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WIND-DRIVEN WAVES SIMULATION FOR PORT ENGINEERING IN THE RUSSIAN ARCTIC USING MIKE BY DHI MODELS

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ABSTRACT

The Arctic Ocean plays an important role in worldwide logistics. To date, the major shipping routes are located here. There are huge resources of oil and natural gas. These features make this area perspective and interesting for future development and require new port facilities and engineering constructions to solve specific tasks. At the same time, the Russian Arctic is characterized by harsh hydrometeorological and ice conditions. Modern climate change significantly contributes to the rapid changes in this region. Wind-driven waves are high-energetic ocean phenomena influencing port facilities and must be considered during engineering works. We used two wave modules of MIKE by DHI numerical model, MIKE 21 Spectral Wave (SW) and MIKE 21 Boussinesq wave (BW), to find a more accurate solution on the shallow water of the Arctic bay. SW module aims to wave climate description including the transformation of wind-driven waves and swell propagation while the BW module simulates direct traveling of wind waves from deep to shallow waters and their breaking. We tested these two modules in the potential port area in the Arctic semi-closed bay and compared the main parameters of the waves' field (wave height, wavelength, and period, etc.).

Basically, the SW module has more parameters and has more options for forcings and climate conditions. The BW module solves enhanced Boussinesq equations but there are difficulties related to the model assumptions and it might be the limitation for the wide usage of this module to sole the real engineering tasks.

KEY WORDS: Wind-driven waves; Numerical modeling; Russian Arctic; MIKE 21.

INTRODUCTION

High-resolution numerical model MIKE is now widely used for oceanographic research and engineering works. We tested MIKE 21 wave modules for applications in engineering studies in the Laptev Sea. The analysis is done for the main parameters of the wind-driven waves field – maximum, mean, and significant wave height, wave period, and wavelength. The wave breaking process and diffraction are also considered in our simulations. Numerical experiments are performed in the shallow Faddey Bay (the Laptev Sea) in the natural conditions and inside the potential port area with the simplest constructions (2 piers). Additionally, we tested the capabilities of MIKE 21 BW module to describe direct wave propagation in the potential port area (MIKE 21, Boussinesq wave module, 2017).

The region of studies is randomly chosen. It is the Faddey bay, the semi-closed natural bay in the Laptev Sea with coordinates 76.45-76.91 N 106.41-108.01 E (UTM zone 48) (Figure 1a and 1b). The nearest permanent meteorological station is the Cape Andreya where we took wind observations for our simulation (Water cadaster, 2013). Wind-driven waves are an important factor that significantly influences the ocean state and should be considered during engineering construction works (Liu et al., 2016). But in the Arctic region, the action of this kind of waves is limited to the ice-free period of spring, summer, and autumn (Alexandrov et al., 2000). While the studies of wind-driven waves are very important and of our interest for our future projects with hydrometeorological support of Arctic engineering we would like to find a better and more precise way to describe this phenomenon. We designed several numerical experiments to describe how the wind-driven waves can act in the extreme conditions of the Russian Arctic and inside the potential port area.

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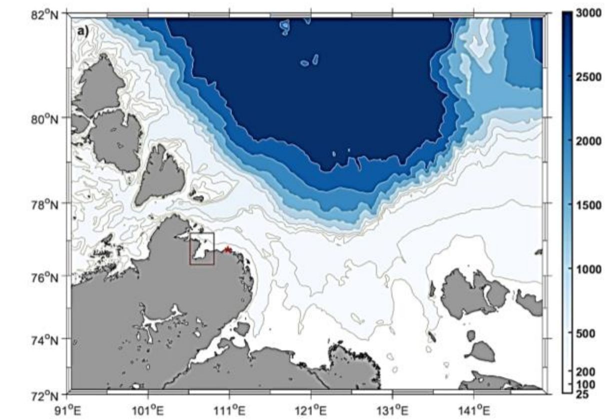

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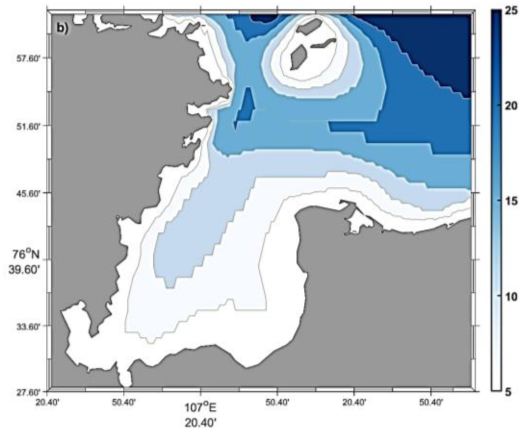

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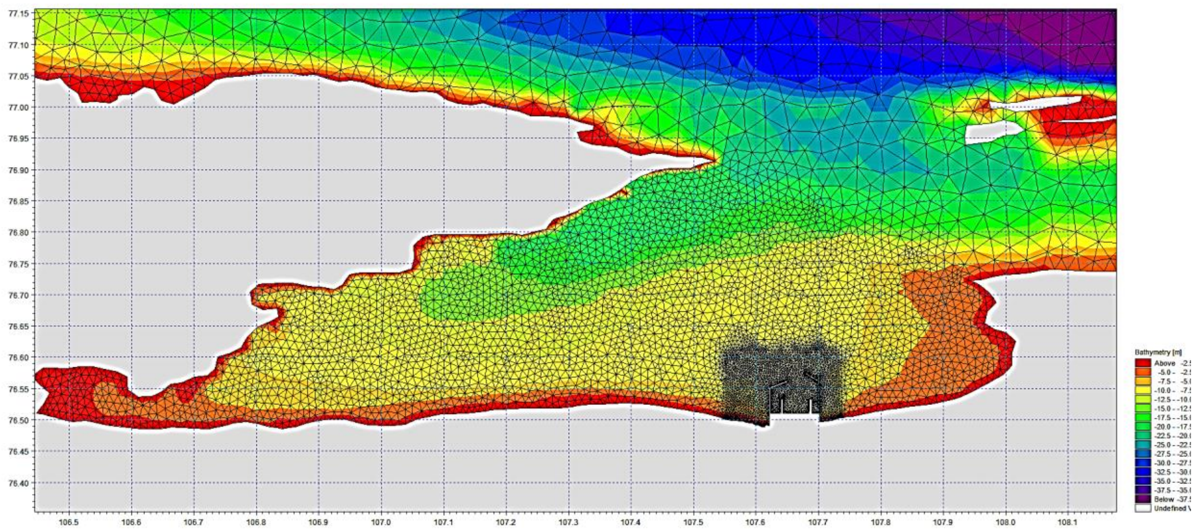

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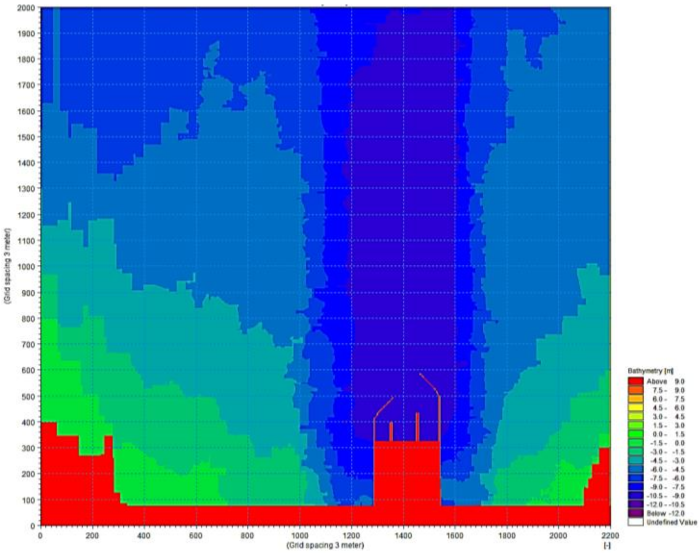

Figure 1. Geographical position of the studied region and model mesh: a) the Laptev Sea, red star denotes the meteorological station Cape Andreya; b) the Faddey Bay; c) numerical mesh used with the MIKE 21 SW module; d) numerical mesh used with the MIKE 21 BW module

The area of interest is very complex and characterized by 1) harsh hydrometeorological and ice conditions (Alexandrov et al., 2000; Bauch et al., 2018; Janout et al., 2017; Liu et al., 2016); 2) complex orography with indented coastline and small islands that impact on ocean processes and 3) shallow water conditions (maximum depth 21 m) that makes harder the description of wind-driven waves transformations.

MODEL DESCRIPTION AND EXPERIMENT DESIGN

We set up two numerical experiments with MIKE 21 SW module and one with MIKE 21 BW (Table 1). MIKE by DHI is a non-linear hydrodynamic numerical model developed for oceanographic application by DHI Water&Environment. MIKE 21 Spectral Wave uses the unstructured mesh and simulates the growth, transformation, and breaking of wind-driven waves offshore and nearshore and describes wave climate (MIKE 21, Spectral wave module, 2017). The model applies the fully spectral formulation (Komen et al., 1994; Young 1999). MIKE 21 SW can be used for the description of wave growth depending on wind, non-linear wave-wave, wave-current or wave-topography interactions, energy dissipation due to white capping, bottom friction, and wave transformations due to depth changes.

Basically, wave density spectrum is a function of wave direction θ and relative angular frequency σ and varies in time and space. The approach is based on the solution of wave action conservation equation with dynamical frequency cut-off (MIKE 21, Spectral wave module, 2017):

$$\frac{dN}{dt} + \nabla(\vec{v}N) = \frac{S}{\sigma}, \quad (1)$$

where $N(\vec{x}, \sigma, \theta, t)$ is action density, $\vec{v}(c_x, c_y, c_\sigma, c_\theta)$ - propagation velocity of wave group, σ – relative angular frequency, S – source term of wave energy.

In shallow water regions, it is important to precisely describe the triad-wave interactions. Non-linear transformations of wind waves nearshore caused by the generation of sub and super harmonics. The approach describing this process is published in (Eldeberky and Battjes, 1995, 1996). Diffraction is also included in MIKE 21 SW simulations. We have got spectral characteristics (peak period, peak direction etc.) as well as basic wave parameters such as wave height, wave period and wavelength as model output.

MIKE 21 Boussinesq Wave module gives the solution of enhanced Boussinesq equations with the implicit scheme (Sorensen et al., 2004). The module describes refraction, diffraction, wave breaking, partial reflection and transformations, non-linear wave-wave interaction and can describe the frequency and directional spreading (MIKE 21, Boussinesq wave module, 2017). The advantage of the Boussinesq wave approach is a better description of directional wave train and its transformation in shallow water with frequency dispersion. The main feature is the exclusion of vertical coordinate.

Two numerical experiments with MIKE 21 SW are set up. The first one is for natural conditions in the Faddey bay and the nearest Laptev Sea area. The unstructured triangular mesh for three different regions (Figure 1c): the Laptev Sea, the Faddey bay, and the potential port area. There are four sub-experiments with these two configurations (with and without port facilities) depending on wind forcing. We study extreme weather situations and relative wind wave field. The extreme storm is characterized by maximum wind speed observed on the nearest meteorological station and comes from the most wave-prone direction (N, E, NE, NW) (Table 2). We set up experiment 1a describing storm conditions in the natural Faddey bay with a wind speed of 18 ms^{-1} from the northern direction, the duration is 24 hours, (similarly, experiment 1b for the storm with a wind speed of 20 ms^{-1} from E direction, 1c – 16 ms^{-1} from NE, 1d – 21 ms^{-1} from NW). In the second experiment, we added the potential port area and constructions inside. The structure of the experiment is similar to experiment 1.

Table 1. Design of numerical experiments with MIKE 21SW and BW

<table>
<tr><th>Number of experiment</th><th>Module</th><th>Duration</th><th>Forcing</th><th>Mesh</th><th>Configuration</th><th>Area</th></tr>
<tr><td>1</td><td rowspan="2">MIKE 21 SW</td><td>24 hours (2880 points, 30 sec discretization)</td><td rowspan="2">Wind observations</td><td rowspan="2">Triangular flexible</td><td>Natural Bay</td><td>the Laptev Sea, the Faddey Bay</td></tr>
<tr><td>2</td><td>24 hours (2880 points, 30 sec discretization)</td><td>Potential Port</td><td>the Laptev Sea, the Faddey bay, the potential port</td></tr>
<tr><td>3</td><td>MIKE 21 BW</td><td>25 minutes (12001 points, 0.125 sec discretization)</td><td>Wind observations</td><td>Rectangular regular</td><td>Potential Port (6 km×6.6 km, 3 m grid spacing)</td><td>the Faddey bay, the potential port</td></tr>
</table>

The third experiment is performed with MIKE 21 BW for the storm coming from N direction. The northern direction is the most wave-prone direction for the Faddey bay conditions (Water cadaster, 2013). Relative wind speed is 18 ms^{-1}.

Table 2. Long-term wind characteristics used here as forcing for the numerical model

Cape Andreya station	Coordinates	Time	Regime Wind Parameters			
90011	76.75 N 110.43 E	1986-2004	N	NE	E	NW
			18 ms^{-1}	16 ms^{-1}	20 ms^{-1}	21 ms^{-1}

As the results, we have got wind-driven wave parameters and compared experiments output in different situations (wind speed and direction or with/without port constructions). In the end, we would like to conclude which approach allows us better to describe the wave situation inside and outside Arctic port areas and which we can use in our future works.

RESULTS AND DISCUSSION

Wind-driven waves in the Faddey bay and wave field inside the port area

Numerical modelling of the wave field parameters was performed in spectral domain with the frequency range of 0.0055-0.9597 Hz with the separation of the wind-driven waves and swell at the frequency of 0.125 Hz. Nikuradse roughness was used as bottom friction parameter and set up as 0.02. The water area of natural bays of the Russian Arctic Seas is poorly covered by observations and the Faddey bay is not covered with observations. That is why here we compared our modeled results with previously observed wave heights on the hydrometeorological station to understand the regional characteristics of the wave field along the coast of the Taymyr peninsula. Table 3 contains wave heights from experiments with the MIKE 21 SW and observations on station.

The nearest observational point is the Cape Andreya station. There mean wave height is 0.3-0.5 m. The mean maximum wave height is 0.6-1.1 m with the absolute maximum wave height of 2.5 during the storm event from the N direction. This is consistent with the results published in (Liu et al., 2016). The chosen region (the Faddey bay) is characterized by rather calm wind-wave conditions. In our experiments, the results have shown that in the bay entrance significant wave height is between 0.6 and 4.2 m with a maximum of 1.2-8.2 m (Figure 2). The relative mean wave period is between 6.0 and 7.9 seconds, mean wave direction is N. The most dangerous situation we described in the storm came from the NW direction when the significant way height at the Faddey bay entrance is 1.7-3.5 m with a maximum of 2.8-6.8 m. A similar distribution is shown for the area of the port entrance. Significant wave height is between 0.6 and 2.6 m (maximum 1.1-5.7 m), mean wave direction is N. There is no significant difference in our results for experiment 1 and experiment 2 at the bay and port entrances. Inside the potential port area, wave height is significantly smaller in experiment 2 which is the expected situation. Inside the port area, significant wave height reaches 0.04-1.1 m. Maximum wave height is 0.1-4.7 m with a mean wave period of 5 seconds. In general, wave height is 2 times smaller in experiment 2. In all experiments mean wave direction is N.

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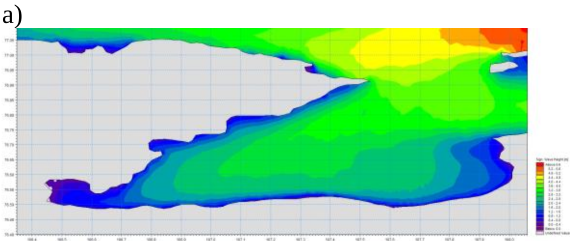

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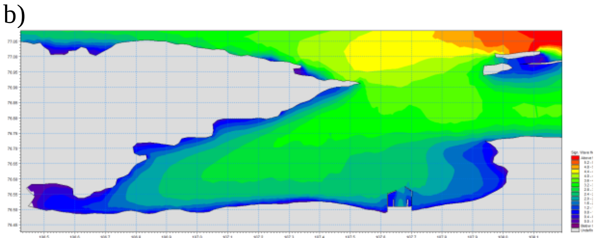

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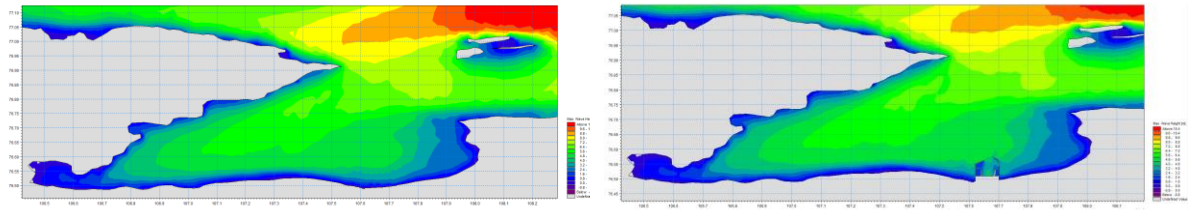

Figure 2. Output of MIKE 21 SW module for the storm from N direction: a) significant wave height in the natural bay; b) significant wave height with the potential port constructions; c) maximum wave height in the natural bay; d) maximum wave height with the potential port constructions

MIKE 21 SW module overestimates wave height in comparison to observation and published data. But the experiments are performed for the extreme storm conditions. We also checked different initial conditions for our MIKE 21 SW run. It is recommended to use a zero spectrum as initial conditions for this kind of model run (MIKE 21, Spectral wave module, 2017). Our results do not show any significant difference between run with zero spectrum and JONSWAP spectrum as initial conditions.

Table 3. Spatially averaged significant and maximum wave height inside the potential port area in experiments with and without the port facilities and observed mean wave heights from observation on the Cape Andreya station

	N	NE	E	NW
H_{mean} observations (regional)	0.4	0.4	0.3	0.5
H_{max} observations (regional)	2.5	2.0	1.3	2.2
H_{sign} SW without port	2.47	1.92	0.64	2.80
H_{max} SW without port	4.63	3.59	5.63	4.70
H_{sign} SW with port	1.53	0.86	0.20	1.28
H_{max} SW with port	3.70	2.48	5.10	3.77

Solution of Boussinesq equations in shallow water environment

MIKE 21 BW module is designed for the description of directional waves propagating and transforming inside port and harbor areas. The BW module solves the enhanced Boussinesq equation:

$$n\frac{\partial \xi}{\partial t}+\frac{\partial P}{\partial x}+\frac{\partial Q}{\partial y}=0, \tag{2}$$

$$n\frac{\partial P}{\partial t}+\frac{\partial}{\partial x}\left(\frac{P^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{PQ}{h}\right)+\frac{\partial R_{xx}}{\partial x}+\frac{\partial R_{xy}}{\partial y}+F_x+n^2gh\frac{\partial \xi}{\partial x}+n^2P\left[\alpha+\beta\frac{\sqrt{P^2+Q^2}}{h}\right]+\frac{gP\sqrt{P^2+Q^2}}{h^2C^2}+ n\psi_1=0, \tag{3}$$

$$n\frac{\partial Q}{\partial t}+\frac{\partial}{\partial y}\left(\frac{Q^2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{PQ}{h}\right)+\frac{\partial R_{yy}}{\partial y}+\frac{\partial R_{xy}}{\partial x}+F_y+n^2gh\frac{\partial \xi}{\partial y}+n^2Q\left[\alpha+\beta\frac{\sqrt{P^2+Q^2}}{h}\right]+ \frac{gQ\sqrt{P^2+Q^2}}{h^2C^2}+n\psi_2=0, \tag{4}$$

where ξ – free surface elevation, P and Q – flux density in the x and y directions, ψ_1 and ψ_2 – Boussinesq dispersion terms, F_x and F_y – horizontal stress term in x and y directions, h – total water depth, n - porosity, C – Chezy resistance number, α and β – resistance coefficient for laminar and turbulent flow in porous media. The approximation describes the roller celerity:

$$(c_x, c_y)=(c\cdot\cos\theta\,, c\cdot\sin\theta), \tag{5}$$

$$c = f_v\sqrt{gh},\qquad (6)$$

Where f_v is a factor determined by linear shallow water theory. Manning coefficient was used as bottom friction parameter and set up as 32.

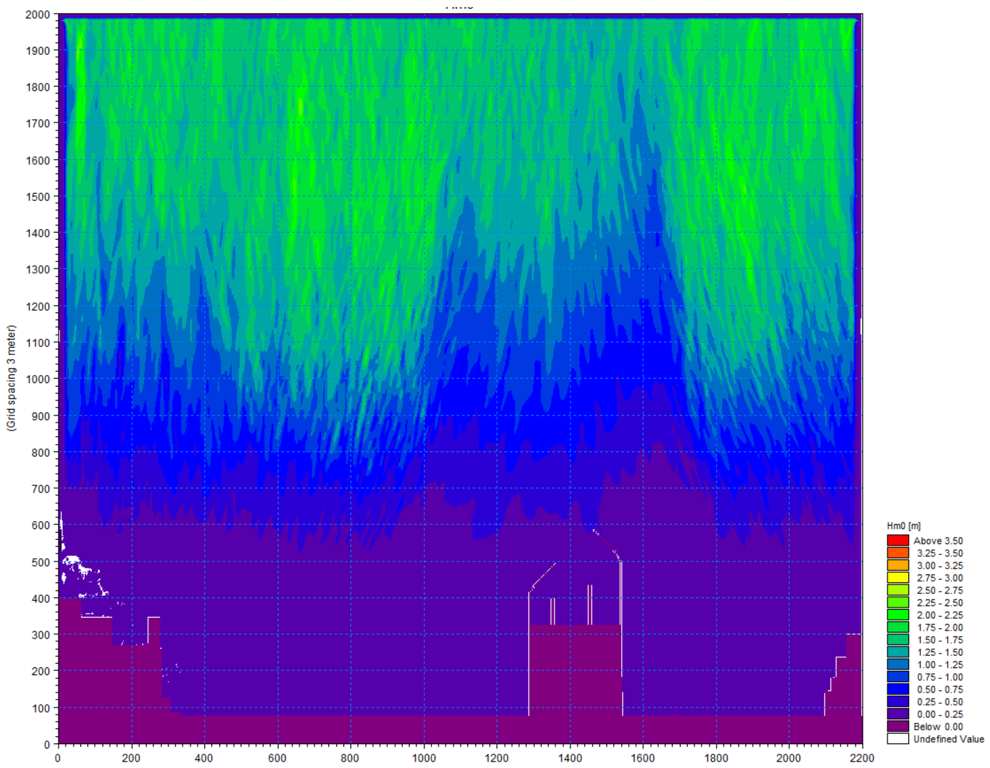

Figure 3. Significant wave height from MIKE 21 BW run

Experiment 3 shows that significant wave height inside the Faddey bay also reached 2-3 m, rather inside the port area this parameter is 0.2-.7 m (Figure 3). Waves propagate from the north direction and reflect from the coast and port facilities (Figure 4). These processes can not be described inside MIKE 21 SW.

CONCLUSIONS

Here, we presented our results of wind-driven waves modeling with MIKE 21 by DHI in the Russian Arctic. The model has two modules MIKE 21 SW and MIKE 21 BW for simulation of wind-driven waves and computation of spectral characteristics and parameters solving Boussinesq equations with considering nonlinearity and frequency dispersion. MIKE 21 SW has more spectral and linear parameters as output and can describe wave situation on large water areas. For the Faddey bay, wave height in the numerical experiment is overestimated in comparison to the in-situ observations on the hydrometeorological station Cape Andreya. The module can be validated with observed data during the model setup. Clarification of the bottom friction coefficient in the MIKE 21 SW module can solve the problem with overestimation of wave heights inside the area of interest. The MIKE 21 SW module could be potentially used in future works related to the numerical modeling of wind-driven wave field in the Russian Arctic. MIKE 21 BW module can describe the direct propagation of the wind wave and catches the small-scale transformation and wave interactions. Figure 4 shows us that the used Boussinesq approximation showed inappropriate results: wavelength is around 100 m between wave crests while the depth is limited to 10 m and shallower. This kind of approximation does not work properly in this shallow water area. Also, the difficulties with the setup such as a requirement to have several artificial layers and closed boundaries with artificial land make the application of this module limited for real tasks. The forcing is also determined and does not allow to study of different situations of storm events. MIKE 21 SW is more appropriate and convenient for us to use for engineering purposes.

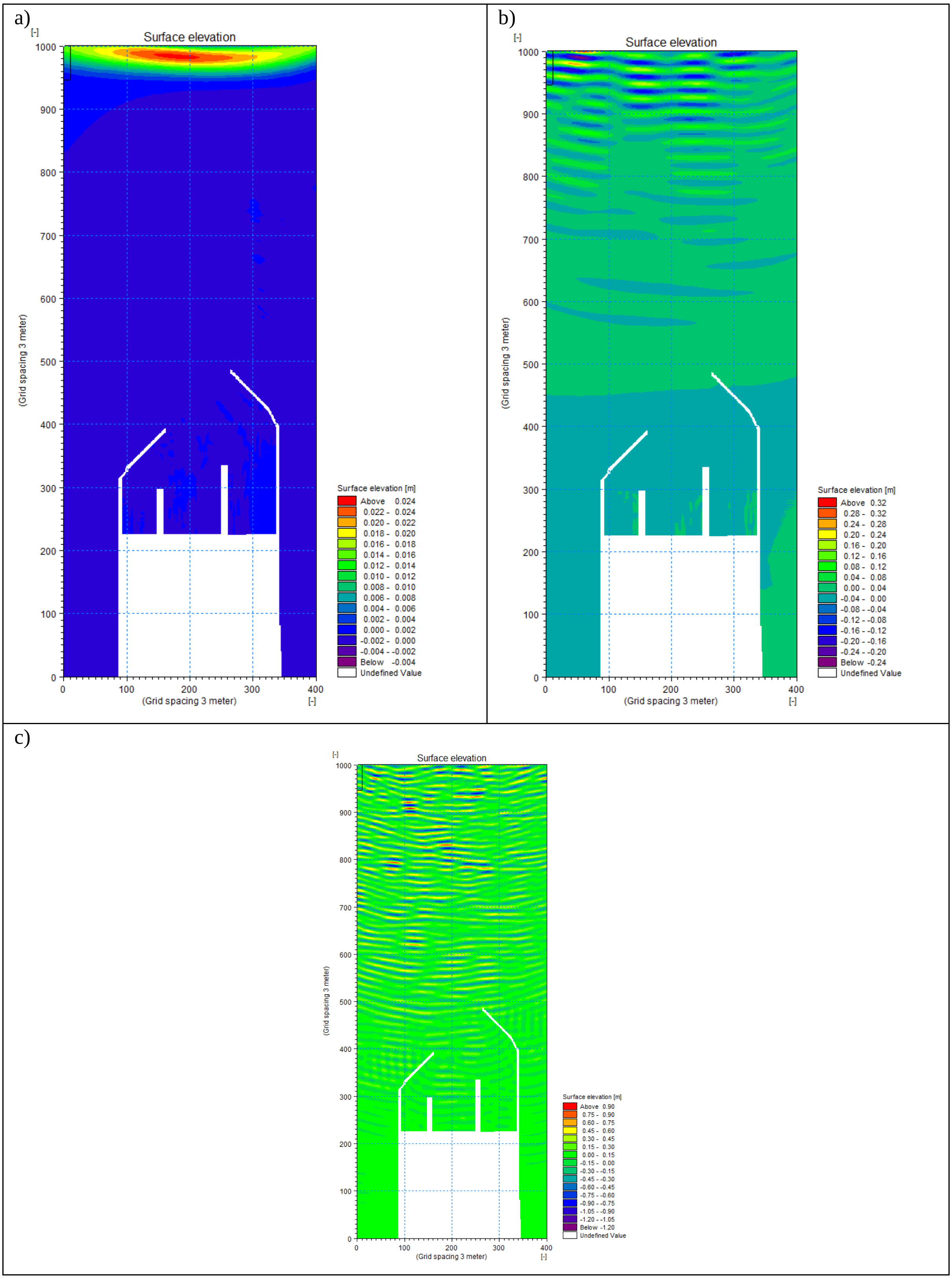

Figure 4. Output form MIKE 21 BW run, three snapshots with the surface elevation: a) time step 2200; b) time step 3296; c) time step 6000

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Co-authors personal contribution: NS developed the idea, set up the MIKE 21 SW model, developed the model configuration and performed all experiments with the MIKE 21 SW, AB developed the model configuration and performed all experiments with the MIKE 21 BW, AE provided the financial support for this work and publication, contributed to the idea development, all co-authors equally contributed to the text writing and editing the manuscript.

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