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Evaluation of the Wind Speed and Wave Heights Simulation in the Kara Sea Using the COSMO-CLM and WAVEWATCH III Models

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Abstract
Purpose. The work is aimed to obtain the quality estimates of the results of modeling the wind speed and wave heights in the Kara Sea.
Methods and Results. The COSMO-CLM model was used to simulate the atmospheric conditions, and the WAVEWATCH III model – to obtain the wave parameters with high resolution in the coastal zone. Eight COSMO-CLM-based numerical experiments including various model options and grid sizes from 12 to 2.8 km were carried out for the periods September – October, 2012 and August – September, 2014. To assess the quality of wind speed and wave height modeling, the data of the CryoSat and SARAL satellites, as well as the coastal weather stations were used. Statistical indicators for assessing the quality of wind and wave reproduction for different model configurations were obtained. The wind speed assessing was best provided by the COSMO-CLM model configuration with the ~ 12 km resolution in the basic domain and the ~ 3 km resolution in the nested one; at that in both cases the "spectral nudging" technology was used. Verification using the weather stations data and the satellite measurements performed for the model optimal configuration, has shown that for the wind speed, the average correlation coefficients were ~ 0.8, the bias varied from 0.1 to 0.4 m/s, and the RMS error was 1.7–1.8 m/s. As for the wave height assessments, the best result was obtained when the wind fields with the 3 and 10 km resolutions were applied (the RMS error was ~ 0.4 m and the correlation coefficient was ~ 0.87).
Conclusions. It is shown that in all the cases, application of the "spectral nudging" technology improves quality of the wind speed and wave height modeling performed due to the COSMO-CLM – WW3 system for the Kara Sea region. Quality of the results of wind field reproduction using the COSMO-CLM model with the ~ 3 km resolution is comparable to quality of the ERA5 and CFSv2 reanalyses. Since mesoscale modeling provides a more detailed wind field spatial structure, especially in the coastal regions, the results permit to use the wind fields with the 3 km resolution for a wide range of scientific and applied tasks.

Keywords: Kara Sea, wind speed, wind waves, WAVEWATCH III, unstructured mesh, COSMO-CLM, simulation

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Introduction

Currently, there is an increased interest in the study of hydrometeorological conditions of the Arctic seas, associated with an intensive economic development of this region: active exploration, mining and transportation of minerals are taking place here, fishing and shipping are developing. One of the key limiting factors for economic activity, shipping, development of coastal infrastructure, subject to destruction in storm conditions, is the wind-wave regime. The study of hydrometeorological conditions in the Arctic seas of Russia is a priority task due to the development of offshore oil and gas fields, the development and provision of navigation along the Northern Sea Route and related infrastructure.

To provide hydrometeorological services, it is important to study the frequency of extreme winds and waves, their interannual variability, as well as the causes leading to their occurrence. The field data on waves in the Arctic are practically absent; therefore, diagnostic and prognostic calculations of numerical wave models are used to ensure navigation and offshore operations. As a driving force (forcing), these models use diagnostic or predictive wind fields from global weather forecast models [1–3]. Let us note that the Arctic seas are also characterized by a low availability of meteorological observations [4]. Therefore, numerical models of the atmosphere are often the only source of data on wind speed. In modern meteorological reanalyses, the near-water wind data obtained from satellite altimeters are assimilated [5, 6]. Assimilation of altimeter data by reanalyses somewhat complicates the use of satellite data to assess the quality of reanalyses, since these data are no longer independent. The root-mean-square error (RMS) for wind speed according to the data from the SARAL satellite when compared with the data from meteorological buoys is 1.5 m/s [7], and for the CryoSat satellite, the standard deviation is 1.2–1.3 m/s [8]. To reconstruct the wind regime of water areas with a complex coastline, it seems appropriate to use regional models with high spatial resolution.

There is a number of works devoted to the study of the wind-wave regime of the Kara Sea. The features of the wind regime and the wave climate of the Kara Sea are given in the handbook [1], where, based on the NCEP/NCAR reanalysis and the WAVEWATCH III (WW3) model, the frequency of wind and waves of various probability was calculated. In particular, it was demonstrated that in the Yamalo-Yugorsky region of the Kara Sea, the wind speed (10 min averaging) with a frequency of once a year is 22.5 m/s, the wave height of 50% probability with a frequency of once a year is more than 3 m, and the wave height of 0.1% probability is more than 8.6 m. From October to April, the average duration of weather windows, when the wind speed does not exceed 10 m/s, is no more than 3 days. That is, a significant part of the year in the Kara Sea is dominated by stormy weather, and therefore it is extremely important to develop methods for accurate diagnosis and forecasting of wind and waves. In [9], based on wave modeling, an increase in storm activity in the Kara Sea over the past 39 years is demonstrated. It is primarily due to an increase in the duration of the ice-free period and an increase in acceleration due to a smaller area of ice. In [1], based on

[1] Lopatoukhin, L.I., Boukhanovsky, A.V. and Chernysheva, E.S., 2013. *Reference Data on Wind and Wave Regime of the Barents and Kara Sea Shelf*. St. Petersburg: Russian Maritime Register of Shipping, 334 p.

the SWAN model and nested grids, modeling of waves in the Kara Sea and the Gulf of Ob was carried out. The information about wave parameters and wave height trends is also given in papers [10, 11].

In [2], the calculation of the wind field was performed using the WRF model, and the wave parameters for the Kara and Pechora seas are modeled using the Russian atmospheric wave model. The estimates of the accuracy of wind speed calculations when compared with the data from weather stations showed a correlation of 0.8–0.9, which confirms the positive effect of the use of wind forcing of mesoscale models with high spatial resolution. The operational forecasts of wind wave parameters in the Kara Sea are available on the website of the Arctic and Antarctic Research Institute (Available at: http://old.aari.ru/clgmi/forecast/_fc_1.php).

However, it is important to analyze the quality of mesoscale meteorological models, taking into account the possibility of reproducing hazardous phenomena in the region under consideration, for example, such as lee storms or polar mesocyclones [12, 13], which make a significant contribution to the overall frequency of storms. The work [12] presents a successful reproduction of the Novaya Zemlya bora using the WRF model and its effect on wind waves. It was demonstrated in [14] using individual examples that high-resolution COSMO-CLM modeling (~ 3 km) in the Arctic region with a complex coastline and topography makes it possible to adequately describe mesoscale circulations, including those associated with high wind velocities. In [15], the successful use of the COSMO-CLM model with a resolution of ~ 3 km for the coastal zone of the Kara Sea was demonstrated.

In this work, the results of eight original numerical experiments based on the COSMO-CLM model were used as wind forcing. Based on the measurement data, the estimates of the quality of modeling results of the wind speed and wave parameters were obtained. The purpose of this work is to demonstrate the feasibility of using mesoscale models for the analysis and forecast of storm conditions in the Kara Sea. The paper presents retrospective calculations of near-water wind and wind waves with high spatial resolution.

Materials and methods of research

Mesoscale model COSMO-CLM. The COSMO-CLM non-hydrostatic model (version 5.0) [16, 17] was used as the main tool for modeling atmospheric dynamics. The COSMO-CLM is a climate version of the COSMO regional mesoscale model developed by the *Consortium for Small-scale Modeling*, which includes national weather forecasting services of a number of countries, including the Russian Federation (Roshydromet). The climate version of the model is being developed within the framework of the international scientific CLM-Community [2].

The COSMO-CLM (CCLM) model is based on the Reynolds equations describing the dynamics of a compressible fluid in a humid atmosphere [18, 19]. The model equations are solved on a latitude-longitude grid (λ, φ) with a shifted position of the North Pole, the hybrid value μ (σ–z-system) acts as a vertical coordinate, the numerical scheme is implemented on an Arakawa type *C* grid [20].

[2] Climate Limited-Area Modelling Community. *CLM-Community*. 2022. [online] Available at: https://clmcom.scrollhelp.site/clm-community/ [Accessed: 24 June 2022].

External parameters describing surface properties are aggregated using the EXTPAR [3] tool from various sources: GLOBE (surface orography), MODIS (soil and albedo properties) and Globcover2009 (vegetation cover, root depth, land proportion, etc.) – and during preprocessing are re-interpolated to the grid of the COSMO model.

In many works [21, 22], it was demonstrated that the use of the "spectral nudging" technology contributes to a better assimilation of the features of large-scale meteorological fields due to the additional use of forcing data (in this case, reanalysis) not only on the lateral boundaries of the computational domain but also within it. Therefore, in this work, a number of experiments was carried out to study the effect of applying "spectral nudging" on the quality of reproduction of surface wind and waves.

A more detailed description of the physics and dynamics of the model and parameterizations of subgrid processes can be found on the model documentation page [4].

The COSMO-CLM regional model is used by the consortium members to solve a wide range of problems, including modeling the dynamics of the atmosphere and the wind regime at high latitudes. The first results of reconstructing cases of storm waves in the Arctic seas using the COSMO-CLM model combined with the wave model are given in [15, 23].

WAVEWATCH III model. To calculate the parameters of wind waves in the Kara Sea, the spectral wave model of the third generation WAVEWATCH III version 6.07 was applied [5]. This wave model takes into account the non-linear three-wave interactions that are characteristic of enclosed and shallow water areas, the effects of wave breaking and diffraction at shallow depths, and the sea ice impact.

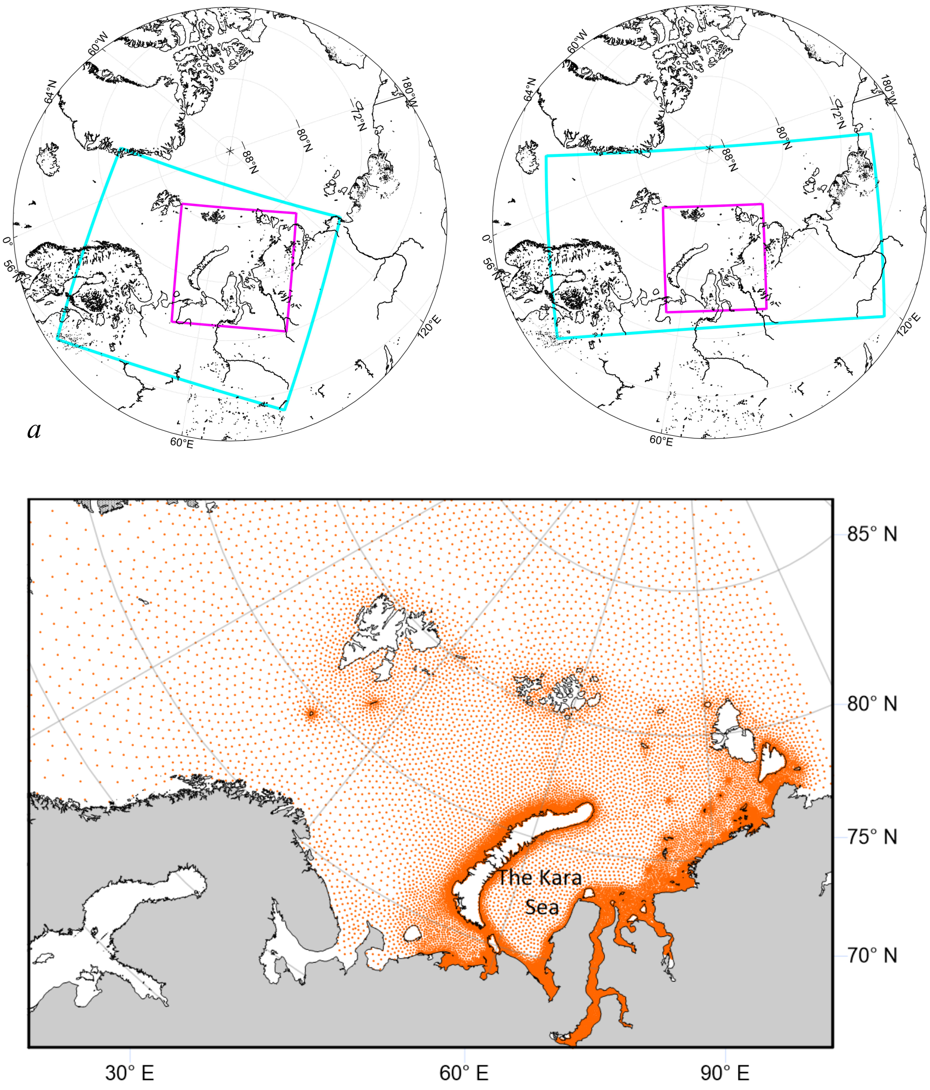
The ST6 scheme was applied to generate waves, the DIA scheme – to calculate nonlinear interactions, and the IC0 scheme – to take into account the ice effect. The effect of bottom friction is taken into account according to the JONSWAP scheme, the dissipation of wave energy is parameterized depending on the ratio of the phase and group velocities of the waves, as well as the depth at the point. The spectral resolution of the model is 36 directions ($\Delta\theta = 10°$), the frequency range σ is 36 intervals from 0.03 to 0.843 Hz. The total time step for integrating the complete wave balance equation is 15 min, the time step for

[3] Asensio, H., Messmer, M., Luthi, D. and Osterried, K., 2018. *External Parameters for Numerical Weather Prediction and Climate Application EXTPAR v5_0. User and Implementation Guide*, 45 p. Available at: https://www.cosmo-model.org/content/support/software/ethz/EXTPAR_user_and_implementation_manual_202003.pdf [Accessed: 20 December 2022].

[4] Consortium for Small-Scale Modelling. *COSMO Core Documentation*. 2022. [online] Available at: http://www.cosmo-model.org/content/model/documentation/core/default.htm [Accessed: 24 June 2022].

[5] Tolman, H., Abdolali, A., Accensi, M., Alves, J.-H., Ardhuin, F., Babanin, A., Barbariol, F., Benetazzo, A., Bidlot, J., 2019. *User Manual and System Documentation of WAVEWATCH III Version 6.07*. College Park, USA. [online] Available at: https://www.researchgate.net/publication/336069899_User_manual_and_system_documentation_of_WAVEWATCH_III_R_version_607 [Accessed: 18 December 2020].

integrating the functions of sources and sinks of wave energy is 60 s, and the time step for energy transfer over the spectrum is 450 s.

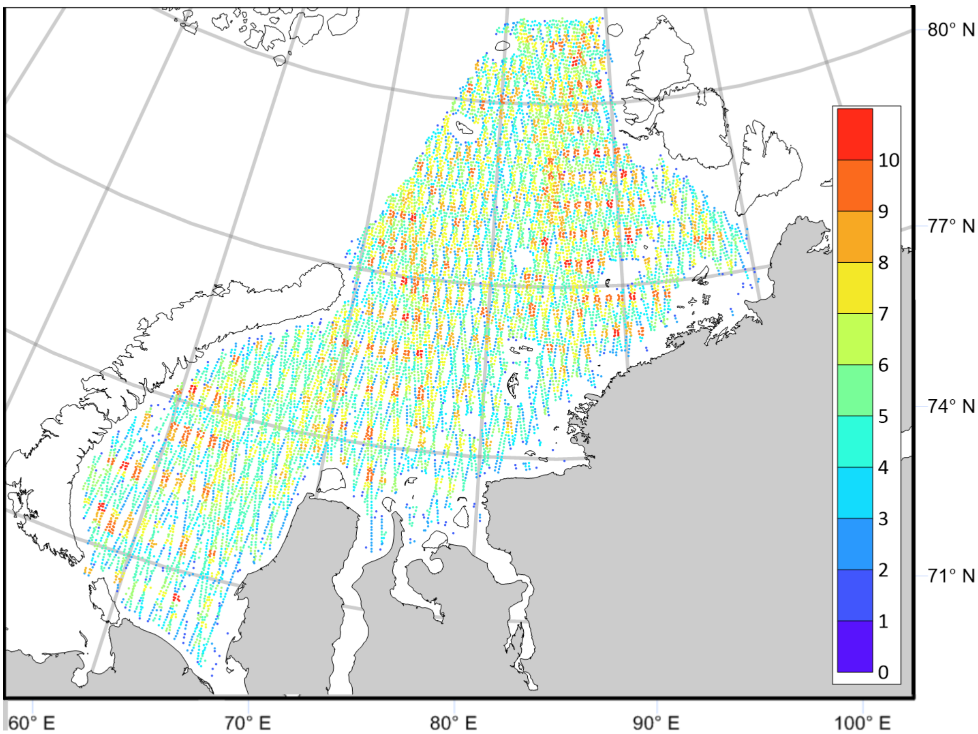


F i g. 1. Layout of the boundaries of the COSMO-CLM simulation domains (*a*): *on the left* – the main (blue rectangle with the 12 km resolution domain, pink square with the 2.8 km resolution domain; *on the right* – the additional one (blue rectangle with the 10 km resolution domain, pink square with the 3 km resolution domain); the unstructured mesh for calculating wind waves in the Kara Sea (*b*)

The calculations were carried out on a non-structural triangulation grid consisting of 37729 nodes. This grid covers the waters of the Barents and Kara seas, as well as the entire northern part of the Atlantic Ocean (Fig. 1, *b*). For the Kara Sea, the step is 10 km in the open sea and 700 m near the coast. The depth marks for the computational grid for deep water were obtained from the ETOPO1 bottom topography database, and for the coastal zone detailed navigation charts were digitized. A more detailed description of the model configuration and features of the experiments are described in [9, 24].

When modeling the waves, we used the wind data from the COSMO-CLM mesoscale model with different spatial steps and time step of 1 h. The ice concentration data with a time step of 1 h were obtained from the NCEP/CFSv2 reanalysis with a resolution of ~ 0.2°. The wind velocity data from the four closest nodes (from mesoscale models with different spatial resolutions) were linearly interpolated onto the wave model grid.

Satellite data. To assess the quality of wind and wave modeling for the experiments in 2012, the data from the CryoSat satellite were used; for the experiments in 2014, the data from the CryoSat and SARAL satellites were applied. The significant wave height and wind velocity data have a spatial resolution of ~ 7 km along the track and are available on the RADS (Radar Altimeter Database System) database website [6].



F i g. 2. CryoSat altimeter data for September – October, 2012. Color indicates the points density at the 13 × 13 km square

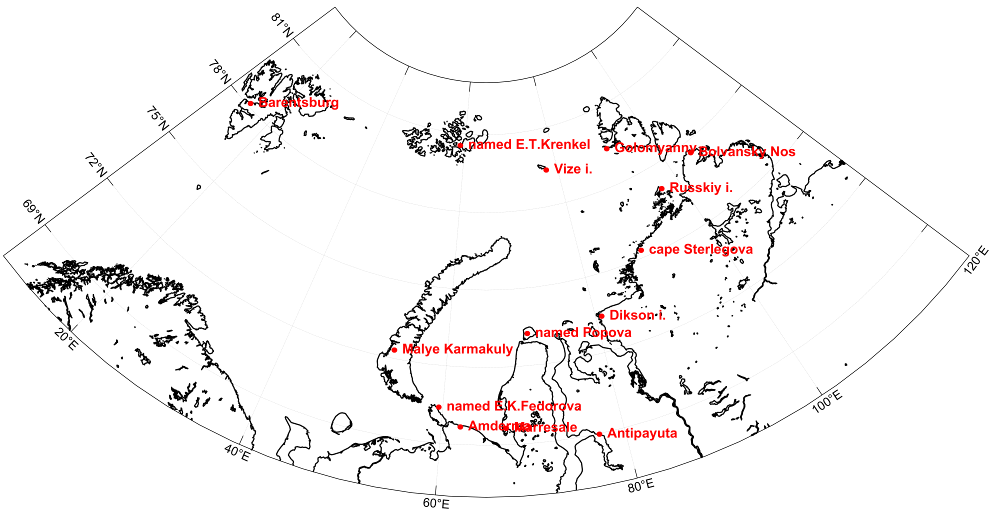
When assessing the quality of simulation data, the distance between the satellite data points and the computational grid points of the wave or meteorological model did not exceed 10 km.

[6] DEOS. *Radar Altimeter Database System.* 2014. [online] Available at: http://rads.tudelft.nl/rads/rads.shtml [Accessed: 24 June 2022].

Values were filtered out from satellite data if the points were closer than 12 km from the coast or from the ice edge, since strong emissions are observed in these cases.

After filtering and selecting the nearest points for the wave model grid for September – October 2012, an array of wave height data from the CryoSat satellite, consisting of ~ 7500 values, was obtained. For 2012, when comparing the satellite data on wind speed with the data of the meteorological model, the array of satellite data amounted to ~ 8000–15000 values, depending on the spatial resolution of the experiment. For August – September 2014, the array of wind velocity data from the SARAL satellite was ~ 8000–14000, from CryoSat it was ~ 6000–11000. The scheme of tracks of the CryoSat altimeter for September – October 2012 is given in Fig. 2.

Data of weather stations. The results of all experiments were also verified using 3-hour wind velocity data from coastal and island meteorological stations in the Kara Sea and its environs from the RIHMI-WDC database (Available at: http://meteo.ru/data), estimates were made for the nearest to the weather stations nodes of the COSMO-CLM model grid for the following periods of experiments: September – October 2012 and August – September 2014. The comparison was carried out for 14 weather stations (Fig. 3), the sample length at each station for each experiment was 488 values, which enables us to make more or less sound statistical estimates. The standard statistical metrics were calculated: mean error, RMS deviation, standard deviation, and correlation coefficient. The stated meteorological stations are located in different parts of the Kara and partially Barents seas and are characterized by very different local conditions, which is the reason for their choice for evaluating the simulation results.



F i g. 3. Weather stations whose data were used to verify the COSMO-CLM experiments

Description of numerical experiments. For the Kara Sea, several numerical experiments were carried out with the COSMO-CLM model; wind fields were obtained at a height of 10 m with different spatial resolutions using "spectral nudging" and without it for September – October 2012 and August – September 2014. For September – October 2012 for all forcing options, the calculation of wind wave parameters was carried out using the WAVEWATCH III model.

The model configuration was adapted with regard to the specifics of the Arctic region hydrometeorological conditions, in particular, the number of vertical levels of the model was increased for better resolution of the surface layer processes (50 levels in total, including up to 10 levels in the boundary layer, the height of the lower level is 20 m), which is thinner in the Arctic than in temperate latitudes. This is important for the correct reconstruction of the surface wind fields, which are the main subject of study in this paper.

The experiments were carried out according to the standard scheme of nested grids, i.e. on the base computational domain, ERA-Interim global reanalysis data with a horizontal grid step of 0.7° (~ 75 km) [25] were used as initial and boundary conditions, and on the nested computational regions – the output of the simulation on the base region with reduced horizontal resolution and simulation region. Two schemes of nested grids were used (see Fig. 1, *a*). In the main scheme, the basic computational domain with a resolution of 0.12° (~ 12 km) covers the North Atlantic, the Barents and Kara seas, and the polar regions. Such a coverage seeks to take into account the predominance of westerly transport processes in the atmospheric circulation in the region, as well as the propagation and impact of waves and swells in the Atlantic on processes in the Kara Sea. The nested modeling area with a resolution of 0.025° (~ 2.8 km) covers completely the water area of the Kara Sea, with some extension to the west. In the additional scheme (Fig. 1, *b*), as in [26], the vast territory of most of the Arctic is used as the base area with a grid step of 0.108° (~ 10 km). The nested grid with a step of 0.03° (~ 3 km) covers the Kara Sea in much the same way as in the main scheme.

It should be noted that due to the pole-shifted grid used in the COSMO-CLM model, it is possible to avoid the problem of convergence of meridians and, accordingly, a sharp decrease in the grid spacing in kilometers near the pole. Thus, the given grid steps in kilometers are quite uniform over the model areas, although they are not constant, at the edges of the areas they slightly exceed the indicated values. Further in the text, experiments on computational domains according to the main scheme with grid spacings ~ 12 km and ~ 2.8 km are called CCLM12 and CCLM2.8, and according to the additional scheme with grid spacings ~ 10 km and ~ 3 km – CCLM10 and CCLM3, respectively.

The standard model configuration for two nested grid schemes has been supplemented with variants with "spectral nudging" technology (hereinafter referred to as "*_sn*" appended to the name). In the "spectral nudging" from the reanalysis, the fields of temperature and zonal and meridional wind velocities in the layer of 850 hPa and higher with a horizontal scale of ~ 500 km and more were assimilated. The experiments in test mode with a reduced model time step *dt* and a larger nested domain were also carried out, but these results were not considered in this work.

The experiments according to the described schemes were carried out for two periods: August – October 2012 and July – September 2014. The periods were chosen based on considerations of the smallest sea ice area in the Kara Sea, so that the ice cover had the least possible effect on wave characteristics, as well as given the availability of more observational data over the years. In all cases, the model started a month earlier than the specified period (in the so-called spin-up mode) in order to sufficiently adapt the model fields in time. All calculations were carried out using Lomonosov-2 supercomputer of the computer complex of Lomonosov Moscow State University [27].

Research results and discussion

Evaluation of the numerical modeling results of the wind speed field.

As a result of the simulation, the wind speed fields at a height of 10 m were obtained for September – October 2012 and August – September 2014. For these periods, the wind velocity module obtained from the simulation data and from the SARAL and CryoSat satellite data in the Kara Sea were compared.

In Tables 1–3, the statistical data for assessing the quality of the results of the wind speed module modeling obtained from satellite data are given.

Based on the comparison of estimates for different experiments, it can be concluded that all experiments without “spectral nudging” demonstrate lower correlations and larger errors compared to experiments with the inclusion of “spectral nudging”. This trend persists for different periods and when compared with the data from different satellites, it is an additional confirmation of the obtained conclusion. It is also necessary to note an increase in the correlation coefficient and a decrease in the RMS with an increase in the spatial resolution for experiments with “spectral nudging”.

In Fig. 4 the scatterplots for some of the experiments are given. It can be seen that for the experiment without “spectral nudging”, the scatterplot has a large spread of values, the correlation is smaller (0.63 vs. 0.82), and RMSE is larger (2.87 vs. 1.96 m/s). Out of base domains, the CCLM12_sn experiment showed the best results with minor differences from CCLM10_sn. In general, the correlation coefficients reach ~ 0.83–0.85 in the best configurations, and RMS deviation is ~ 1.8 m/s. At the same time, among experiments on the nested domains, CCLM3_sn turned out to be better in terms of statistics.

Table 1

Assessment of quality of the wind speed simulation results based on the CryoSat data for September – October, 2012

Experiment	September				October				September – October			
	N	*BIAS*	*RMSE*	*R*	*N*	*BIAS*	*RMSE*	*R*	*N*	*BIAS*	*RMSE*	*R*
*CCLM*2.8	7176	−0.322	2.760	0.517	7794	−0.442	2.637	0.720	14970	−0.385	2.697	0.657
*CCLM*2.8_*sn*	7176	−0.450	2.043	0.714	7794	−0.292	2.017	0.825	14970	−0.368	2.030	0.796
*CCLM*3	7050	−0.909	3.083	0.406	7679	−0.312	2.655	0.717	14729	−0.598	2.868	0.629
*CCLM*3_*sn*	7050	−0.308	2.020	0.748	7679	−0.493	1.893	0.852	14729	−0.404	1.955	0.817
*CCLM*10	4249	−0.799	3.193	0.388	4549	−0.392	2.700	0.724	8798	−0.589	2.949	0.624
*CCLM*10_*sn*	4249	−0.187	1.885	0.777	4549	−0.571	1.830	0.869	8798	−0.386	**1.857**	**0.835**
*CCLM*12	4081	−0.353	2.677	0.556	4304	−0.565	2.592	0.732	8385	−0.462	2.634	0.676
*CCLM*12_*sn*	4081	−0.280	1.773	0.785	4304	−0.557	1.806	0.872	8385	−0.423	**1.790**	**0.844**

N o t e: *N* is data amount in a sample; *BIAS* is a systematic error; RMSE is a root mean square error; *R* is a correlation coefficient; *STD* is a standard deviation.

Table 2

Assessment of quality of the wind speed simulation results based on the CryoSat data for August – September, 2014

Experiment	August				September				August – September			
	N	*BIAS*	*RMSE*	*R*	*N*	*BIAS*	*RMSE*	*R*	*N*	*BIAS*	*RMSE*	*R*
*CCLM*2.8	4473	0.249	2.713	0.610	6664	1.004	2.918	0.584	11137	0.701	2.837	0.622
*CCLM*2.8_*sn*	4473	0.202	2.169	0.731	6664	0.588	2.045	0.798	11137	0.433	2.096	0.784
*CCLM*3	4409	0.105	3.086	0.441	6557	0.484	2.728	0.569	10966	0.332	2.877	0.546
*CCLM*3_*sn*	4409	0.408	2.102	0.764	6557	0.768	1.909	0.823	10966	0.623	1.989	0.811
*CCLM*10	2690	0.001	3.859	0.142	3946	0.672	3.101	0.473	6636	0.400	3.429	0.385
*CCLM*10_*sn*	2690	0.451	1.914	0.815	3946	0.793	1.821	0.849	6636	0.654	**1.859**	**0.845**
*CCLM*12	2528	0.225	2.627	0.639	3691	1.118	2.941	0.599	6219	0.755	2.818	0.644
*CCLM*12_*sn*	2528	0.537	1.964	0.796	3691	0.663	1.676	0.877	6219	0.612	**1.799**	**0.852**

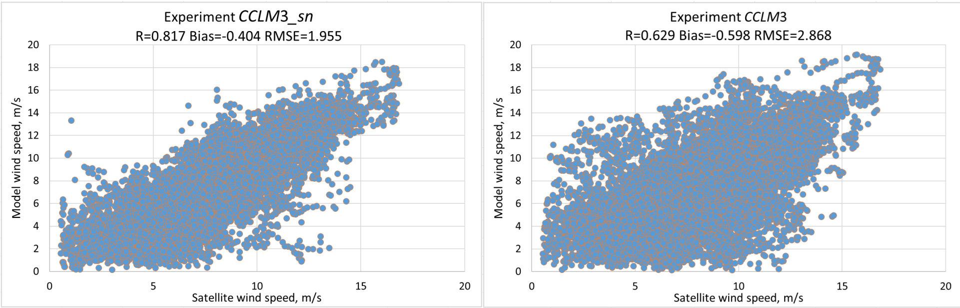
N o t e: the designations are as in Table 1.

Table 3

Assessment of quality of the wind speed simulation results based on the SARAL data for August – September, 2014

Experiment	August				September				August – September			
	N	*BIAS*	*RMSE*	*R*	*N*	*BIAS*	*RMSE*	*R*	*N*	*BIAS*	*RMSE*	*R*
*CCLM*2.8	5540	−0.578	2.753	0.674	8433	−0.382	2.948	0.576	13973	−0.382	2.948	0.576
*CCLM*2.8_*sn*	5540	−0.755	2.454	0.734	8433	−0.598	2.055	0.775	13973	−0.598	2.055	0.775
*CCLM*3	5470	−0.731	3.399	0.466	8309	−0.693	2.822	0.550	13779	−0.693	2.822	0.550
*CCLM*3_*sn*	5470	−0.520	2.240	0.780	8309	−0.442	1.882	0.793	13779	−0.442	1.882	0.793
*CCLM*10	3734	−0.972	4.497	0.079	5601	−0.619	3.204	0.439	9335	−0.619	3.204	0.439
*CCLM*10_*sn*	3734	−0.655	2.030	0.831	5601	−0.474	1.740	0.826	9335	−0.474	**1.740**	**0.826**
*CCLM*12	3450	−0.535	2.732	0.679	5154	−0.384	3.003	0.565	8604	−0.384	3.003	0.565
*CCLM*12_*sn*	3450	−0.540	1.987	0.827	5154	−0.492	1.743	0.832	8604	−0.492	**1.743**	**0.832**

N o t e: the designations are as in Table 1.



a *b*

F i g. 4. Scatterplots for wind velocity based on the model and the CryoSat satellite data for 2012: *a* – the CCLM3_sn experiment; *b* – the CCLM3 experiment

We consider the results of assessing the quality of reconstructing the wind speed module for various experiments based on weather station data. Summary statistical characteristics of the verification of experiments based on station data are given in Tables 4, 5 with the addition (for comparing the quality) of similar estimates for the data of three modern reanalyses, including the latest generation with high resolution: ERA-Interim [25], ERA5 [28] and NCEP/CFSv2 [29].

T a b l e 4

Assessment of quality of the wind speed reconstruction based on the weather stations data for September – October, 2012

Data source	*R*	*BIAS*	*RMSE*	*STD*
		Experiments		
*CCLM*12*_sn*	0.77	0.13	**2.19**	**1.96**
*CCLM*10*_sn*	0.69	0.38	2.45	2.31
*CCLM*12	0.61	0.08	2.84	2.69
*CCLM*10	0.56	0.16	2.97	2.83
*CCLM*3	0.60	−0.04	2.75	2.71
*CCLM*2.8	0.58	−0.51	2.85	2.72
*CCLM*3*_sn*	0.74	−0.40	2.25	2.14
*CCLM*2.8*_sn*	0.75	−0.01	**2.24**	**2.17**
		Reanalysis		
ERA-Interim	0.73	0.39	2.25	2.05
*ERA*5	0.79	0.25	**2.05**	**1.80**
NCEP-CFSv2	0.79	0.43	2.21	1.98

T a b l e 5

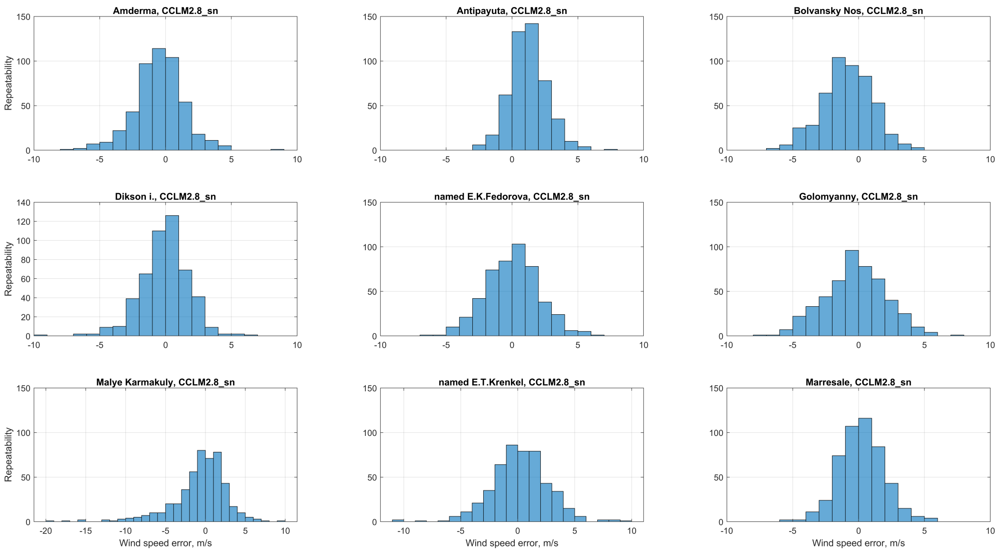
Assessment of quality of the wind speed reconstruction based on the weather stations data for August – September, 2014

Data source	*R*	*BIAS*	*RMSE*	*STD*
		Experiments		
*CCLM*12_*sn*	0.77	0.39	**2.06**	**1.91**
*CCLM*10_*sn*	0.77	0.42	2.13	2.00
*CCLM*12	0.60	0.46	2.79	2.68
*CCLM*10	0.45	0.35	3.26	3.15
*CCLM*3	0.42	−0.19	3.20	3.12
*CCLM*2.8	0.60	0.46	2.82	2.73
*CCLM*3_*sn*	0.74	−0.09	**2.15**	**2.07**
*CCLM*2.8_*sn*	0.72	0.31	2.25	2.16
		Reanalyses		
ERA-Interim	0.79	0.39	1.82	1.72
*ERA*5	0.78	0.38	**1.75**	**1.51**
*NCEP-CFSv*2	0.69	0.52	2.10	1.96

After analyzing the summary results of verification, we can conclude that the use of the “spectral nudging” technology unambiguously improves the reconstruction of surface wind speeds compared to the basic configuration of the model. At the same time, among the basic domains, the CCLM12_sn experiment showed the best results, being noticeably better than CCLM10_sn. In general, the correlation coefficients reach 0.77, and systematic errors do not exceed 0.5 m/s, RMS are about 2 m/s. At the same time, among the experiments on nested domains, CCLM3_sn from the base domain with a grid step of 10 km turned out to be statistically better. This can be explained by the fact that the “spectral nudging” technology worked better on a smaller domain, but more detailed mesoscale dynamics was better reconstructed on a nested domain in the CCLM10_sn – CCLM3_sn scheme. The difference between CCLM3_sn and CCLM2.8_sn experiments is not so great, and nested grid experiments from 10 to 3 km are more often characterized by underestimation of wind speeds. It should also be noted that the period of 2014 was generally characterized by larger errors than the period of 2012; the described patterns are consistently manifested in the groups of experiments for both periods.

As for the analysis of errors at individual stations, in the experiment on the base domain, the values of the correlation coefficients for stations were 0.5–0.7, 0.6 on average; the worst values were at E.T. Krenkel and Russky Island stations (~ 0.45). At the same time, the values of the average errors for most stations are quite satisfactory (less than 1 m/s, on average − 0.08, except for Bolvansky Nos, Antipayuta and Malye Karmakuly stations), which reflects the fact of a realistic reconstruction of the dynamics and variability of synoptic-scale processes for two months. In particular, at Malye Karmakuly station, the errors (up to 15–20 m/s) are associated with the frequently observed extreme wind speed there due to the Novaya Zemlya bora, the formation and variability of which is significantly affected by mesoscale processes and the indented coastline [12, 30]. In addition, taking into account the fact that the weather station data were compared with the model data at the nearest grid node, the additional sources of inaccuracies and error factors are the distance between these points, which in some cases reaches several kilometers, as well as the discrepancy between the underlying surface in the model mask (land/sea) and real conditions of the indented coastline and rugged terrain.

On nested domains, the statistical characteristics of the errors are generally the same, except for the RMS which at some stations decreases, especially at those where the RMS was maximum (average RMS is 2.25 m/s compared to the maximum value of 2.84 m/s), see also [15] for details. Considering that according to the official methodology for estimating the accuracy of the wind forecast, the error should not exceed ±4.5 m/s [7], it can be recognized that the calculation results are quite qualitative, and can be used in subsequent calculations of wind waves. As an example, the histograms of error distribution at some stations for the CCLM2.8_sn experiment in 2012 are given in Fig. 5.



F i g. 5. Examples of the error distribution histograms at some stations for the CCLM2.8_sn experiment, 2012

The verification results enable us to solve the question of how comparable the errors in the performed model experiments are with the errors of the existing arrays of hydrometeorological information of a coarser resolution, such as the ERA-Interim and ERA5 reanalyses from ECMWF, NCEP-CFSv2 from NCEP

[7] Hydrometcenter of Russia, 2019. [*Manual on Short-Range Weather Forecasts for General Purposes: RD 52.27.724-2009*]. Obninsk: IG-SOTSIN, 62 p. (in Russian).

(Tables 4 and 5). It can be seen that only the best model configurations using "spectral nudging" are comparable in quality with the presented reanalyses, but by some measures they lose a little to them. This can be explained by several causes. Firstly, in the reanalyses, a full assimilation of the data of all observations, including the near-water satellite wind [28, 9], takes place, and in the COSMO-CLM experiments, the reanalysis is used only as initial and boundary conditions, taking into account the "spectral nudging", no additional data assimilation occurs.

Secondly, the detailing of global fields by mesoscale models can manifest itself in the reconstruction of phenomena, including those associated, for example, with wind intensifications that are somewhat shifted relative to their real position. In such situations, the point-to-point comparison will show significant errors, despite the fact that the phenomenon and its properties were actually reconstructed and more successfully than on a coarse grid of global reanalyses [14, 15]. Comparing the results of wind speed verification based on satellite and station data, we can state that the errors are comparable, and it is important that these estimates were obtained from independent data sources.

Thus, in their best configurations of the COSMO-CLM mesoscale model, despite the lack of observational data assimilation, they turn out to be comparable in quality to global reanalyses. At the same time, mesoscale modeling data were obtained on a more detailed grid, which is more important for a number of applied problems in terms of reconstructing processes of the corresponding scale, including in the coastal zone. At the same time, it should be emphasized that a significant problem is the complexity of assessing the quality of mesoscale modeling results. In particular, in the coastal zone the possibility of comparison with satellite data is absent.

At the same time, for the correct modeling of waves, it is more important that the integral wind energy over the water area is reconstructed correctly (scale of about 50–100 km), which is associated with the mechanism of wave generation and propagation. With regard to the abovementioned circumstances, we can consider the results of model experiments to be quite successful.

Summarizing the results, among the presented set of configurations, we can consider the configurations with the use of "spectral nudging" on the base 12 km domain (CCLM12_sn), as well as on the nested 3 km domain, i.e. CCLM3_sn, to be optimal from the point of view of reconstructing the surface wind speed. Perhaps it would be more optimal in the future to use the CCLM10_sn – CCLM3sn downscaling scheme.

However, for a more complete analysis of the quality of mesoscale experiments, it seems important to analyze the results of verification of wind wave fields, which is given in the next section.

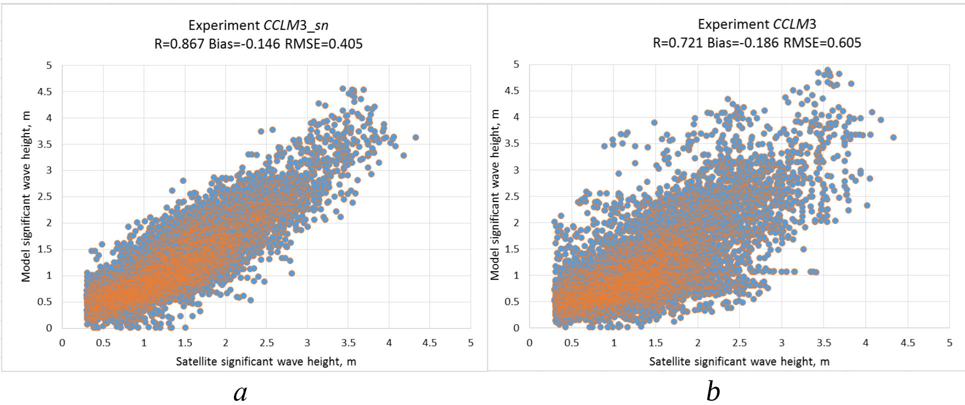
Evaluation of the results of wind wave numerical modeling. Next, the significant waves heights was compared according to the results of the WAVEWATCH III model using the wind fields from CCLM experiments with different spatial resolutions with the data obtained from the CryoSat satellite. The comparison results for September – October 2012 in the Kara Sea are presented in Table 6. The data array for comparison includes ~ 7500 values.

T a b l e 6

Assesment of quality of reconstructing the heights of significant waves based on the data of simulation and the CryoSat satellite for September – October, 2012

Experiment	*BIAS*	*RMSE*	*R*
*CCLM*2.8	−0.134	0.541	0.754
*CCLM*2.8_*sn*	−0.154	0.418	0.862
*CCLM*3	−0.186	0.605	0.721
*CCLM*3_*sn*	−0.146	**0.405**	**0.867**
*CCLM*10	−0.158	0.618	0.711
*CCLM*10_*sn*	−0.140	**0.405**	**0.867**
*CCLM*12	−0.185	0.555	0.746
*CCLM*12_*sn*	−0.204	0.414	0.875

Based on the results obtained, it turns out that the wave height is reconstructed more successfully when using wind fields from the experiments with "spectral nudging". The smallest errors were obtained for the CCLM3_sn and CCLM10_sn variants. The use of forcing with "spectral nudging" certainly gives a higher quality of wind wave modeling, which is demonstrated in the scatterplots (Fig. 6).



F i g. 6. Scatterplots for the heights of significant waves based on the model and the CryoSat satellite data for September – October, 2012: *a* – the CCLM3_sn experiment; *b* – the CCLM3 experiment

In general, the quality of the wave height reconstruction in the CCLM3_sn experiment is quite satisfactory, the scatter of points is small and approximately corresponds to modern estimates obtained for wave models [1, 3, 8, 10, 11].

It should be noted that statistical indicators for the wave height turned out to be better than similar results for wind speed. This is due to the fact that the wind field is much more variable, and mesoscale models contain pulsations of different spatiotemporal scales. For the field of wind waves, on the contrary, there is a cumulative effect of energy transfer from wind to wave for the water area, which leads to a smaller spread of values and higher correlation coefficients. It can also be assumed that the integral energy flux from wind to wave when using wind fields from the mesoscale meteorological model is set correctly, since systematic errors for wave heights are small. Previously, it was demonstrated that when comparing the height of significant waves according to direct and satellite measurements and according to the results of modeling using NCEP/CFSR wind, correlation coefficients of ~ 0.89–0.94 and RMS of ~ 0.31 to 0.39 m were obtained [9, 24].

Thus, the obtained results of wind wave reconstruction using the wind fields from the CCLM experiments for the open sea showed a slightly worse result than when using the NCEP/CFSR wind fields. This may be due to different sample lengths. Nevertheless, for the open sea, it is more reasonable to use global wind reanalyses, and for the coastal zone, to take into account orographic effects, it is more reasonable to use the data from mesoscale models.

Conclusions

1. Eight numerical experiments for the Kara Sea water area with configurations of the COSMO-CLM mesoscale model on domains with different spatial resolutions from 2.8 to 12 km were carried out.

2. Estimates of the quality of wind speed reconstruction based on satellite data and weather station data were obtained. When compared with satellite data, the best result was obtained for the CCLM12_sn configuration: RMSE = 1.7…1.8 m/s, R = 0.83…0.85. The CCLM10_sn and CCLM3_sn configurations are slightly inferior in quality. When compared with weather station data, the best result was obtained for the CCLM3_sn configuration: RMSE = 2.1…2.2 m/s, R ~ 0.75. Slightly inferior in quality to the *CCLM*2.8_*sn* and *CCLM*10_*sn* configurations.

3. Calculations of wind wave parameters based on the WAVEWATCH III wave model have been performed. Estimates of the quality of wave height reconstruction were obtained using wind fields from various configurations of the COSMO-CLM model. The best performance was obtained using forcing configurations CCLM3_sn and CCLM10_sn, where RMSE = ~ 0.4 m, R = ~ 0.87.

4. Thus, it is shown that the use of the “spectral nudging” technology improves the reconstruction quality of the wind and wave speed module by the COSMO-CLM – WW3 system for the Kara Sea region in all cases.

5. At the same time, the results of COSMO-CLM modeling using “spectral nudging” are somewhat inferior in quality to modern ERA5 and CFSv2 reanalyses. Since the differences are small, and mesoscale modeling enables to reconstruct a more detailed structure of the wind field, especially in coastal areas, the simulation results allow the use of wind fields with a resolution of 3 km for various scientific and applied problems.

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