High-resolution wind speed modeling, and an assessment of mesoscale peculiarities caused by coastline parameters and relief of near-shore Kara Sea regions

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Abstract. Complex shorelines and coastal relief strongly influence wind speeds. Since the Arctic is poorly covered by ground observations, one of the most reasonable approaches to investigating these events is hydrodynamical high-resolution modeling. In this work we apply a model COSMO-CLM to reproduce wind fields and characteristics in different rugged shore conditions. Some model experiments are designed with this regional climate non-hydrostatic atmospheric model COSMO-CLM to investigate the best configuration to reproduce the mesoscale circulations in the Arctic coastal zones considering different relief conditions on the example of the Kara Sea. Some mid-term experiments of a three-month timespan, Aug-Oct of 2012 and Jul-Sep of 2014, are conducted over the Arctic domain and specially over the Kara Sea region using a downscaling approach with ~12 and ~3 km horizontal grids. These periods are characterized by some storm events. The purpose of these experiments is to reproduce the surface wind and wave characteristics in the best way, especially near the shorelines during the storm events. Verification of these experiments has shown the best configuration of the COSMO-CLM with a “spectral nudging” technique and reducing the model time step. However, the verification and detailed investigation of the model runs raise a question about the quality of this verification, and how relevant are the wind station data in different coastline and relief conditions. Therefore, an additional analysis is carried out from a synoptic overview of the influence of the coastline configuration on different mesoscales and for different regions. Malye Karmakuly (Novaya Zemlya island), Belyi and Dikson Islands are considered as different examples to study the wind and wave regimes. Although the model cannot describe the dynamics on all scales using a 3-km resolution, it can realistically simulate the islands’ wind shadows, tip jets, downslope winds, vortex chains, etc. on different scales. It justifies further research to apply a finer resolution to learn detailed properties of mesoscale circulations and extreme winds. This analysis has shown a need to predict better these circulations by using numerical modelling.

1. Introduction
The Arctic region is most sensitive to global climate changes, particularly the temperature increase is most intense over the globe here [1 – 3], which is referred to Arctic amplification. This warming and the accompanying environmental changes affect the Arctic climate, the frequency of extreme weather events, and spatial patterns. Arctic warming taking place above the “global warming” signal and resulting mainly from dynamic processes in the atmosphere provide a poleward heat advection [4, 5]. The sea-ice area decline during the summer season contributes to polar amplification, among other important factors [6, 7]. However, it is favorable to increase the extreme winds and the frequency of wind waves over the Arctic Ocean region [8, 9].

The Kara Sea and the surrounding mainland areas are mirroring these main features in general. The authors of [10] have shown that the maximal winter temperatures increase to 20 C including the
surface layer, observed north from the Novaya Zemlya island based on COSMO-CLM modelling (15 km grid) over the Kara region for 2000 – 2016. The Barents-Kara Sea region warming has not only a regional climate effect, but impacts the stratospheric circulation regime [11], the Arctic Oscillation [12], Eurasia, including the Siberian temperature conditions [13 – 15], etc. via the climate system feedbacks.

Many severe atmospheric processes developed within meso-γ and meso-β scales, i.e. the representative sizes of the first dozens of km [16]; therefore, they have limited predictability. At the same time, there is very scarce information about the spatial structure of these features, because the Arctic region is one of those less provided with a ground observation network over the world. The coastal areas in the Arctic described the most severe hydrometeorological events caused by a combination of large-scale hydrodynamical conditions, surface properties (e.g., slit winds, tip jets, barrier effects, bora, etc. [17, 18]), mesoscale circulations (e.g., polar lows), but they are often an essential part of synoptic-scale systems. Forecast of severe hydrometeorological events in Arctic coastal zones is crucial for the coastal ports, transport infrastructure, shelf oil and gas production objects, icing conditions, leads to significant costly damage, and, occasionally, to human casualties. Despite a clear trend to reduce the horizontal grid during the last years, the appearance of regional reanalyses, e.g., ASR, NAAD [19, 20], these resolutions are not enough to the wide range of hydrometeorological information consumers, infrastructure building, Arctic marine operations, and other tasks based on meteorological information, and over the coastal areas especially, where it is just most important and demanded. Since the Arctic is poorly covered with ground observations, one of the most reasonable approaches to investigating these events is high-resolution hydrodynamical modelling.

The main goal of this work is an investigation of the ability of the mesoscale non-hydrostatic model to reproduce atmospheric circulation features over the coastal area of the Kara Sea in conditions of strong winds and surface inhomogeneity within different spatial scales.

2. Data and methods

2.1 Atmospheric model description
In this work we have applied the COSMO-CLM [21] model to reproduce the wind field and characteristics in different rugged shore conditions. This regional mesoscale model is being developed by the Consortium for Small-Scale Modeling, including some national weather services. The climate version of the model is developed within the framework of the international science community CLM-Community [22]. The COSMO-Model is based on the primitive thermo-hydrodynamical equations describing compressible flow in a moist atmosphere. The model equations are solved in rotated latitude-longitude coordinates with a tilted pole, which minimizes the problem of longitude convergence at the pole point. The numerical scheme is implemented on the Arakawa-C grid [23]. The height coordinate is a terrain-following hybrid Gal-Chen coordinate μ (σ-z system), which is an analog of the σ-coordinate from the surface (Z₀) to an intermediate level Zᵢ, and higher than the Zᵢ level it is a simple Z-coordinate [24, 25]. This representation of the vertical coordinate allows one to avoid problems related to inhomogeneity of the surface relief.

The standard configuration of the COSMO-CLM v.5.0 model includes a two-time-level split-explicit Runge-Kutta scheme with splitting of acoustic and gravity waves and 5th order of horizontal advection numerical approximation; Smagorinsky diffusion. Two-stream radiation scheme after [26] short and longwave fluxes (employing eight spectral intervals); precipitation formation by a bulk microphysics parameterization including water vapor, cloud water, cloud ice, rain, and snow with 3D transport for the precipitating phases; a mass-flux convection scheme [27] with equilibrium closure based on the moisture convergence for moist and shallow convection; subgrid-scale turbulence is
parameterized by prognostic turbulent kinetic energy closure at level 2.5, including effects from subgrid-scale condensation and thermal circulations; a surface layer scheme based on turbulent kinetic energy including a laminar-turbulent roughness layer. It allows one to separate the model values on the solid surface and at the roughness level. More detailed documentation is given in [28].

It is important to reproduce surface wind fields more correctly, which is the main subject of this study. Therefore, the vertical resolution of the model was increased to 50 levels in total, including 10 levels in the surface layer, which contributes to more successful reproduction of extreme wind speeds and gusts.

2.2 Experimental design

Some model experiments designed with the regional climate non-hydrostatic atmospheric model COSMO-CLM investigated the best configuration to reproduce mesoscale circulations in the Arctic coastal zones considering different relief conditions. A good testbed for such experiments is the Kara Sea, because there are different conditions of the coastline, relief peculiarities, islands of various scales, etc.

The experiments were carried out using a standard nesting domains scheme, i.e. the base domain forced by global reanalysis data as initial and boundary conditions, and the nested domain forced by modelling output over the base domain, reducing the horizontal grid and time step, as well as the modelling area. The experiments covered two three-month periods, Aug-Oct 2012 and Jul-Sep 2014, characterized by some storm events. Runs were simulated over the Arctic domain and, specifically, over the Kara Sea region using horizontal resolutions of ~12 and ~3 km. A scheme of the model domains is shown in Figure 1.

![Map of modelled domain boundaries. The base domain is cyan, and the nested domain is magenta.](Figure 1)

The focus of these experiments was to reproduce surface wind characteristics in the best way, especially near the shorelines during storm events. Different options of the experiments were used to
reveal the best COSMO-CLM model configuration, namely the “spectral nudging technique”, changing the time step and the nested domain area.

Verification of the wind speed was performed at 15 coastal meteorological stations of the Kara Sea and its surroundings based on the near-neighbour method and showed the best configuration of the COSMO-CLM with the “spectral nudging” technique, and reduced the model time step (not shown). This configuration did not show any significant improvement compared with some global reanalysis data (ERA-Interim [29], NCEP-CFSv2 [30] and ERA5 [31]), having the RMSE ~2 m/s, the bias ~0.2 m/s, and the correlation ~0.78. Analysis of the error probability distribution functions allows one to conclude that extreme wind speeds are reproduced better using finer resolution, and the average values remained at the same level. However, the statistics at individual stations has shown that those having maximal errors (e.g., Antipayuta, Dikson i., Malye Karmakuly) correspond to the worst reanalysis statistics, and wherein worser than the model. It means that in some cases the regional model captures the most intense wind speeds formed by mesoscale processes better over the 2-month averaging period. Taking into account this, we can consider the results of the model experiments as satisfactory and reasonable. However, the verification and detailed investigation of the model runs raise a question about the quality of this verification and how relevant are the wind station data in different coastline and relief conditions.

3. Results and discussion

3.1 Detailed analysis of experiments
An additional scale analysis of the case studies was carried out for different regions, from a synoptic overview to the influence of coastline configurations on different mesoscales. Malye Karmakuly (Novaya Zemlya island), Belyi Island and Dikson Island were considered as different examples with different conditions of obstacles overflow and their impact on the wind regime. The model wind speed outputs were investigated during the periods of storm events on 9–11 October, 2012 and 19–20 October, 2012. The “spectral nudging” and reduced time step model configuration is analyzed further as the best one according to the verification results (marked below as “sm+dr”).

First, we considered the Belyi Island region, where the station named Popova is located (Figure 2). The Belyi Island separated from the Yamal Peninsula by the Malygin Strait of about 10-km width is about 40 km across, the terrain is flat, and there are no uplands. The region was covered by strong southern winds ~15 m/s on 11 October, 2012 10 h GMT, established almost in the entire troposphere. The 3-km grid experiment analysis showed a slowdown of the flow over the island, and the wind shadow phenomenon occurred with a significant wind speed decrease (by 5 m/s and more) at the northern leeward island coast extended over the sea by 20–30 km. The island is framed by jets of different intensity and width (10–20 km). The model wind speed bias was 1-2 m/s and, therefore, the COSMO-CLM could capture the spatial scales of the island, changes in the surface type (land-sea), its impact on the wind field structure and the interaction with the sea.
Figure 2. Wind speed and direction at Popova station (Belyi Island) region on 10 October, 2012, 9 h GMT for experiment with ~3 km grid, “sn+dt”.

The relative vorticity pattern (Figure 3) drew attention due to elongated alternating bands of positive and negative values 100 km long and more, up to 10-km width. These bands are permitted by the given ~3 km grid, i.e. they could be determined by at least four grid points considering the relative vorticity calculation technique. An interesting feature is a manifestation of positive vorticity maxima at the eastern coast associated with a decreased wind speed module by the transition from the background sea flow to the shadow zone leading to intensification of the cyclonic vorticity. The existence of the elongated vorticity zones of opposite signs alternating inside the flow could be a manifestation of vortex chains.

Figure 3. Relative vorticity ($10^{-3}$ m/s$^2$) for experiment ~3 km grid “sn+dt” on 11 October, 2012 10 h GMT in Popova station (Belyi Island) region.
The wind behavior at the eastern Kara Sea coast is considered in the next example in the Yenisey Gulf region, with a large Sibiryakov Island and Dikson Island (3-4 km across). The latter is separated from the Taymyr Peninsula by a narrow strait of 1-2 km width (Figure 4). There is rocky terrain unlike the Belyi Island, but the altitude is low, up to 25 m. Steady strong southern winds 15 m/s and more were observed at the Dikson Island station on 19–20 October, 2012 for many hours within the layer up to 600 mb. This is caused by a dipole SLP structure including a cyclone centered over the Kara Sea and an anticyclone over the north of Eastern Siberia. The model has reproduced a strong airflow over the sea from the Yenisey Gulf disturbed by the wind shadow from the large Sibiryakov Island (the wind speed decreased by 10 m/s). One should note the wind shadow on the leeward side of Dikson Island (by 5 m/s).

![spectral nudging + dt experiment, 3 km, 19-Oct-2012 20:00:00](image)

**Figure 4.** The same as in Figure 2, for Dikson island, 19 October, 2012 20 h GMT.

A significant wind speed increase is observed in the Dikson Strait (more than 20 m/s) with a width of up to 10 km. Its formation is determined by a decline of the friction force there, as well as by rocky terrain at the coastal sites creating a peculiar “corridor”. It is notable that the stream is conserving its shape at the exit from the strait. The vorticity pattern analysis (not shown) showed the above-mentioned vorticity band alternation of opposite signs inside the flow. Cyclonic vorticity maxima are noted again at the eastern coasts of Sibiryakov and Dikson Islands. The reason is the same as for Belyi Island. However, the effect of the anticyclonic vorticity maximum appeared on the western coast of the larger Sibiryakov Island clearly.

The last example is the case study of strong winds at the western coast of Novaya Zemlya Island on 10 October, 2012 observed at the Malye Karmakuly station, which is well-known for maximal wind speeds over the Eurasian Arctic [32, 33]. This region is characterized by the presence of bays, bights, a rugged shore, and a mountain range of more than 700-m altitude with glaciers a few kilometers apart from the coast. Such terrain is favorable for katabatic stock winds and downslope windstorms formation (Novaya Zemlya bora), enhanced over different coastline sites.
The experiment with a ~3 km grid using the “spectral nudging” technique has given realistic results corresponding to measurement data at the Malye Karmakuly station. A maximum of modelled wind speeds of 25 m/s is observed over the whole length of the station bight (Figure 5) and is clearly manifested on the leeward slope. The wind speed pattern gets more patched, reflecting inhomogeneity of the background flow as well, as an influence of the complicated coastline configuration. One should note the absence of these effects in the ~13-km experiment, i.e. the model responded to a more detailed description of the surface. The wind shadow is not pronounced clearly. Streams of 10–20 km width could be registered, as in the previous examples, as well as areas of a significant decrease in the wind speed by 10–15 m/s, stretched along the river valleys. The latter is likely associated with ruggedness of the valleys, leading to a wind speed reduction.

![Figure 5](image_url). Wind speed and direction at Malye Karmakuly station region, on 10 October, 2012, 9 h GMT for ~3 km experiment, *_sn_dt.*

The relative vorticity pattern is given in Figure 6. The cyclonic and anticyclonic vorticity areas are well seen with horizontal scales of 10 – 30 km around and a strong vorticity gradient over land corresponding to stock downslope winds, apparently. Linearly stretched vorticity zones of the same sign are well manifested again of more than 100 km length and ~10-15 km width, probably enhanced by tip jets. Vorticity bands could also be traced in the river valleys. In this way, the transition to a more detailed surface description played a key role in approach of the model simulation to a realistic pattern. The model was capable of reproducing a downslope windstorm, although the physical mechanisms responsible for the bora phenomenon are implemented in the model not completely using the given resolution.
4. Conclusions and perspectives

The principal task of this research was to estimate the capability of the mesoscale model COSMO-CLM to reproduce the sophisticated atmospheric circulation features related to surface properties that impact the airflow. The investigation was focused on the mesoscale processes developed in the atmosphere by the influence of obstacles such as islands and moderate mountainous terrain. Wind shadows, channel winds, rotation vortices, tip jets, downslope windstorm features, propagation of atmospheric gravity waves were revealed using a spatial scale and vorticity analysis. The capability of the model to reproduce such patterns reliably and physically including extreme winds is a real help to further investigations in the area of physical description of these objects by applying different hydrodynamical parameters.

Quantitative assessments of the features of mesoscale circulations showed a significant influence of the shore, relief, and bathymetry conditions on the mesoscale wind and wave characteristics near the coastline. This analysis raised an important question about the reliability of coastal wind observations depending on local geographical conditions and has shown a need to better predict these circulations by using numerical modelling.

It should be noted that the high-resolution model COSMO-CLM creates a realistic pattern at the expense of an imitation of the mechanisms defined by the parameterizations of subgrid processes. Mesoscale modelling could be a reliable source of information about the mesoscale circulations in sparse observation network conditions in the Arctic. Regional climate models with a horizontal grid step of about a few kilometers could be used in the future to carry out an adequate wind climatological assessment of high resolution in conditions of absence of other hydrometeorological information sources. These studies could have wide applications to estimate and detail the observed Arctic climate changes. This work will be continued in this direction, with study of the above-mentioned quantitative parameters of mesoscale effects, assessment of coastline characteristics, and terrain impact on wind properties, etc.
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