Preliminary assessment of the variability of UK offshore wind speed as a function of distance to the coast

Rolando Soler-Bientz[1] and Simon Watson[1]

[1]Centre for Renewable Energy Systems Technology. Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, LE11 3TU, UK.

R.Soler-Bientz@lboro.ac.uk, sbientz@msn.com

Abstract. In the UK, there is an interest in the expected offshore wind resource given ambitious national plans to expand offshore capacity. There is also an increasing interest in alternative datasets to evaluate wind seasonal and inter-annual cycles which can be very useful in the initial stages of the design of wind farms in order to identify prospective areas where local measurements can then be applied to determine small-scale variations in the marine wind climate. In this paper we analyse both MERRA2 reanalysis data and measured offshore mast data to determine patterns in wind speed variation and how they change as a function of the distance from the coast. We also identify an empirical expression to estimate wind speed based on the distance from the coast. From the analysis, it was found that the variations of the seasonal cycles seem to be almost independent of the distance to the nearest shore and that they are an order of magnitude larger than the variations of the diurnal cycles. It was concluded that the diurnal variations decreased to less than a half for places located more than 100km from the nearest shore and that the data from the MERRA2 reanalysis grid points give an under-prediction of the average values of wind speed for both the diurnal and seasonal cycles. Finally, even though the two offshore masts were almost the same nearest distance from the coast and were geographically relatively close, they exhibited significantly different behaviour in terms of the strength of their diurnal and seasonal cycles which may be due to the distance from the coast for the prevailing wind direction being quite different for the two sites.

1. Introduction

Wind power has seen a rapid expansion in capacity in recent years; the global capacity has more than quadrupled since the beginning of this century [1]. Offshore wind generation in particular has the potential to make a substantial contribution to future energy needs as the wind in the marine environment is generally higher than onshore and less variable. In the UK in particular, there is an interest in the expected offshore wind resource given ambitious national plans to expand offshore capacity. Since the end of 2014, the UK had the largest capacity of offshore wind generation worldwide [1].

The behavior of the wind has a critical impact on the economic viability of an offshore wind farm. However, the assessment of the wind climate in a marine environment is particularly challenging due to the difficulty and high cost of installing and maintaining meteorological masts, particularly as measurements are exceeding 100m above sea level in many cases. Observations from ships are a potential source of information but they suffer from ship motion and are sparse in space and discontinuous in time. Satellite scatterometers offer spatially well-distributed data but short records and data are irregular in time and space [2]. Measurements from anchored buoys and meteorological towers

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

are sparse offshore in time and space and influenced by local effects. In addition, such measurements may be fine for site specific information, but it is challenging to extrapolate such data beyond the measurement site [3], [4] and [5]. In addition, meteorological masts have a high cost (>£10million). There is, therefore, an increasing interest in alternative datasets to minimize the requirement for offshore masts. These alternatives include global reanalysis datasets. Reanalysis data are available at different heights over long term time periods facilitating the interaction between wind generation models and climate models [6] and [7].

The use of reanalysis dataset as input time series to simulate wind-power applications [8] could be very useful on the aggregated level to model wake losses and to correct for systematic errors on long and short time scales [9]. In particular, the Modern-Era Retrospective analysis for Research and Applications (MERRA) reanalysis dataset has been used to produce wind-power generation time-series, which have strong correlation with the data measured in a power system [10]; to describe seasonal and inter-annual variability and to quantify the frequency of extreme events [11].

The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA2) is used in this paper [12][13] as a source of offshore wind speed data around the UK. The MERRA2 reanalysis replaced that of MERRA introducing among other things several improvements in the assimilation system, in the model and in the spatial resolution. MERRA2 uses the upgraded version 5.12.4 of the Goddard Earth Observing System Model, Version 5 (GEOS-5). MERRA2 is managed by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC) [12].

The MERRA2 grid has 576 points in the longitudinal direction and 361 points in the latitudinal direction, corresponding to a resolution of 0.625°×0.5° (a grid cell of 5/8° longitude by 1/2° latitude, known as native resolution). It also corresponds to a spatial resolution of approximately 50 km in the latitudinal direction.

Data from MERRA2 are available in a number of different file types which classify the variables according to different time and spatial scales. In particular, in this paper, the standard name of the assimilated GEOS-5 MERRA-2 data collection used was: **tavg1_2d_slv_Nx** (M2T1NXSLV) which corresponds to time averaged data with an averaging interval of 1 hour (**tavg1**) containing two dimensional fields (**2d**) in a single level (**slv**) with native resolution (**N**) just in the horizontal plane (**x**) [13].

Using the MERRA2 dataset and data from offshore masts, this paper examines the average wind speed, diurnal and seasonal cycles as a function of distance from the coast. An empirical expression is introduced to represent the average wind speed relative to the distance from the coast for the whole study period and for each season. Results for the MERRA2 dataset are compared with measurements from two offshore masts.

2. Study region

As was stated above, in this paper, we used wind speed data from the MERRA2 reanalysis dataset and data recorded from offshore mast stations. The two masts, London Array (LA) and Greater Gabbard (GG), are located offshore of the South East coast of England (see the two small white arrows in Figure 1), while the MERRA2 grid points were selected as the closest grid points to the offshore masts, plus an additional adjacent matrix of 5 x 5 points in order to cover distances to the shore up to approximately 250 km. A total of 35 MERRA2 grid points were initially used in this research which were located in Figure 1 with pins and ID numbers.

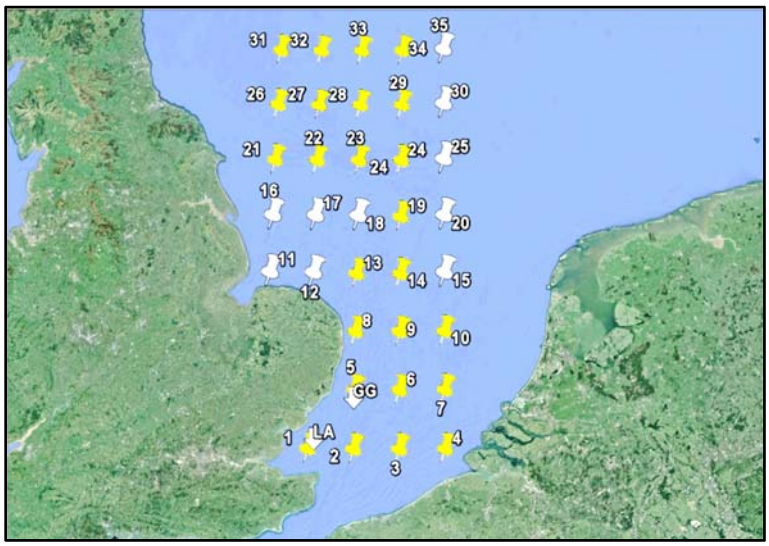

Figure 1. Map of the UK showing the study region. The small arrows indicate the location of the offshore masts: London Array (LA) and Greater Gabbard (GG). The pins represent the positions of the 35 MERRA2 grid points used in this paper.

Even though the MERRA2 datasets runs from 1980 up to the current date (~36 years), for the purpose of this research, a period of 6 years was selected as the study period, concurrent with the period of wind data available for the two offshore mast datasets. Wind speed at 50m height was used from the MERRA2 dataset and for the offshore masts the wind speed data available closest to 50m height were used. In order to reduce the number of simultaneous values to be plotted in a single chart, the results shown in the next section were analysed for the 35 MERRA2 grid points and 10 of them representing the whole range of variations of the study parameters were selected to be plotted along with the two offshore masts results. These 12 points will be referred in this paper as the "selected study points" and they are represented in Figure 1 by white pins and arrows. Table 1 shows for these selected study points their geographical coordinates, distance to the nearest coast and the direction of the nearest coast.

Table 1. Geographical coordinates, distance and direction to the nearest coast sorted by the distance to the nearest coast.

ID number	Latitude [Degree]	Longitude [Degree]	Nearest coastal distance [km]	Nearest coastal direction [Degree]
11[a]	53	0.625	3	167
12[a]	53	1.25	6	188
LA[b]	51.5940	1.38563	26	304
16[a]	53.5	0.625	28	245
GG[c]	51.9434	1.92210	29	344
17[a]	53.5	1.25	60	197
18[a]	53.5	1.875	73	209
15[a]	53	3.125	101	252
20[a]	53.5	3.125	117	113
25[a]	54	3.125	144	126
30[a]	54.5	3.125	182	140
35[a]	55	3.125	223	143

[a] Selected MERRA2 grid point
[b] London Array offshore mast
[c] Greater Gabbard offshore mast

3. Diurnal and seasonal cycles

The diurnal cycles computed over the whole study period for the selected study points have been plotted in Figure 2. In the case of the offshore masts, even though both masts are located approximately at the same distance from the coast, the London Array (LA) mast shows more influence from the land (manifested in the larger magnitude of the diurnal pattern) than the Greater Gabbard (GG) mast, particularly during the morning. This is because the coastal distance for the prevailing south-westerly wind direction is half that for the LA mast compared to the GG mast (see Figure 1 and Figure 3).

In the case of the MERRA2 grid points, the points 11, 12, 16, 17 and 18 show a clear influence from the land diurnal cycle. The points 15, 20 and 25 receive a smaller influence from the land diurnal cycle while the points 30 and 35 show almost no influence from the land diurnal cycle.

In general, it can be seen that the averages of wind speed over the diurnal cycle are smaller for the MERRA2 grid points located at similar distance of the shore than the averages recorded by the offshore mast stations. As was mentioned earlier the rest of the 35 MERRA2 grid points showed similar trends relative to their distance from the coast and are not presented for the purposes of clarity.

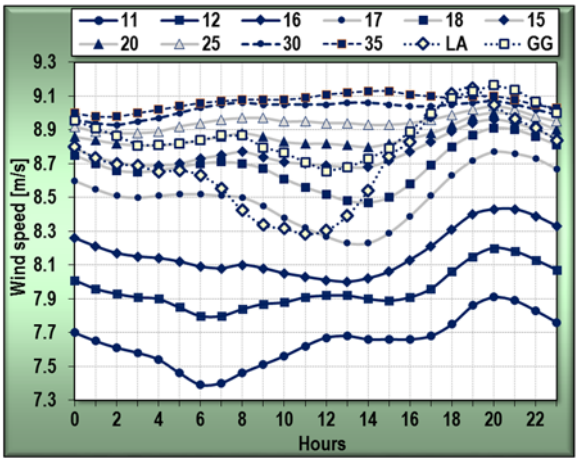

Figure 2. Average diurnal patterns of the wind speed over the whole study period of the selected MERRA2 grid points and the two offshore masts (LA and GG).

The frequency distribution of the wind direction is presented in Figure 3 below. It can be seen that the direction of the prevailing wind is around the sector located at 240 degrees. This could have some influence over the wind pattern in particular for the sites closer to the shore, as was already pointed out. This prevailing trend is even stronger for the two offshore masts which also show smaller peaks around 30-60 degrees not observed in the reanalysis data.

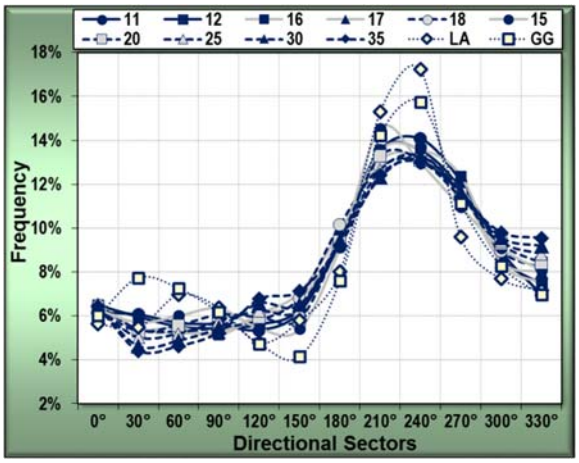

Figure 3. Wind directional frequency distribution over the whole study period for the selected MERRA2 grid points and the two offshore masts (LA and GG).

Figure 4 below presents the average wind speed for each season for every selected study point over the whole study period. As can be seen the average wind speed decreases in the Summer season and reaches a maximum over the Autumn-Winter seasons. Although the absolute values of the wind speed vary as a function of the distance to the coast, the magnitude of the seasonal cycles does not show much variation for the MERRA2 data points.

In the case of the offshore masts, there was a significant decrease in the average wind speed of the LA mast for the Autumn season which could be related with some particular local conditions around this mast location. In this case, as well as in the case of the diurnal cycles, the average values of the wind speed for the selected MERRA2 grid points are smaller than the averages wind speed recorded by the offshore mast stations.

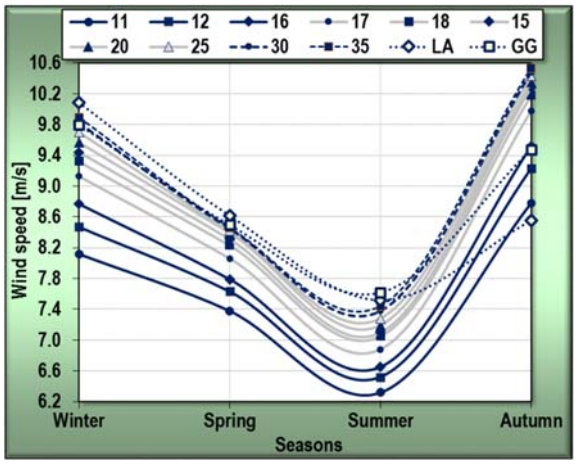

Figure 4. Average of the wind speed for each season over the whole study period of the selected MERRA2 grid points and the two offshore masts (LA and GG).

In order to better show the degree of variability of the diurnal and seasonal cycles over the whole study period, a parameter was defined as the difference between the maximum and minimum divided by the average wind speed over the study period, see equation (1) below.

$$\frac{\Delta U}{U_{avg}} = \frac{(U_{max} - U_{min})}{U_{avg}} \quad (1)$$

Figure 5 presents the parameter defined by equation (1) over the diurnal cycle for the MERRA2 grid points and the offshore masts. It can be seen that, as was mentioned before, the variations within a cycle are larger for the points located closer to the shore than those located further away. Specifically, the points located more than 150km from the nearest coast show less than the half of the variation of the sites located up to around 90km from the nearest coast. The much larger fractional variation in the diurnal cycle for LA when compared with the reanalysis data is apparent.

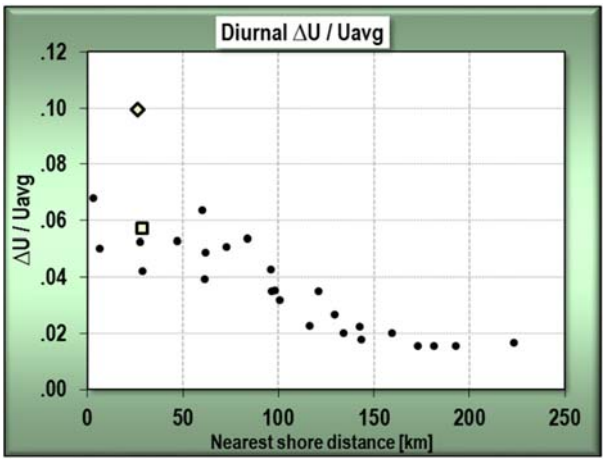

Figure 5. Variations of the average wind speed for the diurnal cycle over the whole study period for the MERRA2 grid points and for the offshore masts: LA (rhombus) and GG (square).

In the case of the seasonal patterns, Figure 6 presents the variations of the average wind speed as defined in equation (1) for the MERRA2 grid points and the offshore masts. It can be seen that other than the two points less than 30km from the coast that the seasonal cycles seem to be almost independent of the distance to the nearest shore, though interestingly there is some evidence for a peak in amplitude at around 70km from the coast What is clear is that the fractional variation seen at the offshore masts is significantly less than that of the reanalysis data.

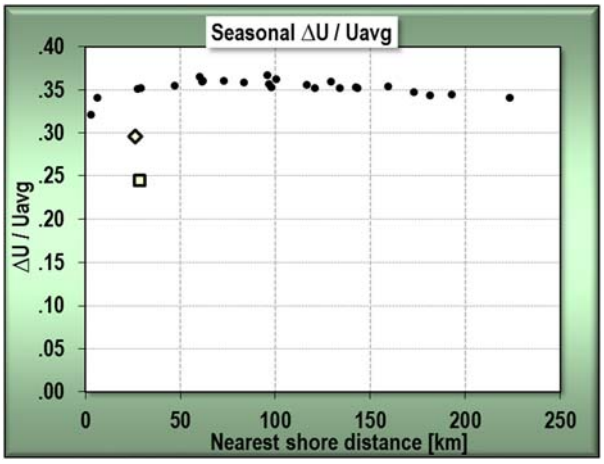

Figure 6. Variations of the average wind speed for the seasonal cycle over the whole study period for the MERRA2 grid points and the offshore masts: LA (rhombus) and GG (square).

4. Analysing average wind speed as a function of the coastal distance

The average wind speed as function of the distance to the nearest coast for the MERRA2 grid points and the offshore mast have been plotted in Figure 7 and Figure 8 for the whole period and for each season, respectively.

It can be seen that there is a relationship between average wind speed and distance. There is evidence of the average wind speed reaching an asymptotic value at large distances. Although all the points considered are offshore, clearly, the average wind speed at the coast would be expected to be non-zero. With this in mind, an empirical expression for the average long term offshore wind speed as a function of distance from the nearest coast is proposed of the form:

$$u = u_0 * \left[a - \left(\frac{x_0}{x+x_0}\right)^{1/2}\right] \qquad (2)$$

Table 2. Values of $\mathbf{u_0}$ and $\mathbf{x_0}$ used to fit equation (2) to the average 50m wind speeds showed in in Figure 7 and Figure 8.

	u_0 [m/s]	x_0 [km]	R^2	Estimated bias
Whole period	2.59	55.94	0.9998	-0.0010
Winter	2.71	34.49	0.9997	-0.0021
Spring	2.14	1.72	0.9997	0.0005
Summer	1.84	1.17	0.9985	0.0020
Autumn	2.79	9.92	0.9994	0.0070

where **u** represents the average wind speed at a distance **x** from the nearest coast line, **a** is a dimensionless constant equal to 4. The empirical parameter $\mathbf{x_0}$ is a distance scale which reflects how quickly the wind speed adjusts to the offshore conditions. The value of $\mathbf{u_0}$ and $\mathbf{x_0}$ were fitted for the whole study period and by season using a least squared fit in the Mathematica programming evironment. The fits are shown as dotted lines in Figure 7 and Figure 8; and the values of $\mathbf{u_0}$ and $\mathbf{x_0}$ are given in Table 2 along with the coefficient of determination R^2 and the estimated bias for each fitted value.

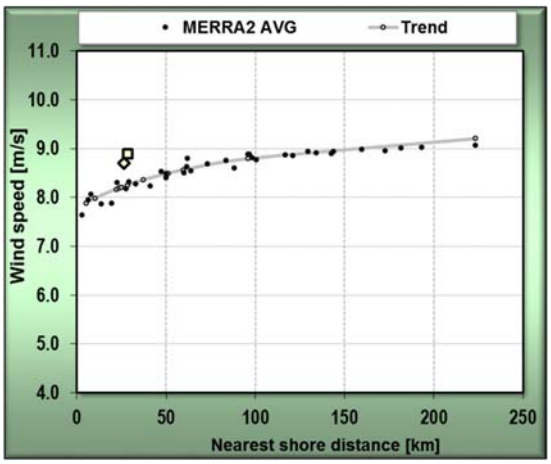

Figure 7. Distribution of the averages wind speed relative to the nearest shore distance and the interpolation function, as represented by equation (2) and table 2, over the whole study period. The average wind speed for the offshore masts is represented for LA by a rhombus and for GG by a square.

The average wind speed would equal $\mathbf{u_0}$ at the coast and would asymptote at large distances to $4\mathbf{u_0}$, however, it should be stressed that the fit has only been made between the closest site at 3km and the

furthest at 223km, so would only strictly be valid in this range. Although it can be seen that there is some degree of scatter for the values at each site around the trend lines, the empirical expression in equation (2) does provide a reasonably good fit to the data over a range of distances between ~5km and ~220km from the coast, with the possible exception of the summer season.

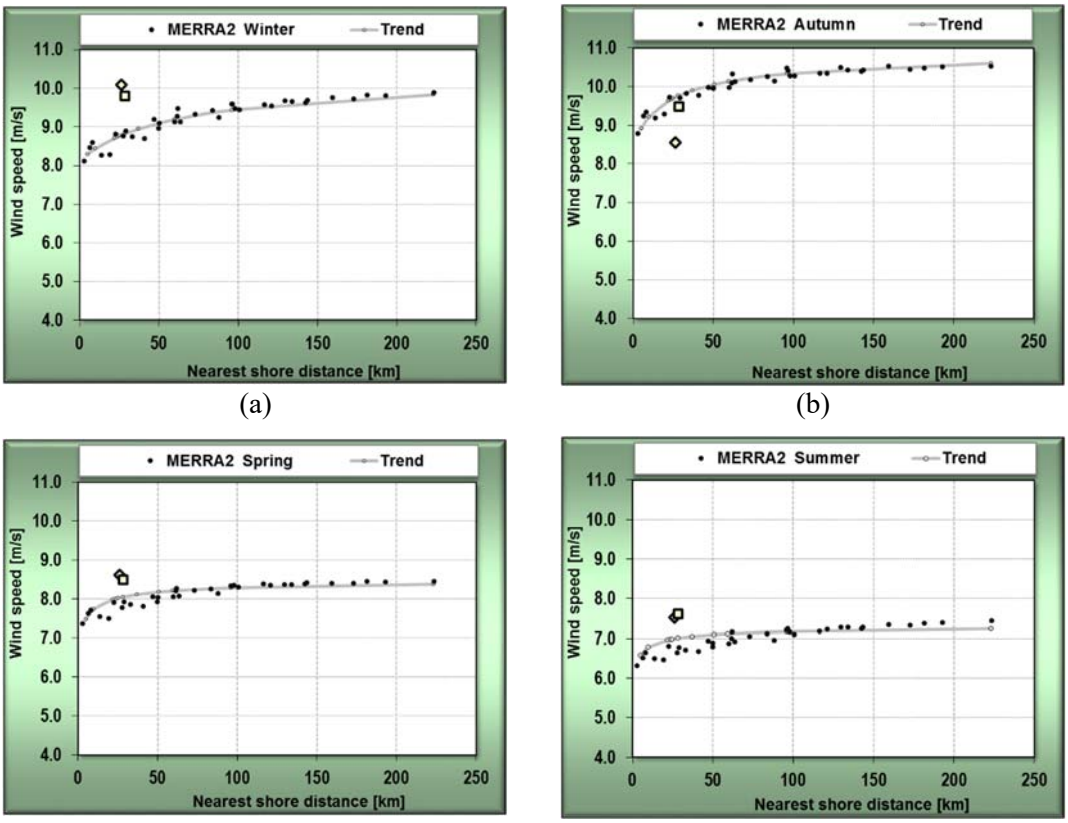

Figure 8. Distribution of the average wind speed relative to the nearest shore distance and the proposed interpolation curves, following equation (2) with the values listed in table 2, over each particular season (a) Winter, (b) Autumn, (c) Spring and (d) Summer. The average wind speed for the offshore masts is represented for LA by a rhombus and for GG by a square.

Figure 7 shows clearly that the reanalysis data significantly under-predicts the overall average wind speed at both LA and GG. Looking at Figure 8, this is also true by season with the exception of the autumn where there is an over-prediction.

5. Conclusions

This paper has used 50m long term reanalysis data from MERRA2 in order to study the spatial characteristics of the offshore wind speed close to the UK's development sites. A comparison was made between these data and measurements from two offshore masts. Trends in mean wind speed, diurnal and seasonal variation were studied as a function of distance from the coast. A relatively simple two-parameter empirical expression was identified to estimate wind speed based on distance from the coast giving a reasonable fit to the data, though this needs to be validated further by analysing data from a larger number of sites and a greater range of distances from the coast.

From the results presented in this paper, it can also be concluded that:

- The position of the coast for the prevailing wind direction seems to have a dominant effect over the magnitude of the diurnal cycle This was clear from looking at the results for London Array and

Greater Gabbard where the distance to the coast for the prevailing wind direction is significantly different but the nearest distance to the coast is almost the same.

- Data from the MERRA2 grid points located more than 150 km from the nearest coast show a magnitude in the fractional diurnal variation which is less than half of that for grid points located 90km form the nearest coast.
- The data from the MERRA2 grid points used in this research consistently seem to under-predict the measured of wind speed overall and for the diurnal and seasonal cycles, with the exception of the autumn season.
- The fractional variation in magnitude of the seasonal cycles seem to be independent of the distance to the nearest shore for distances above the 30km, though there is some evidence for a peak at around 70km.

References

[1] Global Wind Energy Council (2015). Global Wind Statistics 2014. Global Wind Energy Council, Brussels, Belgium. Available from http://www.gwec.net/wp-content/uploads/2015/02/GWEC_GlobalWindStats2014_FINAL_10.2.2015.pdf, last accessed 12th March 2016.

[2] Bentamy, A. and D. Croize-Fillon, Spatial and temporal characteristics of wind and wind power off the coasts of Brittany. Renewable Energy, 2014. 66(0): p. 670-679. 0960-1481. http://dx.doi.org/10.1016/j.renene.2014.01.012.

[3] Foley A M, Leahy P G, Marvuglia A and McKeogh E J 2012 Current methods and advances in forecasting of wind power generation *Renewable Energy* **37** 1-8.

[4] Jung J and Broadwater R P 2014 Current status and future advances for wind speed and power forecasting *Renewable and Sustainable Energy Reviews* **31** 762-77.

[5] Okumus I and Dinler A 2016 Current status of wind energy forecasting and a hybrid method for hourly predictions *Energy Conversion and Management* **123** 362-71.

[6] Pryor S C, Barthelmie R J and Schoof J T 2006 Inter-annual variability of wind indices across Europe *Wind Energy* **9** 27-38.

[7] Rose S and Apt J 2015 What can reanalysis data tell us about wind power? *Renewable Energy* **83** 963-9.

[8] Göransson L and Johnsson F 2013 Cost-optimized allocation of wind power investments: a Nordic–German perspective *Wind Energy* **16** 587-604.

[9] Olauson J and Bergkvist M 2015 Modelling the Swedish wind power production using MERRA reanalysis data *Renewable Energy* **76** 717-25.

[10] Kubik M L, Brayshaw D J, Coker P J and Barlow J F 2013 Exploring the role of reanalysis data in simulating regional wind generation variability over Northern Ireland *Renewable Energy* **57** 558-61.

[11] Cannon D J, Brayshaw D J, Methven J, Coker P J and Lenaghan D 2015 Using reanalysis data to quantify extreme wind power generation statistics: A 33 year case study in Great Britain *Renewable Energy* **75** 767-78.

[12] The MERRA-2 data are available online through the Goddard Earth Sciences (GES) Data and Information Services Center (DISC) at http://disc.sci.gsfc.nasa.gov/mdisc/).

[13] Global Modeling and Assimilation Office (GMAO) (2015), *tavg1_2d_slv_Nx: MERRA-2 2D single level, time averaged 1-hourly (p-coord, 0.625x0.5), version 5.12.4*, Greenbelt, MD, USA: Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC), Accessed **11/07/2016** at doi: 10.5067/VJAFPLI1CSIV.

[14] April 2016, The Crown Estate; *The Marine Data Exchange*; at http://www.marinedataexchange.co.uk/.