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Special aspects of wind wave simulations for surge flood forecasting and prevention

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Abstract
The paper is focused on several issues of wind wave simulations with SWAN model for the tasks related to prevention of surge floods in St. Petersburg. It introduces main objectives that are pursued through the use of the model as well as covers problems of computational mesh generation and model parameter calibration. We also examined several assumptions on the necessity to take ice fraction and sea level rise into account in wind wave simulations.

Keywords: wind waves, storm surges, model calibration, grid generation

1 Introduction

Storm surges is a common hazard for many coastal cities. However, a solution to flood protection in each case is almost unique, mostly due to geographical features and operational requirements. The most well-known flood protection systems are in Amsterdam [1], Rotterdam [2], Venice [3], London [4], New Orleans [5], and St. Petersburg [6]. There are also several new dams and barriers in the world that are being designed or constructed, e.g. New York barriers.

In St. Petersburg, storm surges are caused by deep cyclones that cross the Baltic Sea along its center line from south-west to north-east. Such cyclone rises water level by its low-pressure center and initiates the propagation of a long progressive wave. The height of the wave increases as it travels through shallow and narrow water area of the Gulf of Finland. Additionally intensified by the wind, that wave leads to fast sea level rise in St. Petersburg. In 2011, Saint Petersburg Flood Prevention Facility Complex (the Barrier) [6] was introduced into services and became a reliable protection from inundations. The barrier consists of dams which are equipped with floodgates for ship passage and water exchange (Fig. 1). As storm surges are irregular and complex events, the Barrier is aided by

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simulation-based Flood Warning System (FWS) intended to support optimal decision making on floodgate operations [7, 8].

The FWS is based on a complex of various numerical models and data sources, which are combined to form an operational workflow [9]. The essential elements of the complex are hydrodynamic models parameterized with sea wave prognostic fields according to the wind-over-waves coupled (WOWC) approach [10]. Following that approach, sea surface roughness, induced by wind waves, can be taken into account to produce more precise water level forecast. Moreover, wind wave forecasts are necessary to estimate potential wave-impact loads on floodgates during maneuvering operations. It is considered that the safety of the flood barrier is assured if wind wave parameters (e.g. significant wave height, spectrum peak period, etc.) in its immediate vicinity fit into the predetermined limits. Thus, the functional purpose of wind wave simulations in surge flood forecasting and prevention tasks is to provide two types of forecasts:

- Large-scale forecasts that cover potential areas of storm surge initiation and propagation, and that are terms of forcing in hydrodynamic models;
- Fine-grained forecasts that cover the local area of flood protection constructions, and that are necessary to predict possible floodgates malfunctions due to heavy wave-impact loads.

Calculations of subsequent wind wave forecasts are initiated regularly upon receipt of corresponding meteorological forecasts, and must finish over a fixed, relatively short period.

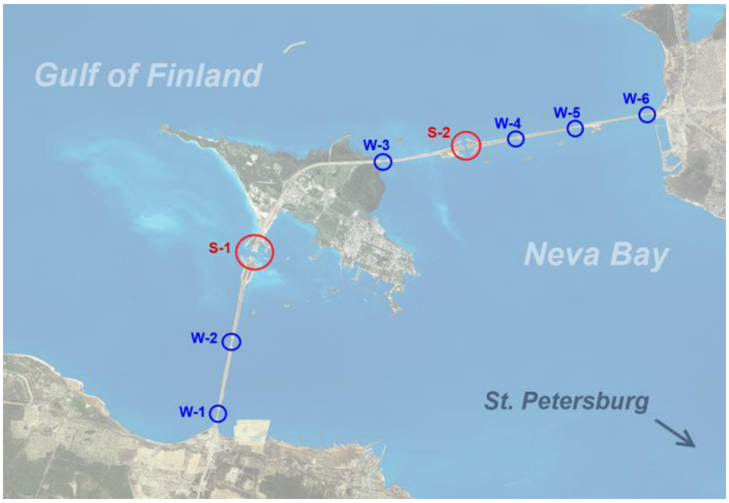

Figure 1: Saint Petersburg Flood Prevention Facility Complex scheme

In modern applied research studies, third-generation spectral wave models are a common choice for sea wave forecasting and hindcasting. The most widely used models are WAVEWATCH III [11] and SWAN [12]. The later is used in the current version of the FWS, as it contains additional formulations for shallow water.

SWAN is used in a wide range of applications: from spectral wave climate simulations [13] to freak wave occurrence probability studies [14]. The model is based on the wave action balance equation (1) with sources and sinks (e.g. in [15]).

$$\frac{dN}{dt} = S_{in} + S_d + S_b + S_{nl} \tag{1}$$

Here $S = \sum_i S_i$ is a source and sink function, which defines sea waves formation, propagation and dissipation. Principal members of this sum are wind energy transmission (S_{in}), wave energy dissipation (S_d), bottom interaction with waves (S_b) and nonlinear wave interactions (S_{nl}). Parameters for wind energy transmission, wave energy dissipation, bottom interaction with waves were used for model calibration (section 3).

2 Computational grids

Generation of a computational grid is a crucial step towards producing high-quality simulation results. In our work, we decided to start with the simplest, so structured rectilinear mesh in the geographical domain was our first choice. The combination of two rectangular grids, one nested into another, allows to obtain accurate forecasts over a satisfactory period. Still, there is room for improvements through the use of unstructured grids.

2.1 Rectangular grids

The main objective of SWAN simulations is to provide the hydrodynamic model with proper forcing. Thereby, it is necessary to forecast wind wave parameters in the whole Baltic Sea. We came up with a rectangular grid consisting of 46060 points: 188 points spaced by ~0.11° in zonal direction, and 245 points spaced by ~0.05° in meridional direction. The difference in zonal and meridional spacing is due to high latitudes, so the actual spacing between grid point is about 6 km in both directions. Taking into account that most of the grid points are located on the land, we are left with only 11632 of "wet" points, where calculations are actually performed. This grid is later referred to as coarse. As it is shown in Table 1, sea wave forecast based on the coarse grid has adequate accuracy to be used to estimate wave-impact loads during the floodgate operations. However, forecast refinement is still desirable as the bathymetry along the barrier sufficiently varies due to fairways, which may lead to significant differences in sea wave parameters.

Part of the operational workflow of the FWS is shown in figure 2. It is obvious that there is a time gap between coarse grid simulations and the decision-making stage, which is due to the necessity to produce sea level forecast. Thus, we can introduce an optional workflow step to refine wind wave forecast using nesting.

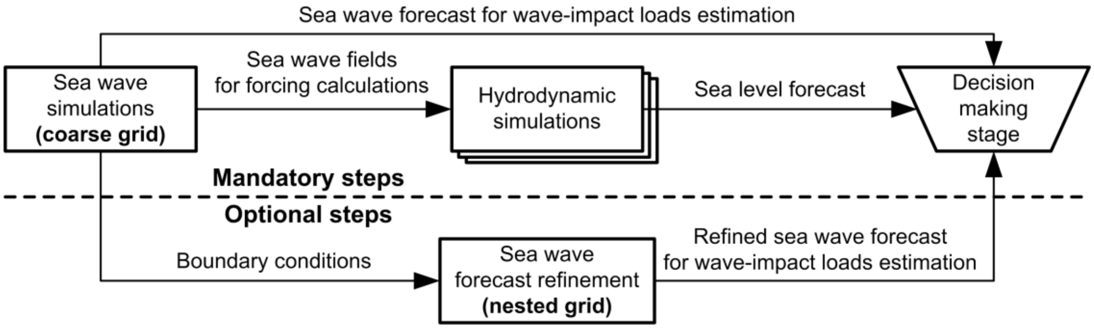

Figure 2: Part of the workflow for sea level forecasting

Considering the fact that floods in St. Petersburg are mainly caused by western winds, sea waves that propagate from the inner (eastern) water area of the barrier during the flood situation can be neglected. That is why sea wave forecast refinement is based on a grid that covers only the local water area of the barrier in order to decrease computational load. The nested grid consists of 14112 points (9362 of them are "wet"): 128 points in zonal direction, and 112 points in meridional direction. Grid cells are about several hundreds of meters in each direction (see figure 3).

Table 1 represents characteristics of significant wave height and spectrum peak period forecast errors. The presented results show that forecasts accuracy can be improved through the use of the nested grid in cases of storm waves (over 70 cm), which usually associated with surge floods. First of all, the use of the nested grid provides a reduction (about 40 %) of a systematic error (BIAS). MAE mostly represent a random error and its values change from weak positive to weak negative effect.

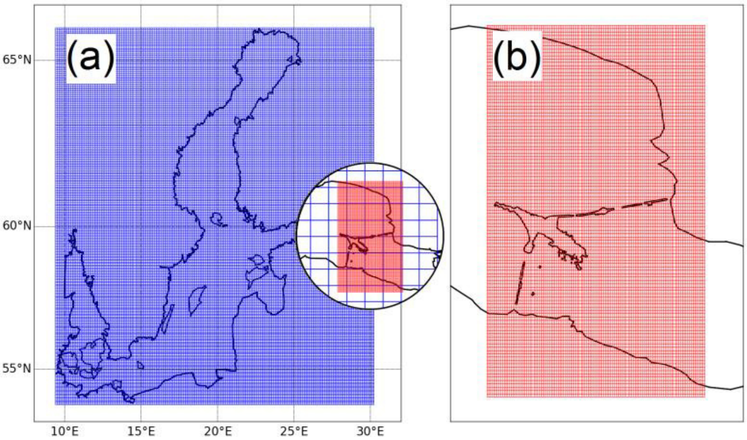

Figure 3: Rectangular meshes for simulations of wind waves in the Baltic Sea: (a) coarse grid; (b) nested grid

Minimum significant wave height, cm	S-1				S-2			
	Coarse grid forecast error		Nested grid forecast error		Coarse grid forecast error		Nested grid forecast error	
	BIAS	MAE	BIAS	MAE	BIAS	MAE	BIAS	MAE
Significant wave height, cm								
0.0	2.1	8.1	8.0	11.1	11	11.8	4.6	8.5
70.0	-4.4	16.1	1.8	14.5	-16.5	16.5	-6.1	18.5
Spectrum peak period, s								
0.0	-0.4	0.7	-0.8	1.0	0.7	1.0	0.4	0.8
70.0	-0.8	0.9	-1.0	1.1	2.5	3.0	-0.7	0.7

Table 1: Characteristics of wind wave forecast errors in the area of ship gates (S-1 and S-2)

2.2 Unstructured grid

There is an important issue that orthogonal structured grids are not sufficiently flexible to fit an arbitrary geometry [16]. However, unstructured grid can increase the accuracy of the simulation results in regions of the most interest, still decreasing the calculation time by reducing the density of points in remote areas (figure 4). In our case this means that we can satisfy both our goals through one calculation.

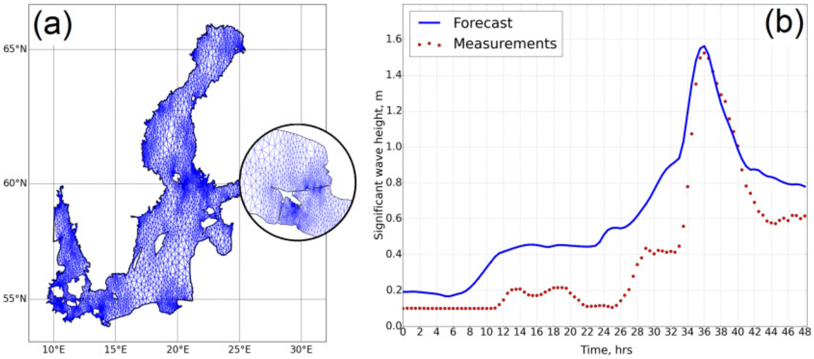

Figure 4: Results of numerical experiments associated with unstructured grid generation:
(a) an example of unstructured grid for simulations of wind waves in the Baltic Sea;
(b) significant wave height forecast in the area of ship gate S-1 obtained through the use of unstructured grid

Generation of a robust unstructured mesh is a significantly complex problem. Despite the fact that simulation results are satisfactory in most cases, we are yet unable to provide a reliable general solution. Regular numerical artifacts that occur through the use of unstructured grid prevent its introduction into the FWS.

3 Calibration

As every complex numerical model, SWAN has its omissions. One of the options to compensate them is to perform a parameter calibration. The problem is that SWAN has numerous of parameters, and it seems to be impossible, or at least redundant, to tune all of them. That is why it is necessary to distinguish those of them that influence wind waves forecasting results more. The impact of the following parameters was determined during this research study: wind factor, whitecapping dissipation factor and bottom friction coefficient (formula 1). Sensitivity analysis showed that the model results were weakly sensitive to whitecapping parameterization, so we left it with default values. Bottom friction usually has a significant impact on simulation results in nearshore regions. The level of influence depends on the strength of sea waves and shallowness of the water area. This parameterization type is usually important only for nearshore points. It should be tuned for a certain region considering a certain bathymetry. The most unstable parameter (its optimal value) is a wind factor due to the natural atmosphere dynamics. Moreover, an optimal value of wind factor varies with sources of meteorological forecasts (i.e. models that produce wind forecasts). As the FWS requires several alternative sources of atmospheric forecasts (for reasons of robustness), it leads to a necessity of a common procedure for the best parameter value identification.

Two main integral criteria (MAE- and RMS-criterion) were used to assess a quality improvement for each parameter variant. The first criterion is an integral root mean square (RMS) error of a forecast which minimizes a deviation of the error (2). The second criterion is an integral mean absolute error (MAE) of a forecast (3).

$$S_\Sigma = \sum_k \alpha_k \frac{\sum_{t=1}^{T} \beta_{k,t} (\sqrt{RMS^2})_t^{(k)}}{\sum_{t=1}^{T} \beta_{k,t}}, RMS_t = \sqrt{\frac{\sum_t (Er_t - \overline{Er})^2}{N-1}} \tag{2}$$

$$M_\Sigma = \sum_k \alpha_k \sum_{t=1}^{T} \beta_{k,t} (MAE)_t^{(k)}, MAE_t = \frac{\sum_t |F_t - M_t|}{N} \tag{3}$$

Here F is a forecasted wave height, M is an observed wave height, N is a size of sample and $Er_t = F_t - M_t$. $P = \{P_k\}_{k=1}^{n}$ is a set of points (used for quality assessment), is a total number of points, $T = \{T_t\}_{t=1}^{m}$ is a set of timestamps, α_k are weight coefficients that identify priority grades for points, and $\beta_{k,t}$ are weight factors that identify measure of trust for input data set.

Hereafter, we represent the results of wind friction coefficient calibration calculated for autumn of 2013. Integral criteria MAE and RMS with confidence intervals are shown in figure 4. Additional characteristics wMAE and wRMS represent MAE and RMS criteria for wave heights that exceed a certain threshold. In our research we set two thresholds for wave height: 40 and 70 cm.

Figure 4 shows that only MAE and RMS estimations have narrow confidence intervals (that do not cover error value for a default wind friction parameter). Therefore, results of quality assessment using MAE and RMS criteria could be considered statistically significant. MAE and RMS criteria have different optimal values. The minimum of bivariate function $f(MAE, RMS)$ could be found using a diagram from a figure 5. The figure 6 shows that the value of optimal wind factor is between values 0.8 and 0.9.

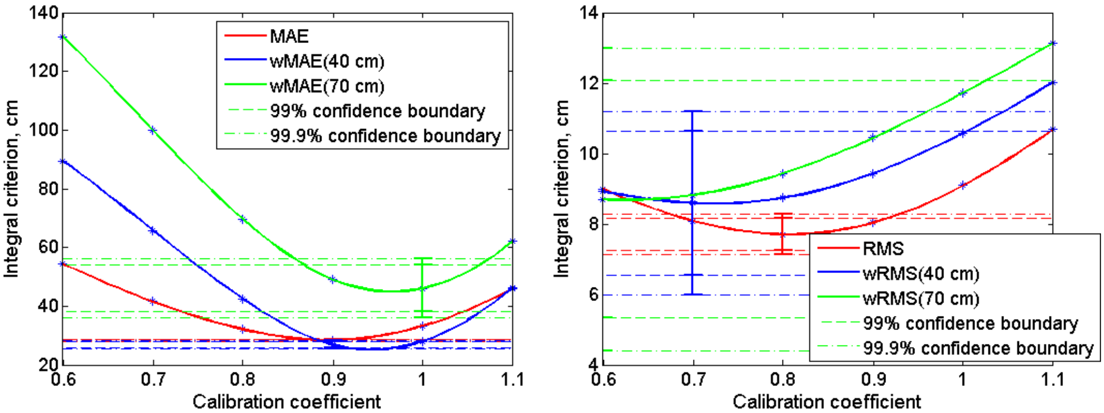

Figure 4: Integral criteria RMS and MAE assessment with confidence interval bounds

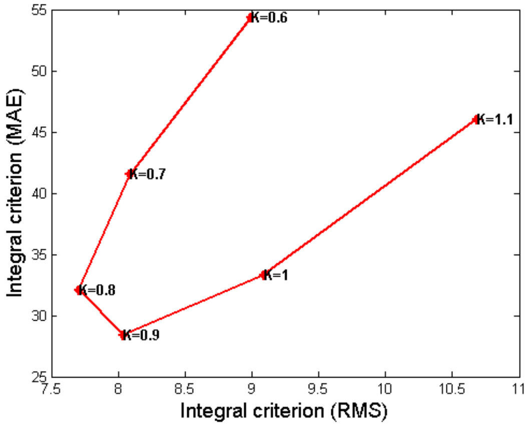

Figure 5: Bivariate function diagram

4 Minor aspects

Most of the floods in St. Petersburg occur in winter [6] when ice covers a significant part of the Gulf of Finland. Ice fraction forecasts are taken into account by hydrodynamic models of the FWS. In the meanwhile, ice also has a substantial impact on sea wave propagation, so we attempted to find out if it was necessary to account for ice in wind wave simulations. Unfortunately, SWAN does not support explicit ice treatment, so we had to apply a workaround. Ice fraction forecasts were used to eliminate grid points associated with concentration that exceeded a certain cut-off. Resulting sea wave fields were then used to parameterize a hydrodynamic model. Our experiments showed that it was reasonable to take ice fraction into account in wind wave simulations in cases when it was not accounted for in hydrodynamic simulations as this allowed to decrease sea level overvaluation. Otherwise, ice treatment in sea wave simulations could be omitted. Hence, current version of the FWS is configured to account for ice only by hydrodynamic models.

Wind wave parameters are tightly interconnected with depth of an ambient sea region. Bottom friction causes wave transformation (first of all, wave height reduction) in shallow water regions. Sea level changes significantly during a storm surge, and it may increase wave forecast errors. To avoid this effect, sea level rise (according to previous sea level forecast) is taken into account in wave simulation on the nested grid. It should be noted that we do not have to account for sea level variations in simulations on the coarse grid because of the comparatively deep depth of open parts of the Baltic Sea. Our research showed that accounting for the variability of sea level could provide changes in wave simulation results up to 60% (in the shallowest regions near the Barrier). But this difference is almost neglectable near the ship gates (S-1 and S-2) due to the significant depth of the fairways.

5 Conclusions

The key aspect of simulations for surge flood prevention is to provide accurate forecasts in cases of significant sea level rise. This means that it is more important to represent corresponding characteristics in ranges that are specific to flood situations, which sometimes have to be done at the expense of quality in general case. In this paper we highlighted an importance of calculation grid generation to obtain a sufficient quality of wind wave simulation results. Also we suggested a solution for SWAN model calibration task with emphasis on storm wave characteristics. Additional aspects (the variability of sea level and ice treatment) that could not provide a significant improvement of wave forecast accuracy were discussed.

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