Mesoscale high-resolution modeling of extreme wind speeds over western water areas of the Russian Arctic

Vladimir S Platonov and Alexander V Kislov

Lomonosov Moscow State University, Faculty of Geography, Department of Meteorology and Climatology. 119991, Moscow, Leninskie Gory MGU, 1, GSP-1

vplatonov86@gmail.com, avkislov@mail.ru

Abstract. A statistical analysis of extreme weather events over coastal areas of the Russian Arctic based on observational data has revealed many interesting features of wind velocity distributions. It has been shown that the extremes contain data belonging to two different statistical populations. Each of them is reliably described by a Weibull distribution. According to the standard terminology, these sets of extremes are named ‘black swans’ and ‘dragons’. The ‘dragons’ are responsible for most extremes, surpassing the ‘black swans’ by 10 – 30 %. Since the data of the global climate model INM-CM4 do not contain ‘dragons’, the wind speed extremes are investigated on the mesoscale using the COSMO-CLM model. The modelling results reveal no differences between the ‘swans’ and ‘dragons’ situations. It could be associated with the poor sample data used. However, according to many case studies and modeling results we assume that it is caused by a rare superposition of large-scale synoptic factors and many local meso- and microscale factors (surface, coastline configuration, etc.). Further studies of extreme wind speeds in the Arctic, such as ‘black swans’ and ‘dragons’, are necessary to focus on non-hydrostatic high-resolution atmospheric modelling using downscaling techniques.

1. Introduction

Investigation and modelling of the extreme wind velocities conditions in Arctic is presently one of the most important tasks for the purposes of ensuring the safety of infrastructure (the increasing exploration Arctic offshore oil and gas fields, development of navigation over the Northern Sea Route) and accompanying port facilities. In the maritime sectors, the extremes of low-level winds can generate huge oceanic waves and storm surges that consequently may lead to the damage of marine structures (ships, drilling platforms) and coastal erosion. This is especially the case during the cold period in the Arctic, where regular events of intense wind velocities are typically observed. The quantitative analyses and modelling of spatial variation of extreme wind patterns are important for effective wild fire management and sustainable long-term urban development on fire-prone landscapes. It is therefore worthwhile to properly assess the distribution of wind extremes and their origin.

The main features of wind conditions over Arctic basin are described in [1]. Particularly, the duration of periods when the wind speed doesn’t exceed 15 m/s, is about 3 – 6 days in winter months. Then, the stormy weather much of time is prevailing over the Arctic basin, therefore it is very important to develop methods of an accuracy extreme wind conditions forecasting.

Analysis and forecast of the main hydrometeorological fields are frequently not fully adequate to the observations. In [2] it were compared different reanalyzes at meteorological stations north of 60° N
and shown that over the most points errors are considerable and correlation coefficients are not significant. These conclusions are confirming a necessity and relevance of regional atmospheric modelling over the Arctic region using high-resolution techniques for purposes of reproducing extreme wind patterns.

2. Data and methods

2.1. Study area and data description
Wind velocity at the boundary layer has strong spatio-temporal variability, therefore its correct simulation is still associated with significant errors. It is especially relevant to Arctic seashores with complicate surface and to poor data areas. There are many papers dedicated to the wind extremes’ climate analysis as well as to an estimation and reproducing of wind speed extremes in the long-term datasets. Thus, [3] considered the 23-year dataset of wind speed and sea waves and concluded that wind extremes are underestimated by method of a sampling peaks above a certain threshold. [4, 5] estimated the NARR reanalysis over the USA Arctic region and inferred that 95th percentile increased from 7 m/s in 1979 to 10.5 m/s in 2009.

Many studies [6, 7, 2, 8] have shown a definite advantage of mesoscale atmospheric models in the reproduction of wind velocity pattern against the most modern reanalyses. Cited papers noted that decreasing of horizontal resolution of the regional atmospheric models (e.g., WRF or HIRHAM [9]) brings the wind speed spectra closer to the well-known “-5/3” law, however there are significant underestimations of the wind speed on mesoscale comparing to the observations. Nevertheless, the mesoscale modelling demonstrates more adequate description of the extreme wind field patterns comparing to reanalyses definitely.

This study was performed over the Arctic region from the Kola Peninsula until Chukotka Peninsula including both coastal area (predominantly) and inland territory. Strong wind speed events are often noted in the region in the cold time of year during the passage of meteorological synoptic storms. Wind speeds of more than 30 m/s are observed during this time over the marine surface, inducing high waves of more than 4 m. A dataset of observed hourly 10-minute mean wind speed data from stations was obtained, with the record period varying from station to station. For the present study, we used the period 1966-2013, which was covered by data of 40 Russian stations.

2.2. Statistical methods and data analysis features
Research in the statistical analysis of extreme values has flourished over the past several decades: new probability models, inference and data analysis techniques have been introduced; and new application areas have been explored [10 – 12].

Extreme value analysis of wind speeds ($U$) is generally performed through implementation of the following idea. Beginning with a parent distribution whose cumulative distribution function (cdf) is $F(U)$, the distribution is sampled $n$ times, and the maximum value of the $n$ samples is obtained. This maximum value has a cumulative distribution function of its own of simply $F^*(U)$. This relationship leads to the extreme value theory noted by Fisher and Tippett [13] that for sufficiently long sequences of independent and identically distributed random variables, the maxima of these sequences can be fit to one of three limiting distributions. This result has been quantitatively refined by Gnedenko [14]. One representative of these three limiting distributions is the Weibull distribution, which has traditionally been used for the statistical modelling of wind extremes (see [15]).

In another approach, the Pareto distribution is applied to the peaks of independent storms that exceed a sufficiently high threshold (see [15] and [16]).

Statistical method of the extreme value analysis of wind speeds is important because it allows us to detect their statistical model. Note that the same statistical distribution suggests a common originating mechanism. We plan to use such idea to interpret of the extreme wind records.

It is a condition of extreme value analysis that the extremes selected for examination have to be independent. Annual (or seasonal) maximum wind speeds chosen from each year are statistically
independent. However, when several data points are taken from each season, there may well be several clustered maximum speeds from a single storm. Such events are unlikely to be statistically independent. Various strategies are invoked to remove dependent events before proceeding with a statistical analysis. A simple method is to require a minimum time separation or “deadtime” between selected events. Working with Arctic wind climate, we use the autocorrelation coefficient $r(t)$ to establish a “deadtime” between consequent wind fluctuations. Its value is a measure of the correlation of neighbouring wind events. It was shown to be less than 0.05 for $r$ equal to 48 or 72 hours. Therefore, we use a “deadtime” of 72 hours. The same values (48 – 60 h) were used earlier [17 – 19].

There were revealed many interesting features of wind velocity statistical distribution. In figure 1 we plot several empirical cdfs on the bases of station measurements. Configuration of empirical points in the form of columns is determined by the fact that the data are quantized due to specified accuracy of measurement. Pictures are the “Weibull Plots”, which are a specific nonlinear transformation of the data, and a straight line is recovered if the sample is Weibull. We can see that at all sites, we found that the empirical cdfs consistently deviate from the theoretical line starting with certain large threshold values ($U_{th}$). This deviation means that the standard Weibull model doesn’t describe the empirical cdf, starting from a certain threshold $U > U_{th}$. In this way, the greatest extremes namely, which are the most important, should to be described by some other law, not by the standard Weibull distribution.

Note additionally that application of a sufficiently high threshold and, consequently, detection of especially high wind speeds allows us to describe for their approximation the peaks-over-threshold modelling approach, using the Pareto distribution. It has a cumulative distribution function

$$\Phi(U) = 1 - \left(\frac{U_{th}}{U}\right)^\gamma$$  \hspace{1cm} (1)

It is worth mentioning here that the threshold value is not assigned a priori (as is usually done [16]), but is explicitly estimated previously.

Generally, the implemented analytical approach allows us to detect that the majority of extreme wind speed events (below the threshold value) adhere to the Weibull distribution. The same statistical distribution of population could be considered a result of the same organization principle, and this suggests a common generating mechanism for each representative of this population. This idea allows us to understand that a large extreme is not distinguished from its small siblings apart from its large power. The occurrence of large extremes looks like the appearance of a few black swans in a flock of white swans. This terminology was introduced by N N Taleb [20], as a metaphor to describe an event that comes as a surprise.

![Figure 1](image1.png)

Figure 1. Empirical cumulative distribution functions of wind speed maxima (station observations, cold period) for 72 hours’ time step records straightening on the coordinate axis of the Weibull distribution, and linear regression line corresponding to the Weibull function for station Teriberka.
However, there are extreme wind speed events located above the threshold value that are much more pronounced than predicted by the extrapolation of ‘black swans’ law distributions in their tail. They adhere again to the Weibull distribution. Such events were termed ‘kings’ (taking into account the special position of the fortune of kings, which appear to exist beyond the Zipf law distribution of the wealth of their subjects [21]) or ‘dragons’ (to stress that we address a completely different, beyond the normal, type of animal). D. Sornette [22] introduced the concept of ‘dragon-kings’ to refer to such extreme events. The same statistical distribution suggests a common generating mechanism different from that responsible for extrema at $U \leq U_{th}$.

It is not clear to what extent such excessively metaphoric terminology is required for our case because it was originally introduced to describe unique extraordinary events. However, it allows us to mark events that adhere to different Weibull distributions. Therefore, we will use below these terms: ‘swans’ or ‘black swans’ (hereafter BSs) and ‘dragons’ (hereafter the Ds).

2.3. Global climate models estimation
The next step of our analysis was to investigate to what extent the above-mentioned peculiarities of wind extremes are simulated by climate models. We analysed a dataset of wind simulation of the INM-CM4 climate model [23–25]. The establishment of the correspondence between wind simulation products and near-surface observations could help us to assess the quality of modelling products and their capability to reproduce the wind extremes. Apart from that, it is important to advance our understanding of the origin of the BSs and the Ds.

According to cdfs on the bases of the INM-CM4 simulations we concluded that the Weibull distribution is a good approximation of the modelled wind speed extremes. We found very small deviation in cdfs from the theoretical line starting with certain large threshold values. Keeping in our mind that noticeable deviation was a typical feature of empirical cdfs and using our terminology, we can conclude that the INM-CM4 model wind speed extremes are the BSs and there are no the Ds.

This conclusion is supported not only by the specific location of points along a theoretical line but also by the fact that modelled wind speed extremes themselves are close to observation data adhering the BSs besides the Zimnegorsky Mayak data and the Teriberka data, where observed $U(0.99)$ are almost half times greater than modelled values. Probably, this is due to inadequate distribution of land and sea in the INM-CM4. Their geographical peculiarities are the same (the maxima are at the coastal area).

2.4. Regional model and experiments description
The discovered phenomenon of the absence of the representatives of the Ds in modelling data is very important. It means, the global climate models are not capable to reproduce many processes and effects responsible for the extreme wind cases referred to Ds type formation. Therefore, an investigation and analysis of BSs and Ds phenomena is appropriate to carry out on the mesoscale. Since the mesoscale hydrodynamic atmospheric modelling with high resolution is the widespread method of an investigation of detailed structure of meteorological fields including wind speed, we have tried to estimate possible genetic differences appearing in Ds and BSs cases using the regional model. We have sorted out from many numbers of these cases a few ones to execute the model experiments for the following dates: 15 – 17.12.1997, 29 – 30.10.2000, 26.01.2002, 12.12.2013 (see Table 1). The period of each experiment was about 7 days with the extreme event in the middle of period.

In this study, we have used the climate version of COSMO model (COSMO-CLM). It is well-known non-hydrostatic regional atmospheric model developed by German Weather Service (DWD) and CLM-Community (see CLM Community site [26, 27]). COSMO-CLM model is based on the primitive Navier-Stokes equations describing the dynamics of compressible fluid in the moist atmosphere. Model equations are solving on the rotational grid ‘latitude-longitude’ $(\lambda, \varphi)$ with pole tilt. It helps to minimize the problem of meridians convergence.
over the pole. The numerical scheme is realized on Arakawa C-grid, the vertical coordinate is hybrid Gal-Chen coordinate.

Table 1. Dates of extreme wind speed cases used for performed experiments.

| ‘BSs’        | ‘Ds’        |
|--------------|-------------|
| 15.12.1997   | 17.12.1997  |
| 29 – 30.10.2000 | 12.12.2013  |
| 26.01.2002   |             |

Model runs were performed for the unified large domain with spatial resolution of 0.12°, covered the Barents Sea, part of Kara Sea, northern European territory of Russia and the surrounding water areas. Driving conditions came from ERA-Interim reanalysis (~0.75° resolution). After that, the downscaling technology was performed for the different ‘small’ domains (resolution about ~2.8 km), inside the ‘large’ domain (see figure 2). Information about parameters of experiments is shown in the Table 2. Standard configuration of COSMO-CLM model (version 5.0) was applied: Runge-Kutta integration scheme with 5th advection order; 40 vertical levels; prognostic TKE-based scheme for turbulence. More detailed description of COSMO-CLM model parameterizations could be found in the COSMO Model documentation (http://www.cosmo-model.org/content/model/documentation/core/default.htm).

Figure 2. Model domains used in experiments and meteorological stations used for verification.

Table 2. Main parameters of the performed experiments.

| Parameters of experiments | Two model domains using downscaling |
|---------------------------|------------------------------------|
| Experiment’s duration     | Approx. 7 days (extremes ~in the middle) |
| Horizontal resolution     | 0.165° (~18 km) 0.025° (~2.8 km) |
3. Modelling results and discussion

3.1. Modelling results

Considering the main modelling results for extreme wind speed cases, it should be noted that COSMO-CLM model reproduced the common atmospheric patterns and the dynamics of synoptic-scale processes very well for all cases. It was revealed by comparison modelling results with the weather charts.

Figure 3. Sea level pressure and wind direction patterns on 12.12.2013, 06 UTC (hPa, left top), wind direction and gusts (m/s, right top), detailed map (bottom).

Further, we'll consider the reproducing of atmospheric circulation during different situations. In case of 29 – 30.11.2000 there are occurred an increasing of wind speed over the southern edge of Novaya Zemlya Island and in the Kara Strait. On the northeastern periphery of the moderate cyclone moved over the south of the Barents Sea. The strong northeastern winds were quasi-parallel to the strait, and initiated katabatic accelerations and wind gusts over the south-western coast of Novaya Zemlya. The mean wind velocities in the strait came to 20 m/s, gusts were up to 24 – 26 m/s. The wind pattern over the seashores is spotted and striped and associated with the mesoscale effects, such as a hydrodynamic impact of land and increasing of velocity over the strait, obviously.

The next situation, on 12.12.2013 (see figure 3) was characterized by the maxima wind speed among the examined and one of the best reproduced by model. The strong cyclone with the 965 hPa isobar minima at the center, displaced from the NW to the SE of the Barents Sea, and highly condensed isobars located quasi parallel to the coastline. This combination of factors and the long maintenance of this situation could lead to formation of outstanding extreme wind speed values, exceeded 30 m/s in averages and 35 m/s in wind gusts. Wherein, the maxima wind area continued for
many hundreds kilometers to the sea. More detailed map demonstrates (see figure 3) very significant wind shear near the coast: from 12 to 20 m/s in average velocities, from 26 to 32 m/s in gusts.

The next investigated case refers to 26.01.2002. The intense cyclone shifted over the north of the European Russia. Coupled with a strong pressure gradient it led to increasing of wind speed up to 22 – 24 m/s on the Barents Sea coast and up to 30 m/s on the White Sea coast. This case was reproduced by model with many significant errors: the correlation coefficient was 0.64, mean and RMS errors exceeded 4 m/s as on coarse as on high resolutions.

The last considered case is perhaps the most interesting, because there were two consequent extreme situations during three days, relating to the two different types: BSs and Ds. There are 15.12.1997 and 17.12.1997, respectively (see figure 4). The strongest anticyclone on the south, extreme pressure gradient and isobars quasi-parallel to the coastline – these factors combined to the super extreme situation. It was enhanced by its long duration, evolving, and moving the cyclone to the east. As a result, the wind speed maxima was observed over the narrow coastal band few tens of kilometers wide. The average wind speeds exceeded 30 m/s. This case was sufficiently reproduced by model with the both resolutions.

3.2. Error statistics analysis and discussion

We have done an elementary verification according to the simple method of comparison observational data with modelling results. It is the ‘nearest neighbor’ method without any interpolations, weighting coefficients etc. Many errors statistics for each case study, namely correlation coefficients, mean and median errors, RMSE, standard deviations are listed in the Table 3. We can see there are no significant differences in errors between coarse and high resolutions, except the mean errors. It could be associated with the used estimation method. In general, the COSMO-CLM model reproduces the synoptic-scale dynamics and general synoptic-scale wind velocity patterns well as both with the coarse (18 km), and high resolutions. Model with 2.8 km resolution succeed to reproduce detailed spotty wind pattern, caused by local orography or/and dynamic factors.

**Table 3.** Error statistics for performed experiments (meteostation Teriberka).

| Experiment | statistics | Correlation coefficient | Mean error | Median error | RMSE | STD |
|------------|------------|-------------------------|------------|--------------|------|-----|
| 2013 18 km |            | 0.90                    | -1.49      | -1.00        | 3.63 | 3.34 |
There are many features by interpretation and estimation these statistics results. COSMO-CLM model with 2.8 km resolution succeed to reproduce the detailed extreme wind speed pattern, caused by local orography and dynamical factors, usually. On the one hand, the model underestimates the real observed average wind speeds and gusts on the seacoast by 4 – 5 m/s systematically. On the other hand, these extreme velocities of air particles (20 m/s) doesn’t make a certain physical sense to estimate model errors at the certain station point. We have to take into account that during 10 minutes of the average wind speed measurement the air particle could be moved on many kilometers or a few tens kilometers from sea to the land, i.e. many model grid points. Therefore, we should in future estimate wind velocity values for some surrounding area, according to the distance, corresponding to wind velocities. Taking into account these reasons, we can ascertain, that COSMO-CLM model reproduces wind velocity pattern quite adequately, but using the resolution 5 km and less, only.

### 4. Conclusions

Extreme value analysis has been implemented to estimate the statistical properties of extreme wind speed over the European and Siberian parts of Arctic region from the Kola Peninsula to the Chukotka Peninsula.

It was shown that for all stations a volume of observed samples of extreme wind speed are composed of two sets of variables. All samples of each population have the same statistical properties but one population is sharply different from another. So different origin of strong wind events adhering to two groups can be concluded. Using metaphoric terminology, we marked these events as the ‘black swans’ (BSs) and the ‘dragons’ (Ds). However, the global climate model extreme wind speeds dataset (INM-CM4 data) consist of only the BSs. Therefore, we have applied the mesoscale nonhydrostatic climate model COSMO-CLM to reproducing and investigation the physical mechanisms of BSs and Ds formation.

Analyze has shown that model reproduces the synoptic-scale dynamics and general synoptic-scale wind velocity patterns well as both with the 18 km, and 2.8 km resolutions and, in general, simulates wind speed quite adequately.

With respect to revealing many differences between ‘BSs’ and ‘Ds’ situations, there were found no clear distinctions. It could be associated with a poor sample of cases. Based on examined cases, we can assume it caused by the rare overlay of large-scale synoptic factors (strong pressure gradient, orientation of the isobars with respect to coastline) and many local meso- and microscale factors (surface, coastline configuration etc.). In the future, further studies of the extreme wind speeds genesis in the Arctic, such as the ‘black swans’ and ‘dragons’, urged to focus on nonhydrostatic high-resolution modeling using downscaling techniques.

### Acknowledgements

Funding for this research was provided by grants from the Russian Science Foundation (Grant No. 11.G34.31.007) and Grant from the Academic Council of Faculty of Geography, Lomonosov Moscow State University.

### References

[1] Reference data on the wind and waves regime of the Barents, Okhotsk Sea and Caspian Sea (In Russian). Ed. by Lopatukhin L, Bukhanovsky A, Degtyarev A, Rozhkov V 2003 SPb Russian Maritime Shipping Register p 213
[2] Lindsay R, Wensnahan M, Schweiger A, Zhang J Evaluation of seven different atmospheric reanalysis products in the arctic. 2014 J. Climate 27 2588 – 606

[3] Vinoth J and Young I Global estimates of extreme wind speed and wave height. 2011 J. of Climate 24 1647–65

[4] Stegall S, Zhang J Wind field climatology, changes, and extremes in the Chukchi–Beaufort Seas and Alaska North Slope during 1979–2009. 2012 J. of Climate 25 8075–89

[5] Hundecha Y, St-Hilaire A, Ouarda T, El-Adlouni S, Gachon P Nonstationary extreme value analysis for the assessment of changes in extreme annual wind speed over the Gulf of St. Lawrence, Canada. 2008 J. of Appl. Met. And Clim. 47 2745–59

[6] Frehlich R and Sharman R The use of structure functions and spectra from numerical model output to determine effective model resolution. 2008 Mon. Wea. Rev. 136 1537–53

[7] Larsen X, Ott S, Badger J, Hahmann A, Mann J Recipes for correcting the impact of effective mesoscale resolution on the estimation of extreme winds. 2012 J. of Appl. Met. And Clim. 51 521–33

[8] Skamarock W Evaluating mesoscale NWP models using kinetic energy spectra. 2004 Mon. Wea. Rev. 132 3019–32

[9] Bøssing Christensen O, Drews M, Hesselbjerg Christensen J, Dethloff K, Ketelsen K, Hebestadt I, Rinke A The HIRHAM Regional Climate Model. Version 5 (beta). 2007 Danish Climate Centre Danish Meteorological Institute p 22

[10] Beirlant J, Goegebeur Y, Segers J, Teugels J, De Waal D, Ferro C Statistics of extremes: theory and applications. 2004 (Wiley Series in Probability and Statistics, John Wiley & Sons Ltd., Chichester)

[11] Coles S An introduction to statistical modeling of extreme values. 2001 (Springer Series in Statistics, Springer-Verlag)

[12] de Haan L and Ferreira A Extreme value theory: an introduction. 2006 (Springer Series in Operations Research and Financial Engineering, Springer)

[13] Fisher R and Tippett L Limiting forms of the frequency distribution of the largest or smallest members of a sample. 1928 Proceedings of the Cambridge Philosophical Society 24 180-90

[14] Gnedenko B Sur la distribution limite du terme maximum d'unésériéaleatoire. 1943 Annals of Maths. 44 423-53 (In French)

[15] Palutikof J, Brabson B, Lister D, Adcock S A review of methods to calculate extreme wind speeds. 1999 Met. Appli. 6 119-32

[16] Brabson B and Palutikof J Tests of the generalized Pareto distribution for predicting extreme wind speeds. 2000 J. of App. Met. and Clim. 39, 1627-40

[17] Coles S and Walshaw D Directional modelling of extreme wind speeds. 1994 J. of the Roy. Stat. Soc. Series C (App. Stat.) 43 139-57

[18] Cook N The designer's guide to wind loading of building structures. Part 1: Background, damage survey, wind data and structural classification. 1985 (Building Research Establishment. Garston and Butterworths, London)

[19] Gusella V Estimation of extreme winds from short-term records. 1991 J. of Struc. Engin. 117 375-90

[20] Taleb N The black swan: The impact of the highly improbable fragility. 2010 (New York, Random House) p 300

[21] Laherrère J and Sornette D Stretched exponential distributions in nature and economy: fat tails with characteristic scales. 1999 The Eur. Phys. J. B 2 525-39

[22] Sornette D Dragon-Kings, Black Swans and the prediction of crises. 2009 Int. J. Terr. Sci. and Engin. 2 1–18

[23] Volodin E, Diansky N, Gusev A Simulating present-day climate with the INMCM4.0 coupled model of the atmospheric and oceanic general circulations. 2010 Izv. Atmos. Ocean. Phys. 46 (4) 414–431
[24] Kislov A, Matveeva T An extreme value analysis of wind speed over the European and Siberian parts of Arctic region. 2016 *Atm. and Clim. Sci.* 6 205-23

[25] Kislov A, Matveeva T, Platonov V Wind speed extremes in Arctic area. 2015 (In Russian) *Fund. and Appl. Clim.* 2015 2 63–80

[26] Böhm U, Kuecken M, Ahrens W, Block A, Hauffe D, Keuler K, Rockel B, Will A CLM – the climate version of LM: brief description and long-term applications. 2006 *COSMO Newsletters* 6 225–35

[27] Rockel B, Will A, Hense A The regional climate model COSMO-CLM (CCLM). 2008 *Met. Zeit.* 17 4 347–48