

Spatial distribution of extreme wind speeds over Sakhalin Island based on observations and high-resolution modelling data

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Abstract. An analysis of extreme wind speeds over Sakhalin region shows that a set of wind speed extremes obtained from observations is a mixture of two different subsets, each of them neatly described by a Weibull distribution. The empirical tail of the pdf diverges from a linearized Weibull model, indicating that another model could fit the most extreme wind speed data better. Each of these subsets is characterized by parameters k and A , regarded as coefficient and free terms of the linear Weibull model, these samples are labelled BSs and Ds. The Ds are responsible for the strongest extremes. Mesoscale modelling is used to investigate a possibility of the models to reproduce these statistical features. A detailed hydrodynamic simulation of major meteorological parameters (1985 – 2014) has been performed for the Sea of Okhotsk and Sakhalin Island with horizontal resolutions of ~ 13.2 , ~ 6.6 , and ~ 2.2 km by using a regional climate model, COSMO-CLM. This dataset is utilized for an investigation of the statistical structure of extreme wind speeds. First, it is shown that a model with a detailed spatial resolution is able to reproduce the statistical structure in general, and a special mechanism is responsible for the generation of the largest of wind extremes. However, a model with a resolution of ~ 13.2 km could not reproduce some essential parts of the wind speed maximum statistical properties, underestimating the parameters k and A of Ds Weibull distribution significantly. This gap could be covered by using a higher resolution, as well as by areal estimation techniques and many others.

1. Introduction

In this paper, we focus on statistical analysis of extreme wind events. Statistical methods of the extreme value analysis of wind speeds are important not only due to their practical value, but also because they allow us to detect their origin, since the same statistical distribution very often suggests a common originating mechanism. From this point of view, it is substantial to understand an extension of the ability of reproduction of wind speed extremes by atmospheric models. Establishment of the correspondence between wind simulation products and observations could perform the assessment of this reproduction and ability. The use of station data will make it possible to evaluate the consistency, in terms of reproduction of the statistical behavior, between the model simulation products and near-surface observations. Studying the statistical properties of extrema, determining their genesis and mechanisms are the basis for constructing a model of complex extreme hydrometeorological phenomena. Wind speed extremes in the sub-Arctic realm of the North-East Pacific region were investigated by extreme value analysis of wind speed obtained from atmospheric simulations of the COSMO-CLM mesoscale model, as well as using observational data.

In our previous paper we analysed datasets of wind observations over the Eurasian part of the Arctic region [1]. Extreme value analysis showed that the observed samples of wind speeds are strictly divided into two sets of variables. Moreover, this feature is marked out at many stations both for the summer and winter seasons [2]. Events exceeding the threshold value are much more pronounced than



the members of the other group (located below the threshold value) predicted by the extrapolation of law distributions to their tail. The situation is the same in different areas of science where the data referring to the same nomenclature adhere to different statistical models. They were termed “Black Swans” (BSs) [3] and “Dragons” (Ds, or “kings”) [4]. This result motivates our interest in the ability to detect, analyze, and understand such different extremes and their nature.

In this paper we extend the analysis of extreme wind speed events in the Sub-Arctic region. The next step of our analysis is an investigation of the above-mentioned peculiarities of wind extremes simulated with a fine spatial resolution by a mesoscale atmospheric model. We used the COSMO-CLM regional climate model developed within the framework of the Consortium for Small-scale Modeling (<http://www.cosmo-model.org>) and CLM-Community (<http://clm-community.eu>).

2. Data and methods

2.1. Weibull distribution approach

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 [5 – 7]. The statistical method of 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 this idea to interpret extreme wind records. In the extreme value theory, it was noted [8] that for sufficiently long sequences of independent and identically distributed random variables the maxima of wind speed samples can fit one of three limiting distributions. One representative of these three limiting distributions is the Weibull distribution, which has traditionally been used for the statistical modelling of wind extremes [9]. In this study we model empirical extremes by the Weibull cdf using the following form:

$$\frac{n}{N} \approx F(U) = 1 - e^{-AU^k}. \quad (1)$$

This expression can be replaced by

$$\ln \left[-\ln \frac{N-n}{N} \right] = k \ln U + \ln A. \quad (2)$$

Thus, this expression allows one to represent the empirical function in the linear Cartesian coordinates of the Weibull distribution (‘Weibull plots’). The model parameters (A and k) can be estimated by using the maximum likelihood approach. The coefficient of determination (R^2) was calculated to estimate the success of linear approximation.

It is also an important condition of extreme value analysis that the extremes selected have to be statistically independent. However, 3-hourly observational data could have several clustered maximum speeds from a single storm and, therefore, such events are unlikely to be statistically independent. A simple method to remove the dependence is to require a minimum time separation or “deadtime” between the selected events, which is equivalent to e-folding time of the autocorrelation function. It was shown earlier that this time is equal to 48 – 72 hours and, therefore, we used a “deadtime” of 72 hours. Moreover, the principal differences between the atmospheric circulation regimes were taken into account. Thus, the summertime and wintertime extremes were analyzed separately and statistically independent. The summer season was defined as June–September and the winter one, as November–March considering monsoonal circulation conditions over the Okhotsk Sea and Sakhalin Island regions.

Many interesting features were revealed in our previous work, concerning the cdf form of wind speed extremes [1, 2, 10]. We found that the empirical cdfs of wind speed extremes at all Russian Arctic stations consistently deviate from the theoretical line starting with certain large threshold values (U_{th}). This deviation means that the standard Weibull model does not describe the empirical cdf starting from a certain threshold $U > U_{th}$. In this way, the greatest extremes, namely, which are most important, should be described by some other law, but not by the common Weibull distribution. The shape of the curve suggests that the sample is composed of two sets of variables, each of them described by its own Weibull function. Very large R-squared values in all cases show great success of

this approximation. The coefficients of regression equations allow us to estimate the parameters k and A in each case. A more detailed description of the Weibull distribution splitting and its application to wind speed extremes data over the Sakhalin island is given in [1, 11]. Finally, the first sample obeying the common Weibull distribution was named “Black Swans” (BSs) according to the metaphorical terminology from [3]; most extremes not obeying the common Weibull distribution were called “Dragons” (Ds) according to [4]. It is worth noting that the coefficients k and A of the Weibull distribution differ significantly in these splitting samples and should be investigated further in observational and modelling data.

2.2. Description of the atmospheric model

We used a wind simulation dataset of the COSMO-CLM regional model for 1985 – 2014 [12, 13] as a source of model data. The COSMO-CLM model was applied as a detailing tool of the reanalysis data. The regional COSMO-CLM model was developed by the CLM-Community (<http://clm-community.eu>) [14]. Dynamic downscaling during the COSMO-CLM simulation was performed through three domains in a nesting scheme (Figure 1). The outer, ‘basic’ domain (grid spacing: ~13.2 km) covers the Sakhalin Island, the Sea of Okhotsk, the Kamchatka Peninsula, the surrounding regions of the Pacific Ocean, and the Asian continent. The model output on the outer domain provides meteorological fields at the lateral boundaries of the intermediate domain (grid spacing: 6.6 km), and the latter, in turn, provides output at the lateral boundaries of the inner domain (grid spacing: 2.2 km). 40 model levels were applied in the vertical direction for the basic and intermediate domains and 50 model levels, for the inner domain. In this paper we will consider model data and statistical analysis over the basic domain only. The experience of the authors in the creation of such a long-term atmospheric model archive based on supercomputer technologies is described in [15].

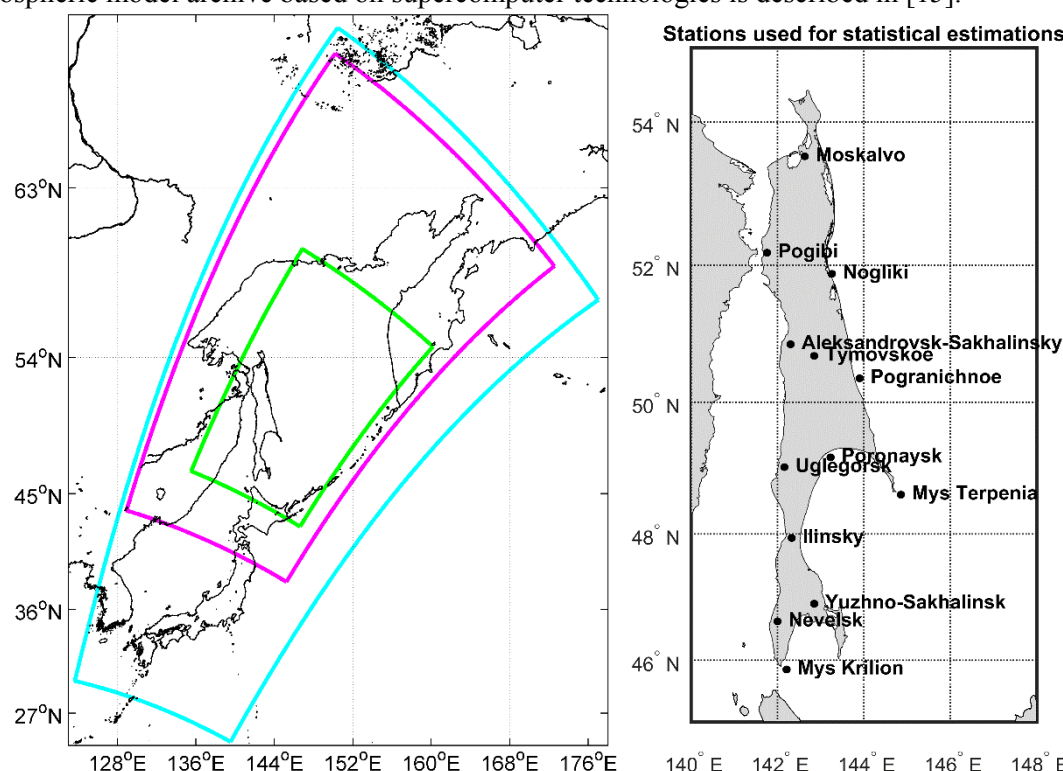


Figure 1. Left: map of the boundaries of model domains with a grid spacing of ~13.2 (cyan), ~6.6 (magenta), and ~2.2 km (green). Right: map of meteorological stations used for statistical analysis.

The COSMO-CLM model based on fully compressible fluid non-hydrostatic equations (Reynolds equations) was realized on a staggered Arakawa grid-C [16]. The COSMO-CLM uses a hybrid Gal-

Chen vertical coordinate system represented as the sigma-coordinate from the surface to the level (Z_F), and as the Z-coordinate above Z_F [17, 18]. The physical parameterizations chosen for the COSMO-CLM are based on extensive development and testing of the COSMO-CLM over a wide-range of Arctic environments [19 – 22]. We used the Tiedtke scheme [23] for the parameterization of convection, the two-stream Ritter-Geleyn [24] radiative transfer model, and the Mellor–Yamada 2.5–level planetary boundary layer and complementary surface layer schemes [25]. More detailed documentation can be found on [\[http://www.cosmo-model.org/content/model/documentation/core/default.htm\]](http://www.cosmo-model.org/content/model/documentation/core/default.htm).

The initial and lateral boundary conditions for the outer domain in the COSMO-CLM are provided by ERA-Interim reanalysis [26] for each 6 hours during 1985 – 2014. To avoid the model drift in the atmospheric circulation, the spectral nudging technique [27, 28] was implemented for temperature, geopotential height, and wind components above 850 hPa in the outer domain. We used the wavenumber 11 to take into account the large-scale synoptic processes (wavelengths: > 1000 km) only. The time output in the entire experiment (1985 – 2014) was 1 hour for all variables. More detailed information about this long-term detailed archive and its verification on observational data can be found out in [12].

3. Results and discussion

3.1. Statistical features in observational data

Figure 2 gives an example of empirical cdfs based on station measurements plotted in the ‘Weibull’ linear coordinates. We found that the empirical cdfs deviate consistently from the theoretical line starting with certain large threshold values (U_{th}); it is typical for all sites. This means that the empirical tail diverges from the Weibull model, indicating that a different model might describe the data well. This is exactly the situation discussed above in Section 2.1. Therefore, we can approximate the common cdf as two different samples, describing each of them by their own Weibull distribution parameters (Figure 3). There are very large R-squared values at all sites ($R^2 > 0.9$ in almost all cases), and the linear terms of the approximation equation give the Weibull parameters k and A for each station and season.

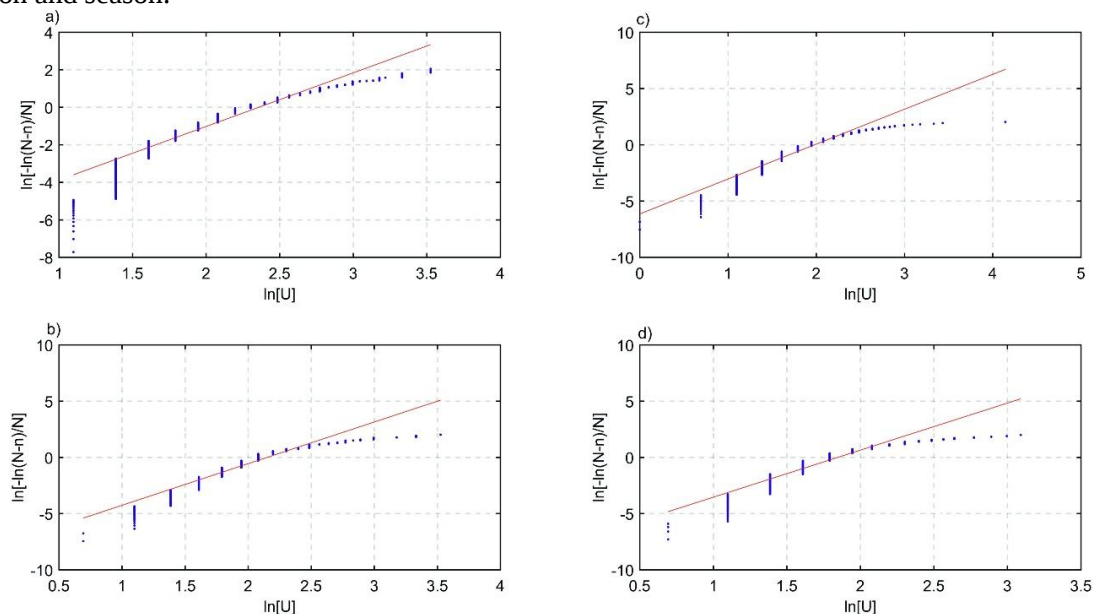


Figure 2. Cumulative distribution functions of wind speed maxima (station observations) in the linear coordinate axis of the Weibull distribution, and linear regression line corresponding to the Weibull function. (a), (b): Aleksandrovsk-Sakhalinsky (winter and summer seasons); (c), (d): Yuzhno-Sakhalinsk (winter and summer seasons).

The Kolmogorov-Smirnov (K-S) test was used to determine whether or not these separated samples referred to the Weibull distribution [1]. It was concluded that in both cases ($U > U_{th}$) and ($U < U_{th}$) the Weibull distribution fits well (but with different parameters A and k) for all stations and seasons.

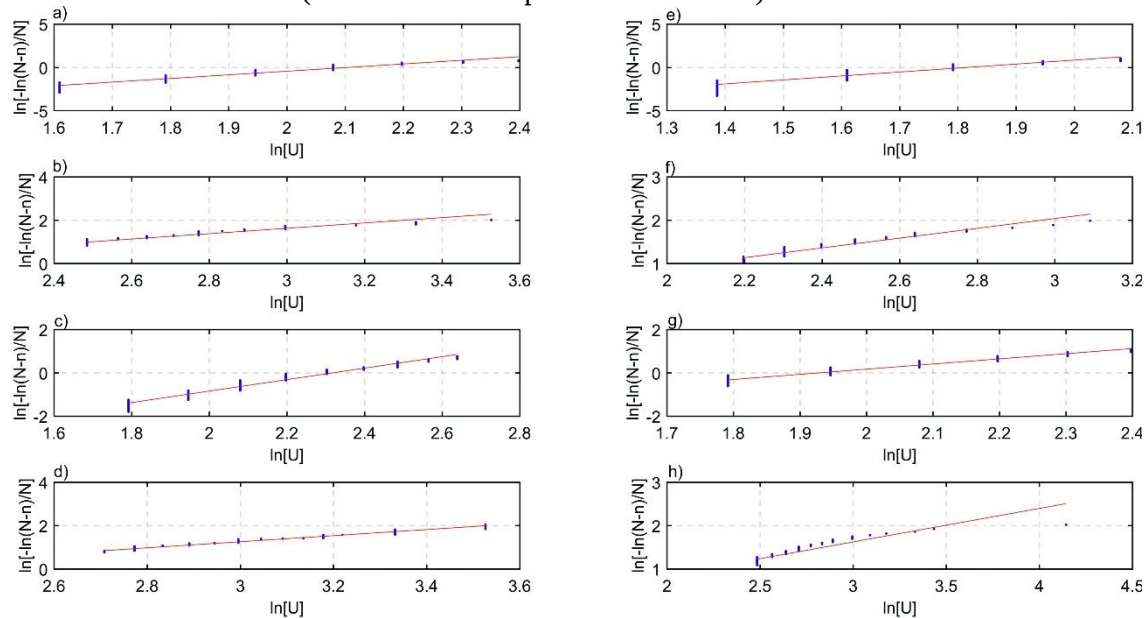


Figure 3. Cumulative distribution functions of wind speed maxima (station observations) in the linear coordinate axis of the Weibull distribution, and linear regression line corresponding to the Weibull function. (a), (b): Aleksandrovsk-Sakhalinsky (summer season); (c), (d) Aleksandrovsk-Sakhalinsky (winter season); (e), (f): Yuzhno-Sakhalinsk (summer season); (g), (h): Yuzhno-Sakhalinsk (winter season). (a), (c), (e), (g) denotes the Weibull distribution for $U \leq U_{th}$ (BSs); (b), (d), (f), (h) denotes the Weibull distribution for $U > U_{th}$ (Ds). $R^2 > 0.96$ in all cases.

A very important feature is that events adhering to the BSs or Ds could be diagnosed easily, and the Ds can be detected evidently based on obvious breaks in the tail of the wind distributions. The estimated parameters of each distribution allow us to calculate the quantiles for both Weibull distributions and use them as metrics of extremes frequency within the BSs and Ds separately, and their ratio for each station and season. In this paper, we have calculated $U(0.99)$ quantile values for all stations and both seasons. An example of these values is given in Table 1 together with the parameters k and A . The ratio between the Ds and BSs can reach up to 30%. The most pronounced feature of the seasonal distribution of the quantile wind speed values is that the maxima (both of the BSs and Ds) are observed in the winter period. Such “winter acceleration” of the wind speed is determined by storms that are typically much more active during the cold season.

3.2. Statistical features in model archive

The next step of the analysis is to investigate how great is the ability of the regional mesoscale atmospheric model to reproduce the peculiarities of wind extremes based on the long-term data archive described in Section 2.2. We used specific model grid points for comparison with each station, defined in [12] as one of the four closest grid points having the least wind speed RMSE.

In Figure 4, several cdfs based on the model archive wind speed data displaying clear deviation of the most extremes from the common linear Weibull law are plotted. Again, as noted earlier in the analysis of the observation data, we propose that these curves show approximations of the cdfs of wind velocity extremes by two different Weibull laws. These features are denoted almost at all grid points and in both seasons. The result of splitting of the original sample is shown in Figure 5. Using our terminology, we can conclude that the COSMO-CLM model wind speed reproduces extremes are

both the DSs and the Ds. It refers to the ability of the model with a detailed spatial resolution to reproduce the statistical structure and the special mechanism responsible for the generation of the largest wind extremes. However, the observed extremes characterized by $U(0.99)$ are almost half times greater than the modeled values. Apart from this, the ratio between the modelled Ds and BSs can reach only up to 10%. It is significantly less than what was established for the observations (up to 30%, see above). However, the most extreme wind speed parameters referred to the same stations in the observations and model data, and the model reproduced well the fact of increased winter extremes compared to the summer ones.

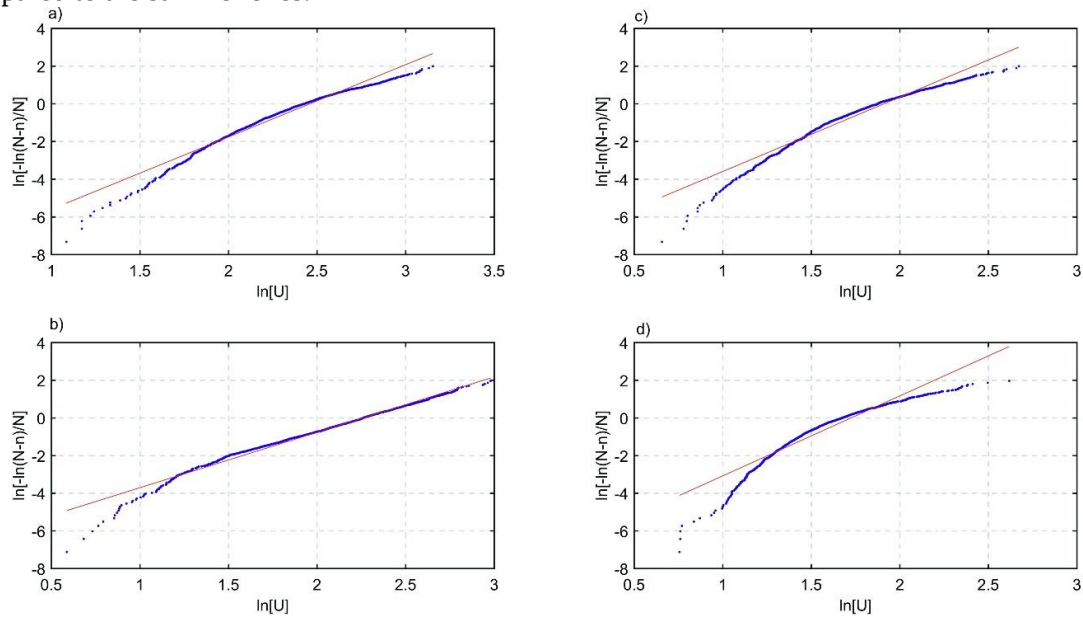


Figure 4. Cumulative distribution functions of wind speed maxima simulated by COSMO-CLM at grid points corresponding to Aleksandrovsk-Sakhalinky (a), (b); Yuzhno-Sakhalinsk (c), (d); ((a), (c) – winter season, (b), (d) – summer season) in the linear coordinate axis of the Weibull distribution, and the linear regression line corresponding to the Weibull function. In all cases $R^2 > 0.94$.

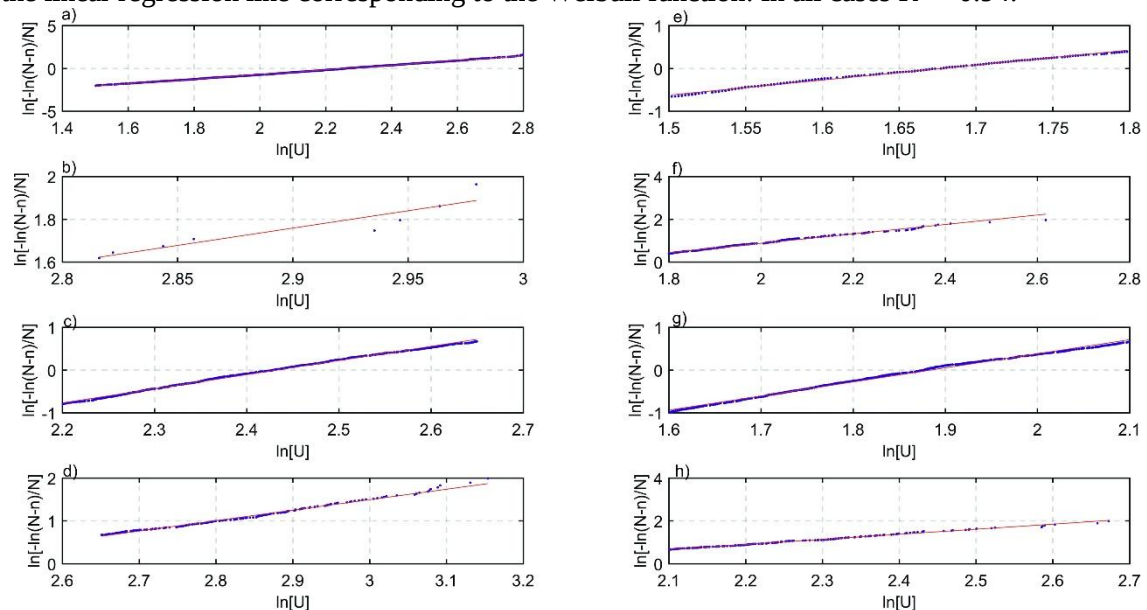


Figure 5. Cumulative distribution functions of wind speed maxima simulated by COSMO-CLM at grid points corresponding to Aleksandrovsk-Sakhalinky ((a) and (b) – summer season), Yuzhno-Sakhalinsk ((c) and (d) – summer season), Aleksandrovsk-Sakhalinky ((e) and (f) – winter season);

Yuzhno-Sakhalinsk ((g) and (h) - winter season) in the linear coordinate axis of the Weibull distribution, and the linear regression line corresponding to the Weibull function. (a), (c), (e), (g) the Weibull distribution for $U \leq U_{th}$ (BSs); (b), (d), (f), (h) the Weibull distribution for $U > U_{th}$ (Ds). In all cases $R^2 > 0.96$.

Further analysis was made to compare the coefficients k and A and $U(0.99)$ quantiles between the model and observational data according to BSs and Ds samples separately (Tables 1 and 2). A good agreement was shown for BSs, and it is truer for k -values, which are mostly belonging to the interval 3 – 5. At the same time, the coefficients A are overall overestimated by the model. This means that the model slightly marks up the extremity of the BSs wind speed sample. However, the Weibull distribution parameters related to the Ds samples obtained by the model are significantly different. For instance, the k -values, which are responsible for the slope of the approximation line, are overestimated (approx. 1 – 2 more). In this way, the Ds' slope is closer to the BSs' slope, and the difference between the BSs and Ds is getting smaller than in reality. Another important feature is overestimation of the coefficients A by almost an order of magnitude, which corresponds to significant underestimation of the extremity of the Ds wind speed samples by the mesoscale model.

The value of $U(0.99)$ for summer characterizes the maximum wind speed, which is exceeded, on average, once every five warm seasons. Similarly, the value of $U(0.99)$ for the cold period of the year characterizes the maximum wind speed, which is exceeded, on average, two times every three cold seasons. The $U(0.99)$ quantiles for the Ds sample reproduced by the model are lower (12 – 22 m/s at most), i.e. the extremity of the wind speed maximum is underestimated. The quality of reproduction of the statistical parameters by the model also depends on the characteristics of the underlying surface and the sea-land spatial distribution. The spread commonly decreased on the flat seashore stations, and increased over inlands and highly indented coastlines [11].

Table 1. Weibull cdf linear coefficients k and A and $U(0.99)$ quantiles for BSs and Ds samples for each station for summer seasons samples.

Station name	k, BSs	A, BSs	U(0.99), BSs	k, Ds	A, Ds	U(0.99), Ds
Aleks-Sakhalinskiy	4.1865	0.0001	11.8	1.2366	0.1244	18.6
Ilinsky	3.9613	0.0001	14.2	1.2720	0.1023	19.9
Mis Krilion	3.6026	0.0001	20.4	1.2659	0.0611	30.4
Mys Terpenia	3.7125	0.0001	16.2	1.5952	0.0331	22.1
Moskalvo	4.1973	0.0001	13.5	0.7612	0.4237	23.0
Nevelsk	2.0733	0.0077	21.9	0.5785	0.7964	20.8
Nogliki	5.0588	0.0000	9.9	0.9384	0.3619	15.0
Pogibi	3.1347	0.0006	17.4	0.6615	0.6039	21.6
Pogranichnoe	3.1523	0.0034	9.9	0.8091	0.5757	13.1
Poronaysk	4.2868	0.0002	11.0	0.9296	0.3872	14.3
Timovskoe	4.7739	0.0001	10.0	1.6805	0.0669	12.4
Uglegorsk	3.9439	0.0002	12.1	1.3076	0.0970	19.1
Yuzhno-Sakhalinskiy	4.5687	0.0003	8.6	1.1295	0.2591	12.8

Table 2. Weibull cdf linear coefficients k and A and $U(0.99)$ quantiles for BSs and Ds samples for model grid points corresponding to each station for summer seasons samples.

Station name	k, BSs	A, BSs	U(0.99), BSs	k, Ds	A, Ds	U(0.99), Ds
Aleks-Sakhalinskiy	2.7143	0.0021	16.9	1.6214	0.0527	15.6

Ilinsky	3.5517	0.0016	9.4	2.4723	0.0135	10.6
Mis Krilion	3.8268	0.0004	11.2	2.2385	0.0135	13.5
Mys Terpenia	3.0395	0.0008	17.6	2.1199	0.0081	19.9
Moskalvo	3.0096	0.0019	13.2	1.8035	0.0313	15.9
Nevelsk	2.8194	0.0017	16.6	2.1632	0.0092	17.7
Nogliki	4.6550	0.0001	9.7	2.2289	0.0177	12.1
Pogibi	4.1251	0.0001	14.0	2.7077	0.0029	15.3
Pogranichnoe	2.5881	0.0064	12.7	2.0431	0.0210	14.0
Poronaysk	4.6764	0.0002	8.8	2.1930	0.0233	11.1
Timovskoe	3.7620	0.0020	7.8	2.7027	0.0137	8.6
Uglegorsk	3.0589	0.0039	10.1	2.1907	0.0228	11.3
Yuzhno-Sakhalinskiy	3.5080	0.0028	8.2	2.2061	0.0291	9.9
Val	3.8642	0.0002	11.1	2.0280	0.0168	13.3
Komrvo	3.1297	0.0017	12.6	2.1544	0.0148	14.3

4. Conclusions and perspectives

An extreme value analysis has been implemented to estimate the statistical properties of extreme wind speeds over the Sakhalin Island region based on the long-term COSMO-CLM model dataset and observations.

It was shown for all stations that the observational 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. Using metaphoric terminology, we marked these samples BSs and Ds. Within the framework of a 30-year high-resolution regional data set of the sub-Arctic region, generated by the COSMO-CLM model, we reproduced several important aspects of wind speed extremes. First of all, we found among them samples adhering to various populations which can be interpreted as BSs and Ds. The analysis showed the ability of the mesoscale atmospheric model to capture the specific physical mechanism that generates wind speed extremes. However, the model with the given resolution was not able to reproduce some essential parts of the statistical properties of wind speed maximum: there are large discrepancies concerning the absolute values of the modelled extremes, which are almost two times smaller than the observed values. Although the main statistical characteristics of the BSs samples were reproduced satisfactorily, the time parameters of the Ds samples were significantly underestimated by the mesoscale atmospheric model. These gaps could be covered by using a higher resolution, as well as by other areal estimation techniques, and many others. Future investigations will be dedicated to specific physical mechanisms of Ds formation, scaling problems, and resolution dependencies.

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References

- [1] Kislov A, Matveeva T 2016 An extreme value analysis of wind speed over the European and Siberian parts of Arctic region. *Atm. and Clim. Sci.* **6** 205 – 23

- [2] Kislov A V, Matveeva T A, Platonov V S 2015 Wind speed extremes in Arctic *Fund. and Appl. Climat.* **2** 63 – 80 (In Russian)
- [3] Taleb N *The black swan: The impact of the highly improbable fragility.* 2010 (New York, Random House) p 300
- [4] Sornette D Dragon-Kings 2009 Black Swans and the Prediction of Crises *International Journal of Terraspace Science and Engineering* **2** 1 – 18
- [5] 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) p 497
- [6] Coles S, Bawa J, Trenner L, Dorazio P *An introduction to statistical modeling of extreme values* 2001 (Springer Series in Statistics, Springer-Verlag) p 208
- [7] de Haan L and Ferreira A *Extreme value theory: an introduction* 2006 (Springer Series in Operations Research and Financial Engineering, Springer) p 417
- [8] Fisher R and Tippett L 1928 Limiting forms of the frequency distribution of the largest or smallest members of a sample *Proceedings of the Cambridge Philosophical Society* **24** 180-90
- [9] Palutikof J P, Brabson B B, Lister D H and Adcock S T. A 1999 Review of Methods to Calculate Extreme Wind Speeds *Meteorological Application* **6** 119 – 32
- [10] Platonov V S and Kislov A V 2016 Mesoscale high-resoluion modeling of extreme wind speeds over western water areas of the Russian Arctic *IOP Conference Series: Earth and Environmental Science* **48**
- [11] Kislov A, Platonov V 2019 Analysis of observed and modelled near-surface wind extremes over the sub-arctic northeast pacific *Atmospheric and Climate Sciences* **9** 1 146 – 58
- [12] Kislov A V, Rivin G S, Platonov V S, Varentsov M I, Rozinkina I A, Nikitin M A, and Chumakov M M 2018 Mesoscale atmospheric modelling of extreme velocities over the Sea of Okhotsk and Sakhalin Island *Izvestiya, Atmospheric and Oceanic Physics* **54** 322 – 6
- [13] Platonov V, Kislov A, Rivin G, Varentsov M, Rozinkina I, Nikitin M, and Chumakov M 2017 Mesoscale atmospheric modelling technology as a tool for creating a long-term meteorological dataset *IOP Conference Series: Earth and Environmental Science* **96**
- [14] Rockel B, Will A, Hense A 2008 The regional climate model COSMO-CLM (CCLM) *Meteorologische Zeitschrift* **17** 4 347 – 8
- [15] Platonov V S, Varentsov M I 2018 Supercomputer technologies as a tool for high-resolution atmospheric modelling towards the climatological timescales *Supercomputing Frontiers and Innovations* **5** 3 107 – 10
- [16] Arakawa A, Lamb V R 1977 Computational design of the basic dynamical processes of the UCLA general circulation model *Methods in computational physics* **17** 173 – 265
- [17] Gal-Chen T, Somerville R C J 1975 On the use of a coordinate transformation for the solution of the Navier-Stokes equations *Journal of Computational Physics* **17** 209 – 28
- [18] Schär C, Leuenberger D, Fuhrer O, Lüthi D, and Girard C 2002 A new terrain-following vertical coordinate formulation for atmospheric prediction models *Mon. Wea. Rev.* **130** 2459 – 80
- [19] Rockel B, Geyer B 2008 The performance of the regional climate model CLM in different climate regions, based on the example of precipitation *Meteorologische Zeitschrift* **17** 4 487 – 98
- [20] Van Pham T, Brauch J, Dieterich C, Früh B, Ahrens B 2014 New coupled atmosphere-ocean-ice system COSMO-CLM/NEMO: assessing air temperature sensitivity over the North and Baltic Seas *Oceanologia* **56** 2 167 – 89
- [21] Haas R and Pinto J G 2012 A combined statistical and dynamical approach for downscaling large-scale footprints of European windstorms *Geoph. Res. Let.* **39** L23804 1 – 6
- [22] Varentsov M I, Verezemskaya P S, Zabolotskikh E V, Repina I A 2016 Quality estimation of polar lows reproduction based on reanalysis data and regional climate modeling

- Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa* **13** 4 168 – 91 (In Russian)
- [23] Tiedtke M 1989 A comprehensive mass flux scheme for cumulus parameterization in large-scale models *Mon. Wea. Rev.* **117** 1779 – 800
- [24] Ritter B, Geleyn J F 1992 A comprehensive radiation scheme for numerical weather prediction models with potential applications in climate simulations *Mon. Wea. Rev.* **120** 303 – 25
- [25] Herzog H-J, Vogel G, Schubert U 2002 LLM – a nonhydrostatic model applied to high-resolving simulations of turbulent fluxes over heterogeneous terrain *Theor. Appl. Clim.* **73** 67 – 86
- [26] Dee D P *et al* 2011 The ERA-Interim reanalysis: Configuration and performance of the data assimilation system *Quart. J. R. Met. Soc.* **137** 553 – 97
- [27] Von Storch H, Langenberg H, Feser F 2000 A spectral nudging technique for dynamical downscaling purposes *Monthly weather review* **128** 10 3664 – 73
- [28] Feser F, Barcikowska M 2012 The influence of spectral nudging on typhoon formation in regional climate models *Environmental Research Letters* **7** 1 1 – 10