Wind resource and site assessment in the German Bight: Extreme Winds at Meso- to Microscale

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Abstract

Since the resource and site assessment at inaccessible offshore locations cannot solely rely on expensive in-situ measurements, alternative methods based not only on the direct long term measurements are required. Mesoscale models used for numerical weather prediction (NWP) are limited area models with a high horizontal and vertical resolution, simulating the local flow over the regional features such as the coastline, the orography or due to convection. The extreme wind conditions, in addition to the wind distribution, are required for design optimization of the wind turbines and their structures, to be able to assess the risks involved with large investments in the offshore wind farms.

In the following, the validated Weather Research and Forecast (WRF) model simulations are used to estimate the wind resource over the German Bight in the North Sea. The WRF simulations dynamically downscale the 6 hourly global analysis (FNL) from NCEP at 1 degree resolution to 3 km horizontal resolution which resolves sites of the individual offshore wind farms. In addition, the FINO-1 measurements are used to determined the microscale turbulence and offshore site specific gust characteristics.

1 Introduction

Since accurate assessment of local wind resources is vital for the planning and the management of offshore wind farms, where in-situ measurements are scarce and expensive, the validated mesoscale wind field simulations of the marine atmospheric boundary layer can provide a suitable alternative dataset. The boundary layer flow over the coastal regions is quite complex due to the land-sea surface discontinuity at the coast which affects both the surface roughness and the thermal stability. Growing interest in harvesting offshore wind energy requires the development reliable methodology for estimating the wind resources and extreme turbulent conditions at the offshore sites.

In this study, we propose a methodology for the wind resource and site assessment studies at the meso- and microscale using numerical simulations and in-situ measurements. We determine the wind distribution for the wind resource assessment in the German Bight by using the Weather Research and Forecast mesoscale model (WRF) for the marine atmospheric boundary layer wind field simulations. Since the site assessment entails other than the wind field distribution, also detailed knowledge of the extreme conditions, the measurement data from the offshore FINO-1 platform is additionally analysed. For the determination of the extreme winds, additional long term wind measurements from a selected weather station are used. The distribution of the extreme turbulent discrete gust, required for optimizing loads on the rotor blades, are determined seperately also from the measurements on the FINO-1 mast.

2 Resource Assessment Methodology

The wind resource assessment at the site level is required to provide not only information on the mean wind field and distribution, but also on the extreme conditions at the relevant time resolutions and scales. In this section, the measurements and the WRF model used for resource and site assessment study are presented, followed by a brief discussion on the proposal of developing a unified approach for wind field assessment at different time scales for the offshore wind resource mapping.

2.1 FINO-1 Measurements

The FINO-1 measurement tower is located at the German Offshore Test Field site (Borkom-West) in the German Bight about 40 km from the coast in a water depth of around 35m. The wind measurements are taken at heights above sea level of $30-100$m, at 10m increments. However, due to the flow modifications caused by the massive mast structure, only measurements at 40m, 80m and 100m are used where sufficient high quality data is available. The 100m measurements are not distorted, since the cup anemometer is located at the top of the mast while at 40m, 60m and 80m cup and sonic anemometers provide data on both sides of the mast. Measurements of a number of additional fields, such as temperature and wind direction at different heights and humidity are also available. More detailed information on the FINO-1 measurements are given in [Neumann et. al., 2004] and references therein.

2.2 Mesoscale model (WRF)

Weather Research and Forecasting Model (WRF) is a mesoscale numerical weather prediction model developed by the National Center for Atmospheric Research (USA) with the ability to simulate the atmospheric flow on the grid resolution ranging from 100 km to 1 km. WRF Version 2.2 is a non-hydrostatic, prognostic model with explicit description of pressure, momentum and temperature. The numerical solution is computed onto the rectangular structured staggered grid by finite difference schemes. The vertical coordinate is the terrain following eta coordinate.

The physical package of WRF consists of a set of parameterization schemes for cumulus, radiation, planetary boundary layer, microphysics, and surface processes. The physical parametrisations in WRF can be selected from from simple robust models to complex higher order schemes. A multi-species (ice,graupel,sleat,snow,water) mix-phase wet physics scheme is used. The mesoscale models need to resolve the computationally expensive smallest scales, while the large scales are computationally not expensive and in agreement with the global fields. On the coarse scale of the first two domains, where the mesoscale model lacks ability to resolve convective events, cumulus parameterization besed on the Kain-Fritsch scheme is used. This parameterization is also used in latest version of the GFS model to compute the operational analysis (FNL). Convection parameterization in the third domain is not used since the resolution is high enough to resolve the convecton processes. The planetary boundary layer parameterization is based on the turbulent kinetic energy (TKE) parameterization. Surface layer below the first model level is parameterized using Monin-Obukhov similarity theory.

The initial and lateral boundary conditions are taken from the Final Analysis (FNL) from NCEP at $1^\circ \times 1^\circ$ spatial and 6 hourly temporal resolution. The horizontal grid sizes of the lowest resolution domain is 27 km, the nested domains have each 1/3 lower grid size. The third and final nested domain has the grid size of 3 km with 108×105 grid cells. There are 35 vertical levels, with the top layer is set at 50 hPa and 24 levels below 100 m. The Sea Surface Temperature (SST) are taken directly from the $1^\circ \times 1^\circ$ FNL data while the complex land surface scheme is only initialized by the FNL data.

2.3 Proposal for unified approach towards wind resource and site assessment

The massive increase in offshore wind energy utilization will require high quality wind resource and site assessment studies to reduce the high risks involved with large financial investments. Since it is neither feasible nor desirable to construct a large number of offshore measurement masts, the validated, representative and long time scale high resolution mesoscale simulations can supplement the measurements. The mircoscale turbulence characteristics determined by the high quality mast measurements are universal and may be used over the domain with similar surface characteristics. This approach is in particular useful for the offshore sites with very homogeneous but time dependent surface conditions due to the waves. However for the near offshore domain, the situation is more complex, where the mesoscale circulation patterns such as the land-sea breeze are more comman with mixed land and sea microscale turbulence characeristics [Vicker et. al., 2001]. An additional, seperate detailed analysis and measurements for validation of the mesoscale circulation will be required. In complex terrain, the surface conditions are even more heterogeneous and less predictable. Validated high resolution turbulence resolving CFD simulations will be required to describe the wind field over the whole domain in addition to the measurements.

3 Wind Resource Mapping in the German Bight

The region of investigation is the inner third domain in Fig. 1 (right), which includes the German North Sea coastline, some large islands and the German Bight including the proposed wind farm sites Fig. 1 (left) of the german offshore wind farms.

The boundary layer wind field (10m) dataset has been created for the German Bight using the 6 hourly NCEP/NCAR reanalysis data on a low ($2.5^\circ \times 2.5^\circ$) horizontal resolution, to examine the long term seasonal, interannual and decadal variability. In Fig. 2, the two dimensional probability density function of the wind speed

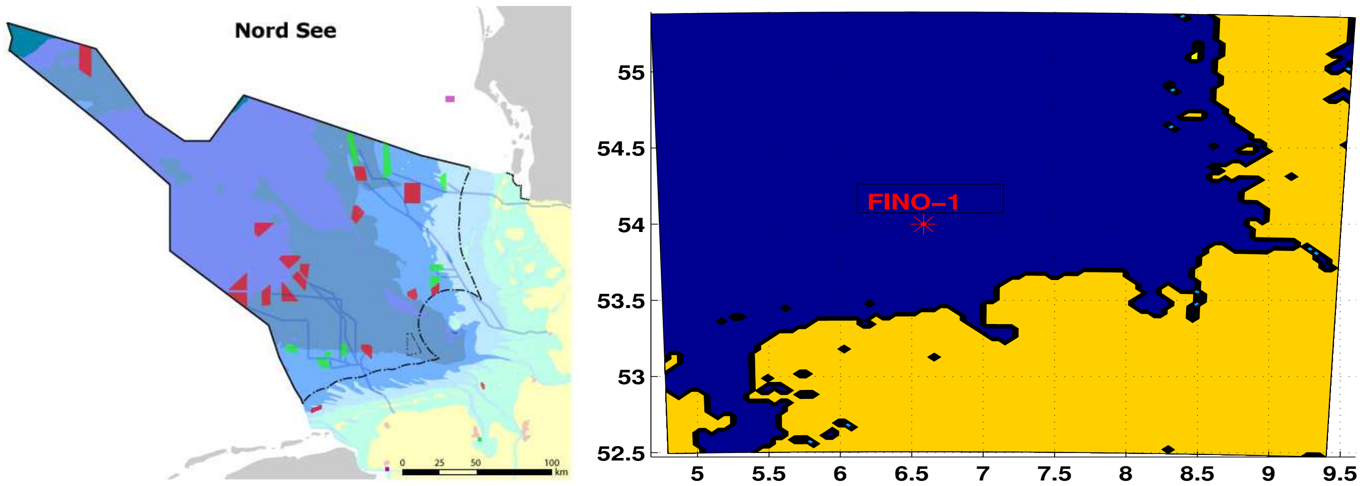

Figure 1: The FINO-1 measurement site with the location of the Offshore Test Field (left) and the 3. nested WRF domain (right)

(left, in %) and the wind direction (right, fractional) is depicted showing the seasonal variability on a climate revelant time scale of 56 years. The higher wind speeds are more comman in the winter with a shift of the most frequent winds from 3m/s to 5m/s. The dominant wind direction is southwest most of the year, with some additional northernly peaks in the summer.

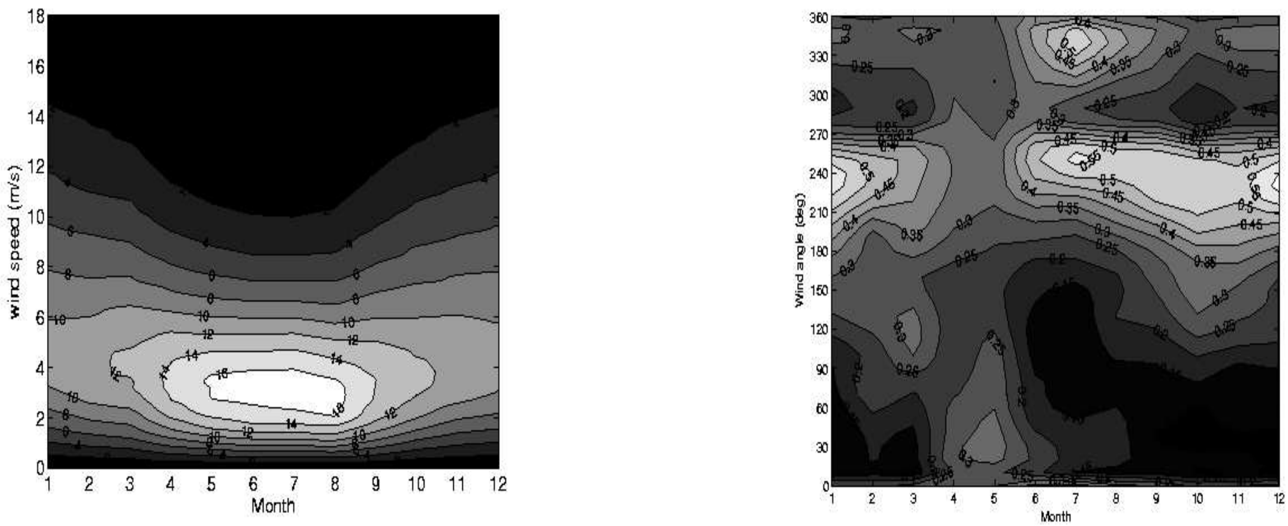

Figure 2: Seasonal variability of wind speed and wind direction distribution over FINO-1 in a time period from 1950-2005 with the NCEP/NCAR reanalysis data

3.1 WRF Simulations

The mesoscale simulations presented here have been performed on the high resolution 3. domain with a 3 km grid size for 2004 and 2005 on an hourly resolution with a 6 hour spinup period and 48 hour forecast horizon using the 6 hourly FNL operational analysis. Previous study [Beran, J. et. al., 2006] with a similarly setup MM5 model has shown that the 48 hour forecasts are quite accurate with high correlations to measurement The mean wind field (Fig. 3) is computed from the wind speed time series extracted from the simulations. The mean wind with speeds of around 10m/s at 100m are quite high in the offshore domain, whereas closer to the coast a strong wind gradient is observed. The coastline and the islands are not yet adequately resolved to provide equally reliable high quality results.

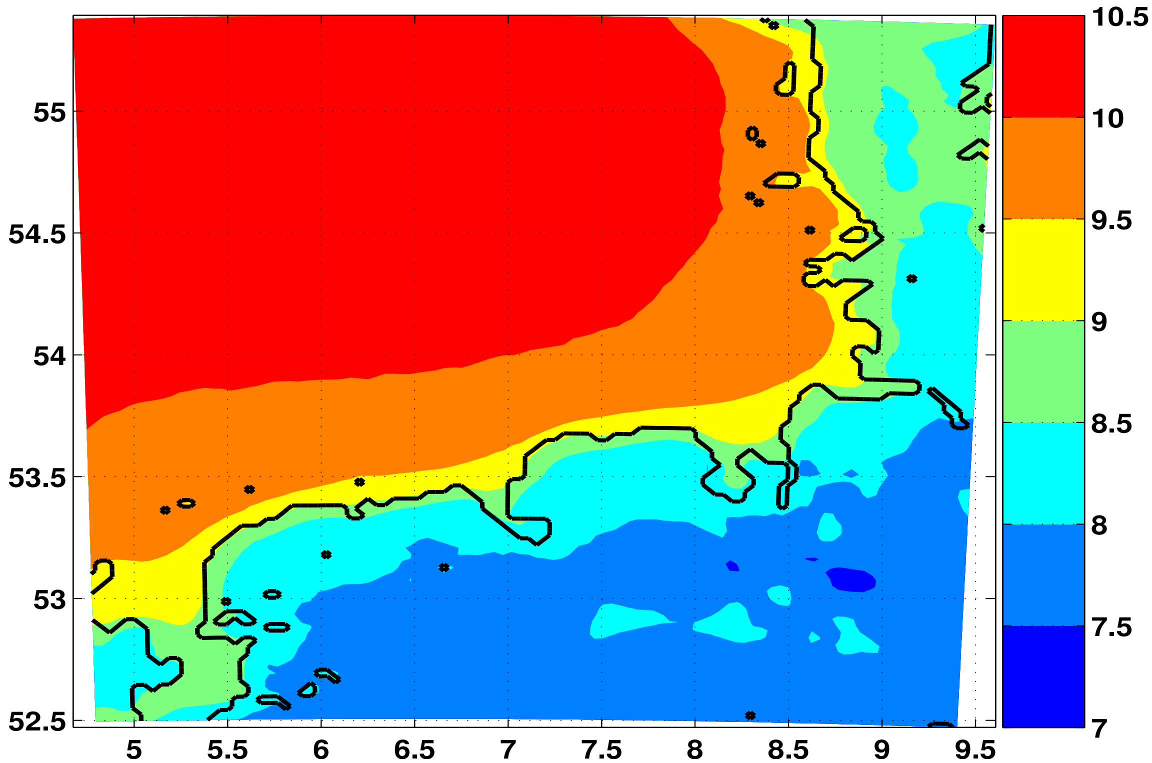

Figure 3: The mean wind field at 100m in the 3. nested WRF for 2004 and 2005

For validating the simulations at 40m, 80m and 100m heights at the FINO-1 site, the wind speed distribution is computed from the measurements, the driving large scale circulation (FNL) and the high resolution WRF model shown in Tab. 1. The 10 minute averaged measurements have however some missing data, while the hourly WRF and 6 hourly data FNL data are complete. Both the mean and the scale parameter A of the Weibull wind speed distribution deviate from the observation in a similar manner. The deviations from the observations are larger for the lower level (40m) than the higher level (100m) for WRF data. Since the lowest level of the FNL data is at nearly 100m, the values below 100m are extrapolated using the log law. The added value of mesoscale modelling is obviously improving the deviations of the mean wind speed from 16.6% for the FNL data of to 3.2% for WRF data at 40m dramatically whereas at 100m they improve from 15.1% for the FNL data to 1.8%. The standard deviation of the WRF data also matches the observations quite well with a slight underestimation of 1.2% at 40m to 3.8% at 100m compared to 20.9% underestimation of the FNL data for both heights.

Parameters	FINO-1			WRF			FNL		
	40m	80m	100m	40m	80m	100m	40m	80m	100m
A	10.13	10.72	11.15	10.44	11.11	11.33	8.45	9.22	9.47
k	2.31	2.25	2.22	2.41	2.39	2.34	2.46	2.43	2.42
mean	8.98	9.49	9.88	9.27	9.86	10.06	7.49	8.17	8.39
std. dev.	4.12	4.47	4.69	4.07	4.37	4.51	3.26	3.60	3.71

Table 1: Comparison of the wind field distribution parameters in the measurements from the FINO-1 site, the WRF simulations and the FNL operational analysis

We will exmaine the characteristics of the missing measurement data to determine any biases. The overestimation of WRF wind speed maybe due to missing measurement data during strong wind. The measurements are not

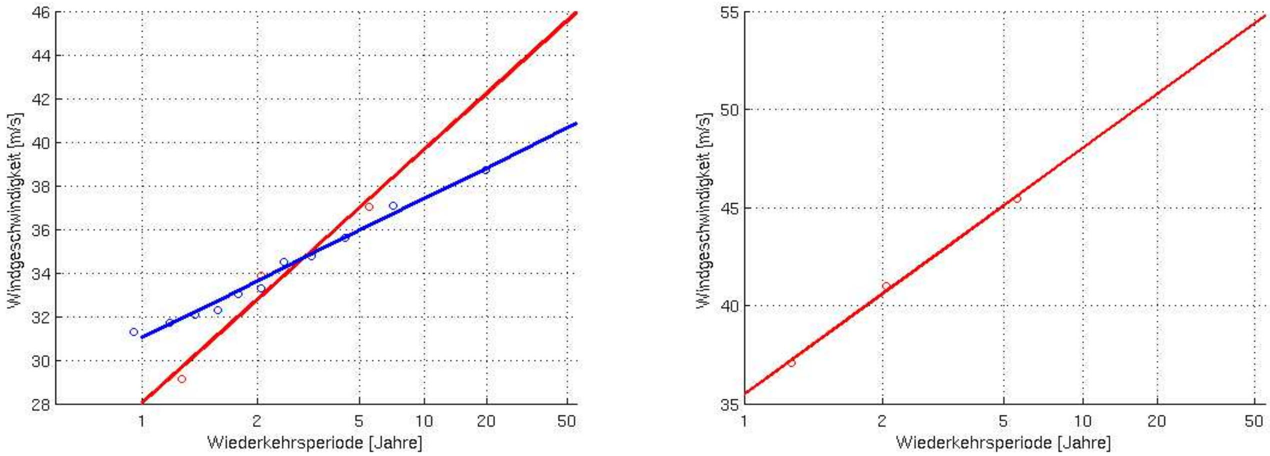

Figure 4: The extreme mean winds at FINO-1 based on observations (left, red) and 10 year extrapolated data (left, blue). The wind maxima for the 3 years are also presented (right) based only on measurements.

required for the mesoscale simulations and therefore an independent dataset. The mesoscale simulations offshore thus provide a valuable resource assessment dataset. Further validations at other locations are however desirable, before the WRF offshore dataset can be freely available for individual resource assessment. A more detailed analysis of the dataset has shown [Sušelj K. et. al., 2007] that the mixing is too high in the boundary layer flow resulting in deviation in profiles. Modification of the boundary layer parametrisation will be necessary to correct the wind profiles, which will increase the qualilty of the simulations.

3.2 Extreme Conditions

The extreme wind speed with one and 50 year return periods are important from an engineering perspective to deisgn for extreme loads. The standard Gumbel Distribution [Palutikof, 1999],

$$F(U) = \exp(\exp(-\alpha(U-\beta)))$$

where $F(U)$ is the cum. probability and the parwameters α and β depends on the $\overline{U_{max}}$, which is the mean max. value, is used in this study to compute the extreme wind speed. However this method requires atleast 10 years of data to extrapolate to long return periods U_T,

$$U_T = -\alpha^{-1} \ln\ln\frac{T}{T-1} + \beta.$$

This method is selected since the longer time series represents the climate variabilty better than selecting more cases from a shorter time series. However since measurements are available for only a short time series of 3 years, the wind data at 10m from a selected weather station at Borkum, with the same predominant wind direction as at FINO-1 is used to extrapolate the 3 year measurements at FINO-1 to the 10 years of available weather station measurements [Sood, A. et. al., 2007]. The predominant wind direction is from the sea reaching the measurement mast without large disturbances from land and a high correlation of 0.89. This reduces the hourly extreme wind speeds with a 50 year return period from about 45.5m/s to 40.8m/s. The extreme gusts from FINO-1 measurements however cannot be compared to a longer dataset.

3.3 Extreme Turbulunt Discrete Gusts

Some discrete gusts relevant for load optimization on the rotor blades und the turbine structure are described in the IEC 61400-1 3.ed Standards and GL Offshore Guidelines (2005). The Extreme Operating Gusts (EOG) are defined in the GL Offshore Guidelines (2005) as

$$V(z,t) = V(z) - 0.37\, V_{gustN} \sin((3\pi t)/T)(1 - cos(2\pi t)/T))$$

for $t <= T$ and

$$V_{gustN} = \beta \left[\frac{\sigma_1}{0.1(D/\Lambda_1)}\right]$$

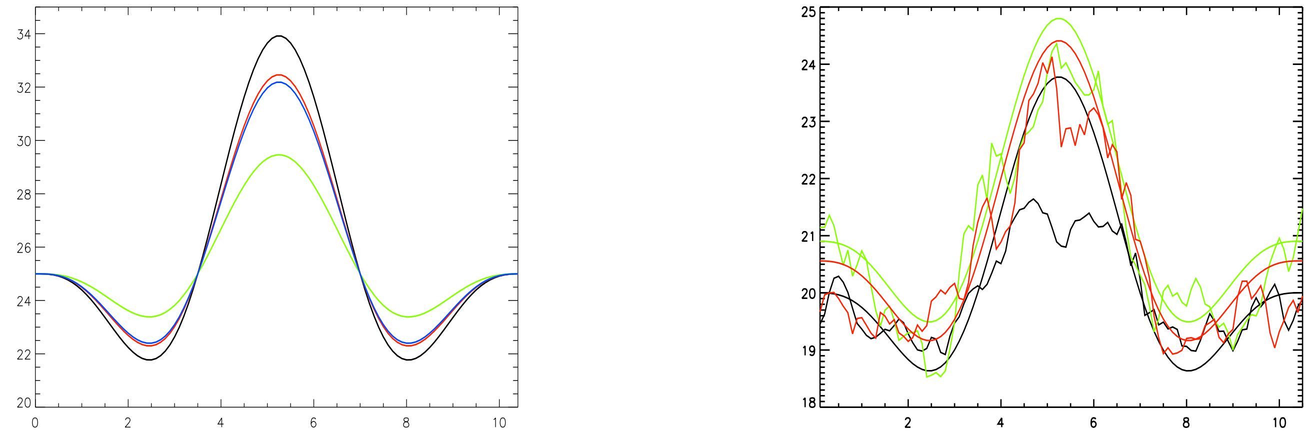

Figure 5: The EOG from the GL Offshore Guideline at site class I A (left, black), with 18% turbulence intensity, at site class I C (left, blue) with 14.5% turbulence intensity, IEC 61400-1 standard (left, red), and 9% turbulence intensity (left, green). Some examples of the EOG in December 2006 data at 80m (fluctuating line) and the EOG from the Standards with 9% turbulence intensity (smooth curve)

where $\Lambda_1 = 21m$ for hub height above 30m is the turbulence scale parameter, $D = 116m$ is the rotor diameter, σ_1 is the standard deviation of the longitudinal wind velocity

$$\sigma_1 = I_{15}(15m/s + aV_{hub})/(a+1)$$

where the parameters $a = 2$ and $I_{15} = 0.18$.

The 10 Hz dataset was prepared by removing obvious measurement errors. The EOG shape was correlated to the data set in the window defined by the EOG peiod T and moved along the measurement time series. The segments of the time series with sufficiently high correlated shape to the EOG were seperated. The amplitude of the EOG was matched by reducing the turbulence intensity.

Gust Duration	height 40m	80m	Correlation Coefficient
3	12	8	> 0.95
5	11	12	> 0.925
10.5	7	12	> 0.90
20.5	1	3	> 0.90

Table 2: EOG with Wind Speeds > 20 m/s and different periods at 40m and 80m height in December 2006

4 Discussion and Conclusions

The reliable and accurate wind and site assessment will help promote offshore wind energy and reduce costs by optimizing design and evaluating risks better. In this study, we did a preliminary investigation of the possibility of using the mesoscale model simulations for large scale wind resource assessment application. The 1.2% deviation of the simulated mean wind field from the measurements in 2 years of simulations at 100m, which is the proposed hub height for the modern large 5MW wind turbines, is quite low. Since also the standard deviation of the simulated wind field matches the standard deviation of the measurement with a deviation 3.8%, it is feasible to use the mesoscale simulations for wind resource assessment. The proper tuning of the boundary layer parametrisation for offshore conditions using the FINO-1 platform data can improve the wind profile considerably allowing additional benefits.

The extreme wind analysis will improve with the avaiability a longer timeseries of in situ measurement data. The discrete gusts like the EOG have been shown to exist in the offshore measurement data with about half the amplitude of the EOG defined in GL Offshore Guidelines (2005). A more thorough analysis considering two point correlations will be computed and other extreme gusts such as extreme shear and extreme directional change will be analysed. The statistical properties of microscale turbulence must also be considered in addition to the discrete gusts.

The offshore mapping of the wind resource should consider providing not only the high resolution wind distribution in the domain, but also the prevalent extreme conditions and the microscale turbulence properties.

5 Literature

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