Assessment of Extreme Surge Simulation Accuracy in the Sea of Azov for Various Types of Atmospheric Forcing and Ocean Model Parameters

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Abstract: This paper focuses on numerical modelling of an extreme surge in the Taganrog Gulf on March 24, 2013 to study its formation features and identify the requirements for an accurate reproduction of atmospheric and marine circulation in the Sea of Azov. Two versions of the three-dimensional σ-model of marine circulation INMOM (Institute of Numerical Mathematics Ocean Model) with different spatial resolutions of ~4 km and ~250 m were originally used. Additionally, two types of atmospheric forcing were used during the simulations of these models: Era-Interim reanalysis and WRF (Weather Research and Forecast Model) model data. The paper shows that, according to the obtained results, the accuracy of an extreme surge reproduction in the Sea of Azov was more dependent on the quality of atmospheric forcing than on the spatial resolution of the marine circulation model. Additional simulations were performed with three different configurations within the INMOM version with a spatial resolution of ~250 m and with the use of the WRF atmospheric forcing. Configurations varied in types of the model: baroclinic, barotropic and shallow water approximation. However, simulation results of the models with different configurations were practically identical to each other.

1 INTRODUCTION

The Sea of Azov with its coastal cities, intensive navigation, developed fishing and recreational potential has great economic importance. Therefore, forecasting of extreme storms in it is especially valuable. It should be noted that the strongest impact of the storm on economic activities is connected to the sea level fluctuations in the Sea of Azov due to surges. Nowadays, numerical modelling is a widely applied approach for their simulation. Although it has reached high level of accuracy for the Sea of Azov (Popov and Lobov, 2016; Filippov, 2012), further attempts to improve the accuracy of simulation results should still be made. Numerical modeling results depend on various factors, especially on the use of atmospheric forcing and a configuration of the marine hydrodynamics model with its physical parametrizations and spatial resolution. This article examines these factors and their influence on the simulation results with numerical modelling of an extreme surge that occurred on March 24, 2013. According to the data from a series of observations for 1881-2013, this surge is the second strongest after the historical surge of 1997. Observational data for the surge of 2013 is available and can be used for the appropriate setting up and verification of models. In the present study, several versions of the three-dimensional σ-model of marine circulation INMOM (Institute of Numerical Mathematics Ocean Model) with different spatial resolution and various types of model configurations are used as models of sea

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dynamics. During simulations of these models two types of atmospheric forcing are used.

2 METHODOLOGY

Three-dimensional σ-coordinate model of marine circulation INMOM is used to calculate the circulation in the Sea of Azov. It was developed at the INM RAS (Institute of Numerical Mathematics of the Russian Academy of Sciences) (Diansky, 2013). The model is based on so called system of primitive equations in approximations of hydrostatics and Boussinesq expressed in the generalized orthogonal coordinates in horizontal direction and in σ-system of coordinates in vertical direction. Such system with an additional applied linearization is of the following form:

$$D_t u-(l+\xi)vH=-\frac{H}{r_x}\left(\frac{1}{\rho_0}P_x+\frac{1}{\rho_0}\frac{\partial p_a}{\partial x}-g\frac{\partial \zeta}{\partial x}\right)+\frac{\partial}{\partial\sigma}\frac{v}{H}\frac{\partial u}{\partial\sigma}+Fu \tag{1}$$

$$D_t v+(l+\xi)uH=-\frac{H}{r_y}\left(\frac{1}{\rho_0}P_y+\frac{1}{\rho_0}\frac{\partial p_a}{\partial y}-g\frac{\partial \zeta}{\partial y}\right)+\frac{\partial}{\partial\sigma}\frac{v}{H}\frac{\partial v}{\partial\sigma}+Fv \tag{2}$$

$$div_h\boldsymbol{u}+\frac{1}{H}\frac{\partial\omega}{\partial\sigma}=\frac{1}{H}\frac{\partial\zeta}{\partial t} \tag{3}$$

$$\widetilde{D}_t\theta=\frac{\partial}{\partial\sigma}\frac{v_\theta}{H}\frac{\partial\theta}{\partial\sigma}+D\theta+\frac{\partial R}{\partial\sigma} \tag{4}$$

$$\widetilde{D}_t S=\frac{\partial}{\partial\sigma}\frac{v_S}{H}\frac{\partial S}{\partial\sigma}+DS \tag{5}$$

$$\rho=\hat{\rho}(\theta,S+35‰,p_w)-\hat{\rho}(0,0,\rho_0 g\sigma H) \tag{6}$$

Here H – depth of the ocean being at rest; r_x and r_y – metrical coefficients, $\boldsymbol{u}=(u,v)$ – horizontal velocity vector, u and v – zonal and meridional components of the current velocity; ω – vertical velocity in the σ – system of coordinates; ζ – deviation of the ocean level from its undisturbed state; θ – potential temperature; R – penetrating solar radiation flow; S – salinity net of the constant value of 35‰; ρ – deviation of the water density from a certain average density profile which depends only on the hydrostatic pressure $\rho_0 gz$ with the average density in the ocean $\rho_0=1.025g/cm^3$ at the depth $z=\sigma H$. Non-linear state equation $\hat{\rho}(\theta,S+35‰,p_w)$ for the water density computation, considering compressibility due to the hydrostatic pressure p_w, is taken from (Brydon, 1999). Coriolis parameter is $l=2\widetilde{\Omega}sin\phi$, where $\widetilde{\Omega}$ – angular rate of the Earth rotation considering the annual rotation around the Sun, and ϕ – geographical latitude; ξ – summand which describes the additional pulse transfer in curvilinear coordinates;p_a - atmospheric pressure on the ocean surface; $v.v_\theta,v_S$ – coefficients of vertical turbulent viscosity and diffusion; P_x and P_y– components of the horizontal pressure gradient; D_t, $\widetilde{D}_t$ – operators of transfer; D – operator of lateral diffusion of heat and salt which is chosen to be equal for θ and S.

Various versions of this model were successfully used in numerical simulations of the World Ocean circulation (Gusev and Diansky, 2014; Diansky, 2013), as well as for the circulation in the western seas of the Russian Arctic (Diansky et al., 2014, Diansky et al., 2015), the Black, Caspian, Japanese and Baltic Seas (Diansky et al., 2012; Zakharchuk et al., 2016; Stepanov et al., 2014; Zalesny et al., 2012). The global version of INMOM serves as an oceanic block of the Earth system model created at INM RAS, participating in international programs for research and prediction of climate change (Volodin et al., 2013).

This paper used two versions of the INMOM model for reproducing the Sea of Azov circulation: the BAMS model, which includes basins of the Black, Azov and Marmara Seas with a horizontal resolution of ~ 4 km, and the AS model, which includes the Sea of Azov basin with the Kerch Strait and the adjacent waters of the Black Sea (up to about 100 m) with a horizontal resolution of ~250 m. Fomin and Diansky (2018) provide a detailed description of BAMS and AS models' configurations and physical parametrizations.

3 RESULTS AND DISCUSSION

3.1 Analysis of the Impact of the Atmospheric Forcing and the Spatial Resolution of the INMOM Model on the Sea of Azov Circulation

The quality of atmospheric forcing is one of the key factors affecting the accuracy of marine dynamics' calculation. Therefore, two different types of an atmospheric forcing were used to calculate the atmospheric impact: one was from the Era-Interim global atmospheric reanalysis with spatial resolution of 80 km and the other one was from the regional atmospheric model WRF with spatial resolution of 10 km, calculated at the Zubov State Oceanographic Institute.

Module and components of wind speed with a resolution of 6 hours from the coastal weather stations in Taganrog and Kerch were used to validate obtained results of calculations using the WRF model and the Era-Interim reanalysis. Detailed results of this verification were discussed in the work of Fomin and Diansky (2018). Verification results of meteorological characteristics showed that, in comparison with the Era-Interim reanalysis, the data in the WRF model reproduced meteorological characteristics over the Sea of Azov Sea more accurately, especially during storms.

We used both versions of the INMOM model, BAMS and AS models, for the simulation of the 2013 surge in the Taganrog Gulf with meteorological parameters from the Era-Interium reanalysis, as well as the WRF model. Experiments were carried out for the period from January 1 till March 31, 2013. We used January climatic fields of temperature and salinity, and zero current velocity fields as initial conditions. Moreover, it was assumed that there was no ice field in the Sea of Azov.

The AS model with a spatial resolution of 250 m was applied for simulation of the Sea of Azov dynamics using Era-Interium reanalysis, as well as WRF atmospheric characteristics. We only used the WRF data in the numerical experiments with the BAMS model with a spatial resolution of 4 km. We used sea level observations at the Taganrog station in order to estimate the accuracy of simulated sea level, especially during the storm situations, using AS and BAMS models.

At first, we analysed the results from the AS model, as an a priori more accurate model because of its higher spatial resolution, and assessed the impact of the atmospheric forcing type on the reproduction of the storm surge in the Sea of Azov. Hereinafter, the analysis was carried out for the sea level deviation from the average value. The average value was calculated for the period of 01.02 - 03.31.2013.

Figure 1 shows verification results of the modelled sea level using the AS model with atmospheric characteristics from the Era-Interim reanalysis and from the WRF model, as well as the observation data from the Taganrog station. According to the calculation results, sea level during the extreme surge on 24.03.2013 was more accurately reproduced with the WRF model data. The maximum value of the sea level using WRF forcing for the Taganrog station was 194.7 cm. At the same time, the maximum sea level according to the observations reached 223.4 cm. The correlation coefficient reached 0.92 for the WRF data, and equaled 0.88 for the data from the Era-Interim reanalysis. However, the standard deviation of the sea level was smaller for the WRF data than for the Era-Interim data: 19.8 cm and 21.3 cm, respectively.

Thus, calculations using WRF forcing made it possible to improve the storm surge simulation and the quality of the sea level variability.

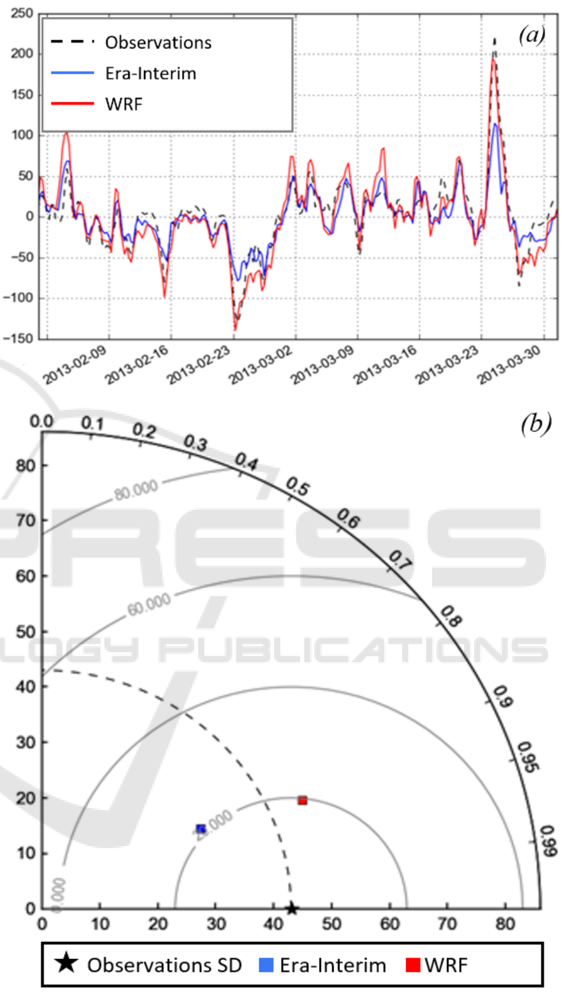

Figure 1: a) Comparison between the sea level observations from the Taganrog station (black line) and the sea level simulated by the AS model using Era-Interium reanalysis (blue line) and the WRF data (red line); b) the Taylor diagram for the experiments. Black star corresponds to the standard deviation for measurement data; blue square – Era-Interium reanalysis; red square – WRF model.

Therefore, WRF forcing was more suitable for the simulation of the storm surge in 2013. For this reason, the research of the horizontal resolution of two versions of the INMOM model (AS and BAMS models) was carried out using meteorological parameters from the WRF model. Results of the verification of the simulated data with observation data showed that the AS model with horizontal resolution of 250 m reproduced sea level slightly better (Figure 2).

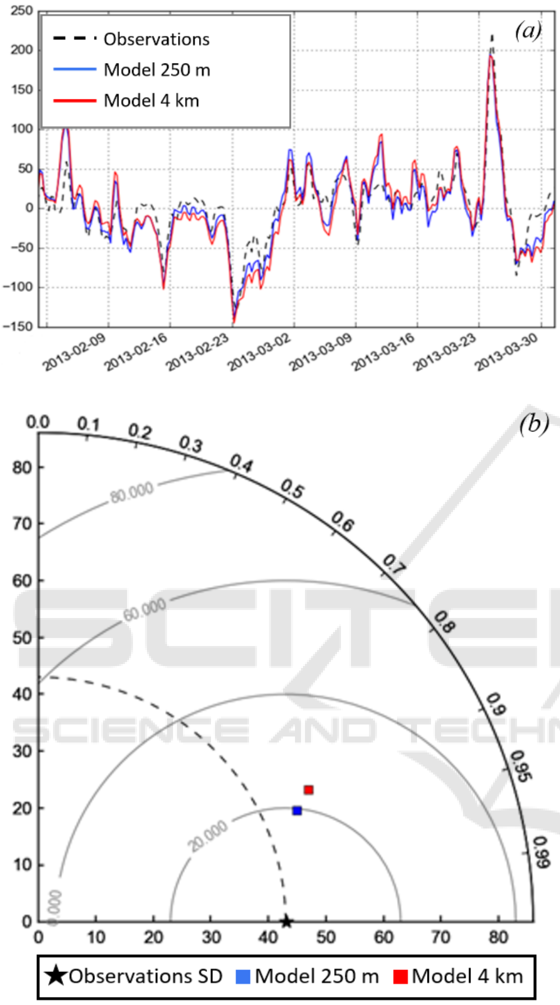

Figure 2: a) Comparison between the sea level observations from the Taganrog station (black line) and sea level simulated by the AS model (blue line) and by the BAMS model (red line); b) the Taylor diagram for the considered experiments. Black star corresponds to the standard deviation for measurement data; blue square –for the AS model; red square – for the BAMS model.

3.2 Effects of the INMOM Configuration on the Azov Sea Circulation

One more experiment was conducted in order to estimate the influence of the INMOM model configuration on the quality of simulated hydrodynamical parameters.

We conducted a comparative analysis of the sea level calculated for the period from February 1 until March 31, 2013, using three methods of numerical modelling: three-dimensional baroclinic version of the INMOM model, three-dimensional barotropic version of the INMOM model and shallow water model implemented in the INMOM. In the barotropic model prognostic variables included current velocity and sea level. It was also assumed that the density gradients did not vary.

Figure 3 shows the results of the sea level calculations using three versions of the INMOM model with a spatial resolution of 250 m. Meteorological characteristics were taken from the WRF model. According to the Figure 3, the results of calculations were almost identical. All models realistically described main trends in the sea level variability. In general, the three model versions adequately reproduced the sea levels. Although the storm surge on the March 24, 2013 in the Taganrog Bay was underestimated by all of them, the shallow water model performed worse than other models.

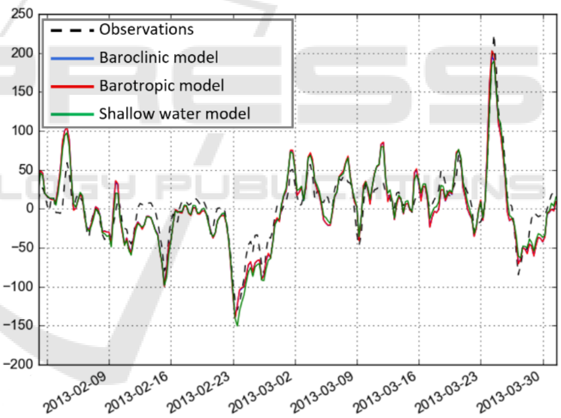

Figure 3: Sea level calculated using baroclinic INMOM model (blue line), barotropic INMOM model (red line) and shallow water model (green lone) from 01.02.2013 till 31.03.2013 in the Taganrog Bay of the Sea of Azov.

The experiments' results showed that the non-hydrostatic WRF model calculations of the atmospheric forcing allowed reproducing extreme storm situations with higher accuracy than the Era-Interim reanalysis. A comparison of the results with observational data demonstrated that both the meteorological characteristics, including wind speed and direction, and the sea level variability were reproduced well. Therefore, the proposed approach can be used in the future to predict and prevent emergencies in the studied area of the Sea of Azov.

4 CONCLUSIONS

We examined the basic features of an extreme surge in the Taganrog Gulf on March 24, 2013 using two versions of the INMOM model with different spatial resolutions of ~4 km and ~250 m. Two types of meteorological parameters were used to study the impact of the atmospheric forcing on the Sea of Azov dynamics: Era-Interim reanalysis with horizontal resolution of 80 km and WRF model data with horizontal resolution of 10 km.

We demonstrated that the simulation based on the WRF atmospheric forcing with a higher spatial resolution reproduced the extreme surge with higher accuracy than the simulation based on the Era-Interim reanalysis. At the same time, the results of the sea level simulation during the non-extreme period did not depend much on the type of atmospheric forcing.

For the area of the Taganrog Gulf, increased spatial resolution of the marine circulation model slightly improved the quality of the extreme surge reproduction, particularly in the coastal areas. However, this improvement of the model amounted to no more than 3-5%. Therefore, the formation of the surge was mainly determined by the response of the circulation in the entire Sea of Azov basin to the atmospheric forcing.

Additionally, we carried out the experiments with various configurations of the INMOM model to study the effect of baroclinicity on the storm surge reproduction in 2013. Three versions of the INMOM model with spatial resolution of 250 m were used for these experiments: the baroclinic model, the barotropic model and shallow water model. As expected, for such a shallow basin as the Sea of Azov, the baroclinic factor had a negligible impact on the storm surges reproduction. Thus, simplified models would be suitable for calculating surge levels only. However, if the task was to reproduce the full hydrodynamics of the Sea of Azov, including sea ice, then it was necessary to use complex models of the sea circulation with high quality atmospheric forcing.

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