Mesoscale Modelling of the UK Offshore Wind Resource

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Abstract

Knowledge of the wind conditions at a potential offshore wind farm site is key in reducing investment risk. This is normally done through the use of large meteorological masts. However, the increasing scale of the turbines offshore requires higher and more expensive masts, driving interest in the use of alternatives to extend accurate assessment of the resource. This work examines the use of the WRF mesoscale model for assessing the wind resource at UK offshore sites. A comparison is made with existing data at two offshore sites, Scroby Sands and Shell Flats. In addition, a projection is made of the wind conditions and variability at a potential UK Round 3 site.

Keywords: Offshore Wind Resource, Mesoscale Modelling, UK Round 3

1 Introduction

This research involves the use of the Weather Research and Forecasting (WRF) mesoscale model [1], [2] to assess the wind conditions at selected sites in UK offshore waters. Specifically, the Advance Research WRF model core (ARW) is used in this work. The accuracy of the model is assessed in a number of ways: 1) Through application of several planetary boundary layer (PBL) schemes, both individually and as an ensemble; 2) through the use of time-step ensembles; 3) by the use of different timescale filters; 4) through the use of model 'nudging' using nearby observations. Each model run has its boundary conditions set using output from the National Centers for Climate Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) [3]. This research is therefore concerned with how well a mesoscale model can downscale global forecast analysis data. A comparison is made between model output and observations from meteorological masts at Scroby Sands off the east coast of the UK and two masts at Shell Flats off the north-west coast. Model performance is assessed in terms of ability to predict wind speed and atmospheric stability. Recommendations are made in terms of how best to use the model for offshore wind resource prediction. Finally, a projection is made of the wind conditions at a future potential offshore wind farm site in the UK Round 3 Dogger Bank development zone. The variation in synoptic wind conditions across a large hypothetical 1.2GW wind farm in this area are also assessed including maximum expected wind speed and wind direction differences across the wind farm.

2 Background

WRF has become widely utilised in the atmospheric sciences research field. It has been applied to a full spectrum of investigations which include high resolution simulations, e.g. [4], which are relevant to wind resource assessment.

A number of studies have used WRF for offshore wind resource assessment. In [5], an investigation was undertaken into the performance of WRF compared with the ERA-Interim reanalysis product which was also used as initialisation and boundary data for the model run. The performance of the model was studied in the boundary layer which is of particular relevance to this study. Findings showed the model to offer a higher level of performance than the ERA-interim reanalysis product for the vast majority of variables studied apart from surface pressure. However, this was attributed to the provision of buoy data which was incorporated into the ERA-Interim product but not the WRF model run. The US army have investigated the operational use of WRF, at a high resolution, e.g. 0.3-3km, for the purposes of very short term forecasting and nowcasting applications [6]. For some locations, the use of WRF to create an offshore wind resource assessment product has already been undertaken, e.g. [7] describes a wind atlas for the South Baltic region. Such an application was essential because of the lack of observational data to the south of the region, while output was validated at locations in the domain where observational series were available from Danish and German masts. WRF has the potential to perform well as a wind resource assessment tool and has already been applied in the production of a wind atlas, which makes the next step validating performance for use as a site assessment tool, both in a historical long-term context and short-term operational context. A review was produced [8] for a system which is operational in China whereby GFS forecast data is downscaled by WRF and passed through a Kalman filter for the purpose of day ahead forecasting. It was found that the system performed with an acceptable level of error (16.47% normalised root mean squared error (RMSE)). Some traits of the model itself and setup options have been identified which should be considered when undertaking a wind resource study. The limit to the potential performance of the model is somewhat constrained by computing resource. In order to optimise a model run, outright resolution is often compromised to achieve a quicker model runtime and reduced computational resource requirement. In theory, the higher the simulated resolution, the better model performance would be as more processes are able to be directly resolved. However, it was found [9] that increasing resolution around the 4km range yielded diminishing returns with respect to the subsequent extra requirement in computing resource and instead suggested utilising larger spatial domains and vertical resolution to try and improve resolution of the larger scale features. Operationally, WRF has been shown to possess a high surface wind speed bias, e.g. [10], [11]. Knowledge of such a bias can be beneficial, as it allows for possible systematic correction in future predictions. Such a bias, however, might cause problems in model simulations which involve a coastal interface.

3 Methodology

3.1 Sites

Two observational data series were used for validation in this work namely Scroby Sands, and Shell Flats (Figure 1). Ten-minute averaged data were collected at both sites. At Scroby Sands, temperature, wind speed and wind direction were measured at 33m and 51m, from 1995 to 2000. There were some periods of missing data and this had an influence on model run periods. Two masts were erected at Shell Flats At Mast 1 wind speed, wind direction, temperature, relative humidity, pressure, rainfall and solar radiation with instruments were recorded at 12m, 20m, 30m, 50m, 70m, 80m and 82m above highest astronomical tide (HAT). Observations at Mast 2 were made at 12m, 20m, 30m, 40m and 52m above HAT.

Observational data from two onshore meteorological stations were also used in this study, namely one at Hemsby and one at Squires Gate (Figure 1).

The meteorological conditions at a ‘hypothetical’ site in one of the UK’s Round 3 offshore wind farm development zones (Dogger Bank) were simulated to investigate the expected variability in wind speed and direction as well as atmospheric stability. This is also indicated in Figure 1.

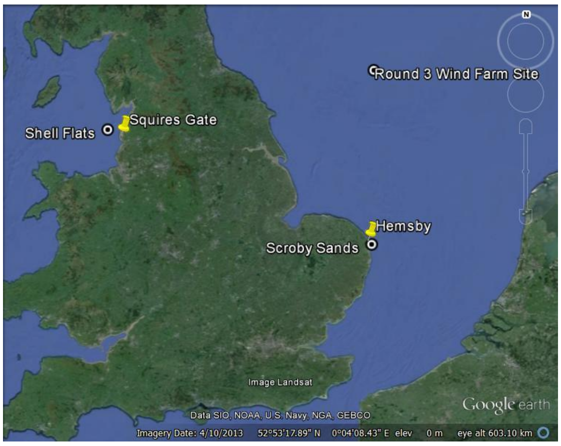

Figure 1: Locations of the three offshore and two onshore sites used in this study (offshore sites are marked as circles and onshore sites as pins).

3.2 Model Set-up

To run the model, two high performance clusters were used namely: Loughborough University’s Hydra cluster which is comprised of 161 compute nodes, each having two six-core Intel Westmere Xeon X5650 CPUs and 24GB of memory; and the UK Engineering and Physical Sciences Council (EPSRC) national supercomputing facility HECToR (High-End Computing Terascale Resource). HECToR has 2816 compute nodes, each with two 16-core AMD Opteron 2.3GHz Interlagos processors and 32Gb of memory. Aside from significant processor power, HECToR possesses advanced data communication hardware such that each 16-core socket is coupled with a Cray Gemini routing and communications chip which translates to data latency between two nodes of around 1-1.5μs. HECToR runs Linux and is available with many selectable modules and compilers, for example, gfortran, PGI, Intel and Cray. Ideally, HECToR would have been used for all runs, but the run-time allocation on this machine is limited due to demand.

Three levels of nested domain were used for the ARW runs as shown in Figure 2 for Scroby Sands. A similar nesting configuration was centred on Shell Flats and the Round 3 site. Nests were offset to give more space for the model to simulate features originating over the Atlantic, where many weather systems which influence the UK originate. The 0.5° CFSR reanalysis product was used to initialise the model, which equated to a grid spacing of around 55km. During the testing phase, breaches of the CFL (Courant Friedrichs Levy) criterion in the vertical plane were causing the model run to stop. The number of vertical levels was reduced to 50 vertical model levels which resolved the issue of numerical stability. Vertical levels were fairly evenly distributed apart from close to the surface where more levels were concentrated to improve resolution in the PBL. 15 levels were located below 500m at 0, 20, 40, 65, 90, 110, 130, 150, 170, 190, 230, 270, 330, 405, and 490m.

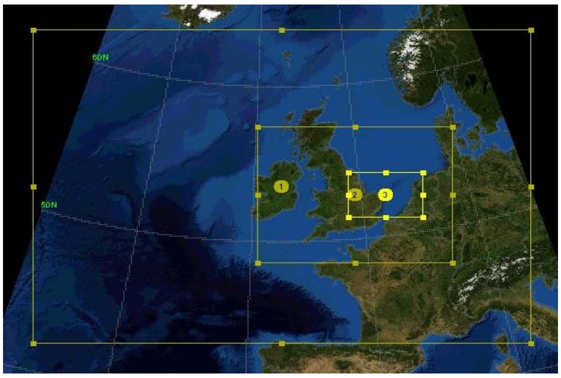

Figure 2: Three nested domains used for the ARW runs with resolutions of 18km (outer), 6km (middle) and 2 km (inner). The set-up for Scroby Sands is shown here.

The dynamical options used for the mesoscale model runs are given in Table 1. Two PBL schemes were used: for initial testing the Mellor-Yamada-Janjic (MYJ) scheme [12] and later the Yonsei University (YSU) scheme [13].

Scroby Sands was studied first for a relatively limited number of test cases in order to 'benchmark' the model. In this case, 34 periods were simulated over a year for model predictions extending from t+0h to t+90h. In the case of Shell Flats, a much larger number of simulations was run to simulate, as far as possible, a continuous period over 18 months. In this case, model runs were undertaken such that 489 days were simulated where each run extended from t+0h up to t+90h which was the longest look ahead time for which model predictions were assumed to provide reasonable predictions, i.e. RMSE errors were not showing a significant increase.

For the hypothetical Round 3 offshore wind farm site, simulations were undertaken to cover a period of one continuous year, once again from forecasts up to t+90h.

Table 1: Dynamical parameters used in the ARW mesoscale modelling for Scroby Sands (SS), Shell Flats (SF) and the Round 3 site (R3).

Model Parameter	Setup
Vertical model levels	50 (SS), 40 (SF, R3)
Nesting Feedback	On
PBL Scheme	Mellor-Yamada-Janjic (MYJ) for SS and Yonsei University (YSU) for SF/R3
Cumulus scheme	Betts-Miller-Janjic
Radiation scheme - Long wave	GFDL
Radiation scheme - Short wave	GFDL
Microphysics option	Ferrier (new Eta) microphysics
Surface layer physics	Monin-Obukhov (Janjic)
Land surface option	Unified Noah land-surface model

3.3 Model Nudging

Observational nudging is an objective analysis technique whereby an observational series is assimilated into the model input data. While large scale model input data are convenient due to global coverage, homogeneous levels and a wide range of variables, coarse resolution might not be exactly representative of conditions at, or near, a site of interest. Nudging the model input using objective analysis is intended to improve the first guess of particular variables at, or close to, a particular site. Given that WRF is updated for the duration of a model run by input and boundary files, nudging is performed throughout the whole run. Nudging was tried using data from Hemsby for the Scroby Sands assessment and in the case of Shell Flats, Mast 1 was used to nudge for simulations at Mast 2. There was the possibility to nudge using data from Squires Gate, but this is not reported in this paper. Only wind speed data were used to nudge the model as this was felt most relevant, though future investigations may use other variables. Nudged and non-nudged simulations were compared.

4 Results

4.1 Scroby Sands

It is clear that due to the limited temporal resolution of the model, the WRF would be unlikely to capture the observed variability at ten-minute intervals. Indeed, performance problems at short temporal scales were found [14], where variation in model output appeared damped in comparison to observations. With the innermost model domain resolution being 2 km, the smallest features which can be expected to be well resolved are around 14km in size. Below 14km, the model is able to account for atmospheric features to an extent, but does so through parameterisation schemes, specifically the planetary boundary layer scheme. Given that the temporal resolution of the runs is 10-minutely, it is unlikely that model performance will be best at simulating high frequency change as the size of atmospheric features responsible for change in wind speed on such a timescale is smaller than the directly resolved scale of the model. In order to investigate model performance on longer timescales at which atmospheric features are directly resolved, temporal filtering was performed on model runs and concurrent observations. Initially, an un-weighted moving average filter was applied to the 10-minutely model output and Scroby Sands observations at intervals of 3, 9 and 17 time steps which corresponded to 30, 90 and 170 minute periods. Subsequently a low-pass Butterworth filter was also developed to filter out frequencies below 60, 180 and 360 minutes. Table 2 summarises the average results from all 34 runs. RMSE and Pearson correlation coefficient between model and observed values is shown. As a benchmark, the wind speed at Hemsby is used as a simple predictor of the wind speed at Scroby Sands and the correlation coefficient calculated. A clear improvement is evident from both of the filtering processes. While filtering should intuitively reduce the variation in a series, the model output must still exhibit similar characteristics to the observations in order for the correlation to improve. Results are improved for the three-hour time increment by a greater margin using the moving average filter over the Butterworth filter and the performance gap compared to the simple Hemsby prediction is reduced.

These results confirm the value of using the model when applied to simulate features of appropriate scale. When done so, model output would seem to a good substitute for measurements at a nearby coastal meteorological station at least in the case of an offshore site relatively close to land.

Table 2: Pearson correlation coefficient and RMSE comparing WRF model predictions and observed data at Scroby Sands with various temporal filters. Hemsby is included as a benchmark predictor.

	Hemsby	**Hemsby MA**	**WRF**	**WRF MA**
Effective temporal resolution (Minutes)	60	180	10	170
Correlation	0.746	0.785	0.639	0.720
RMSE (m/s)			2.2	1.9

WRF Butterworth Filtered

Effective temporal resolution (Minutes)	60	180	360
Correlation	0.662	0.698	0.733
RMSE (m/s)	2.1	2.0	1.8

4.2 Shell Flats

Table 3 summarises the RMSE and correlation coefficients for model predictions when compared with measurements for Mast 2 at Shell Flats. In this case, Squires Gate and Shell Flats Mast 1 are included as predictors and the correlation coefficients reported. Various Butterworth Filtered predictions are compared on timescales between 10 minutes and 360 minutes.

Table 3: Pearson correlation coefficient and RMSE comparing WRF model predictions and observed data at Shell Flats Mast 2 with various temporal filters. Squires Gate and Shell Flats Mast 1 are included as a predictors.

	Squires Gate	**Shell Flats Mast 1**
Effective temporal resolution (Minutes)	60	10
Correlation	0.590	0.940

	WRF Butterworth Filtered			
Effective temporal resolution (Minutes)	10	60	180	360
Correlation	0.856	0.865	0.883	0.901
RMSE (m/s)	2.1	2.1	1.9	1.7

It can be seen in this case that the RMSE is similar as for the Scroby Sands prediction with a reduction with increasing timetable. However, the correlation is significantly higher. In addition, the wind speed data at the onshore site at Squires Gate shows a rather lower correlation than in the case of Hemsby and Scroby Sands. The correlation is lower than that for the WRF model predicted wind speed. The wind speed data from the Shell Flats Mast 1 shows a much higher correlation than Squires Gate and slightly higher than the WRF wind speed.

4.3 Model Nudging

For two periods of a month (July and October 2003) at Shell Flats model runs were undertaken with observational nudging using wind speed only from Mast 1. Statistics for these periods can be found in Table 4 and

Table 5 for July and October, respectively, where the ‘raw’ observations from Mast 1 are presented as a benchmark. July 2003 provided the first case study, where the correlation coefficient between observed and modelled wind speed was improved by the nudging process. Interestingly, the correlation coefficient between observed and simulated direction also improved, albeit marginally. RMSE of the nudged wind speed time series was also found to be lower than the non-nudged series. Similarly, RMSE for wind direction was again slightly improved by nudging the speed with the nudged direction RMSE value slightly lower than that of the non-nudged. October 2003 provided the second case study, in which the correlation coefficient for wind speed was marginally higher for the non-nudged run compared to the nudged run. Similarly, RMSE was marginally higher for the nudged run compared to the non-nudged run. By contrast, a slight improvement in wind direction was observed, with a higher correlation coefficient and a lower RMSE for the nudged run.

From these results, it can be seen that nudging can sometimes improve predictions and other cases not, though this may be related to how good the correlation is initially.

Table 4: Statistics for the July simulation period showing the performance of WRF as a predictor of the wind speed at Mast 2, with and without nudging from Mast 1. Comparison is made with raw data from Mast 1 as a simple predictor. Heights are 40m above HAT.

		Shell Flats Mast 1	**Nudged model (Model + Mast 1)**	**Non-nudged Model**
Speed	**Correlation coefficient**	0.934	0.810	0.739
	RMSE (ms^{-1})	1.2	2.1	2.6
Direction	**Correlation coefficient**	0.886	0.800	0.790
	RMSE (deg)	31.5	44.4	46.9

Table 5: Statistics for the October simulation period showing the performance of WRF as a predictor of the wind speed at Mast 2, with and without nudging from Mast 1. Comparison is made with raw data from Mast 1 as a simple predictor. Heights are 40m above HAT.

		Shell Flats Mast 1	**Nudged model (Model + Mast 1)**	**Non-nudged Model**
Speed	**Correlation coefficient**	0.919	0.888	0.889
	RMSE (ms^{-1})	1.8	1.9	1.9
Direction	**Correlation coefficient**	0.644	0.650	0.622
	RMSE (deg)	50.6	53.6	56.1

4.4 PBL and PBL Ensemble Predictions

To assess the performance of different PBL schemes, 20 test periods were run for Scroby Sands. The results of this study are shown in Table 6: A comparison of PBL schemes in terms of WRF model performance at Scroby Sands with the best performing schemes assessed in terms of highest correlation and lowest RMSE for the 20 cases. In Table 6, the individual PBL schemes are run with nudging using wind speed data from Hemsby, with the exception of one set of simulations using the MYJ scheme where nudging was not included. An equally weighted ensemble of all of the PBL schemes was also analysed. In general across the runs undertaken, statistical performance of the schemes is very similar. The MYNN and ACM2 schemes display the best average statistics, very close to those of the ensemble mean, and perform the best in the highest number of cases for the nudged PBL schemes. Formulation of the ACM2 PBL scheme suggests it should be a capable performer under unstable conditions, which might account for its level of relatively high performance compared to the other schemes as previous work [15] has suggested that unstable conditions persist at Scroby Sands for a large proportion of time. The remaining schemes, MYJ and QNSE are not especially poor performers, though the QNSE scheme does fare less well compared to the other schemes. The technical difference between the MYJ and MYNN schemes is in the formulation of the master mixing length scale, which might be the reason for the observed difference in performance in this study. In the MYJ scheme, the mixing length is a function of height, where in the MYNN scheme, turbulence, buoyancy and surface length scales are all used to form the mixing length scale, which all provide more detailed information regarding the turbulence present contributing to fluxes through the boundary layer. The QNSE scheme displaying the lowest performance is not so surprising, as it is tuned for stable conditions. Further work is required to identify the specific nature of the test cases, for example identifying if they were neutrally, stably or unstably stratified, which could feed into the development of a more ‘intelligent’ ensemble mean with appropriate weighting.

Table 6: A comparison of PBL schemes in terms of WRF model performance at Scroby Sands

PBL Scheme	Number of cases as top performer		Av. Statistics	
	Corr.	RMSE	Corr. Coeff	RMSE (ms^{-1})
MYJ	8	8	0.577	2.4
MYNN	12	8	0.602	2.4
ACM2	11	12	0.599	2.4
QNSE	3	5	0.551	2.5
MYJ (no nudging)	16	12	0.558	2.5
PBL ensemble	10	15	0.607	2.4

4.5 Time Offset Ensemble System (TOES)

As well as ensemble averages over all PBL schemes, an additional ensemble average was studied, namely the Time Offset Ensemble System. As each run was over 90 hours, there was the possibility of starting a new run at intervals during the 90 hours. In this case, the option of starting a run at 24 and 48 hours into the initial run was investigated for Scroby Sands. Ensemble averages were produced of the original, the next reinitialised run t+24 hours later, and a third t+48 hours after the original. For each of the three time offsets, all PBL schemes were run as reported in the previous section giving ensemble averages over time offset and PBL runs. Summary statistics after applying these methods to predicting the wind speed at Scroby Sands are shown in Table 7. This table also includes performance statistics for the PBL ensemble for the corresponding run without time offset averaging. It is seen that the combination of PBL and time offset averaging improves the correlation and reduces the RMSE. This would suggest that TOES are valuable in increasing prediction accuracy and that earlier run information still adds value even when a run period is reinitialised.

Table 7: Summary statistics for the TOES methods applied to Scroby Sands.

Comparison beginning		Corr. Coeff.	RMSE (ms^{-1})
t+24h	PBL Ensemble	0.5591	2.6
	PBL/Time Offset Ensemble	0.6003	2.4
t+48h	PBL Ensemble	0.5862	2.4
	BPL/Time Offset Ensemble	0.6374	2.2

4.6 Atmospheric Stability

For Shell Flats Mast 2, the atmospheric stability was classified using the Bulk and Gradient Richardson number inferred from measured data. This was then mapped to Obukhov length L and classified as either neutral (|L|>1000m), very unstable (-200≤L<0), unstable (-1000≤L<-200), stable (0>L≥200) or very stable (200>L≥1000). The Gradient Richardson number was inferred from temperature data at 12m and 82m and wind speed data from 10m and 82m. Bulk Richardson number was calculated using the same temperature data, but only wind speed at 82m. WRF model Bulk Richardson number data were produced based on temperature data output at 10m and 50m as well as wind speed data at 40m. As noted above the YSU PBL was used.

Figure 3 summarises the stability statistics thus calculated. It can be seen that the observed Bulk and Gradient Richardson number metrics give quite a different picture in terms of the prevailing atmospheric stability. The observed Gradient Richardson number statistics agree broadly with [15] with predominantly unstable conditions, whereas the observed Bulk Richardson number suggests a more symmetrical spread, with fewer very stable or very unstable conditions. The reasons for this may be due to the way the two metrics are calculated; the gradient method can produce large values of the Richardson number when the wind speed values at the two heights are very close together. The Bulk method is relatively immune to this, but the mapping of Bulk Richardson Number to Obukhov length is more tenuous. The modelled Bulk Richardson Number shows a reasonable level of agreement with observations though there are a lower number of neutral conditions and a tendency to predict more stable conditions.

Figure 4 shows the stability statistics this time by direction sector. It can be seen that there are a larger proportion of unstable conditions when the wind blows from the north and more stable from the south reflecting the fact that colder northerly air overlying warmer water will tend to promote unstable conditions whereas warmer southerly air overlying cooler water will tend to promote more stable conditions. The model simulates this trend quite well albeit with a tendency to predict more stable conditions as noted above.

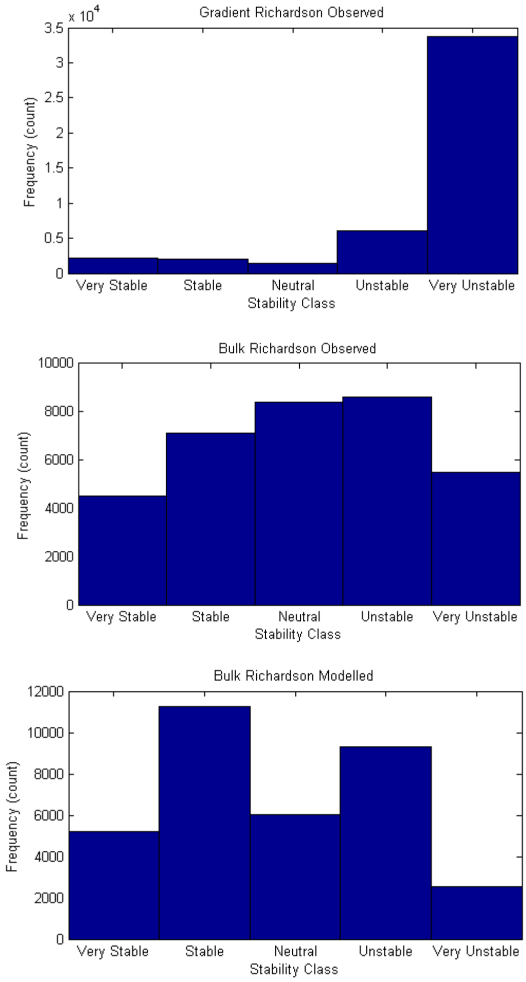

Figure 3: Observed and modelled surface layer atmospheric stability statistics for Shell Flats Mast 2.

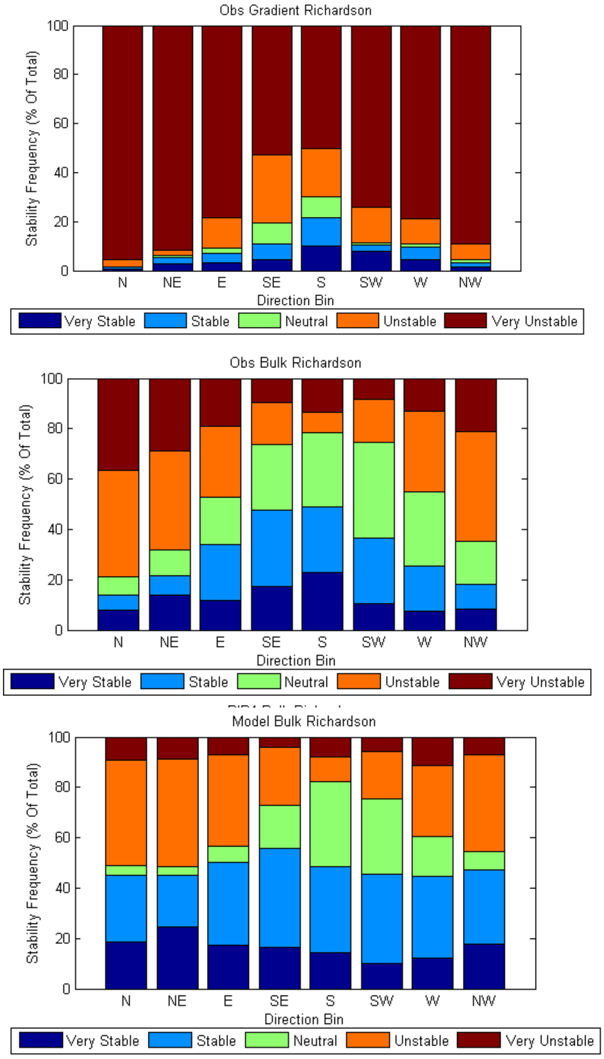

Figure 4: Observed and modelled surface layer atmospheric stability conditions at Shell Flats Mast 2 by direction.

4.7 Round 3 Wind Farm Site

WRF simulations of the wind and stability conditions were carried out at a hypothetical site in the UK’s Round 3 Dogger Bank Offshore Wind Farm Development Zone. Using a mesoscale model provides an opportunity to assess variability across a large area such as a large wind farm spanning over 20km and in this case, data were extracted for a central point and for grid points spanning a hypothetical wind farm site of area 20km x 20km containing 1.2GW of capacity. As for the main Shell Flats study, the YSU PBL scheme was used.

The overall distribution of wind speeds at the site suggests a Weibull-like distribution with scale parameter, C=10.2m/s and shape parameter, k=2.13 at 90m height. Figure 5 shows the projected wind rose for this site with a dominance of wind from the south moving clockwise round to the north-west where the highest wind speeds are projected.

Figure 6 shows the distribution of projected stability conditions at this site. The projection is for predominantly neutral conditions with some stable/very stable conditions observed, though this should be viewed with some caution as the model has a tendency to predict more stable conditions then observed as noted above at least using the YSU PBL scheme. Figure 7 shows the breakdown in stability by direction. The same tendency is noted as for Shell Flats with more stable conditions from the south, though this tendency is less pronounced for the Round 3 site.

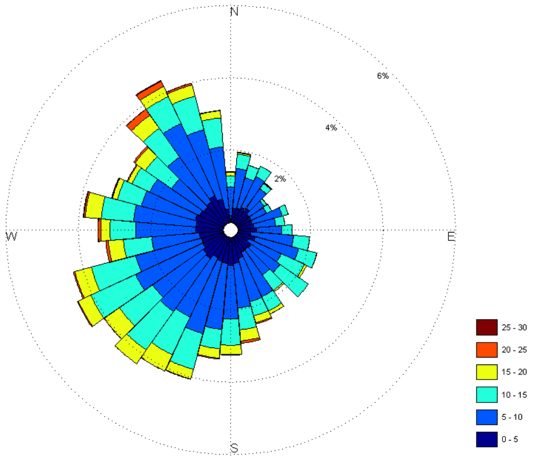

Figure 5: Projected wind rose for the Round 3 site. Colour scale is in units of m/s.

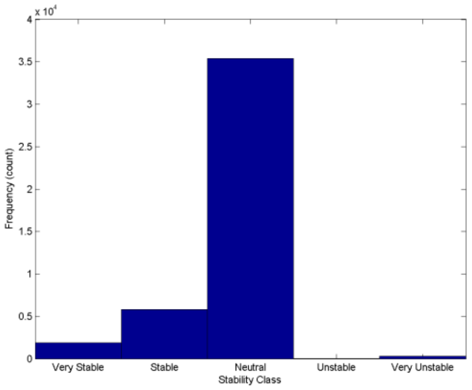

Figure 6: Stability distribution at the Round 3 site.

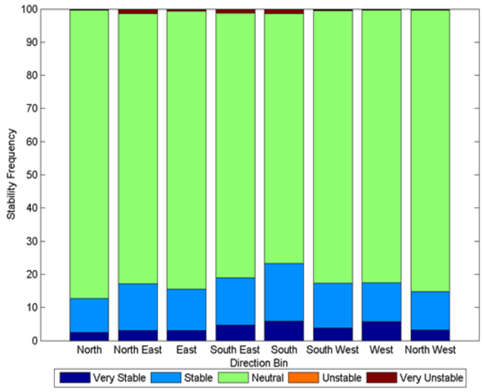

Figure 7: Stability distribution at the Round 3 site by direction.

Three months of simulations were also performed to gain an impression of the deviation in conditions seen across the farm. Due to the size of a Round 3 site, it is entirely possible that turbines at opposite extremities of the farm might be subject to different weather systems at the same time.

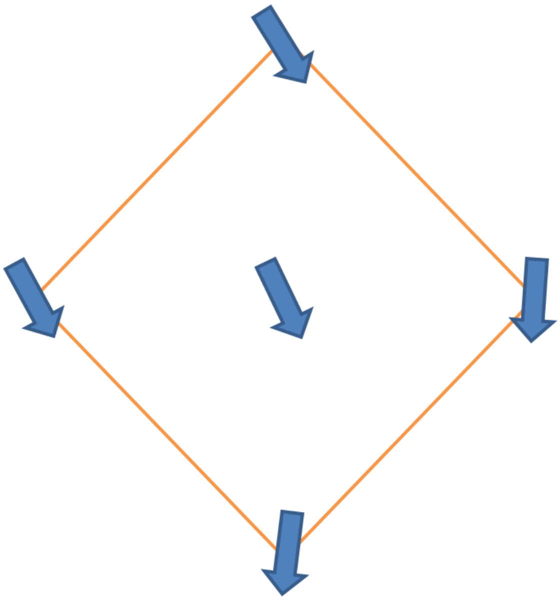

Figure 8: Schematic representation of wind direction variation across the Round 3 site on a certain day during the three-month simulation period.

Figure 8 is an example of one occasion where wind direction was very variable over the extent of the wind farm area with an extreme difference of over 50 degree. This could have significant implications for the overall performance of the wind farm due to wake interactions and highlights the importance of considering synoptic as well as smaller scale turbulent wake meandering and Coriolis effects when considering overall farm performance for such large potential sites.

5 Conclusions

The work presented in this paper has summarised the application of a mesoscale model to offshore wind farm resource assessment. It has been shown that:

- The WRF mesoscale model can predict offshore conditions at two sites relatively close to land with an RSME of 1.7-2.1 m/s depending the degree of temporal filtering employed.
- In some cases, model nudging can improve performance but only when the initial correlation between measurements and model output is less good.
- PBL and time offset ensemble averages show some benefit in reducing RMSE and there is further work to be down to perhaps produce dynamic ensembles if it is known for example that one PBL scheme performs less well under particular synoptic or stability conditions.
- WRF with YSU PBL scheme produces a reasonable representation of the stability conditions at an offshore site albeit with a tendency to more stable conditions than observed.
- A Round 3 site further offshore is likely to experience more neutral conditions than the two sites close to the coast.
- A large Round 3 wind site may experience significant differences in wind conditions across the site on occasion which will have implications for performance.

More work is required to validate against a broader range of sites to generalise the findings of this work.

6 Acknowledgements

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