WAVEWATCH III – WRF high-resolution wind wave hindcast in the North Atlantic: wave model configuration and preliminary results for 1979-2000.

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Abstract. In this study, we present the configuration and validation of the third generation spectral wave model WAVEWATCH III with ST6 physics adjusted for high-resolution wind wave hindcast in the North Atlantic based on 14-km winds from non-hydrostatic numerical weather prediction system WRF-ARW (Weather Research and Forecasting). The adjustment of the wave model consists in obtaining the drag coefficient scaling required for WRF winds based on the sensitivity tests and validated against satellite altimetry data. The wave model validation includes analysis of wind sea and swell components compared to directional wave spectra from NDBC buoy data for 2010. The preliminary results of high-resolution WAVEWATCH-WRF hindcast (1979-2017) are discussed with the focus on mean and extreme values of wind sea and swell in winter season (JFM) in 1979-2000. The mean values of wind sea amount up to 5.5 m with the areas of the largest values and mean wave direction reflecting the corresponding characteristics of the wind. Swell heights amount up to 3.2 m with the area of the largest values being displaced westward relative to the wind sea characteristics.

1. Introduction.
Wind waves play an important role as a component of the climate system and constitute one of the leading processes of sea-air interaction affecting momentum, energy, heat, and mass exchange [1]. Wind waves in the ocean reflect the state of the atmosphere and can integrate and transfer this signal to long distances [2].

Numerical wave modeling with implemented recent findings in wave physics provides a reliable framework for studying wave climate with high resolution over the large spatial and temporal scales. The results of wave modeling are crucially dependent on the quality of atmospheric forcing [3]. Wind stress in wave models is parameterized accounting for 10-m wind speed $U_{10}$ via friction velocity $u_*$ and drag coefficient $C_D$. Atmospheric reanalyses widely used as wave model forcing require the certain adjustment of the model configuration [4] due to the different spatial resolution resulting in the change of the spatial structure of surface winds as well as differing mean and extreme values. It has been found that high-resolution forcing from the mesoscale atmospheric model with boundary conditions from long-term reanalysis with stable configuration allows for improving the accuracy of wave simulations as well as better representation of the extremes [5]. In this study, we discuss the configuration of the spectral wave model WAVEWATCH III (with ST6 physics package) reliable for high-resolution wind wave hindcast forced by 14-km wind from WRF-ARW atmospheric model in the North Atlantic.

In the open ocean, two classes of wind waves usually coexist: wind sea, conventionally defined as young waves under the growth or equilibrium with the local wind, and swell, generated in a distance and hence is considered not to be affected by the local meteorological conditions [6]. Numerical wave modeling allows to investigate the variability of wind sea and swell separately, which is important since the different mechanisms are contributing to these processes and hence these characteristics can demonstrate differing climate trends [7]. Several studies discuss that widely used integral
characteristic of the spectrum – significant wave height – conceals a lot of information about the sea state and consideration of the full directional wave spectra is particularly important for the open ocean [8].

In this study, we present the configuration and validation of WAVEWATCH III model with ST6 physics package for high-resolution wind wave hindcast in the North Atlantic and discuss the preliminary results of the hindcast for 1979-2000 analysing mean wave characteristics with the focus on wind sea and swell components over the winter season (JFM). The manuscript is organized as follows. Section 2 describes configuration of the wave model and algorithm used for the separate validation of wave components (wind sea and swell) against directional spectra from observational data. Section 3 presents the results of the sensitivity tests and demonstrates the reliable model performance using high-resolution winds. In conclusion, we discuss mean values of the main wave components over the period 1979-2000 based on WAVEWATCH-WRF hindcast. Section 4 summarizes the obtained results and provides a brief discussion.

2. Methods.

We used the third generation spectral wave model WAVEWATCH III (hereafter referred to as WW3) forced by the 14-km output from version 3.8.1 of Weather Research and Forecasting model with the Advanced Research core (WRF-ARW, hereafter referred as to WRF) [9]. WRF configuration used for performing a high-resolution dynamical downscaling of ERA-Interim reanalysis is described in detail in [5]. WW3 simulations were performed over the North Atlantic with the horizontal resolution 0.2° covering the area from 20° to 80°N and 95° to 15°E (nested into 1° domain expanding up to the equator to account for swell generated in the tropics). The spectral resolution is 36 directions and 25 frequencies spanning from 0.04 Hz, model output has 1-hour discretization. In WW3 simulations, we used the ST6 scheme [10] for wave energy input and dissipation. The DIA [11] scheme is implemented for non-linear wave interactions and IC0 is used for wave-ice interactions.

2.1. Wind sea and swell separation. In spectral wave models, the raw output in each point of the computational grid is presented by the directional wave spectrum (the snapshot for 18:00 UTC 05-Feb-2010 is shown in Figure 1a) and all further wave characteristics are obtained from these spectra. Since buoys provide the most reliable in-situ measurements of directional wave spectra, in this study we used NDBC buoy data for model verification, analysing temporal evolution of spectral peaks from directional spectra in buoy locations.

Since directional wave spectra in the most cases have more than one peak (Figure 1), in order to find corresponding peaks in the model output and observational data and compare wind waves and swell components we used the combination of two methods. The first step is partitioning of wave spectra into separate areas based on watershed algorithm [12]. On the second step in order to obtain and analyze corresponding peaks from buoy data and wave model output, we use the algorithm described in [13]. The characteristics of spectral peaks and directions difference (D) allows for an accurate account for peaks from buoy and model and is obtained using the following expression:

$$D(f_m, \theta_m) = \frac{1}{f_w} \left[ (f_m \cos \theta_m - f_b \cos \theta_b)^2 + (f_m \sin \theta_m - f_b \sin \theta_b)^2 \right]^{\frac{1}{2}}$$

where $f$ is peak frequency and $\theta$ is wave directions from buoy (b) and model (m) respectively. The threshold of $D = 0.3$ [13] is used for the spectral peaks from buoy data and model output to be considered as the same wave systems.

The analysis presented in this study corresponds to winter season (JFM) since this period is characterised by the largest waves in the North Atlantic. The verification of the simulated wave heights has been conducted for 2010 since the final high-resolution hindcast, which is currently being developed, will cover the period from 1979 to present time.
3. Results.

3.1. WW3 (ST6) adaptation for high-resolution forcing from WRF. ST6 source term in WW3 model is developed upon the field observations with parameterization of wind input based on [14] and demonstrates a good agreement with observational data [15]. This physics package accounts for the dependence of the growth on the wave steepness, airflow separation, negative growth rate under the strong weather conditions and also feature a cumulative turbulent dissipation term which is crucial for wind sea and swell dissipation. The adjustment of ST6 for the various sources of atmospheric forcing is achieved by the scaling of the drag coefficient factor (CDFAC). In this study as a result of a suite of sensitivity tests, we obtained a value of CDFAC = 1.15 which is 15% higher than the recommended value for CFSR reanalysis. Validation of significant wave height from the model output against the observational data has been conducted for Cryosat, Envisat, Jason-1 and Jason-2 corrected satellite data [16] for all seasons of 2010. The model data was co-located with the altimeter data using bi-linear interpolation in the way described in [15,17]. We used normalized bias (NBIAS) to assess model estimates versus altimeter measurements:

\[
NBIAS = \frac{(\bar{y} - \bar{x})}{\sqrt{1/\sum_{i=1}^{n} x_i^2}}
\]

where \(y\) is model data, \(x\) is the altimeter data, the overbar denoting the averaging operator and \(n\) is the number of data points.

Figure 2 represents normalized wave height bias before (a) and after the correction (b) for 14-km WRF winds for Jason-2. The wave model performance has improved the normalized bias from -30% to -7% on average by applying this procedure. The additional increase of drag coefficient scaling (not shown here) has not led to the further improvement of the correspondence to observational data thus it has been decided to use this value in the further model simulations.
3.2. Validation of wind sea and swell from WW3-WRF hindcast. The results of WW3 validation for the wind sea and swell components are presented in Figure 3, each dot represents the comparison between time series from NDBC buoys № 41010, 41004, 44065, 44013, 44025, 44005 and WW3-WRF output in JFM 2010 in the locations shown in Figure 2b. Both wave components demonstrate a good agreement with buoy data with correlation coefficients being on average 0.9 for wind sea and 0.85 for swell. Wind sea is represented better than swell heights which can be possibly explained by their higher values in the buoy location area. The verification of model results against satellites and buoys data presented in this study are in line with the values obtained for the North Atlantic in various numerical experiments [15,17,18].
3.3. Wind wave climate from WW3-WRF hindcast. Mean significant wave heights from high-resolution WW3-WRF simulation for winter seasons (JFM) in 1979-2000 are shown in Figure 4c. The maximum values are located to the south of Iceland and amount up to 4.5 m. Peak phase speed demonstrates eastward direction in the mid-latitudes and turning to the north-east in subpolar latitudes and southward in subtropics. The spatial distribution of significant wave height, in general, reflects the distribution of wind speed (Figure 4f) with the largest mean values amounts up to 8 m/s and located in the eastern mid-latitudes. Wind direction is predominantly northeastward in mid-latitudes and changes to the westward in the subtropics.

![Figure 4](image_url)

**Figure 4.** Mean climate wind sea (a), swell (b), significant wave height (c), wind speed (f) and 90th percentile of wind sea (d) and swell (e) height in JFM 1979-2000.

Mean wind sea and swell height for 1979-2000 (JFM) are presented in Figure 4d and e respectively. The largest values of mean wind sea reach up to 5.5 m and its direction reflects wind direction (Figure 4f) since this component is highly influenced by the local atmospheric conditions. Mean total swell height from model output consists of the sum of up to five swell components where each of them has a different direction and propagate radiantly from the source of generation. The largest values amount up to 3.2 m and their locations are displaced to the west relative to significant wave height and wind sea.

The height of the 90th percentile for wind sea (Figure 4d) amounts up to 8 m in the eastern mid-latitudes and has an additional area with the largest values along the eastern Greenland coast. Interestingly, the direction of extreme wind sea in mid-latitudes (Figure 4d) has more distinctive eastward direction than mean values (Figure 4a), which reflects the role of the westerly winds in the formation of extreme waves and is an interesting avenue for the further investigation. The height of the 90th percentile for swell reaches up to 5.2 m in the central mid-latitudes and has a second area with the largest values in the North Sea.

The spatial distribution of the simulated wave components is consistent with existing wave climate studies for this region [19, 20] while the values themselves can moderately vary due to the different models used and periods analyzed.

4. Conclusions. This paper presents the framework for high-resolution WAVEWATCH-WRF hindcast in the North Atlantic (1979-2017) and analysis of the mean wave components in the winter season in 1979-2000. We discuss the adjustment of the observational-based source term ST6 in WW3 model for WRF winds, which significantly improved the performance of simulated significant wave heights from -30% to -7% in average normalized bias in comparison to Jason-2 altimetry data. The results of wave modeling have been validated for wind sea and swell components and demonstrated a good agreement with NDBC buoys for the winter season of 2010. The analysis of wind wave
components for 1979-2000 reveals that mean wind sea reaches values up to 5.5 m to the south from Iceland with the height of the 90- percentile being up to 8 m with the second area of largest values along the Greenland eastern coast. Mean wave direction for wind sea reflects the spatial distribution of wind direction changing from north-eastward for mean values to eastward for extreme waves. The largest values of swell are displaced westward relative to wind sea and amount up to 3.2 m for mean and 5.2 m for extreme values and largest values are displaced westward.

Acknowledgements. This research was supported by the Russian Ministry of Education and Science (Agreement 14.616.21.0075, Project ID RFMEFI61617X0075). Authors thank Qingxiang Liu and Alexander Babanin for the useful discussion on methods used in this study and Ian Young from University of Melbourne for providing the corrected altimeter data. The latest configuration of WAVEWATCH III model is available by courtesy of NOAA.

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