Extreme Winds in the New European Wind Atlas
Paper

Bastine, David; Larsén, Xiaoli Guo; Witha, Björn; Dörenkämper, Martin; Gottschall, Julia

Published in:
Journal of Physics: Conference Series (Online)

Link to article, DOI:
10.1088/1742-6596/1102/1/012006

Publication date:
2018

Document Version
Også kaldet Forlagets PDF

Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Extreme Winds in the New European Wind Atlas

To cite this article: David Bastine *et al* 2018 *J. Phys.: Conf. Ser.* **1102** 012006

Extreme Winds in the New European Wind Atlas

David Bastine[1,2], Xiaoli Larsén[3], Björn Witha[4], Martin Dörenkämper[2], Julia Gottschall[2]

[1] Jade University of Applied Sciences, Ofener Straße 16/19, 26121 Oldenburg, Germany
[2] Fraunhofer Institute for Wind Energy Systems IWES, Am Seedeich 45, 27572 Bremerhaven, Germany
[3] DTU Wind Energy, Frederiksborgvej 399, 4000 Roskilde, Denmark
[4] ForWind, Institute of Physics, University of Oldenburg, Küpkersweg 70, 26129 Oldenburg, Germany

E-mail: julia.gottschall@iwes.fraunhofer.de, david.bastine@jade-hs.de

Abstract. As a part of the New European Wind Atlas project, we investigate the estimation of extreme winds from mesoscale simulations. In order to take the smoothing effect of the simulations into account, a spectral correction method is applied to the data. We show that the corrected extreme wind estimates are close to the values obtained from offshore met masts. Hence, after further investigations we plan to use the examined approach as a basis for the calculation of extreme winds on the complete New European Wind Atlas, which will be publicly available at the end of the project.

1. Introduction

The European scale project New European Wind Atlas (NEWA) [1] aims at developing a New European Wind Atlas as a standard for site assessment in wind energy. The atlas is being developed on the basis of mesoscale simulations using the Weather Research and Forecasting model (WRF). The simulations will be supported and validated by a large number of field measurements stemming from various met masts and measurement campaigns across Europe, e.g. [2].

One specific feature of the atlas will be the estimation of extreme winds, which play a decisive role for the design of wind turbines and wind farms. In order to make sure that the wind does not exceed a wind turbine's design specification, reliable estimates of extreme winds are crucial. Following the IEC-61400-1:2005 standard [3], we are interested in the 10-min-average wind speed at hub height, which has a recurrence period of 50 years. This wind is often referred to as the 50-year wind.

Estimating the 50-year wind for a site using mesoscale simulations is a very challenging task. Firstly, the mesoscale models describe the orography and surface roughness around the site on relatively coarse grids. Thus, for example, local, small-scale speed-up effects through hills or surface roughness changes may not be captured. Secondly, smoothing is embedded in the mesoscale simulations in order to ensure numerical stability leading to an effective resolution several times coarser than the spatial resolution setup. This smoothing effect leads to a reduced variability of the wind and consequently to an underestimation of extreme winds.

This article focuses on correcting the smoothing effect in the mesoscale modeled winds using the spectral correction method (SCM) [4, 5, 6]. The SCM has shown some promising results in connection with the use of reanalysis data [5]. However, its performance is expected to vary with different model outputs and the simulations from NEWA are of a much finer resolution (3 km) than the modeled data that have been previously used in connection with the SCM (about 50 km).

Hence, the major goal of this work is to examine the performance of the SCM in combination with the simulations used for the New European Wind Atlas. In this article, we present a first study based on simulations covering a period of 10 years in central Europe. At the end of the project 30 years of simulated data will be available and used for the extreme wind estimation. We compare our results to measurements from four different locations. Three of the considered sites are offshore while the last one is on relatively simple and flat terrain. We expect the local effects of orography and surface roughness to be negligible for the offshore sites and partially also for the simple onshore case. This is expected to allow an isolated investigation of the smoothing effect.

The methodology is introduced in Section 2 including the modeling (Section 2.1), measurements (Section 2.2), the estimation of extreme wind (Section 2.3, 2.4). The SCM will be applied to the simulations and the resulting extreme winds will be compared to the estimates from measurements. The results are presented and discussed in Section 3. In the end, final conclusions are drawn in Section 4.

2. Methodology

2.1. Mesoscale Modeling with WRF

The mesoscale wind atlas, as part of the NEWA project, is simulated with the widely used open-source mesoscale model WRF [7] version 3.8.1. For our study, we used simulations of all available ten years (2008-2017) from one sub-domain of the wind atlas covering Central Europe (see Figure 1). The horizontal resolution of the innermost model domain is 3 km. The wind atlas consists of week-long simulations, driven by the new ERA5 climate reanalysis dataset and using the MYNN PBL scheme [8, 9]. The output contains a number of atmospheric variables at several heights from 10 m to 500 m with an output time step of 30 minutes corresponding to an output frequency of $48\,\mathrm{day}^{-1}$. A snapshot of the simulations showing the instantaneous wind speed at 100 m height can be found in Figure 1 for one selected point in time.

2.2. Measurements

In order to validate our estimations of extreme winds, time series of wind speed from four different measurement sites are used, which are briefly described in Table 1. Their locations are shown in Figure 1. FINO1 and FINO3 are located in the North Sea, FINO2 in the Baltic Sea and the met mast Cabauw onshore Western of the Netherlands.

All measurements are performed by cup anemometers and the considered data consists of ten-min-average wind speeds given every ten minutes. Details can be found in [10, 11]. Measurement gaps smaller than six hours have been linearly interpolated. Longer gaps were omitted for the calculation of the spectra. We only use time series which overlap with the completed simulations even though longer measurement time series are partially available.

	FINO1	FINO2	FINO3	Cabauw
height [m]	100	102	90	80
period [years]	10	9	8	10
availability [%]	95	94	83	99
terrain	offshore	offshore	offshore	flat

Table 1. Description of the measurement sites.

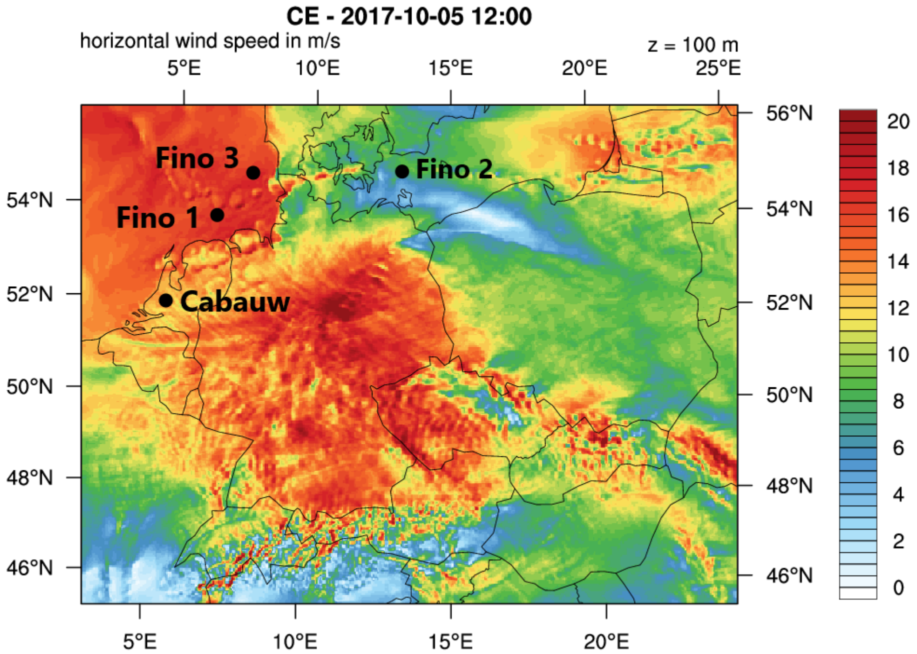

Figure 1. Simulation snapshot of the WRF model domain for central Europe. The color denotes the wind speed in $\mathrm{m\,s^{-1}}$ at a height of 100 m. The black dots represent the approximate positions of the measurement sites.

2.3. Extreme Wind Estimation

We define $u_{max}^{(i)}$ as the annual maximum of the i-th year, while $\langle u_{max}\rangle = \langle u_{max}^{(i)}\rangle_i$ denotes the average annual maximum, which we estimate by the sample mean of the annual maxima. Following e.g. [12, 13] , we assume that the annual maxima are Gumbel-distributed. We estimate the corresponding parameters α and β with the annual maximum method (AMM) [14], which is based on a probability weighted moment procedure. The estimated parameters can be used to estimate the T-year wind u_T, which is defined as the wind occurring with a probability of $\frac{1}{T}$ in one year. It is estimated by

$$u_T = \beta - \alpha \ln[\ln(\frac{T}{T-1})] \approx \beta + \alpha \ln T \;\; (\text{for}\, T >> 1) \qquad (1)$$

The statistical uncertainties, which can be found e.g. in [14, 6], increases with T and is quite high for $T = 50$ years for only 10 years of measurements and simulations. Hence, before the 30-year simulation is ready at the end of NEWA project, we investigate not only the desired 50-year wind but also the average annual maximum, in order to compare quantities with less uncertainty and obtain a more significant validation. Additionally, in the context of the SCM we will also consider the wind $\tilde{u}_{T=1}$ with a recurrence period of $T = 1$ years, representing the wind which is exceeded once a year on average. Note that $\tilde{u}_T$ approximately equals u_T only for $T >> 1$.

2.4. Spectral Correction Method

As already mentioned in the introduction, mesoscale simulations underestimate the extreme winds due to a smoothing of the field variables such as the velocity field. When presented in the spectral domain, the spectral energy level in the mesoscale range is underestimated as can be seen by the comparison with field measurements in Figure 3 for frequencies higher than 1 day^{-1} . It has been shown, for example by *Larsén et al.* [15, 16], that the power spectral density (PSD), also simply called spectrum in the following, usually follows $S(f) \propto f^{-5/3}$ above a certain frequency f_c. The frequency f_c is related to the integral time scale, which is often found to be in the order of 1 day in the mid-latitude here. Setting $S(f) \propto f^{-5/3}$ for $f > f_c = 1.5\,\mathrm{day}^{-1}$ yields a "corrected", hybrid PSD S_{cor}, which is shown as the red dashed line in Figure 3. Note also that the corrected spectrum is extrapolated up to the output frequency of the 10 min-measurements. Choosing the value of f_c is a crucial step in the SCM and can lead to some uncertainty, as will be discussed further in Section 3. In order to reduce the sensitivity to f_c, the exact value of $S_{cor}(f_c)$ is determined by a linear regression (in the log-log framework) for $1.3\,\mathrm{day}^{-1} < f < 1.7\,\mathrm{day}^{-1}$. For spectral peaks exceeding the used extrapolation procedure the original value of the WRF spectrum is kept.

The main idea of the SCM is to estimate a correction factor for the extreme winds based on the original and corrected spectrum following *Larsén et al.* [4, 5]. Under certain mathematical assumptions, such as stationarity and Gaussian-distributed u and $\dot{u} = \frac{du}{dt}$, extreme winds can be expressed based on the PSD or more precisely the spectral moments. We can even find an explicit formula for the wind $\tilde{u}_T$ with a recurrence period of one year. Following [4], it is given by

$$\tilde{u}_T = \langle u \rangle + \sqrt{m_0}\sqrt{2\ln\left(\frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}}T\right)}\ , \tag{2}$$

where $\langle u \rangle$ is the mean velocity and

$$m_j := 2\int_0^\infty d\omega\ \omega^j S(\omega) \tag{3}$$

are the spectral moments. For discrete signals, we have to estimate m_2 by integrating up to only half the sampling frequency of the corresponding signal.

Due to these assumptions made, we expect high uncertainties when using Equation (2) to estimate $\tilde{u}_T$. However, it has been shown that the ratio of the corrected and uncorrected values of $\tilde{u}_T$ can lead to a good description of the smoothing effect and hence a possible correction factor [4, 5]. More precisely, we can estimate the spectral moments for the corrected PSD ($m_j^{(corr)}$) and uncorrected PSD (m_j) and define a correction factor

$$C := \frac{\tilde{u}_T(m_0^{(corr)}, m_2^{(corr)})}{\tilde{u}_T(m_0, m_2)} \tag{4}$$

We choose $T = 1$ year and apply the resulting factor to the extreme wind estimates directly obtained from the original simulations. Hence, the SCM-corrected values $\langle u_{max} \rangle$ and u_T are $C \cdot \langle u_{max} \rangle$ and $C \cdot u_T$, respectively, where u_T has been estimated applying the AMM method to the original WRF simulations (see Section 2.3). Note that in some articles C is also called smoothing effect denoted as SE.

It should be noted again that the SCM method is based on many assumptions and not all of them are fulfilled. Thus, its performance has to be assessed by the comparison with measurements. One reason for the choice of $T = 1$ year to calculate the correction factor, is that some of the assumptions made become problematic for higher T. For example, the non-Gaussian tail of the velocity distribution plays a more important role. Hence, we calculate the correction factor for $T = 1$ year and assume that the smoothing effect on the 50-year wind can be taken into account by the same factor. Numerically, we can also estimate $\tilde{u}_T$ or even u_T for different assumptions such as a non-Gaussian probability density function (pdf) of u, but this is beyond the scope of this paper and will be investigated in a future article.

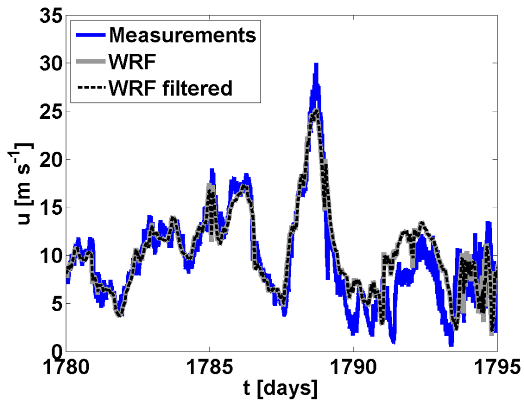

Figure 2. Wind speed time series at the location of FINO1.

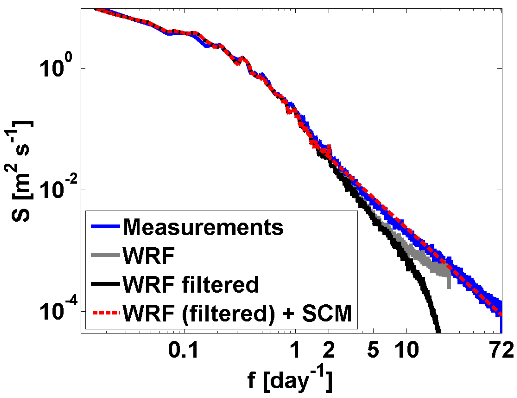

Figure 3. PSD of measurements (blue) and simulations (gray) and filtered simulations (black). The red dashed line shows the corrected PSD based on the filtered spectrum.

3. Results and Discussion

3.1. Properties of the WRF Time Series

Comparing the simulated time series (grey line in Figure 2) with the measured one (blue line in 2), we can clearly see the smoothing effect of the simulations. The measured time series contains a lot more high-frequency dynamics. Consequently, the highest wind speed in the presented time period seems to be around $5\,\mathrm{m\,s^{-1}}$ lower for the simulated time series. The missing fluctuations also manifest themselves in the lower spectral energy level of the WRF simulations for frequencies higher than approximately $1\,\mathrm{day}^{-1}$, as shown in Figure 3.

At the high-frequency end of the original WRF-PSD an upward bend can be observed indicating the presence of high-frequency dynamics on scales even finer than the output frequency of $48\,\mathrm{day}^{-1}$. Since we do not see this behavior in the measurements, such a bend indicates non-physical dynamics at the corresponding short time scales, as pointed out by [17] (see e.g. Figure 10). The observed high-frequency fluctuations can be artificial and numerical noises as a consequence of the high spatial resolution [18]. Thus, the study of [18] shows that a higher resolution does not necessarily lead to a more accurate simulation on small scales. In our case, however, the upward bend is weak enough that no energy is aliased to the low frequencies $f < 3\,\mathrm{day}^{-1}$. Hence, we still expect a good agreement with measurements on larger time scales.

3.2. Sensitivity of the SCM to the Output Time Step of the Simulations

For the extreme winds and the SCM, on the other hand, the higher energy on short time scales might be problematic since the SCM strongly depends on the tail of the spectrum due to the important second-order spectral moment m_2 weighting the spectrum with f^2 (see Equation (3)). Due to the high energy in the tail, the value of m_2 and consequently the SCM method and the resulting extreme wind estimates can be very sensitive to the output time step of the simulation, as illustrated in Figure 4. Choosing the output time step between 0.5 and 2 hours leads to an uncertainty caused by the time step choice in the order of 0.8 ms^{-}1 for the annual average maximum and $2\,\mathrm{m\,s^{-1}}$ for u_{50}.

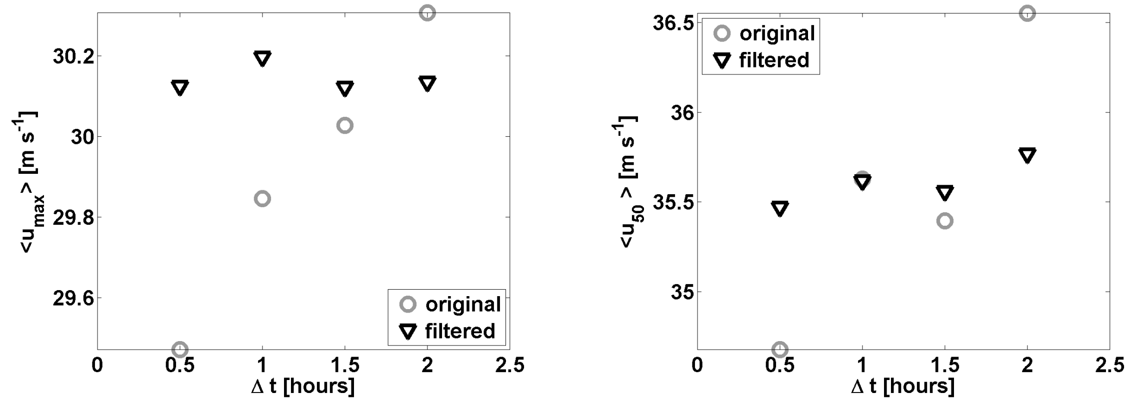

Figure 4. Estimated extreme winds using SCM depending on the output time step of the simulations for the location of FINO1. The gray circles show the estimates based on the original WRF time series, while for the black triangles a running 4-point average has been applied to the WRF data.

Usually, when undesired high-frequency dynamics are present in a signal, this energy is filtered out by a low pass filter, if possible before discretization. However, in our case we could not obtain a low-pass filtered output of the simulations, such as 10- or 30-min-averages but are bound to the saved data of the model which are instantaneous values every 30 minutes. Hence, we decided to apply a simple running two-point average (averaging two consecutive values) to this output corresponding to a filtering time scale of 60 minutes. The applied filter leads to a strong drop in the spectrum, as shown in Figure 3. For such a filtered spectrum, the integrals in Equation (3) are now well-defined since the spectrum approaches zero very fast. Consequently and most importantly, the SCM is now relatively insensitive to the choice of output time steps below 60 minutes. This insensitivity is hard to show for the two-point average since we only have data with an output time time step of 30 minutes. Thus, Figure 4 illustrates this phenomenon for a 4-point running average, reducing energy on time scales shorter than 2 hours. Consequently, the extreme winds estimates are almost constant when applying the SCM to the filtered data showing the filtering the data can lead to a more consistent SCM procedure. In order to keep as much realistic low frequency information as possible but to remove enough non-physical high frequency energy, we apply the SCM to the WRF data filtered with the running two-point average. The filtered data will be simply referred to as the WRF data in the following.

3.3. Application of the SCM
We now apply the SCM method to the filtered WRF time series at the different measurement sites. As a first step, the PSDs of measurements and simulations are estimated at all sites (Figures 3 and 5). After correction, the spectra seem to match the measured ones relatively well for the offshore cases and the uniform terrain in Cabauw. It is remarkable that the diurnal peaks at $f = 1, 2, 3\,\mathrm{day}^{-1}$ are matched really well for Cabauw.

In addition to the corrected spectrum using $f_c = 1.5\,\mathrm{day}^{-1}$, the thin red lines in Figure 5 represent corrected spectra for $f_c = 1.2\,\mathrm{day}^{-1}$ and $f_c = 1.8\,\mathrm{day}^{-1}$. Except for FINO3 these alternative corrected spectra do not differ strongly from the $f_c = 1.5\,\mathrm{day}^{-1}$ case resulting in a small sensitivity of the SCM to f_c. For FINO3, a relatively high sensitivity to f_c is found since at $f_c = 1.2\,\mathrm{day}^{-1}$ is the slope of S still differs strongly from $-5/3$. This leads to an overestimation of the small-scale energy for $f_c = 1.2\,\mathrm{day}^{-1}$ and consequently to a sensitive dependence of the correction factors on f_c for FINO3, as discussed further in the next paragraph.

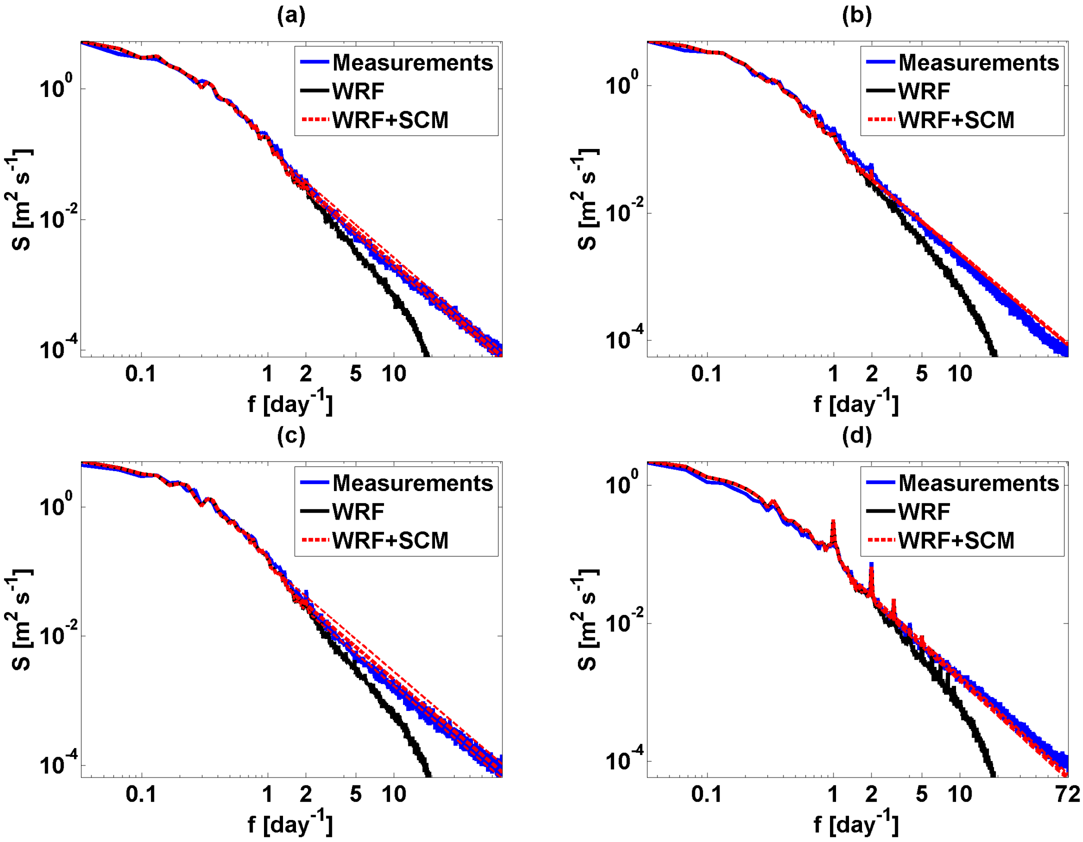

Figure 5. Power Spectral Density of measurements and simulations for all measurement sites: (a) FINO1 (b) FINO2 (c) FINO3 (d) Cabauw. The thick red dashed line shows the corrected PSD for $f_c = 1.5\,\mathrm{day}^{-1}$. In order to investigate the sensitivity on the value of f_c, all figures also include thin red dashed lines showing the corrected PSD using $f_c = 1.2\,\mathrm{day}^{-1}$ and $f_c = 1.8\,\mathrm{day}^{-1}$. Since these lines are often really close to each other, they are not always easy to see indicating a low sensitivity to f_c.

The estimated extreme winds can be found in Table 2. Additionally, we compare the estimated correction factors with the actual ratios of the extreme winds for WRF and measurements in Table 3.

For all three offshore sites the estimated annual average maxima are remarkably close to the measured ones indicating that the SCM seems to be able to take the smoothing effect successfully into account. For FINO1, for example, we find $\langle u_{max} \rangle = 27.8\,\mathrm{m\,s}^{-1}$ for the WRF simulations and SCM-corrected values of $\langle u_{max} \rangle = 30.0\,\mathrm{m\,s}^{-1} \pm 0.7\,\mathrm{m\,s}^{-1}$ close to the measured value $\langle u_{max} \rangle = 30.7\,\mathrm{m\,s}^{-1} \pm 1.1\,\mathrm{m\,s}^{-1}$. The given uncertainty is one standard deviation of the sample mean. The correction factor is approximately $C = 1.08$ for all three offshore cases very close to the ratios of measurements and simulations (1.10, 1.08, 1.12). We estimate the uncertainty of the correction factor caused by the choice of f_c, which has been discussed above, to be around 0.004 for FINO1 and FINO2 and 0.008 for FINO3. These uncertainty needs to be

Annual average max. $[m\,s^{-1}]$	FINO1	FINO2	FINO3	Cabauw
WRF	27.8 ± 0.6	26.2 ± 0.6	27.4 ± 0.6	20.8 ± 0.4
WRF + SCM	30.0 ± 0.7	28.3 ± 0.7	29.6 ± 0.6	22.3 ± 0.4
Measurements	30.7 ± 1.1	28.4 ± 0.8	30.8 ± 1.0	24.4 ± 1.1
50-year wind $[m\,s^{-1}]$				
WRF	32.8 ± 2.3	31.6 ± 2.3	32.2 ± 2.2	24.3 ± 1.5
WRF + SCM	35.9 ± 2.5	34.8 ± 2.5	34.7 ± 2.3	26.1 ± 1.6
Measurements	39.3 ± 3.6	35.3 ± 3.0	38.5 ± 3.5	34.0 ± 3.9

Table 2. Extreme wind speeds: Estimates of average annual maxima and 50-year winds for measurements, WRF simulations and the corresponding corrected value. The statistical uncertainties are denoted as one standard deviation.

	FINO1	FINO2	FINO3	Cabauw
WRF + SCM (Correction factor)	1.08	1.08	1.08	1.07
Annual average maxima (Measurements/WRF)	1.10	1.08	1.12	1.17
50-year wind (Measurements/WRF)	1.20	1.12	1.20	1.38

Table 3. Estimated correction factors and ratios of measured and simulated extreme winds.

investigated further and has to be kept in mind when using the SCM without measurements.

For the 50-year winds, the SCM also leads to values much closer to the measured ones than for the original WRF simulations (Table 2). However, in contrast to the annual average maxima, the 50-year winds are underestimated for all offshore sites but due to the high uncertainties, it is hard to assess if this is a significant result.

One reason for a possible underestimation of the 50-year winds might be that the used WRF setup could have difficulties with the accurate modeling of storms. Furthermore, the smoothing embedded in the simulations might have a stronger effect on the extreme wind estimates for higher T. This will be examined further in the future.

For the onshore site Cabauw, the SCM still leads to an improvement but it is not as good as in the offshore cases. Particularly, the 50-year wind seems to be strongly underestimated. The reason for this underestimation in the estimation and correction of the spectrum, since the corrected spectrum matches the measured one remarkably well. Former results in [6] show that combined with a microscale modeling approach, the SCM can yield a relatively a good estimation at this site. Thus, the small-scale roughness and orography might play a more important role than we expected despite the simplicity of the site. This will be investigated further, when taking small-scale effects are taken into account in a future step of of the project, which will be based on the WAsP methodology.

4. Conclusions and Outlook

The simulations set up for the New European Wind Atlas are based on the open source model WRF and the ERA5 reanalysis dataset. In this article, we examined the combination of these simulations with the SCM, in order to estimate extreme winds.

A spectral comparison of the WRF simulations with the measurements indicates non-physical behavior of the simulations in the high-frequency region, a known phenomenon for mesocale simulations with a relatively high spatial resolution. We illustrated that these high-frequency dynamics can be a significant source of uncertainty for the extreme wind estimation but that in the case of the NEWA data the application of a very simple low-pass filter leads to a robust estimation procedure.

Using the filtered WRF data, the SCM clearly improves the extreme wind estimates of the WRF simulation. Particularly offshore, estimates of the annual average maxima very close to the measured values have been found. The SCM also leads to valuable estimates of the 50-year wind but our results indicate a moderate systematic underestimation, which we will investigate further when more simulated data is available.

For the onshore site Cabauw, the extreme wind estimates also lead to a clear improvement but still show a strong underestimation. It is likely that the small-scale orography and roughness plays a more significant role than expected.

Thus, in a following step, we will combine the SCM with a micro-scale modeling approach based on the WAsP Engineering technique (see e.g. [14, 19, 20]). This way the small-scale orography and roughness can be taken into account. The resulting extreme wind estimates will be compared to measurements of many different met masts placed in sites of different complexity The uncertainties of the combined approach will be investigated in great detail.

We plan to offer two different ways to present the extreme winds in the new European wind atlas. First, the "coarse extreme wind", as estimated in this article, will be given. Despite its uncertainties onshore, it still offers a good first impression of the extreme wind climate in Europe, particularly offshore. Additionally, we plan to add a flag denoting the level of uncertainty corresponding to the specific site. Second, we are going to offer the SCM-corrected generalized extreme wind climate (GEWC) [6], which the user can use as an input to micro-scale modeling such as WAsP Engineering. This way site-specific extreme wind estimates all over Europe can be obtained without having to perform a single measurement. The new European wind atlas will therefore be of great value to the wind energy industry, particularly in the field of resource assessment.

Acknowledgements
The NEWA project is funded by the Federal Ministry of Economic Affairs and Energy under Grant number 0325732. The simulations were performed at the HPC cluster EDDY, located at the University of Oldenburg and funded by the Federal Ministry of Economic Affairs and Energy under Grant number 0324005.

References

[1] New european wind atlas (newa) URL `http://www.neweuropeanwindatlas.eu/`
[2] Mann J, Angelou N, Arnqvist J, Callies D, Cantero E, Arroyo R C, Courtney M, Cuxart J, Dellwik E, Gottschall J *et al.* 2017 *Phil. Trans. R. Soc. A* **375** 20160101
[3] International Electrotechnical Commision 2005 International standard iec 61400-1:2005 Tech. rep. ISBN 2-8318-8161-7
[4] Larsén X G, Ott S, Badger J, Hahmann A N and Mann J 2012 *Journal of Applied Meteorology and Climatology* **51** 521–533 ISSN 1558-8424
[5] Larsén X G and Kruger A 2014 *Journal of Wind Engineering and Industrial Aerodynamics* **133** 110–122 ISSN 0167-6105
[6] Hansen B, Larsn X, Kelly M, Rathmann O, Berg J, Bechmann A, Sempreviva A and Ejsing Jrgensen H 2016 *Extreme Wind Calculation Applying Spectral Correction Method Test and Validation* (Denmark: DTU Wind Energy)
[7] Skamarock W, Klemp J B, Dudhia J, Gill D O, Barker D M, Duda M G, Huang X Y and Wang W 2008 A description of the advanced research wrf version 3 Tech. rep. National Center for Atmospheric Research Boulder, USA
[8] Nakanishi M and Niino H 2006 *Boundary-Layer Meteorology* **119** 397–407
[9] Nakanishi M and Niino H 2009 *Journal of the Meteorological Society of Japan. Ser. II* **87** 895–912
[10] Fino research platforms URL `https://www.fino-offshore.de/en/`
[11] Cabauw experimental site for atmospheric research (cesar) URL `http://www.cesar-observatory.nl/`

[12] Mann J, Kristensen L and Jensen N O 1998 *Bridge Aerodynamics* A/S Storebaelt; Oresundskonsortiet; COWI Consulting Engineers & PlannersEOLEOLAS; COWI Fdn; DTU Tech Univ Denmark; Danish Grp of IABSE; Permanent IntEOLEOLAssoc Nav Congresses (PIANC); DANHIT High Performance Comp & Networking;EOLEOLInt Bridge, Tunnel & Turnpike Assoc (IBTTA); World Rd Assoc (PIARC)
[13] Coles S, Bawa J, Trenner L and Dorazio P 2001 *An introduction to statistical modeling of extreme values* vol 208 (Springer)
[14] Abild J 1994 Application of the wind atlas method to extremes of wind climatology Tech. Rep. Risoe-R-722 (EN) Risoe National Laboratory Roskilde, Denmark
[15] Larsén X G, Vincent C and Larsen S 2013 *Quarterly Journal of the Royal Meteorological Society* **139** 685–700
[16] Larsén X G, Larsen S E and Petersen E L 2016 *Boundary-Layer Meteorology* **159** 349–371 ISSN 1573-1472 URL `https://doi.org/10.1007/s10546-016-0129-x`
[17] Skamarock W C 2004 *Monthly weather review* **132** 3019–3032
[18] Floors R, Hahmann A and Peña A *Journal of Geophysical Research: Atmospheres*
[19] Larsén X G and Mann J 2009 *Wind Energy* **12** 556–573
[20] Wasp engineering URL `http://www.wasp.dk/weng`