Changes of sea waves characteristics in the Arctic basin from model ensemble simulations for the 21st century

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Abstract. A significant reduction of the Arctic sea ice extent enhances the sea waves activity in the Arctic Ocean. In this paper we analyze characteristics of wind waves activity in the Arctic basin using the WAVEWATCH III model simulations forced by wind and sea ice fields derived from the CMIP5 global climate models under different scenarios. A relative contribution of wind seas and swells to the total sea waves activity in the Arctic basin from model simulations is assessed and compared to that based on reanalysis data and satellite observations. Possible changes of sea waves characteristics from model simulations for the 21st century with anthropogenic scenarios are estimated. Regional estimates of various states of sea waves (such as wind seas, swells and their interaction, chop-like events) are performed, in particular for the Atlantic sector of the Arctic basin.

1. Introduction
A significant reduction of the Arctic sea ice extent has been observed over recent decades [1]. It has a great importance for the development of Arctic marine transportation [2-4]. On the other hand, ice retreating should increase risks due to the increase in sea waves activity in the Arctic Ocean [5-10]. It is important to analyze a regional wind wave activity in the Arctic basin as well as a relative contribution from wind seas and swells [11]. Swell waves are generated remotely and can travel for a quite long distances resulting in their significant contribution to the total sea waves activity in the Arctic basin. This study focuses on the analysis of wind waves conditions in the Arctic basin based on model simulations for the 21st century with anthropogenic scenarios.

2. Data and methods used
Characteristics of wind waves in the Arctic basin were analyzed using a two-dimensional spectral numerical model of third-generation wind waves WAVEWATCH III version 5.16 [12]. Numerical simulations were performed for the area north of 50°N at a spatial resolution of 1° in longitude and 0.5° in latitude. The simulated fields of sea ice concentration and surface wind derived from simulations with the CMIP5 global climate models ensemble were used to force the WAVEWATCH III model. Both historical (1990-2005) and anthropogenic (RCP4.5 and RCP8.5 for the period 2006-2100) scenarios have been used (see [4,13,14]).

More detailed analysis was performed with those models showing the most relevant correspondence to observed mean climatological conditions (ice concentration and wave heights) and to their changes during last decades. The analyzed sea waves characteristics are significant wave height, significant wave height of swell, chop occurrence, and wave energy. Different reanalysis data (including ERA-Interim [15] and NCEP/NCAR CFSR [16]) and data based on satellite observations [17] have also been used.
3. Results

In [11] the preliminary results were presented for sea ice edge (with sea-ice concentration ≥ 25%) in the Arctic basin from different model simulations for the period 2006-2016 and its change relative to the period 1990-2005 in comparison with satellite data. Model simulations with the historical scenario for the period 1990-2005 were complemented by simulations with the RCP4.5 scenario for the period 2006-2016. Some of 11 analyzed model simulations, in particular with model versions ACCESS1-3 and inmcm4, show quite reasonable agreement with satellite data both in regional sea ice edge location and its change during last decades.

Similar comparison was done for mean significant wave heights in the Arctic basin in September simulated by WAVEWATCH III with climate forcings (sea-ice concentration and surface wind) derived from CMIP5 global climate models and CFSR and ERA-Interim reanalysis data and satellite observations for the period 1990-2005. It should be noted that some differences in comparison with results from satellite observations are related with inherent uncertainties in satellite data products. In particular, the collocation technique used in this study (taking into account the time and location of satellite measurements) reveals very good agreement of regional features for the mean significant heights of sea waves based on reanalysis and satellite data. The best agreement with the mean significant wave heights in the Arctic basin in September from satellite observations and reanalysis data was obtained for simulations with models ACCESS1-3 and inmcm4, in particular.

In this study we select only those models that show the best agreement with the modern sea ice concentration and wave height fields and also with their changes according to observations and reanalysis data.

Figure 1 presents mean changes in total significant height of sea waves, significant wave height of swell and chop occurrence to the end of the 21st century (2091-2100) under the RCP8.5 scenario relative to the period 1990-2005 as simulated by WAVEWATCH III with climate forcings (sea-ice concentration and surface wind) derived from simulations with the different global climate models. Similar estimates were obtained for changes in separate month, particularly in September.

Our results based on simulations with global climate models under historical and RCP scenarios confirm previous results based on simulations with regional model HIRHAM under SRES scenario [7-9]. Significant wave height and its extremes increase over different inner Arctic basin areas due to reduction of sea ice cover in the 21st century. The opposite tendency with a slight reduction in wave height appears for the Atlantic sector of the Arctic basin.

Results of model simulations demonstrate the complex wave response in the Arctic Ocean to a combined effect of wind and sea ice forcings in a climate-change scenario during the 21st century. Model predictions with spatially inhomogeneous changes for the sea waves conditions for the Arctic basins have been later confirmed [10]. According to satellite and reanalysis data, a qualitative transition to the regional conditions predicted by model simulations is displayed since the second half of the first decade of this century (see also [18]). According to Fig. 1 similar effects are displayed for swell sea waves as well.

Special attention is paid to the interplay between the Arctic wind seas and swells both having comparable heights but propagating in different directions. In particular, according to our simulations the occurrence of such chop-like events increases in the Greenland Sea and for different inner Arctic basin areas and decreases in the Norwegian Sea the Barents Sea in the 21st century under RCP8.5 scenario.
Figure 1. Changes in significant wave height, m (a,b,c), significant wave height of swell, m (d,e,f) and chop occurrence, number of cases per year (g,h,i) to the end of the 21st century (2091-2100) under the RCP8.5 scenario relative to the period 1990-2005 as simulated by WaveWatch III with climate forcings (sea-ice concentration and surface wind) derived from simulations with the different global climate models: ACCESS1-3 (a,d,g), CNRM-CM5 (b,e,h), inmcm4 (c,f,i).

Figure 2 shows annual cycle of the sea waves total energy in the Arctic Ocean from model simulations under historical and RCP8.5 scenarios for two periods (1990-2005 and 2091-2100) normalized to the annual-mean sea waves energy for the period 1990-2005. According to model simulations it can be expected the general increase of the sea waves total energy in the Arctic Ocean in the 21st century for all months.3

4. Conclusion
In conclusion, the significant wave heights in the Arctic basin will increase with a decrease of the sea ice extent under global warming according to the model simulations. The same conclusion is for the extreme significant wave height especially over different inner Arctic areas. The opposite tendency, with a slight reduction in wave height appears for the Atlantic sector of the Arctic Ocean. Regional estimates for wind seas, swell and chop-like event occurrence are performed. Our results demonstrate the complex sea waves response in the Arctic basin to a combined effect of sea ice and wind changes from the ensemble of CMIP5 climate model simulations with the RCP scenarios for the 21st century.
Figure 2. Annual cycle of the sea waves total energy in the Arctic Ocean from model simulations under historical and RCP8.5 scenarios for two periods (1990-2005 and 2091-2100) normalized to the annual-mean sea waves energy for the period 1990-2005. Bold lines correspond to the ensemble-means for three models (ACCESS1-3, CNRM-CM5, inmcm4), while thin lines correspond to separate models.

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