the first stage of atmospheric disturbance moving (up to 2 a.m.) the south-east wind direction remained predominant, but its southern component was increasing gradually. The wind strength became strong and one velocity reached 13 m/s. As a result of preserving of predominant wind direction the peculiar features of wave height space distribution remained the same as on 10 November. In particular the wave heights increased from the south-east to the north-west and had significant gradients near the south coast. But the intensification of wind velocity resulted in small increasing of maximal wave height value up to 0.34 m in the north-west in the Kostiantynivs'ka Bay and minimal value up to 0.1 m in the east end of the bay (Figure 5a). The waves from the south coast propagated to the north-west as in the central part of the bay (Figure 6a). Near the north coast of the Sevastopol Bay waves reached the length of 2 m and period of 1.4 s.

From 3 a.m. to 4 a.m. wind direction became close to southern due to passing of cyclone central part with the minimal wind velocity in the west from the Sevastopol Bay. Wind strength above the bay decreased insignificantly to 11 m/s, varying from the south to the north coast less then on 1 m/s. After short time predomination of south wind the areas with high gradient of wave heights widened from the south coast to the center of bay and meridional component of wave velocity increased.

After 4 a.m. the Sevastopol Bay was subjected by the effect of the storm south-west wind with the predominant west component. At 8 a.m. wind velocity reached the maximal strength of 25 m/s and varied insignificantly from the west to the east of the bay. There was the most dangerous stage of the storm evolution connected with the passing of rear of cyclone. At that stage significant rebuilding of the wave height field occurred. The highest waves were observed along the bay axis but between the Artyleriis'ka Bay and the Pivdenna Bay and in less degree in the Pivnichna Bay intensive waves reached the coast.

The process of wave intensification with time was developing the following way. At first the area with the highest waves for the definite moment of

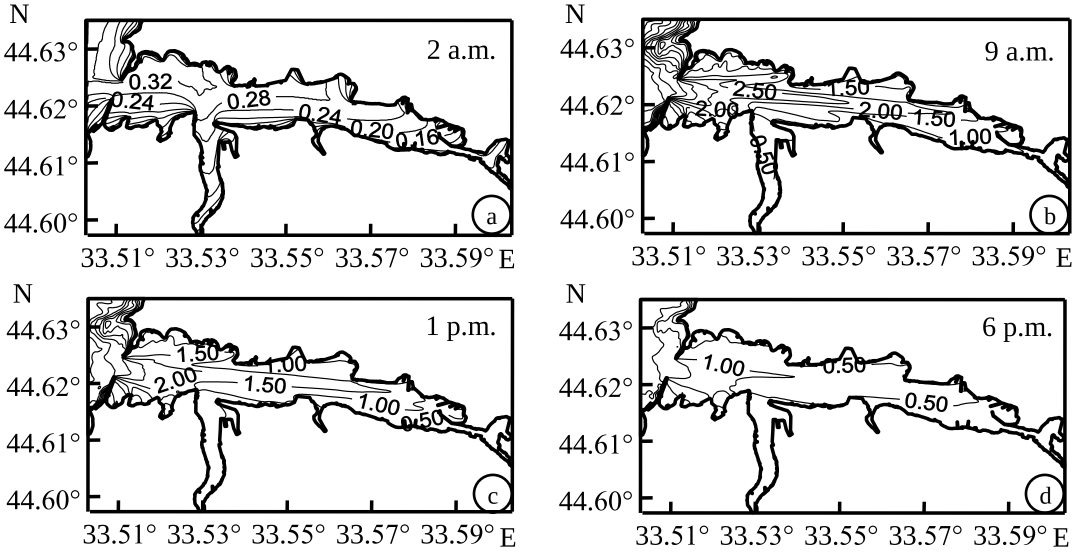

Figure 5. Significant wave heights (m) in the Sevastopol Bay on 11 November 2007 at 2 a.m (*a*), at 9 a.m. (*b*), at 1 p.m. (*c*) and at 6 p.m. (*d*).

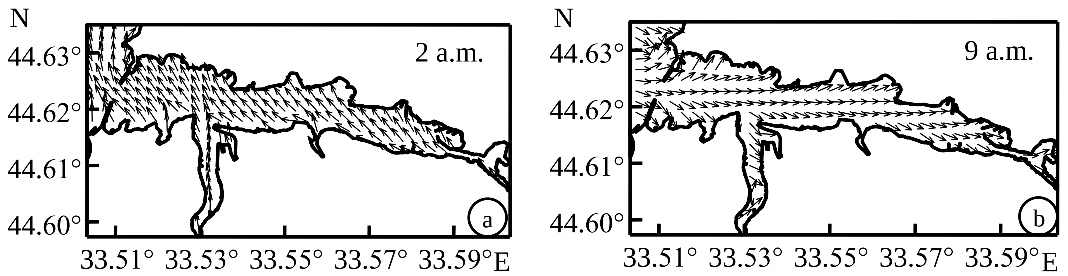

Figure 6. Wave direction in the Sevastopol Bay on 11 November 2007 at 2 a.m. (*a*) and at 9 a.m. (*b*).

time appeared between two piers in the mouth of the bay. Then this area widened predominantly along the Sevastopol Bay axis toward the Sukharna Bay. For instance at 6 a.m. the wave height between the piers was 1.5 m and in the Sukharna Bay one was 0.5 m. At 8 a.m. these values were 3.5 and 1.5 m correspondingly. Due to the sluggishness of wave development process in comparison with the wind change the most intensive waves occurred at 9 a.m. (Figure 5b) when the south-west wind weakened to the value of 23 m/s.

As a result of the common effect of wind, coastline shape and bathymetry starting from 6 a.m. waves in the distance from coast propagated from the west to the east. Near the north and south coasts waves deflected to the north and south correspondingly (Figure 6b). Wave length and period ranges increased significantly with the wind strengthening. For example, at 9 a.m. wave lengths varied from 5 m in the east to 40 m in the west and for the wave periods this limits were 2 and 7 s correspondingly.

After 9 a.m. the wind weakening continued with further cyclone moving but until 11 a.m. wind velocity exceeded 20 m/s. Area with the wave heights more then 2 m still covered significant part of the water area from piers to the Artyleriis'ka Bay (Figure 5c). The coast between the Artyleriis'ka Bay and the Pivdenna Bay was subjected by effect of waves which were not higher then 1.5 m and between the Pivnichna Bay and Sukharna Bay waves near the coast were about 1 m height. Spatial distribution of wave velocity direction was in general unchanged in comparison with the situation depicted in Figure 6b and remained the same till the morning on 12 November. Only in the Pivdenna Bay direction of wave propagation was deflecting gradually to the south. Ranges of wave length and period variations reduced significantly as a result of wind weakening and to the moment under consideration were 3-25 m and 1.5-6.1 s.

After 2 p.m. wind became strong again (13 m/s) with the direction close to western. This direction remained predominant till 10 p.m., but the wind velocity was decreasing gradually to the value of 6 m/s. Wind condition change didn't cause the qualitative rebuilding of wave height and direction fields. Only decreasing of wave height and velocity values occurred. At 6 p.m. intensive waves which height didn't exceed 1 m still reached the coast in the east from the Artyleriis'ka Bay (Figure 5d). Later the wave effect on the coast was becoming less significant and to 10 p.m. waves higher then 0.6 m were not observed near the coast. Maximal wave length at 10 p.m. was near the mouth of the Sevastopol Bay and equaled 10 m. Waves with such length had the periods about 3.6 s.

Conclusion

Wind waves in the bays of south-west part of the Crimea Peninsula are studied by using of SWAN spectral model. Effect of stationary winds with different directions is considered. For the largest Sevastopol Bay the evolution of storm on 11 November 2007 is simulated.

The most intensive waves near the Crimea south-west coast and in the Sevastopol Bay are caused by west wind; the less intensive ones are caused by east wind.

Direction of wave propagation near the Crimea south-west coast coincides with the wind direction only in case of west wind. Under the effect of east wind the wave direction deflects to the south in the southern shallow region. In case of north and south winds the wave deflection to the east shallow region appears almost everywhere including the Sevastopol Bay. In case of west and east winds in the Sevastopol Bay the wave direction deflects from the wind direction to the north and south near the north and south coasts correspondingly.

Waves with the maximal lengths arise near the Crimea south-west coast and in the Sevastopol Bay under the effect of west wind; ones with the minimal lengths arise under the effect of east wind. The most significant variability of wind lengths occur near the Crimea south-west coast in case of south wind and in the Sevastopol Bay in case of west wind.

During the storm on 11 November 2007 the maximal waves in the Sevastopol Bay occurred at 9 a.m. when the rear of cyclone with south-west winds moved over the water area.

In case of west winds the part of coast between the Artyleriis'ka Bay and the Pivdenna Bay is mostly subjected by wave effect. This conclusion is confirmed by the quay destruction on mentioned part of coast on 11 November 2007.

At the moment, regular instrumental measurements of the wind waves in bays of south-west part of the Crimea Peninsula aren't carried out and numerical simulation is the only way to estimate possible danger for coastal zones in different wind situations. The SWAN model has been verified in the conditions of the Black Sea north-west shelf, but its further improvement is restricted by the lack of in-situ observation directly in the region under consideration.

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