UK MERRA Validation With Offshore Meteorological Data

October 2014

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1. Executive Summary

The UK MERRA offshore validation study was undertaken to gain fresh insight into the extent to which reanalysis (MERRA) data could be used in support of, or in some cases in substitution for, meteorological data gathered by offshore masts. The study demonstrates the value of the amalgamation of offshore data by The Crown Estate. By studying the database of offshore meteorological data, The Crown Estate has discovered a number of findings, which include suggestions for further work in order to reduce uncertainty and improve modelling. The offshore wind industry and those providing technical support to it are invited to consider the findings, including the requirement for, and priority of, future work.

2. Introduction

2.1 The Crown Estate

The UK's offshore wind resource is amongst the best globally. As managers of the seabed out to the 12nm territorial limit, and of energy rights (other than fossil fuels) on the UK continental shelf, The Crown Estate facilitates the development of the offshore renewable energy and other marine industries. Since 2001, The Crown Estate has held seven offshore wind leasing rounds increasing in scale and technical complexity as the industry has developed. These leasing rounds have resulted in agreements being awarded for waters around England, Wales, Scotland and Northern Ireland.

The strong project pipeline, growing at 10 per cent per year, has positioned the UK as the most attractive place to invest in offshore wind globally; 2014 was a landmark year for the UK offshore wind industry. Significant milestones have been achieved, including 4 GW of capacity now in operation – sufficient to meet the electricity demands of nearly 3.2 million UK households.

The Crown Estate continues to work closely with industry and government bringing investable opportunities to market. This is done by providing land rights to the seabed, supported by a range of enabling activities, and sometimes by co-investing in development through to the award of planning consent. It supports the drive to reduce the cost of offshore wind, through investment in environmental and technological research and by working with industry to encourage sharing data and best practice. Recent initiatives have ranged from undertaking surveys of mammal and bird populations to identifying the skills gap and assessing careers opportunities in the marine renewable energy industry. The results of much of this work have been made freely available to existing and potential developers and, where possible, to the general public through the Marine Data Exchange. This policy of knowledge sharing is also demonstrated through the provision of free access to survey data and reports collated during the planning, building and operational phases of offshore renewable energy projects and submitted to The Crown Estate as a condition of each offshore agreement (www.marinedataexchange.co.uk) [1].

2.2 Offshore Meteorological Data

As part of the initiatives to encourage and advance the development of offshore wind around the UK, The Crown Estate collects, stores, and analyses data from offshore meteorological masts in the UK. After a period of confidentiality, this data becomes available to the public for use in development, studies, or research. Collecting wind speed data is a critical step in the development process for offshore wind farms and providing access to this data helps industry to expand through increased access to quality wind speed measurements and to improve through advancements in research and technology. The web-based Marine Data Exchange provides access to survey data and reports collected from offshore wind farms. By sharing this data, The Crown Estate aims to promote research and innovation in the industry.

The Crown Estate's collection of offshore measurements in the UK represents a concentration of quality offshore meteorological data that is without precedence elsewhere in the world. Together, the data collected amounts to over 85 years of offshore meteorological measurements from over 25 locations spanning from the late 1990's to the present. These measurements have monitored wind speeds in some locations to heights of over 100m and for periods of more than 8 years. These data form the basis of the information available to undertake this study.

2.3 Reanalysis Data

Reanalysis data, a recreation of historical meteorological conditions using actual observations combined with a global model, provides an estimation of, among others, global historical wind speeds and wind direction. Reanalysis data is an important tool in the wind industry. The modelled data can be used as a source of historical meteorological conditions often required in project analysis during the development, construction, and operation of a wind farm. The traditional use of reanalysis data is as an historical record of wind speed patterns which can be used to correlate with actual short-term wind speed measurements from meteorological masts. However, analysis of other aspects such as absolute wind speeds, wind speed variability, and extreme wind speeds have been considered as well. Reanalysis data reduces the costs and risk of offshore wind farm development by providing a source of long-term meteorological data that is difficult or expensive to acquire through normal meteorological measurement campaigns. By testing and analysing the performance of reanalysis data, wind farm developers can better understand how to use this data to benefit their projects.

3. MERRA

3.1 Modern-Era Retrospective Analysis for Research and Applications

The Modern-Era Retrospective Analysis for Research and Applications (MERRA) [2] is a reanalysis dataset built by the Global Modelling and Assimilation Office of the National Aeronautics and Space Administration (NASA). The model assimilates atmospheric observations into a numerical model called the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5) and provides a resource for a long-term analysis of the Earth's meteorological conditions.

The MERRA model provides a variety of statistics but the outputs of interest for the study are the wind speed and wind direction variables available at 10m and 50m heights. The output data is produced at a temporal resolution of 1-hour and a spatial resolution of 1/2 degrees latitude by 2/3 degrees longitude. The hourly data from the nearest MERRA node to each meteorological mast was acquired from NASA and processed for the analysis in this report.

4. UK Meteorological Measurements

4.1. Measurement Details

The meteorological data from each offshore mast available to The Crown Estate was analysed for quality and suitability for the analysis. In total, 25 devices were found to have meteorological data available, including 22 masts and 3 LIDARS. Figure 1 shows the locations of the masts from which data were available.

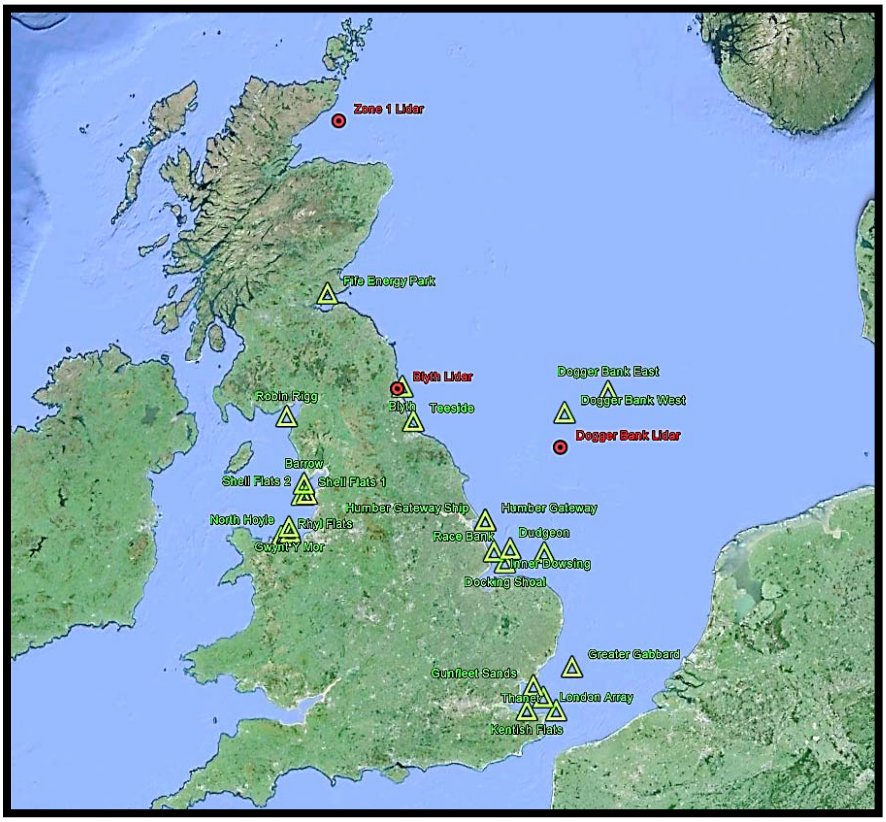


Figure 1: Map of Meteorological Observation Locations

Some data originated from sources with poor documentation, poor mast setups, or unconventional locations like ships or buoys. In these cases, the data was mostly discounted and only used as supporting evidence where necessary. Table 1 summarizes the data available for this report.

Name	Type	Max Height [m msl]	Start Data	End Data	Years Data	Distance MERRA [km]	Distance Shore [km]
Barrow	Mast	N/A	Jun 2006	Dec 2008	2.6	4	8
Blyth	Mast	103	Dec 2012	May 2013	0.4	17	5
Blyth Lidar	LIDAR	170	Oct 2010	Jan 2012	1.3	18	0
Docking Shoal	Mast	90	Jun 2006	Jun 2010	4.0	18	20
Dogger Bank East	Mast	110	Mar 2013	Dec 2013	0.8	11	210
Dogger Bank Lidar	LIDAR	301	Jul 2011	Dec 2012	1.5	17	125
Dogger Bank West	Mast	110	Sep 2013	Dec 2013	0.3	19	149
Dudgeon	Mast	N/A	Feb 2007	Apr 2008	1.2	26	37
Fife Energy Park	Mast	110	Apr 2013	Sep 2013	0.5	28	0
Greater Gabbard	Mast	88	Sep 2005	Jun 2010	4.8	9	28
Gunfleet Sands	Mast	51	Jan 2002	Nov 2006	4.8	27	7
Gwynt Y Mor	Mast	85	Sep 2005	Apr 2008	2.6	12	17
Humber Gateway	Mast	88	Oct 2009	Oct 2012	3.0	23	8
Humber Gateway Ship	Mast	N/A	Apr 2006	Mar 2009	2.9	23	8
Inner Dowsing	Mast	43	Aug 1999	Feb 2008	8.5	29	8
Kentish Flats	Mast	80	Nov 2002	Jan 2005	2.2	19	8
London Array	Mast	82	Dec 2004	Dec 2011	7.1	11	22
North Hoyle	Mast	50	Aug 1999	Jan 2007	7.4	13	10
Race Bank	Mast	90	Jun 2006	Dec 2008	2.5	21	28
Rhyl Flats	Mast	65	Jul 2002	Dec 2008	6.4	25	8
Robin Rigg	Mast	50	Dec 1999	Jan 2001	1.1	34	11
Shell Flats 1	Mast	81	Jun 2002	Sep 2007	2.5	16	16
Shell Flats 2	Mast	51	Jun 2002	Sep 2007	2.5	16	10
Teesside	Mast	50	Jul 2003	Oct 2008	5.3	21	0
Thanet	Mast	N/A	Jul 2005	Jun 2006	0.9	21	14
Zone 1 Lidar	LIDAR	N/A	Jul 2011	Oct 2011	0.2	28	20

Table 1: Details of Meteorological Observations

The maximum measurement height at each mast ranged anywhere from 43m up to 100m with higher heights achievable with the LIDAR devices. The first recorded data started in 1999 at the Robin Rigg and Inner Dowsing sites. The length and time period of all data sets is summarized in Figure 2 below.

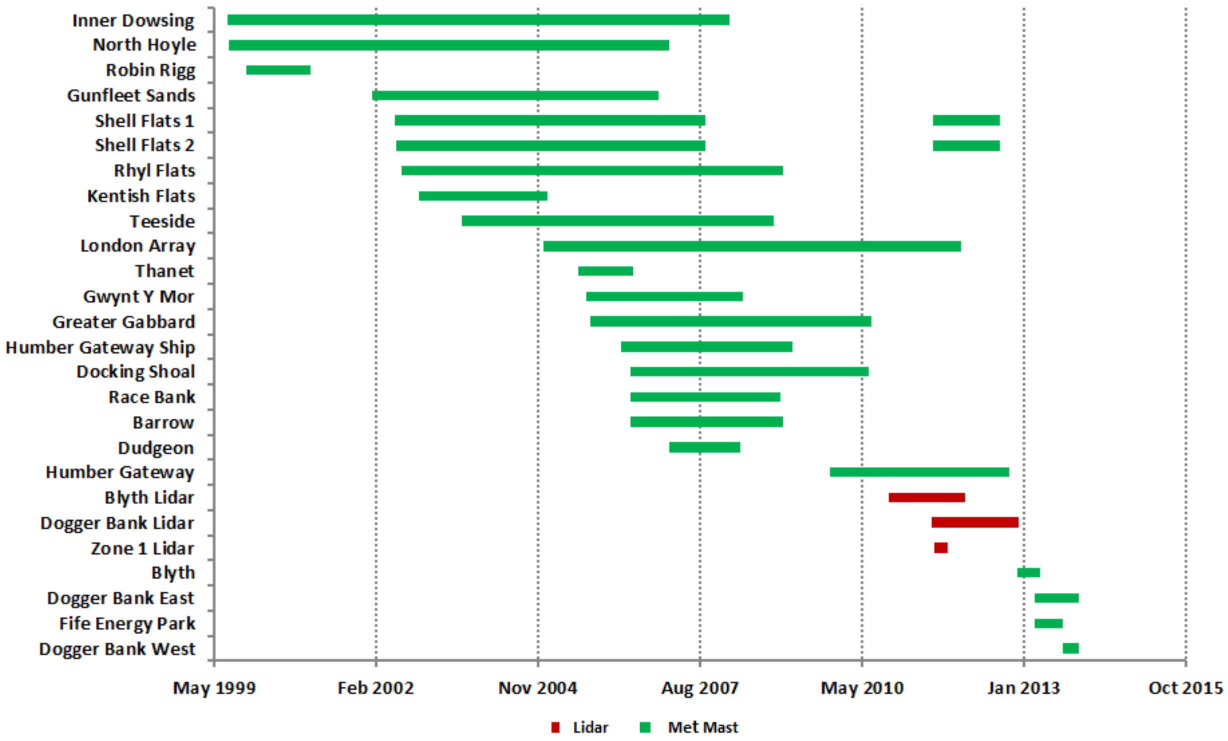


Figure 2: Periods of Data Available from Each Location

In total, the data represents over 85 years of measurements, potentially the largest set of offshore wind data above 10m in the world.

4.2. Measurement QA / QC

The data underwent extensive pre-processing in order to prepare it for cleaning and analysis. All available data was processed where possible working within the limitations of the documentation and data quality. Data was checked for sensor degradation, erroneous readings, channel swaps, sensor swaps, time and directional offsets, and other errors. Data was fixed where possible, or removed where necessary.

For this study, the LIDAR data was not analysed and the Humber ship data was not used, leaving 22 masts available for the analysis. It is noted that the Dudgeon data was situated on a buoy, but since the quality of the data was deemed acceptable and there was a lack of alternative data available for the site, it was used for this analysis.

Where possible, mast effects were removed from the wind speed measurements if two sensors were located at the same height. In directions where one sensor was affected by the mast, the other sensor reading was taken. In directions where both sensors were not affected by the mast, the average of the two sensors was used.

5. Analysis of Correlation Quality

5.1. Previous Studies

Historical studies have analysed reanalysis data performance using offshore met masts around Europe. These studies looked at the correlation quality, absolute wind speeds, directional wind roses, and variability of the meteorological measurements compared to the reanalysis data. Several studies indicated the relatively high correlation quality between offshore meteorological masts and modelled data [3, 4]. In addition, Bethke et al [3] described over prediction of wind speed by the model at low wind speed and under prediction of wind speed at high wind speed. Overall, these studies present a picture of offshore models that have strong correlation with actual measurements, but still have large errors on absolute wind speeds. The results of these studies have been taken into consideration during the analysis performed on the UK meteorological data available to The Crown Estate.

5.2. Correlation Quality

Measurements of correlation quality are important for the wind industry as correlations are the main use of reanalysis data for pre-construction energy assessments. Long-term sources of meteorological information can be correlated to shorter periods of actual site conditions in order to recreate the historical record of wind speeds at a site. This benefit allows developers to delay the installation of expensive offshore masts and to reduce the amount of time the masts need to record wind speed measurements. Figure 3 demonstrates the benefit of correlation of data to long-term meteorological sources allowing for the extension of a short-term data set.

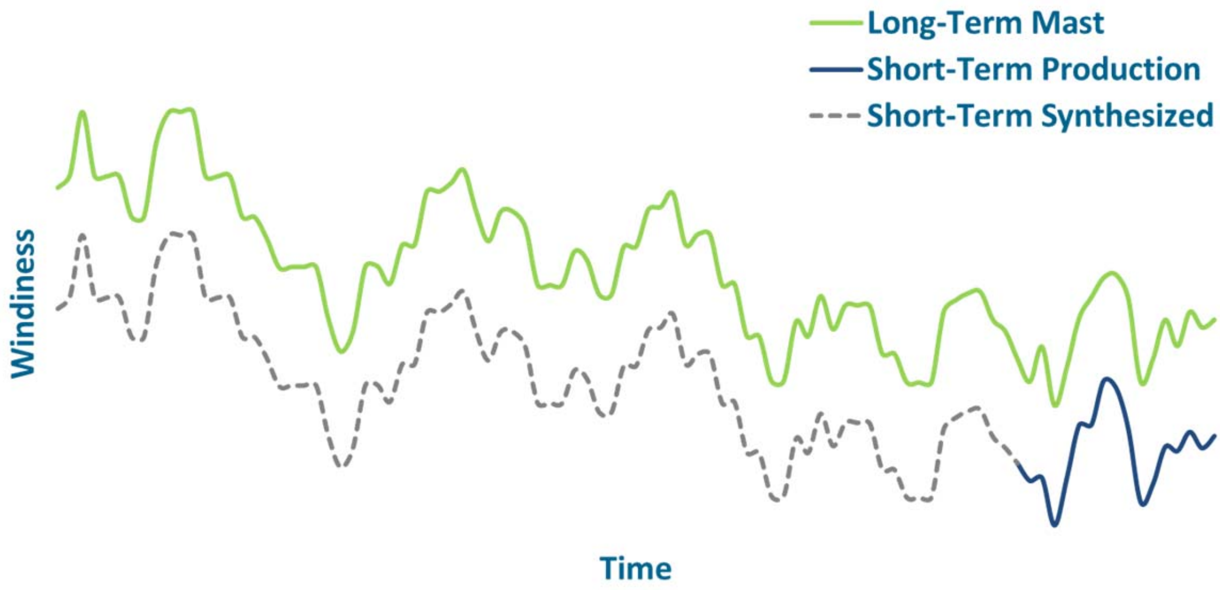


Figure 3: Use of Reanalysis Data for Historical Recreation of Wind Speeds

A simple measure of correlation quality between the meteorological data and the reanalysis data is the coefficient of determination, or R^2 (RSQ). This measure captures the fit of the correlation to a modelled line or curve where optimum correlation equals 1. Using a simple linear relationship of all data between the two datasets, the R^2 of each correlation was calculated for hourly, daily, and monthly values. The results are shown in Table 2.

Name	Max Height [m msl]	Distance MERRA [km]	Distance Shore [km]	RSQ Hourly	RSQ Daily	RSQ Monthly
Barrow	N/A	4	8	0.81	0.92	0.96
Blyth	103	17	5	0.80	0.90	0.97
Docking Shoal	90	18	20	0.84	0.94	0.99
Dogger Bank East	110	11	210	0.91	0.97	0.99
Dogger Bank West	110	19	149	0.93	0.97	0.99
Dudgeon	N/A	26	37	0.84	0.91	0.96
Fife Energy Park	110	28	0	0.64	0.83	0.92
Greater Gabbard	88	9	28	0.85	0.95	0.96
Gunfleet Sands	51	27	7	0.80	0.92	0.97
Gwynt Y Mor	85	12	17	0.78	0.89	0.99
Humber Gateway	88	23	8	0.83	0.93	0.97
Inner Dowsing	43	29	8	0.79	0.91	0.97
Kentish Flats	80	19	8	0.80	0.92	0.96
London Array	82	11	22	0.84	0.94	0.93
North Hoyle	50	13	10	0.74	0.87	0.95
Race Bank	90	21	28	0.86	0.95	0.99
Rhyl Flats	65	25	8	0.73	0.86	0.94
Shell Flats 1 – Early	81	16	16	0.79	0.91	0.95
Shell Flats 1 – Late	81	16	16	0.84	0.94	0.99
Shell Flats 2 – Early	51	16	10	0.69	0.80	0.92
Shell Flats 2 – Late	51	16	10	0.84	0.91	0.98
Teesside	50	31	0	0.72	0.86	0.95
Thanet	N/A	21	14	0.76	0.85	0.90

Table 2: Correlation Quality between MERRA and Mast Data

The results indicate the correlation quality to be relatively high compared to similar measurements onshore. This evidence supports other studies that indicate a strong performance of reanalysis data at offshore sites. The actual graphs for the hourly, daily, and monthly correlations are found in Appendices A, B, and C, respectively.

Table 2 shows an increase in correlation quality going from hourly to daily. When analysing the correlation quality of each mast, there is a noticeable non-linearity in many of the hourly correlations. At wind speeds above 20 m/s the mast wind speeds generally increase at a faster rate than the MERRA data. At wind speeds below 5 m/s the mast wind speeds generally decrease at a faster rate than the MERRA data. In addition, there is a noticeable amount of scatter in the hourly data due to unknown reasons. When the data is re-averaged to daily correlations, much of the non-linearity is removed, presumably due to the general benefits of averaging multiple observations. In addition, much of the scatter is removed, potentially indicating random or diurnal errors in the correlations between the two data sets. The improved linearity of the relationship combined with the decrease scatter of the correlation is the result of the averaging to daily values and consequently, an improved R^2 of the correlation.

Correlation by Height

The MERRA data is a 50m wind speed output; however the correlations undertaken above were done with the tallest available sensor at each mast. To determine if the correlation could be improved with sensors at 50m, masts with sensors at levels closer to 50m were correlated to the MERRA data. For some masts, the distance between the top sensor and the sensor closest to the MERRA height was over 55 m. The results of the hourly and daily correlations are displayed below in Table 3 below.

Name	Max Height [m msl]	"50 m" Height [m msl]	Height Difference	RSQ at "50m" - Hourly	Difference From Table 2	RSQ at "50m" - Daily	Difference from Table 2
Blyth	103	52	51	0.78	-0.02	0.88	-0.02
Docking Shoal	90	60	30	0.83	-0.01	0.94	-
Dogger Bank East	110	53	57	0.91	-	0.97	-
Dogger Bank West	110	53	57	0.93	-	0.98	-
Greater Gabbard	88	52	36	0.86	-	0.95	-
Gwynt Y Mor	85	45	40	0.76	-0.02	0.88	-0.01
Humber Gateway	88	52	36	0.82	-0.01	0.92	-0.01
Kentish Flats	80	50	30	0.79	-0.01	0.91	-0.01
London Array	82	57	25	0.83	-0.01	0.93	-
Race Bank	90	60	30	0.85	-0.01	0.95	-
Rhyl Flats	65	46	19	0.71	-0.02	0.85	-0.01
Shell Flats 1 – Early	81	50	30	0.79	-	0.91	0.01
Shell Flats 1 – Late	81	50	30	0.83	-0.01	0.94	-
Shell Flats 2 – Early	81	30	50	0.69	-0.01	0.78	-0.02
Shell Flats 2 – Late	81	40	40	0.83	-	0.91	-0.01

Table 3: Correlation Quality between MERRA and Mast Data at "50 m"

Negative values in the difference column indicate that the "50 m" sensor had worse RSQ values than the "Max Height" sensor. In general, all but one correlation showed worse correlations or no improvement to the correlation quality. The results of this study suggest that the MERRA data variation is more representative of changes found higher in the atmosphere and that the tallest sensors on each mast should be used to correlate with MERRA.

Correlation by Distance to Shore

Previous work has shown that MERRA data correlations are improved by moving offshore. However, there have been no previous studies to determine how far offshore a mast needs to be located in order to have improved correlations to MERRA. This dataset provides additional insight into the offshore distances over which MERRA correlations improve. Figure 4 shows the correlation R^2 values at each mast for various distances offshore. The points are coloured by the height of the top sensor used in the correlation.

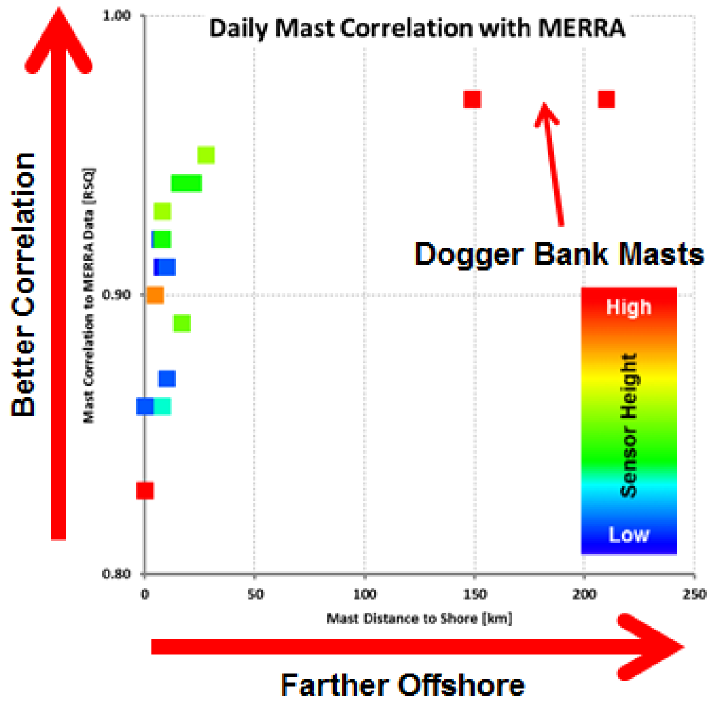


Figure 4: Correlation Quality between MERRA and Mast Data with Respect to Distance to Shore

The Dogger Bank masts clearly benefit from the greater distance offshore and the tall sensors. The Fife Energy Park mast (red square in Figs. 4 and 5), which is essentially onshore, shows a correlation value that is similar to experiences of good onshore masts.

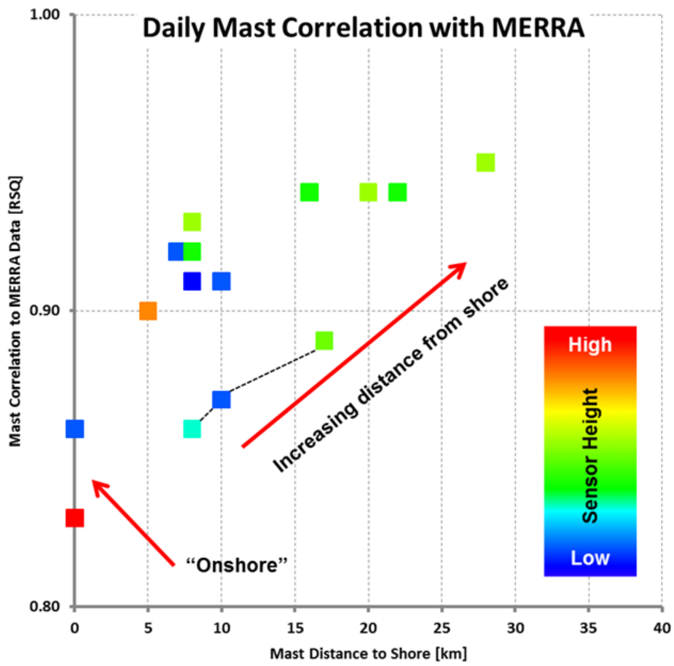


Figure 5: Correlation Quality between MERRA and Mast Data with Respect to Distance from Shore (Zoomed)

Zooming into the near-shore masts, there is a general trend of improved correlations as masts move farther offshore. The three points connected (Figure 5) by a dashed line indicate three masts in the same area correlated to the same MERRA point. This location, in northern Wales, appears to have a lower correlation quality to MERRA, but the correlation continues to improve as the masts move farther offshore. The rest of the points, correlated to other MERRA points, show a similar trend of correlation improvements as masts move farther offshore.

The biggest improvements in correlation appear to occur during the first 5km offshore with gradual increase in correlation quality thereafter. These results suggest that the terrain effects that reduce the correlation quality of onshore masts do not extend far offshore. After 5km, the daily correlation coefficient of all masts, except the northern Wales masts, reach 0.90 or better.

In order to remove differences in the correlation quality due to height of sensors, only masts with sensors close to 50m were used in the following graphs. As calculated in the previous section and as verified below in Figure 6, the height of sensors only makes a small difference in the correlation quality. The same trends are found in the “50m” data including an improving correlation coefficient as masts move farther offshore. There are fewer masts in the graphs as some masts did not have sensors close to 50m.

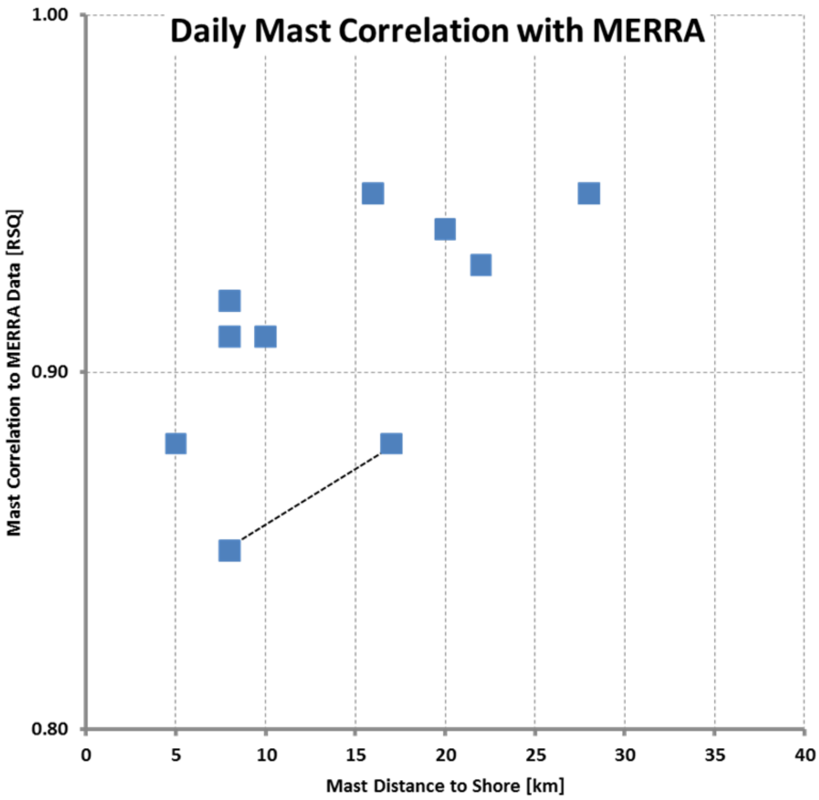


Figure 6: Correlation Quality between MERRA and Mast Data with Respect to Distance to Shore (at “50 m”)

This data does not take into consideration the quality of each mast setup like sensor type, redundant sensors, sensor distance to mast, mast documentation, etc., which may impact the correlation quality of some of the masts. Where available, photos of the masts can be found in Appendix F which provides insight into the expected quality of data that is output from the mast.

6. Analysis of Absolute Wind Speeds

Site wind speeds are a determining factor for site selection when building a wind farm. Understanding the absolute wind speeds at a site before having to build a meteorological mast would benefit developers during site selection and development. While the MERRA nodes do not necessarily correspond to the exact location of a meteorological mast, wind speeds around the sea change less dramatically than wind speeds on land. By comparing the wind speeds at the mast with the wind speeds output by MERRA, the relative differences of the two data sets can be determined.

In order to get a true comparison of mast wind speeds to the MERRA data, only masts with sensors at multiple heights were chosen so that the wind speeds could be extrapolated to 50 m, the height of the MERRA output. The concurrent periods of wind speeds at a mast were compared to the concurrent wind speeds for the MERRA data. As the period of measurements vary at each mast, the absolute wind speed is not necessarily representative of the long-term mean wind speed at the site, but instead provides insight into the relative differences between the absolute wind speeds measured and the MERRA data.

1. For each hour a shear value was calculated to extrapolate the data to a 50 m wind speed
2. The hourly time series between each mast and MERRA point were matched
3. The overall average of the matched time series was calculated and the difference was taken

Name	Mast WS Hourly	MERRA WS Hourly	Difference
Blyth	8.90	8.47	4.8%
Docking Shoal	8.41	7.51	10.6%
Dogger Bank East	9.41	9.00	4.4%
Dogger Bank West	12.00	11.57	3.6%
Greater Gabbard	9.05	8.38	7.3%
Gunfleet Sands	8.16	7.61	6.8%
Gwynt Y Mor	8.90	8.03	9.8%
Humber Gateway	8.63	7.50	13.1%
Inner Dowsing	8.34	7.61	8.8%
Kentish Flats	7.74	7.59	2.0%
London Array	8.66	7.91	8.6%
Race Bank	8.77	8.42	4.1%
Rhyl Flats	7.78	7.45	4.3%
Shell Flats 1 – Early	8.23	7.52	8.6%
Shell Flats 1 – Late	8.99	7.91	11.9%
Shell Flats 2 – Early	8.30	7.52	9.4%
Shell Flats 2 – Late	9.19	7.90	14.0%
Teesside - Onshore	7.77	7.92	-2.0%

Table 4: Differences in Absolute Wind Speeds for the Complete Time Series

All but one mast (Table 4) show that MERRA outputs wind speeds that are lower than the actual measured wind speeds at the site. The less windy mast, Teesside, is located onshore at a dock and is not consistent with the setups of the offshore masts. Overall, MERRA consistently under-predicts overall wind speeds at sites around the UK with an average of 7% error at the offshore masts.

Mast wind speeds relative to MERRA appear to increase between 5km and 10km offshore. Between 10km and 30km offshore, the MERRA wind speeds start to recover. However, even at 150km or more offshore, MERRA wind speeds are still 3-5% lower than actual wind speeds. Figure 7 depicts this change in MERRA relationship as masts move farther offshore.

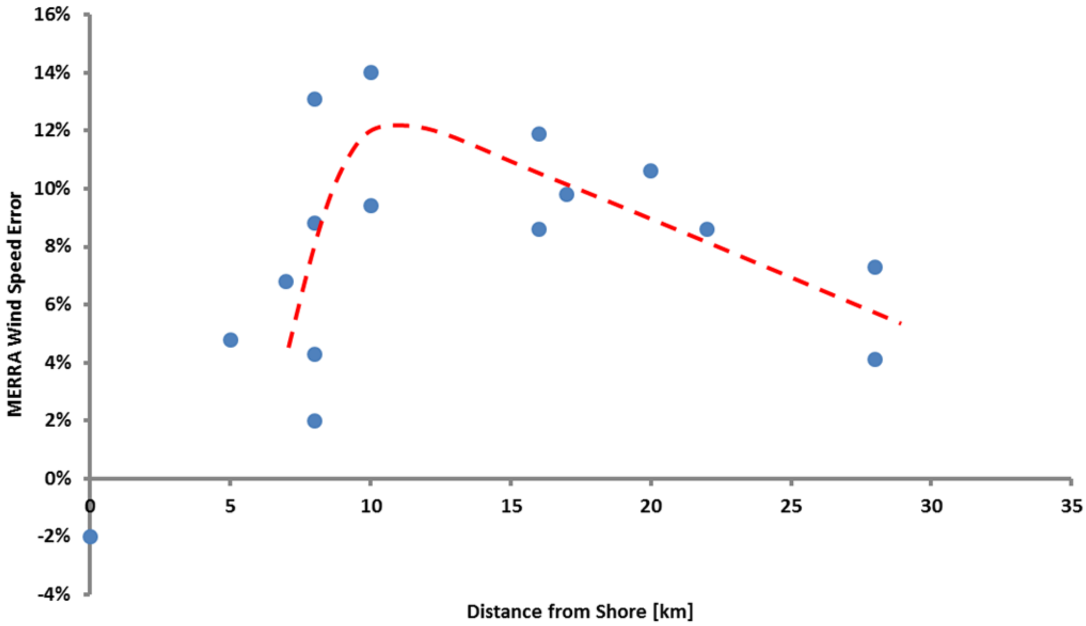


Figure 7: MERRA Absolute Wind Speed Error Based on Distance from Shore

Some variation in the MERRA wind speed error can be attributed to the location of the mast relative to the nearest MERRA point and whether that point is farther or closer to the shore than the mast. In addition, seasonal errors in MERRA absolute wind speeds were not investigated so the MERRA wind speed error could be affected by the measurement period at the mast.

In order to reduce the effect of seasonality and uneven measurement periods, a “mean of monthly means” (MoMM) approach was used to even out non-integer years of data.

1. All data corresponding to a single calendar month (i.e. all January data over all years) was averaged to get a single wind speed average for each of the 12 months of the year.

2. An overall average was calculated by weighting each month by the average number of days in that month.

Due to the need to have data from all 12 months of the year, several masts could not be calculated with the MoMM method. The results are listed in Table 5 below.

Name	Mast WS Hourly	MERRA WS Hourly	Difference
Docking Shoal	8.5	7.6	11.8%
Greater Gabbard	9.0	8.3	8.1%
Gunfleet Sands	8.2	7.7	7.1%
Gwynt Y Mor	8.6	7.7	11.2%
Humber Gateway	8.5	7.4	15.4%
Inner Dowsing	8.3	7.5	10.0%
Kentish Flats	7.7	7.5	2.5%
London Array	8.6	7.9	9.5%
Race Bank	8.9	8.5	3.9%
Rhyl Flats	7.9	7.6	4.3%
Shell Flats 1 – Early	8.3	7.7	9.0%
Shell Flats 1 – Late	9.2	8.1	13.3%
Shell Flats 2 – Early	8.5	7.8	9.4%
Shell Flats 2 – Late	9.4	8.1	15.8%
Teesside - Onshore	7.7	7.9	-1.8%

Table 5: Differences in Absolute Wind Speeds for the MoMM Calculation

The average differences calculated with this method did not drastically change the overall results although the overall error was calculated to be slightly higher using the MoMM method.

No attempt to correct for the relative location of the MERRA node and the mast (i.e. a linear extrapolation between MERRA points) has been undertaken in this analysis.

MERRA Error by Wind Speed

The average error between the MERRA wind speeds and the mast wind speeds at 50m is not consistent between different wind speed periods. The relationship between MERRA and actual offshore wind speeds at 50m is dependent on the actual wind speed. Figure 8 below is a typical error profile found at each of the offshore masts.

1. The shear extrapolated 50m time series from each mast was used
2. For each hour, an error between the mast and MERRA was calculated
3. The average error for each 0.5m/s wind speed bin was calculated

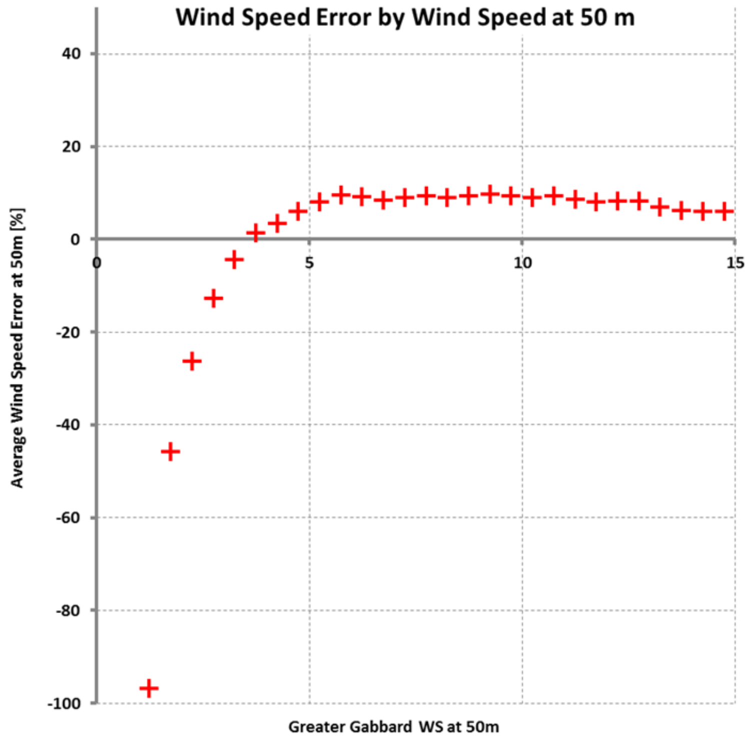


Figure 8: MERRA Absolute Wind Speed Error Binned by Mast Wind Speed

The typical error profile is represented by these two characteristics:

1. For wind speeds below 5m/s, the MERRA wind speed increases relative to the mast, meaning MERRA generally over-predicts wind speeds below 5m/s.

2. Between 5m/s and 15m/s the error is relatively constant with MERRA under predicting wind speeds.

Although not the focus of the study, errors above 20m/s generally increase further which reflects the trend of the hourly correlation data seen in Appendix A. However, the far offshore masts maintained the linear relationship even above 20m/s which suggests the MERRA data captures the higher wind speeds better when far offshore.

Appendix D displays the error graph for each mast tested.

7. Analysis of Directional Correlations

The knowledge of directional wind roses at a site can help developers' site turbine locations before a mast is built. The access to reliable directional data can also be useful for sanity checks of measured wind roses. An analysis of the directional correlations with each mast was undertaken during the study. A description of the data used and the data handling follows.

1. Hourly directional data was used

2. Filtered for wind speeds above 4 m/s at the mast

3. Any bulk offset in the mast data was corrected to line with the MERRA data

The focus of the study was to capture the variation between the MERRA data and the mast data once bulk offsets were taken into account. However, for two masts that were properly documented, the bulk offset was examined between MERRA and the mast. Overall, the bulk offset was determined to be within a reasonable level of less than 10 degrees. However, a full review of the offsets was not undertaken so the study did not determine whether the errors were due to mast or model issues.

Appendix E displays the directional hourly correlations. Figure 9 below is a representative example.

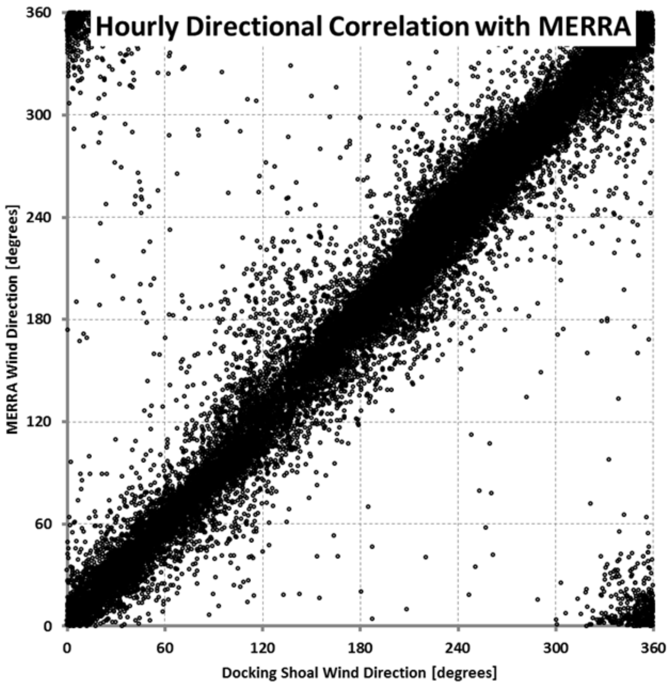


Figure 9: MERRA and Mast Directional Correlations

The data verifies that MERRA performs well with directional consistency in the offshore environment, particularly as a bulk estimate of the wind rose at a given location. As expected, the “onshore” sites, Teesside and Fife, did not perform as well.

For some sites, such as those far offshore, the MERRA directional data could reasonably be used as a substitute for actual directional measurements.

8. Inter-Annual and Inter-Monthly Variation (IAV and IMV)

When financing a wind farm, the inter-annual variability of the wind resource can be the biggest factor in determining the amount of financing provided. In order to ensure that the project will generate more revenue than required each year to repay debt (the debt service coverage ratio), lenders often require a level of conservatism that is dictated by the amount of annual variation expected from a project. Wind speed variation is considered one of the largest contributors to inter-annual variation and is an important value to understand before financing a project. True estimates of inter-annual variation ideally require 30+ years of measurements at a site; however, most sites only collect data for a few years. Access to modelled data like MERRA can provide some guidance to the overall variability of an area as the modelled date extends back several years.

Inter-Annual Variability (IAV)

Where possible, a comparison of the inter-annual variability of the mast with MERRA was undertaken to determine the ability to use MERRA as a proxy for atmospheric variability. Where data was available from masts for 4 full years or more, an IAV comparison was undertaken. The results from the six masts are presented below in Table 6.

For each site the following procedure was undertaken:

1. For each year, the average wind speed is calculated

2. The mean and standard deviation of these years are calculated for the entire period (i.e. the mean and standard deviation of all years). At least 4 years were required for a calculation

3. The IAV is calculated by dividing the standard deviation by the mean

4. The IAV is calculated for each mast and MERRA point and is compared to the 50m sensor IAV.

Name	Max Height [m msl]	Distance MERRA [km]	Distance Shore [km]	Years	Top Sensor IAV	50m Sensor IAV	MERRA Concurrent IAV	% Difference
Docking Shoal	90	18	20	4	5.0%	4.1%	4.2%	-2%
Greater Gabbard	88	9	28	4	2.7%	2.7%	3.7%	-27%
Gunfleet Sands	51	27	7	4	3.6%	3.7%	5.2%	-29%
Inner Dowsing	43	29	8	5	1.6%	1.5%	2.4%	-38%
London Array	82	11	22	5	1.7%	1.6%	2.3%	-30%
Shell Flats 1	81	16	16	5	7.2%	6.6%	5.3%	25%

Table 6: Measured Inter-Annual Variability Mast and MERRA Sites

No masts with more than 5 years of full data were available for this analysis. The results suggest that MERRA does not consistently under predict or over predict inter-annual variability for offshore sites. However, four masts located in the Thames Estuary all show lower IAV than predicted by MERRA, suggesting that MERRA inter-annual variability errors could be regionally biased. This analysis suggests that MERRA does not consistently under predict IAV for offshore sites as has been historically seen at onshore sites.

While MERRA does not capture the true inter-annual variability as seen by each mast, the data can be used to provide an estimate of the inter-annual variability in an area where measurements are lacking. In addition, if MERRA inter-annual variability is regionally biased, a correction could be incorporated for better estimates.

Inter-Monthly Variability

Inter-monthly variability (inter-MV) is generally not considered during the financing of projects, but is an important metric to understand for utilities concerned with grid stability. While inter-monthly variability is not considered random, as it is influenced by seasonality, it is important to understand the magnitude of fluctuation expected from a project from season to season. Table 7 below lists the measured concurrent inter-MV for each mast. For each site the following procedure was undertaken:

5. For each month, the average wind speed is calculated

6. The mean and standard deviation of these values are calculated for the entire period (i.e. the mean and standard deviation of all months)

7. The inter-MV is calculated by dividing the standard deviation by the mean

8. The inter-MV is calculated for each mast and MERRA point and is compared

Name	Max Height [m msl]	Distance MERRA [km]	Distance Shore [km]	Months	Top Sensor Inter-MV	50m Sensor Inter-MV	MERRA Concurrent Inter-MV	% Difference
Barrow	N/A	4	8	27	25%	-	24%	-
Blyth	103	17	5	6	13%	12%	14%	-14%
Docking Shoal	90	18	20	49	20%	18%	21%	-14%
Dogger Bank East	110	11	210	10	27%	26%	28%	-7%
Dogger Bank West	110	19	149	4	21%	19%	21%	-10%
Dudgeon	N/A	26	37	15	21%	-	21%	-
Fife Energy Park	110	28	0	6	16%	-	19%	-
Greater Gabbard	88	9	28	57	16%	17%	19%	-11%
Gunfleet Sands	51	27	7	59	18%	17%	23%	-26%
Gwynt Y Mor	85	12	17	20	29%	29%	28%	4%
Humber Gateway	88	23	8	23	18%	18%	19%	-5%
Inner Dowsing	43	29	8	67	17%	17%	21%	-19%
Kentish Flats	80	19	8	27	19%	19%	22%	-14%
London Array	82	11	22	64	16%	15%	19%	-21%
North Hoyle	50	13	10	59	20%	20%	22%	-9%
Race Bank	90	21	28	31	19%	18%	22%	-18%
Rhyl Flats	65	25	8	39	20%	20%	21%	-5%
Shell Flats 1 – Early	81	16	16	61	18%	18%	20%	-10%
Shell Flats 1 – Late	81	16	16	14	25%	24%	26%	-8%
Shell Flats 2 – Early	51	16	10	38	22%	22%	24%	-8%
Shell Flats 2 – Late	51	16	10	14	24%	24%	26%	-8%
Teesside	50	31	0	46	18%	18%	21%	-14%
Thanet	N/A	21	14	12	19%	-	22%	-

Table 7: Measured Inter-Monthly Variability Mast and MERRA Sites

In general, MERRA predicts a higher inter-MV than masts for offshore projects around the UK.

Intra-Monthly Variability

Intra-monthly variability (intra-MV) is also generally not considered during the financing of projects, but is an important metric to understand for utilities concerned with grid stability. While *inter*-MV considers variability from month to month, *intra*-MV variability considers the variability expected from year to year from a single month (i.e. all Septembers). This metric becomes important for modelling the long-term expectations of a wind farm in any given month which can be input for grid stability models and backup reserve planning. Table 8 below lists the measured concurrent intra-MV for each mast.

For each site the following procedure was undertaken:

9. For each month, the average wind speed is calculated (i.e. average wind speed for each September)

10. The mean and standard deviation of these values are calculated for each calendar month (i.e. the mean and standard deviation of all Septembers). At least three averages for an individual month are required for a calculation

11. The intra-MV is calculated by dividing the standard deviation by the mean

12. The intra-MV for each month is calculated for each mast and MERRA point and is compared

13. The total is calculated by the average of the 12 months

Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Barrow									18.0%	18.3%	18.0%	18.2%	**18.1%**
MERRA									18.0%	18.3%	18.0%	18.0%	**18.1%**
% Difference									0.2%	0.0%	0.1%	0.7%	**0.2%**
Docking Shoal	20.9%	20.7%	20.7%	20.6%	20.6%	22.2%	20.6%	20.5%	20.5%	20.8%	20.3%	20.6%	**20.7%**
MERRA	21.0%	20.7%	20.7%	20.6%	20.6%	22.0%	20.6%	20.5%	20.5%	20.8%	20.3%	20.7%	**20.7%**
% Difference	-0.5%	-0.3%	0.2%	-0.1%	0.0%	1.0%	-0.2%	0.0%	0.0%	0.1%	0.0%	-0.5%	**0.0%**
Greater Gabbard	23.1%	22.7%	22.8%	20.6%	22.8%	22.8%	20.6%	20.2%	23.8%	22.8%	22.7%	22.7%	**22.3%**
MERRA	23.2%	22.7%	22.9%	20.6%	22.8%	22.8%	20.6%	20.3%	24.6%	22.9%	22.8%	22.7%	**22.4%**
% Difference	-0.4%	0.1%	0.0%	-0.3%	0.0%	-0.2%	-0.2%	-0.2%	-3.4%	-0.1%	-0.1%	0.0%	**-0.4%**
Gunfleet Sands	23.9%	22.9%	22.8%	22.8%	22.9%	22.7%	22.7%	22.8%	23.0%	22.7%	22.8%	20.5%	**22.7%**
MERRA	24.3%	23.1%	22.8%	22.8%	22.9%	22.8%	22.7%	22.9%	23.0%	22.7%	22.9%	20.5%	**22.8%**
% Difference	-1.6%	-0.5%	-0.1%	-0.1%	-0.2%	-0.1%	0.0%	-0.6%	0.0%	0.0%	-0.3%	-0.1%	**-0.3%**
Inner Dowsing	24.8%	26.9%	22.8%	22.6%	22.8%	22.7%	22.7%	24.8%	24.8%	24.8%	24.7%	24.6%	**24.1%**
MERRA	24.8%	27.1%	22.8%	22.6%	22.9%	22.7%	22.8%	24.9%	24.8%	24.8%	24.7%	24.6%	**24.1%**
% Difference	-0.2%	-0.7%	-0.1%	0.1%	-0.3%	-0.1%	-0.2%	-0.3%	-0.3%	0.0%	0.0%	0.1%	**-0.2%**
North Hoyle	22.8%	20.4%	22.1%	22.7%	22.9%	23.1%	22.7%	22.9%	23.1%	22.7%	22.4%	23.7%	**22.6%**
MERRA	22.7%	20.4%	22.0%	22.7%	22.9%	23.2%	22.8%	22.9%	23.1%	22.7%	22.8%	23.5%	**22.6%**
% Difference	0.2%	0.2%	0.2%	0.2%	-0.1%	-0.4%	-0.2%	0.1%	0.0%	0.1%	-1.5%	0.8%	**0.0%**
London Array	24.6%	24.7%	23.8%	22.7%	22.7%	22.8%	22.7%	22.8%	22.7%	22.9%	22.7%	24.0%	**23.3%**
MERRA	24.6%	24.7%	23.6%	22.7%	22.7%	22.8%	22.8%	22.8%	22.8%	22.9%	22.7%	24.0%	**23.3%**
% Difference	-0.1%	0.0%	1.2%	-0.1%	0.0%	0.2%	-0.3%	-0.2%	-0.1%	-0.1%	0.0%	0.2%	**0.1%**
Rhyl Flats	18.1%	18.0%	18.0%	18.0%	18.2%	18.1%	20.2%	20.6%	21.2%	21.3%	18.0%		**19.1%**
MERRA	18.1%	18.0%	18.0%	18.0%	18.3%	18.0%	20.3%	20.6%	21.1%	21.8%	17.9%		**19.1%**
% Difference	0.1%	0.1%	0.1%	0.1%	-0.8%	0.2%	-0.3%	0.0%	0.6%	-2.3%	0.5%		**-0.2%**
Shell Flats 1 Early	23.0%	22.7%	22.8%	22.8%	22.9%	25.5%	24.6%	24.8%	26.7%	20.3%	20.5%	20.5%	**23.1%**
MERRA	22.8%	22.7%	22.9%	22.7%	23.0%	25.6%	24.6%	24.8%	26.1%	20.3%	20.5%	20.5%	**23.0%**
% Difference	0.9%	0.0%	-0.3%	0.4%	-0.2%	-0.1%	-0.1%	0.0%	2.4%	0.2%	0.0%	0.1%	**0.3%**
Shell Flats 2 Early	19.3%		17.3%	20.6%	18.2%	22.0%	20.6%	20.6%	20.7%	18.0%			**19.7%**
MERRA	19.1%		17.3%	20.3%	18.2%	21.6%	20.6%	20.7%	20.6%	18.0%			**19.6%**
% Difference	1.0%		0.0%	1.6%	-0.5%	2.0%	-0.1%	-0.6%	0.7%	0.0%			**0.5%**
Teesside	20.7%	20.5%	20.5%	20.4%	21.3%	18.0%	20.4%	20.5%	20.7%	21.8%	18.0%	20.1%	**20.2%**
MERRA	20.7%	20.4%	20.5%	20.4%	21.7%	18.0%	20.5%	20.6%	20.8%	22.3%	18.0%	20.0%	**20.3%**
% Difference	-0.3%	0.6%	0.0%	-0.4%	-1.7%	-0.3%	-0.2%	0.0%	-0.3%	-1.8%	0.0%	0.8%	**-0.3%**

Table 8: Measured Intra-Monthly Variability Mast and MERRA Sites

The ability of MERRA to capture the intra-MV was relatively strong for the offshore sites suggesting that the long-term MERRA data could be used as a proxy for intra-MV in studies and reports or planning by utilities.

9. Analysis of Extremes

Extremes analysis is useful for developers when designing wind farms to ensure the turbine and other design parameters are suitable for the site. Most extremes metrics require knowledge of the max wind speeds of small duration gusts (i.e. 3 seconds). While the modelled data does not produce wind speed information at that time level, the knowledge of max hourly wind speeds can provide initial information about the wind speeds at the site.

For each site the following procedure was undertaken:

1. For every month, determine the max hourly wind speed for MERRA

2. For every month, determine the max hourly wind speed for the Mast at 50m

3. Compare the difference between the two wind speeds for each month

4. Take the average and max differences for each site

The results for each site are listed in Table 9 below. The hourly max wind speeds predicted by MERRA at 50 m are on average about 20 % lower than recorded wind speeds. However, the max difference in some months exceeded 60 %.

Name	Max Height [m msl]	Distance MERRA [km]	Distance Shore [km]	50m Average Monthly Mast Max [m/s]	MERRA Average Monthly Max [m/s]	% Difference	% Max Difference
Blyth	103	17	5	20.7	17.2	20%	25%
Docking Shoal	90	18	20	19.0	15.7	22%	67%
Dogger Bank East	110	11	210	20.2	18.2	11%	28%
Dogger Bank West	110	19	149	22.7	20.2	13%	16%
Greater Gabbard	88	9	28	19.3	18.0	8%	20%
Gunfleet Sands	51	27	7	18.6	17.1	10%	60%
Gwynt Y Mor	85	12	17	20.4	16.6	23%	49%
Humber Gateway	88	23	8	18.8	15.2	24%	45%
Inner Dowsing	43	29	8	19.0	16.0	19%	37%
Kentish Flats	80	19	8	18.5	17.4	7%	38%
London Array	82	11	22	18.4	16.9	10%	48%
Race Bank	90	21	28	19.9	17.9	11%	28%
Rhyl Flats	65	25	8	19.6	15.9	23%	45%
Shell Flats 1 – Early	81	16	16	19.9	16.1	24%	59%
Shell Flats 1 – Late	81	16	16	21.3	16.9	27%	53%
Shell Flats 2 – Early	51	16	10	19.8	16.1	24%	44%
Shell Flats 2 – Late	51	16	10	21.0	16.8	26%	48%
Teesside	50	31	0	19.3	16.2	19%	55%

Table 9: Measured and Predicted Maximum Wind Speeds

10. Conclusions

The availability of a high concentration of offshore measurements in a single study allows the Crown Estate to draw conclusions about the overall performance of MERRA data around the UK. The study involved the processing and analysis of wind data from over 20 offshore masts representing more than 85 years of offshore measurements, potentially representing the largest offshore validation of MERRA data undertaken.

The initial investigations from the data were able to pull out key themes about the performance of MERRA compared to actual measurements. The overall performance of the MERRA data suggests:

1. Offshore correlations are relatively strong with most daily correlations showing linearity and R^2 of 0.9 or greater,

2. Correlations to MERRA improve as masts move farther offshore with the biggest improvements coming over the first 5 to 10km,

3. MERRA data loses linearity in the hourly correlation above ~20m/s at near shore sites,

4. MERRA data loses linearity in the hourly correlation below ~5m/s at near shore sites,

5. MERRA data over-predicts wind speeds below ~5m/s,

6. MERRA data under-predicts wind speeds above ~5m/s,

7. MERRA data directional correlation is strong, particularly for far offshore sites,

8. MERRA absolute wind speeds are not accurate enough for replacement of measurements, but provide a lower bound estimate of offshore wind speeds.

The study of the offshore data suggests that:

a) Correlations to MERRA should be done with the highest reliable sensor on a mast, not the 50m sensor,

b) If possible, linear correlations to MERRA data should be undertaken at the daily level to remove non-linearity in the relationship,

c) If hourly data is required, extra analysis techniques should be incorporated to address non-linearity in the correlations below 5m/s and above 20m/s,

d) Directional correlations can provide measurement backup in the event of a wind vane failure or for early stage pre-measurement planning

e) MERRA absolute wind speeds can be considered a lower bound for offshore wind speeds greater than 5km from shore

f) If an absolute wind speed is needed, a general adjustment to the wind speed based on distance to shore should be calculated

g) MERRA can be used as a relatively good measure of intra-monthly variability

h) MERRA can be used as a proxy for inter-annual variability; however, a regional bias correction would improve the estimate.

11. Future Work

This study was undertaken solely in UK waters. The results of similar analyses have not been studied elsewhere. Although other studies support some of the conclusions found in this report, further work is needed to determine if this information is applicable in other locations.

Future work that should be undertaken includes:

1. Replicating the analysis with ERA-Interim reanalysis data

2. Replicating the analysis with offshore met masts in other locations such as the US

3. Incorporation of the mast data into regional wind maps to improve calibration of absolute wind speeds

4. Investigating the spatial ability of MERRA to differentiate windier areas from less windy areas

The future work may allow developers to increase their understanding of reanalysis data allowing them to reduce uncertainty and improve modelling during the development phase. For example, the study indicates that for far offshore sites, there is greater confidence in the modelling capabilities of MERRA which will allow developers to rely more on the modelled data. As these far from shore sites require greater upfront investment and more risk, the ability to be able to rely on modelled data is a major benefit of this study.

12. References and Resources

[1] The Crown Estate; *The Marine Data Exchange*; http://www.marinedataexchange.co.uk/

[2] National Aeronautics and Space Administration; Modern-Era Retrospective Analysis for Research and Applications; http://gmao.gsfc.nasa.gov/merra/

[3] Bethke, Julia; Kampmeyer, Jens; Kilburg, Max; Mengelkamp, Heinz-Theo; *Verification and performance of wind climatologies in wind energy applications*; EWEA Barcelona, 2014

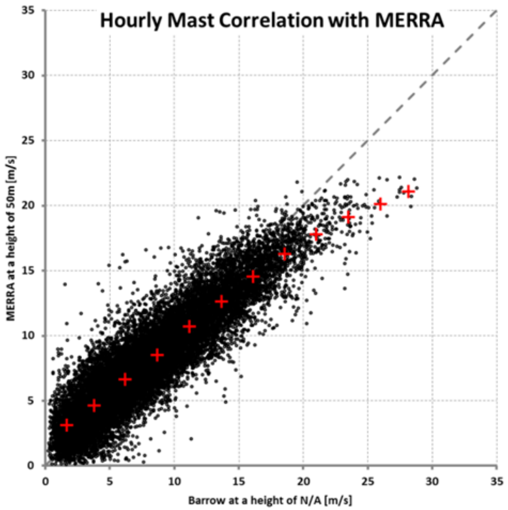
[4] Harrington, Gemma; *Offshore Long-Term References;* WRMA Annual European Meeting, September 2012

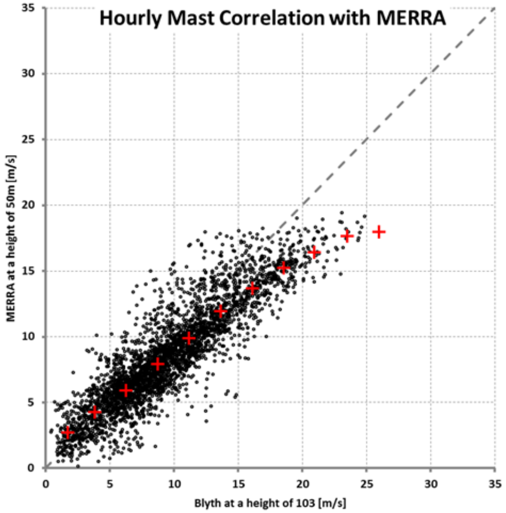
[5] Lileo, Sonia; Petrik, Olga; *Investigation on the use of NCEP/NCAR, MERRA, and NCEP/CFSR reanalysis data in wind resource analysis*; O2 Vind AB, 2011;

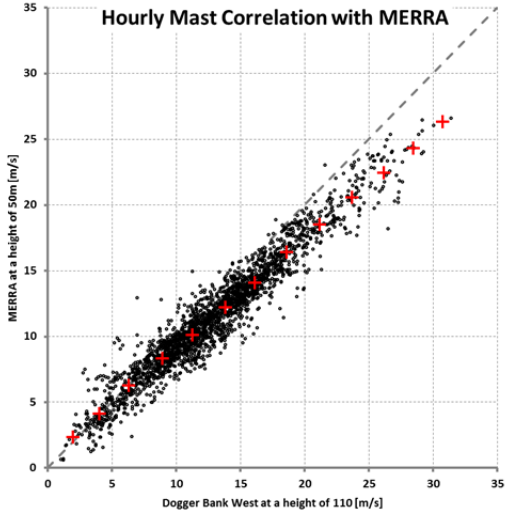
[6] Ramli, Sundus; *Inter-annual variability of wind speed*; Dong Energy; May 2013

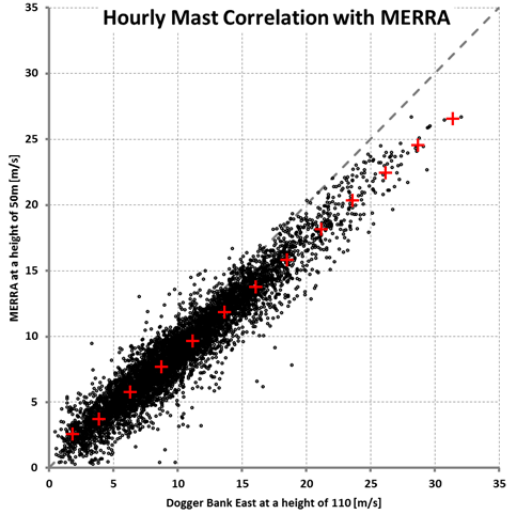
[7] Bailey, Bruce; Green, David; *The Need for Expanded Meteorological and Oceanographic Data to Support Resource Characterization and Design Condition Definition for Offshore Wind Power Projects in the United States*; American Meteorological Society; May 2013

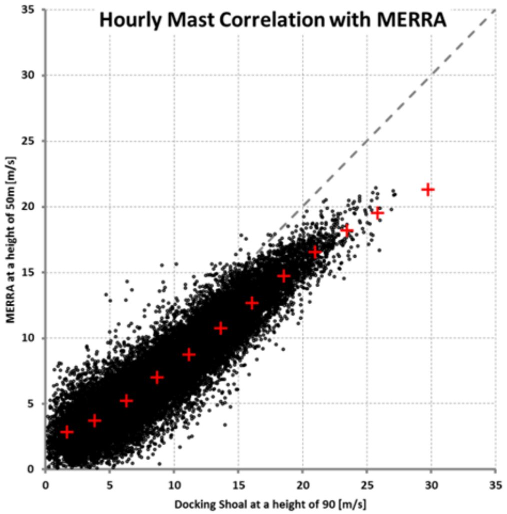
Appendix A – Hourly Correlations with Mast Data

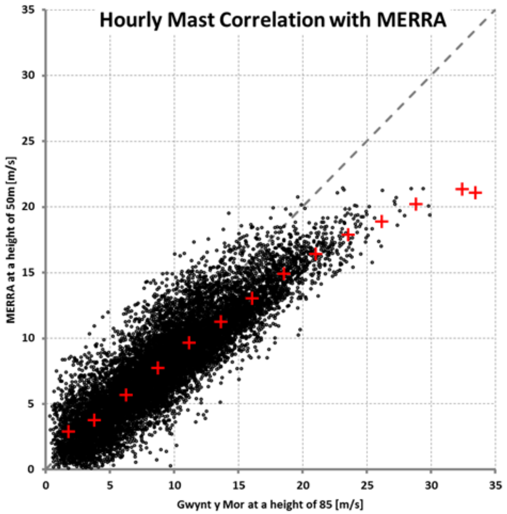


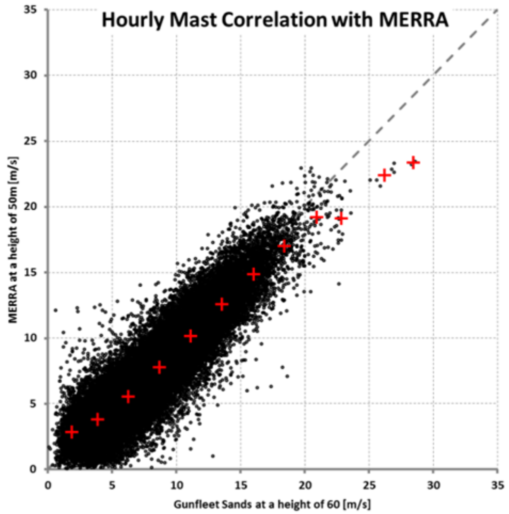


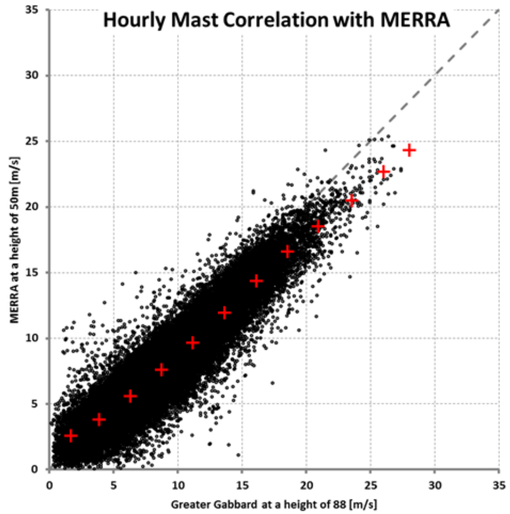


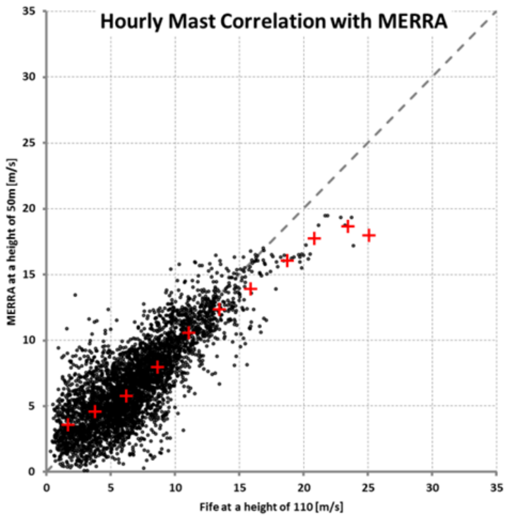


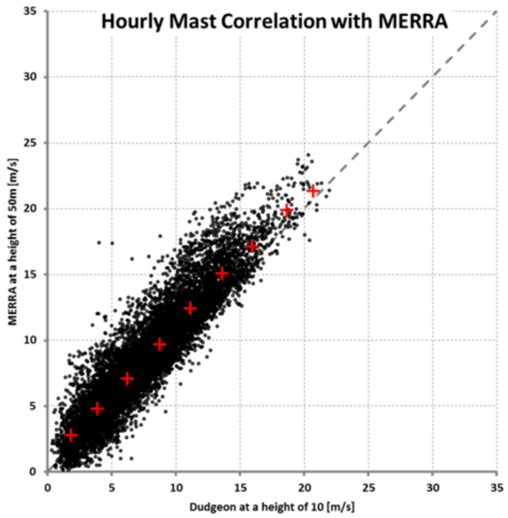


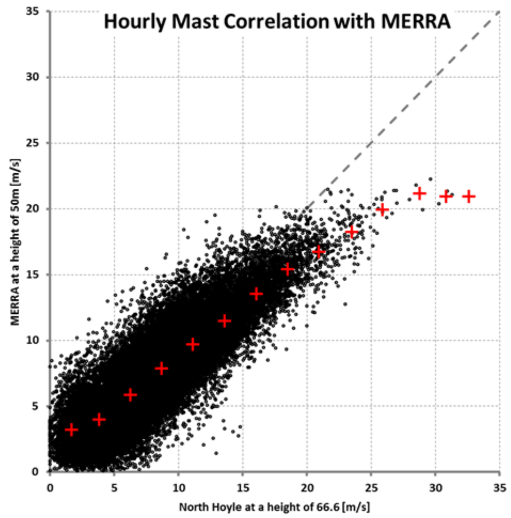


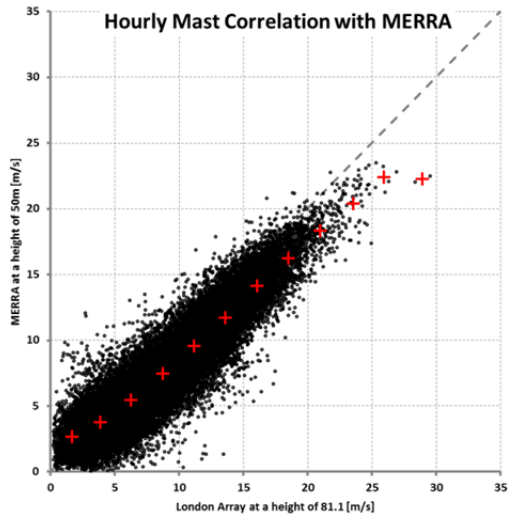


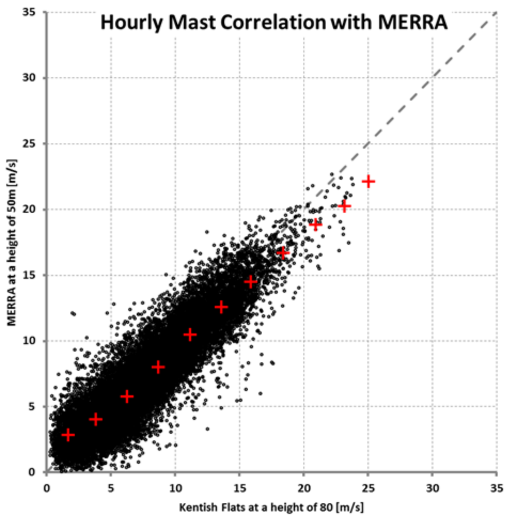


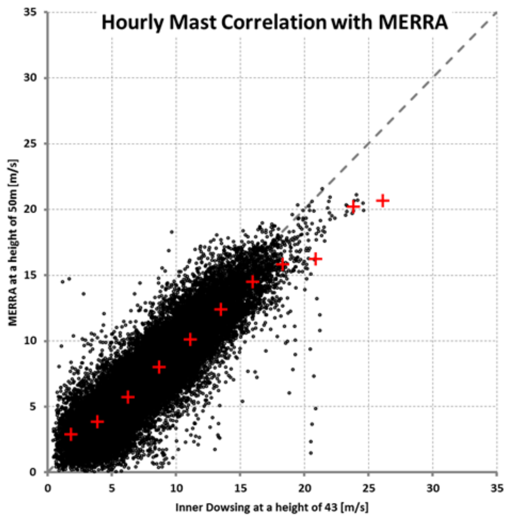

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Fife at a height of 110 [m/s]

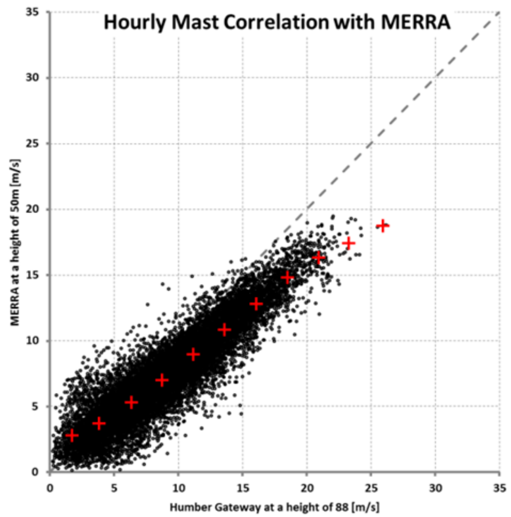

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Dudgeon at a height of 10 [m/s]

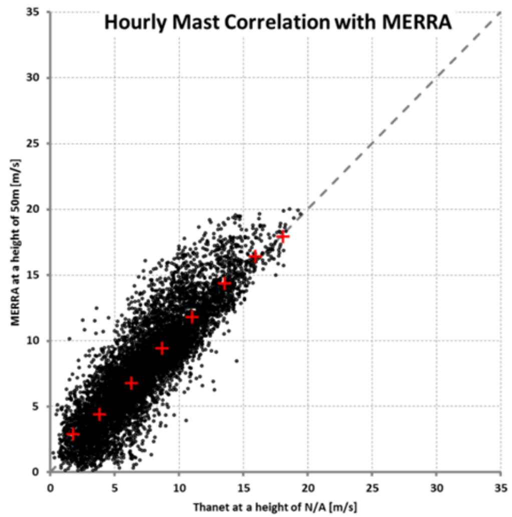

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
North Hoyle at a height of 66.6 [m/s]

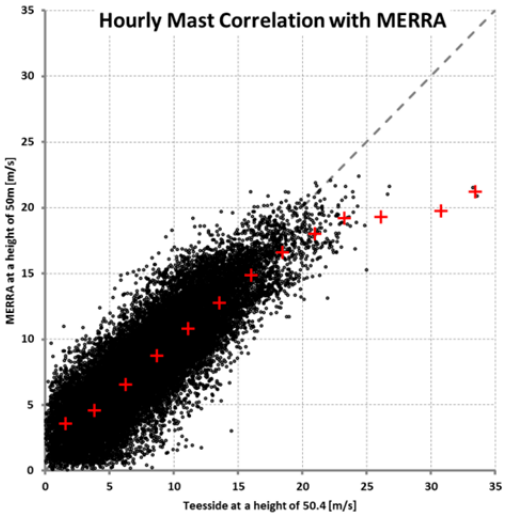

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
London Array at a height of 81.1 [m/s]

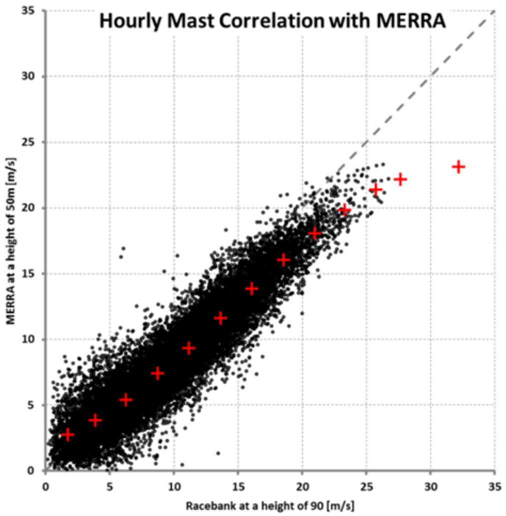

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Kentish Flats at a height of 80 [m/s]

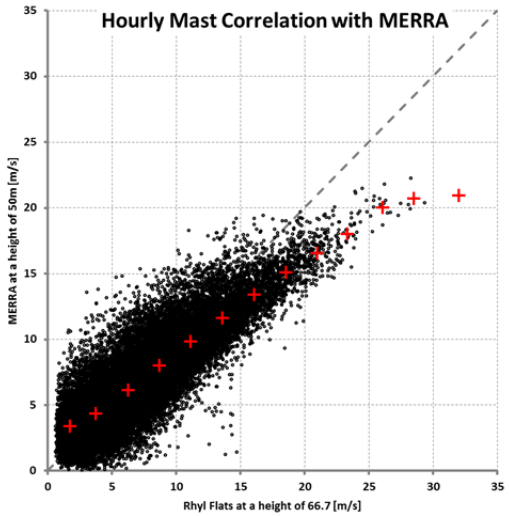

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Inner Dowsing at a height of 43 [m/s]

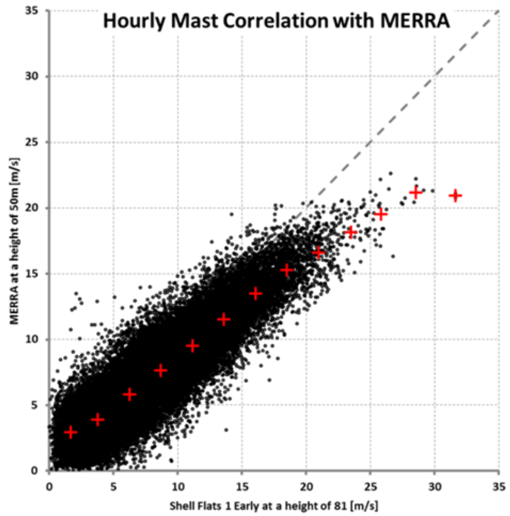

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Humber Gateway at a height of 88 [m/s]

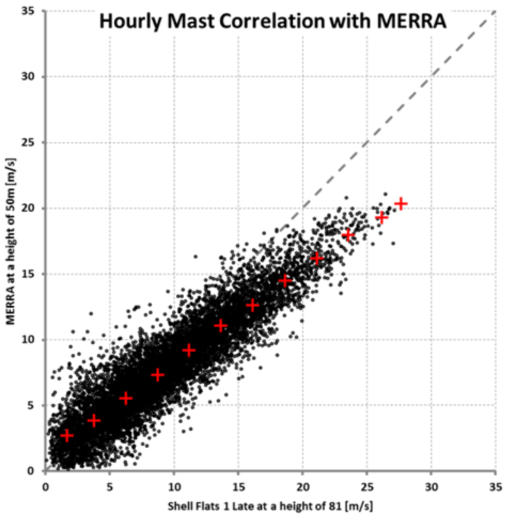

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Thanet at a height of N/A [m/s]

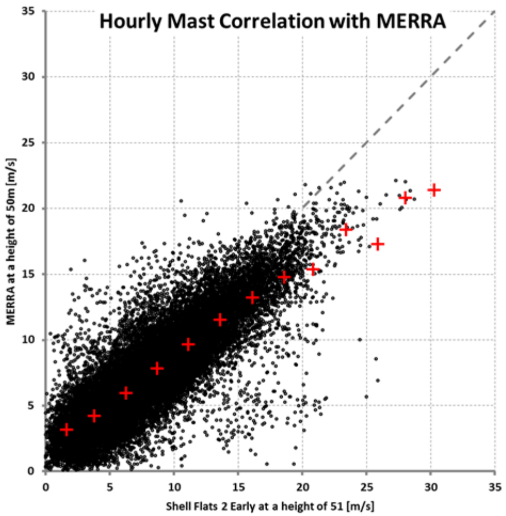

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Teesside at a height of 50.4 [m/s]

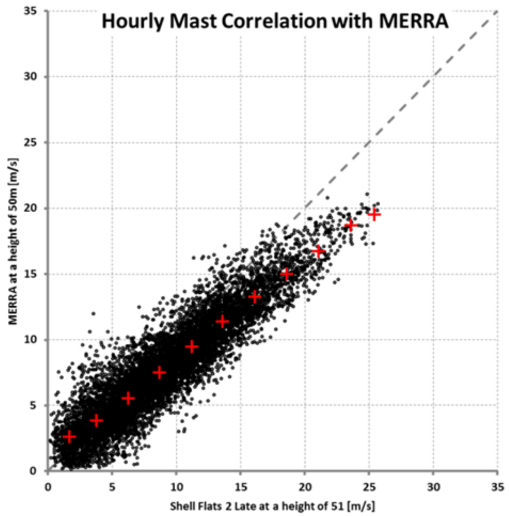

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Racebank at a height of 90 [m/s]


Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Rhyl Flats at a height of 66.7 [m/s]

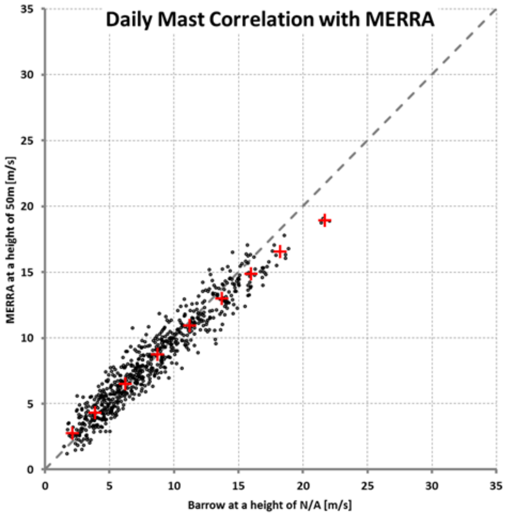

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Shell Flats 1 Early at a height of 81 [m/s]

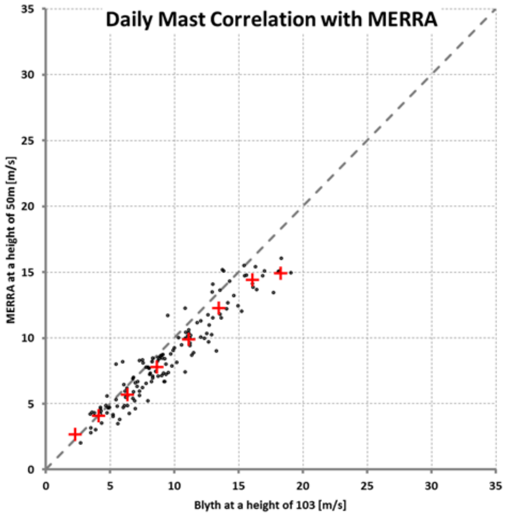

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Shell Flats 1 Late at a height of 81 [m/s]

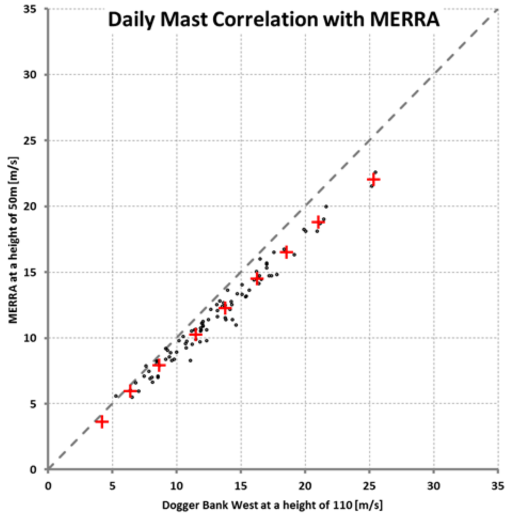

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Shell Flats 2 Early at a height of 51 [m/s]

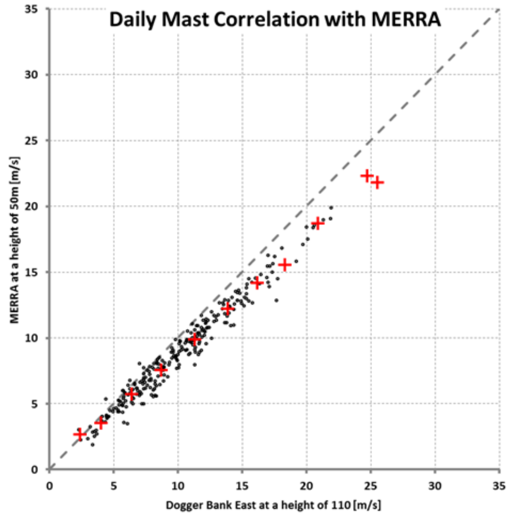

Hourly Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Shell Flats 2 Late at a height of 51 [m/s]

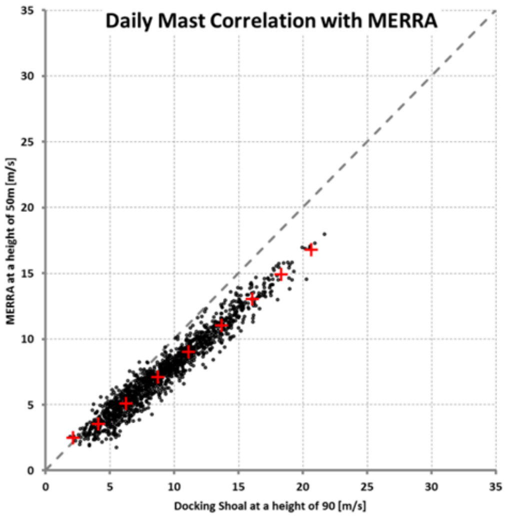
Appendix B – Daily Correlations with Mast Data

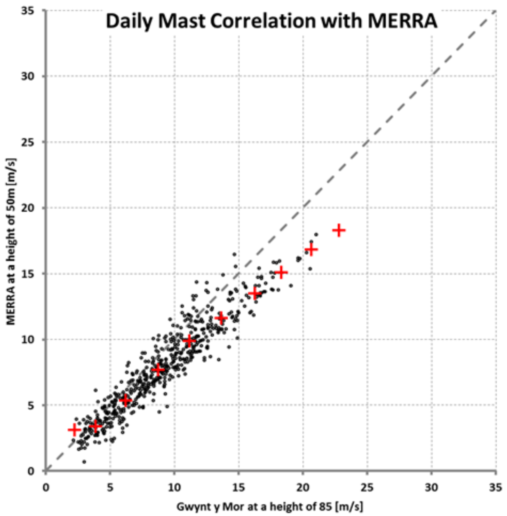


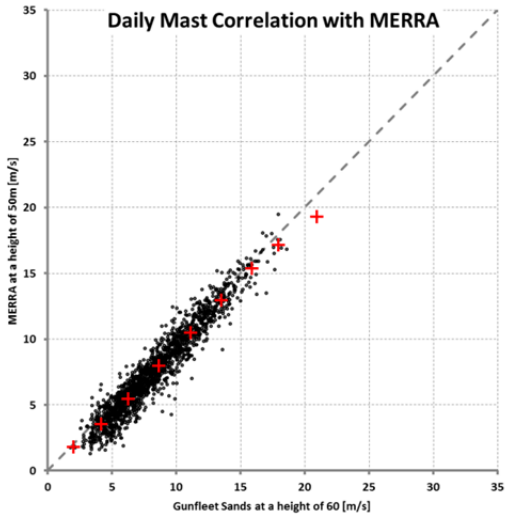


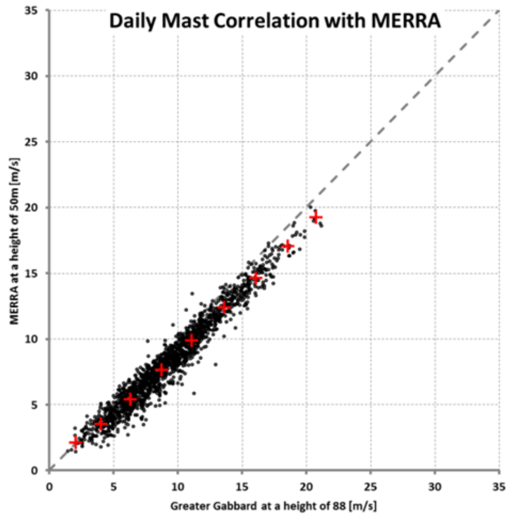


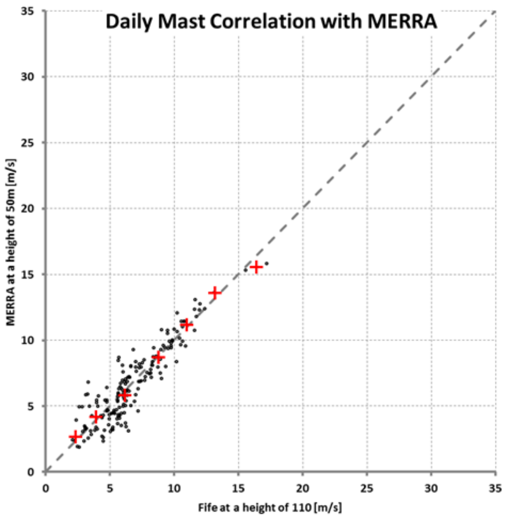


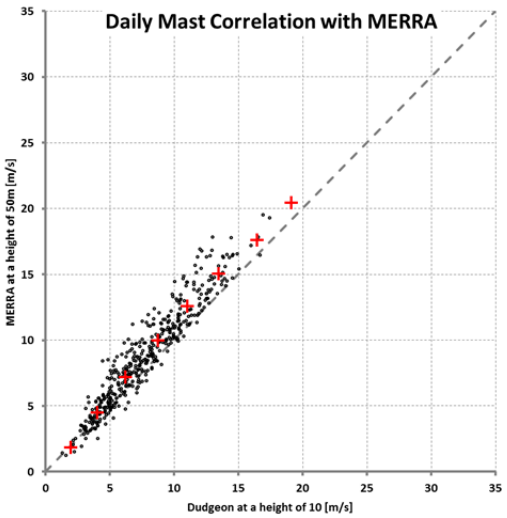


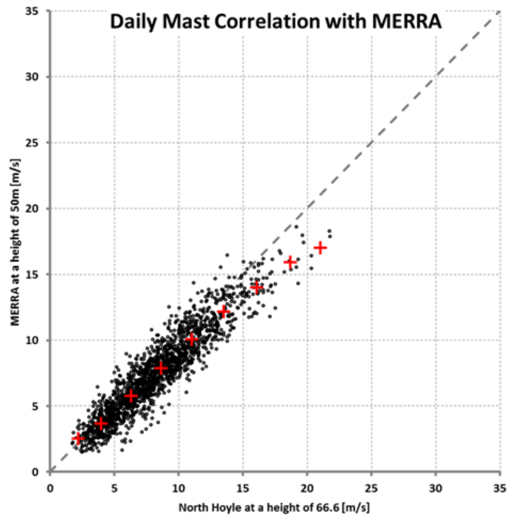


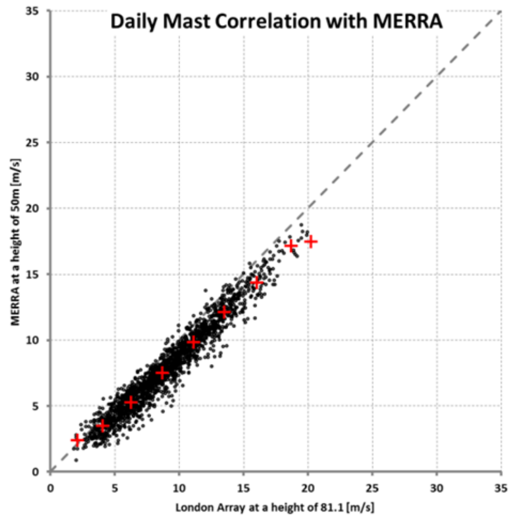


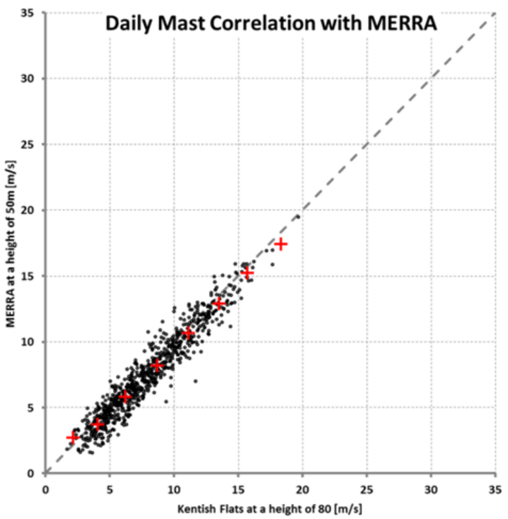


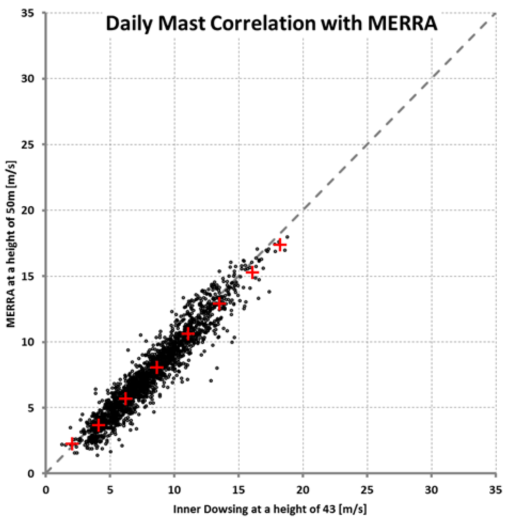

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Fife at a height of 110 [m/s]

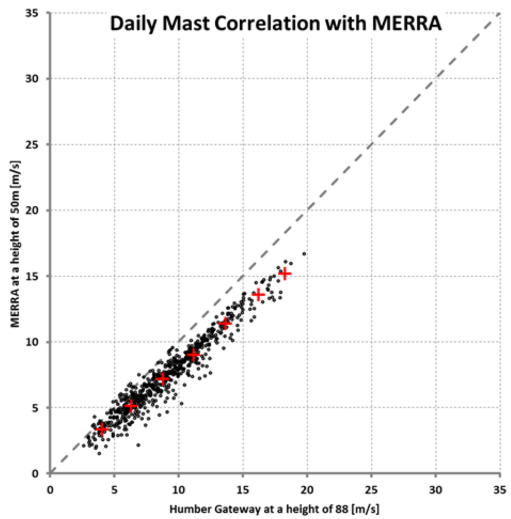

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Dudgeon at a height of 10 [m/s]

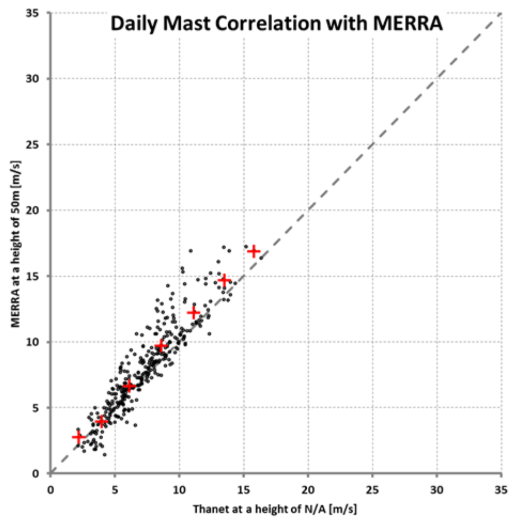

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
North Hoyle at a height of 66.6 [m/s]

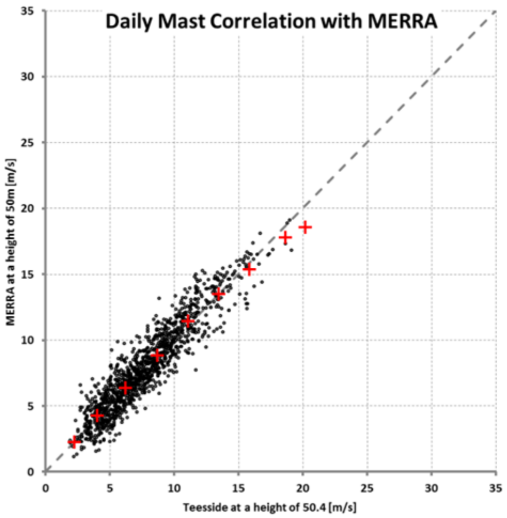

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
London Array at a height of 81.1 [m/s]

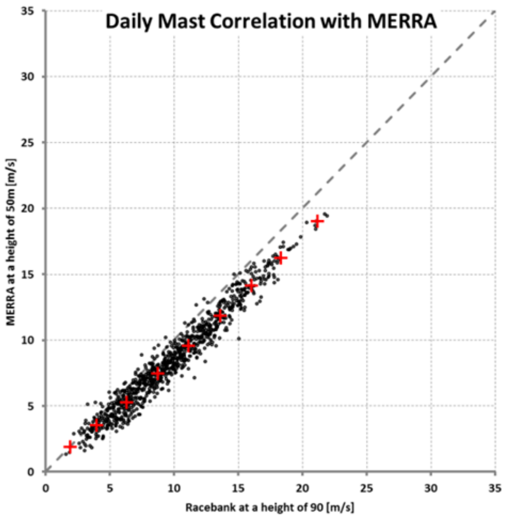

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Kentish Flats at a height of 80 [m/s]

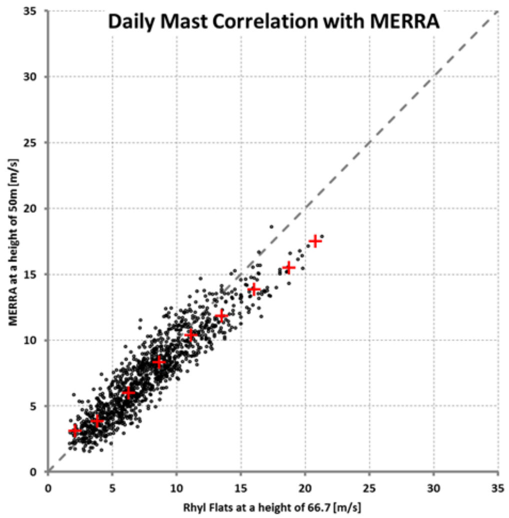

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Inner Dowsing at a height of 43 [m/s]

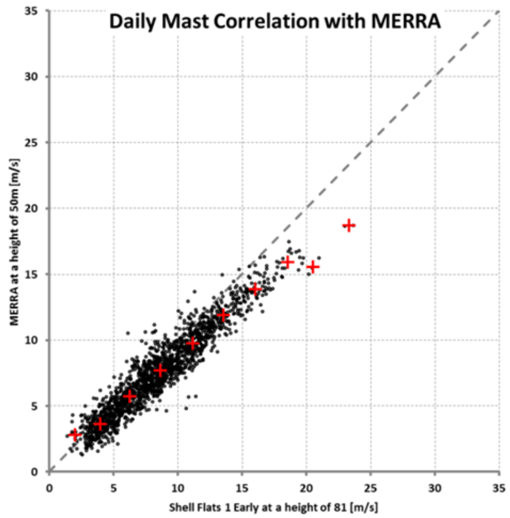

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Humber Gateway at a height of 88 [m/s]

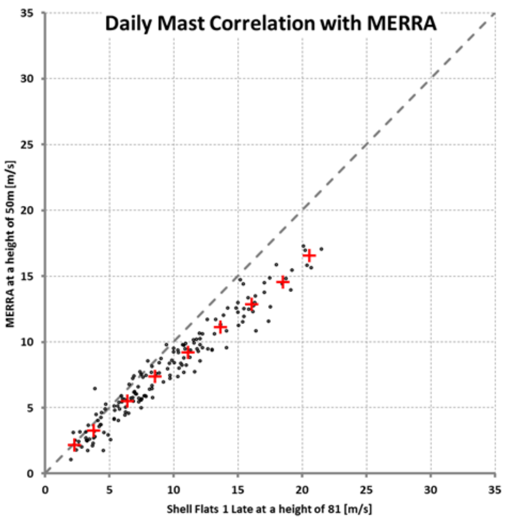

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Thanet at a height of N/A [m/s]

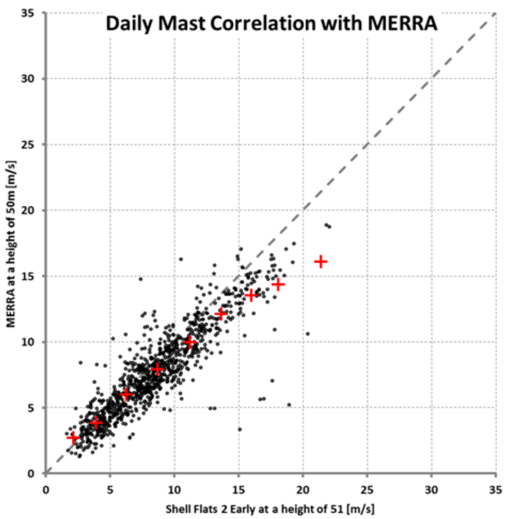

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Teesside at a height of 50.4 [m/s]

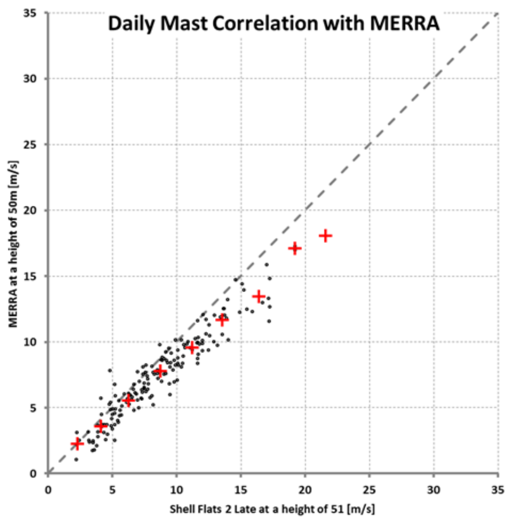

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Racebank at a height of 90 [m/s]


Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Rhyl Flats at a height of 66.7 [m/s]

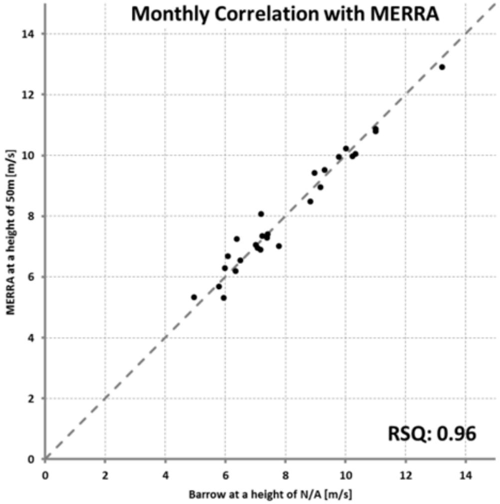

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Shell Flats 1 Early at a height of 81 [m/s]

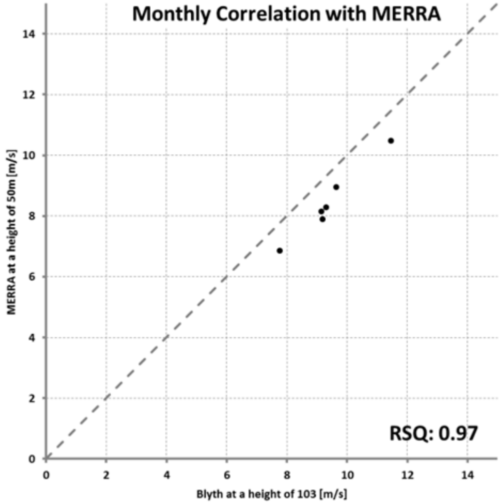

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Shell Flats 1 Late at a height of 81 [m/s]

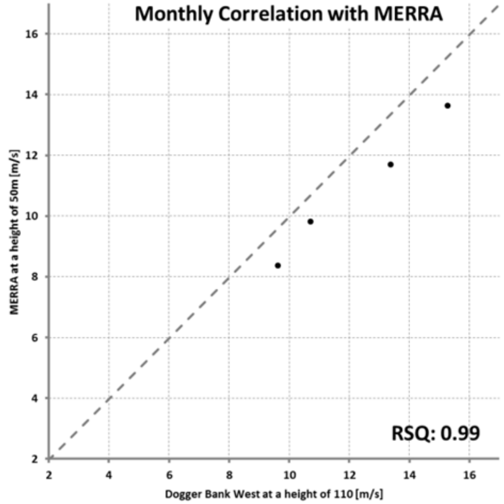

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Shell Flats 2 Early at a height of 51 [m/s]

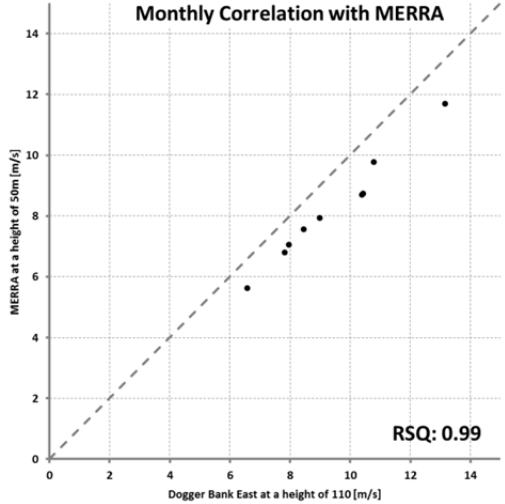

Daily Mast Correlation with MERRA
MERRA at a height of 50m [m/s]
Shell Flats 2 Late at a height of 51 [m/s]

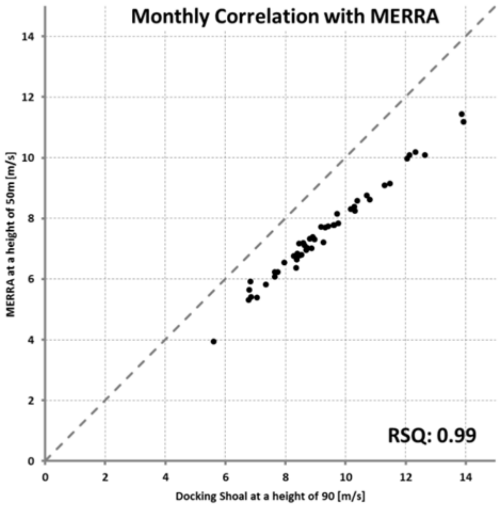
Appendix C – Monthly Correlations with Mast Data

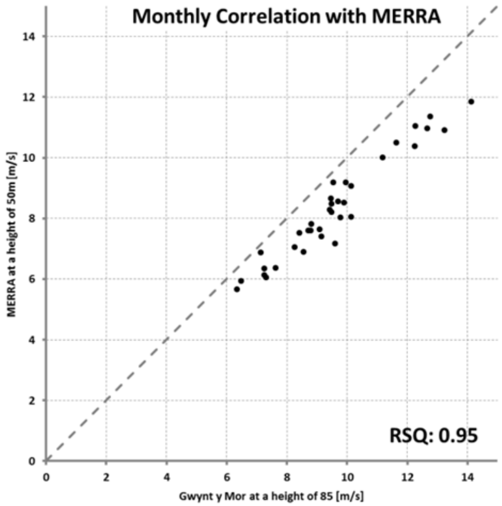


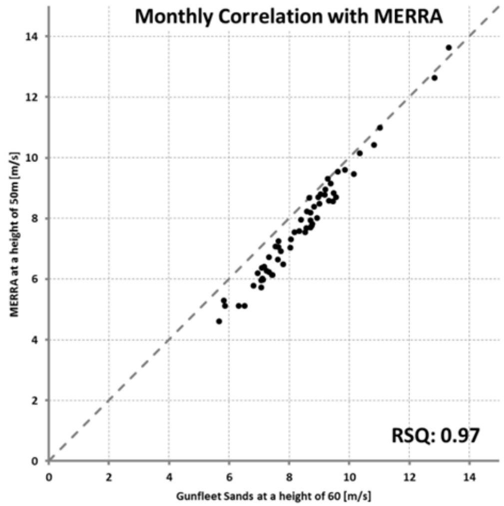


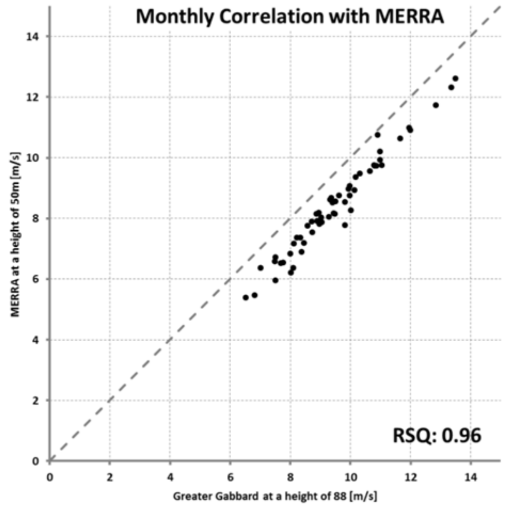


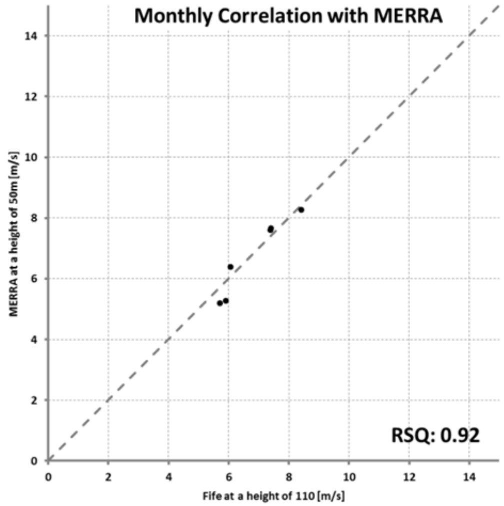


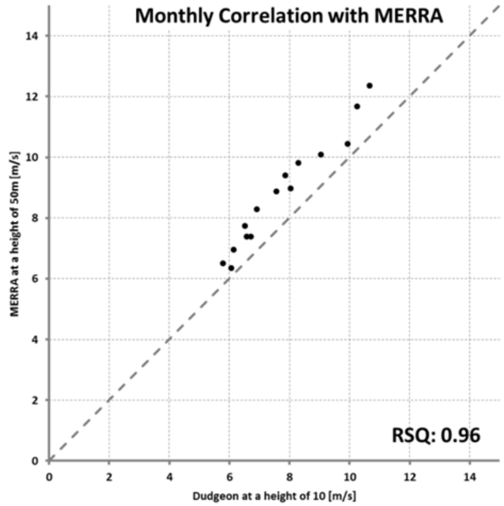


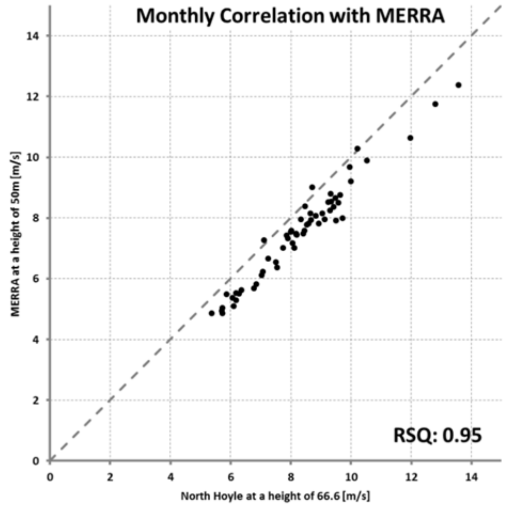


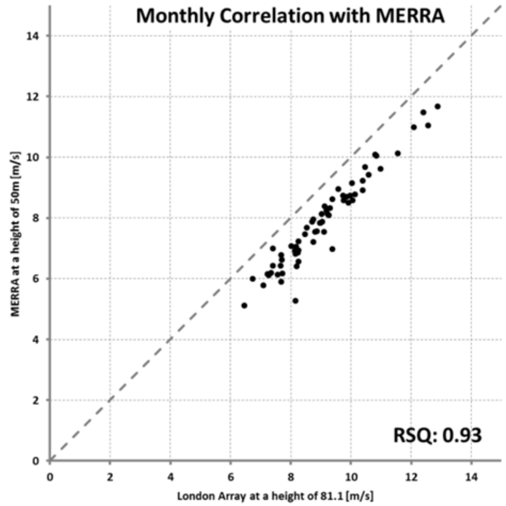


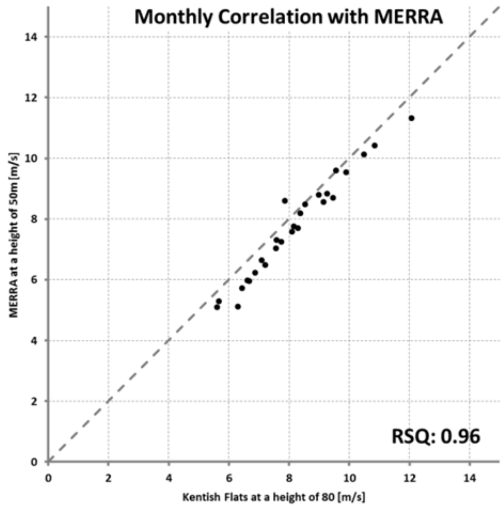


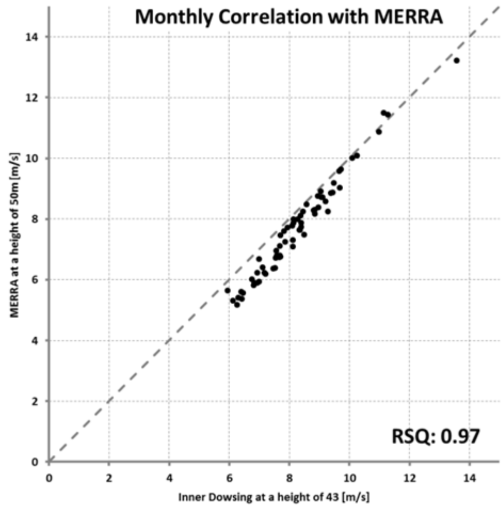

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
Fife at a height of 110 [m/s]
RSQ: 0.92

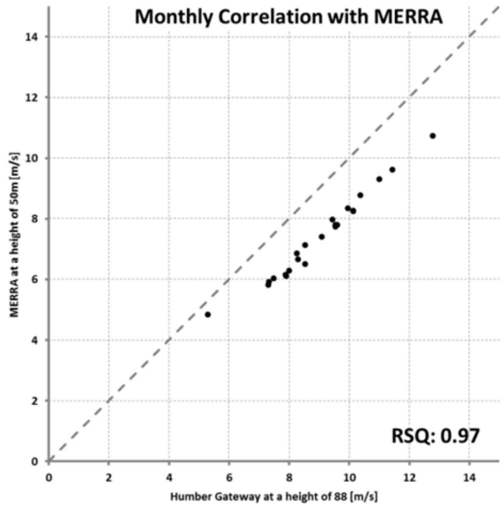

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
Dudgeon at a height of 10 [m/s]
RSQ: 0.96

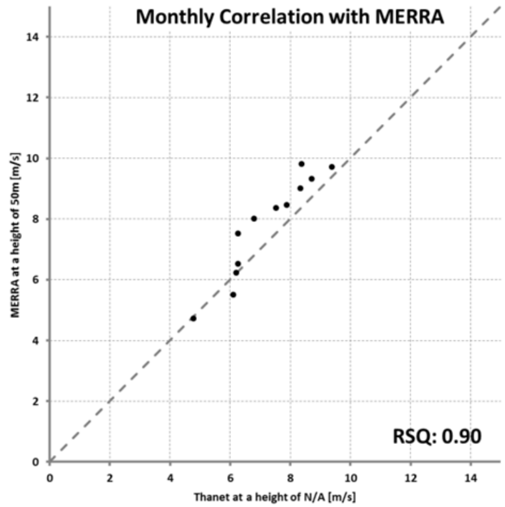

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
North Hoyle at a height of 66.6 [m/s]
RSQ: 0.95

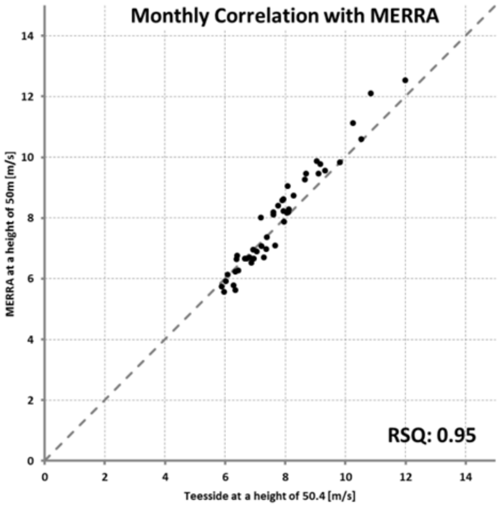

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
London Array at a height of 81.1 [m/s]
RSQ: 0.93

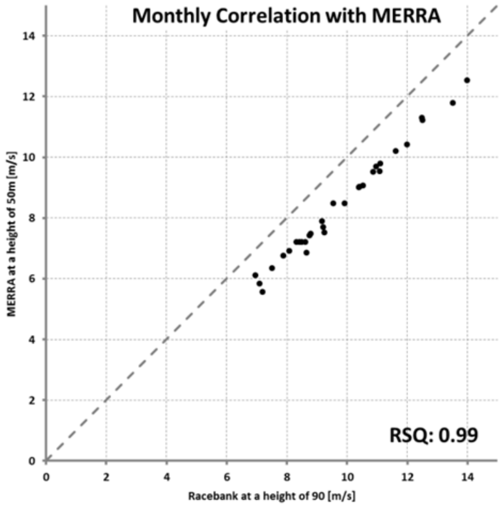

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
Kentish Flats at a height of 80 [m/s]
RSQ: 0.96

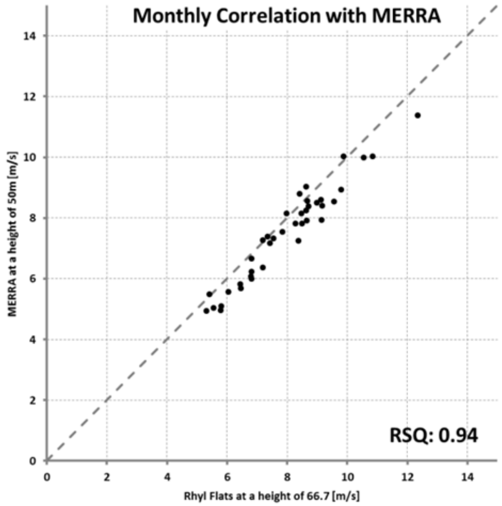

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
Inner Dowsing at a height of 43 [m/s]
RSQ: 0.97

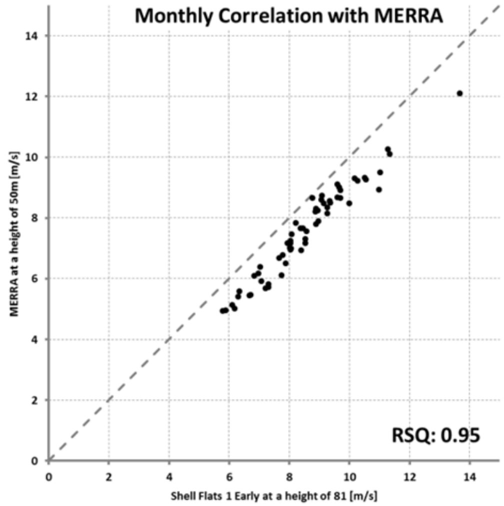

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
Humber Gateway at a height of 88 [m/s]
RSQ: 0.97

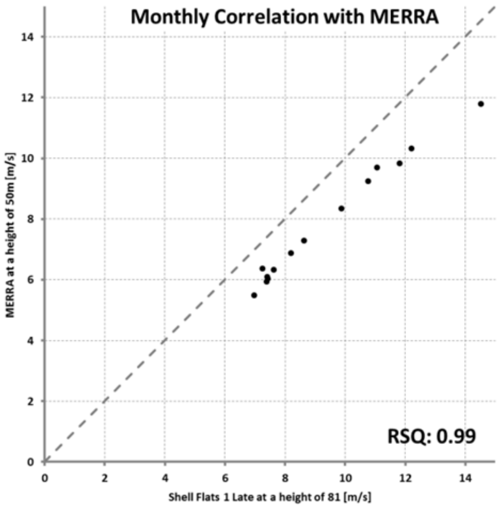

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
Thanet at a height of N/A [m/s]
RSQ: 0.90

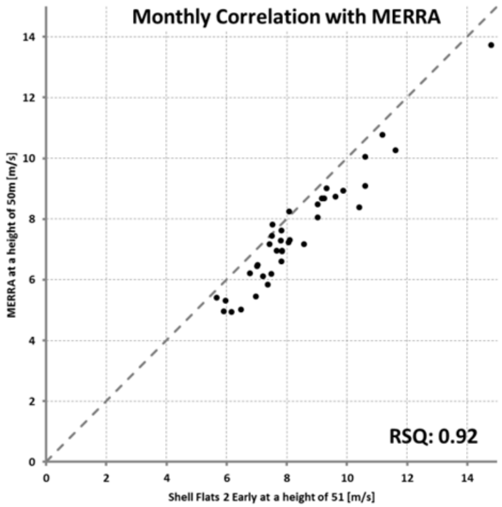

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
Teesside at a height of 50.4 [m/s]
RSQ: 0.95

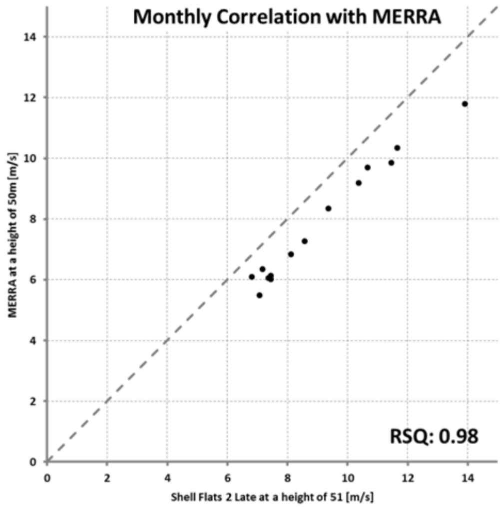

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
Racebank at a height of 90 [m/s]
RSQ: 0.99


Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
Rhyl Flats at a height of 66.7 [m/s]
RSQ: 0.94

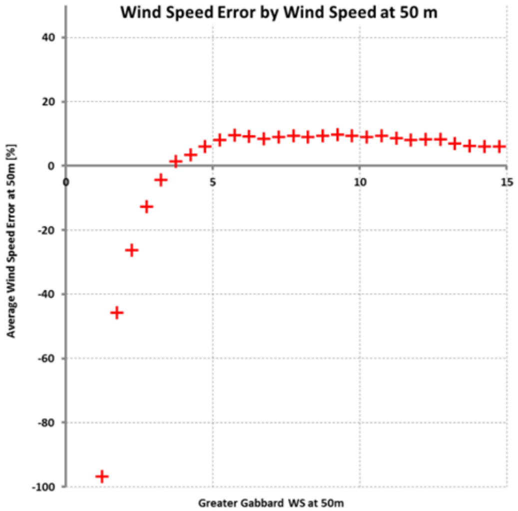

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
Shell Flats 1 Early at a height of 81 [m/s]
RSQ: 0.95

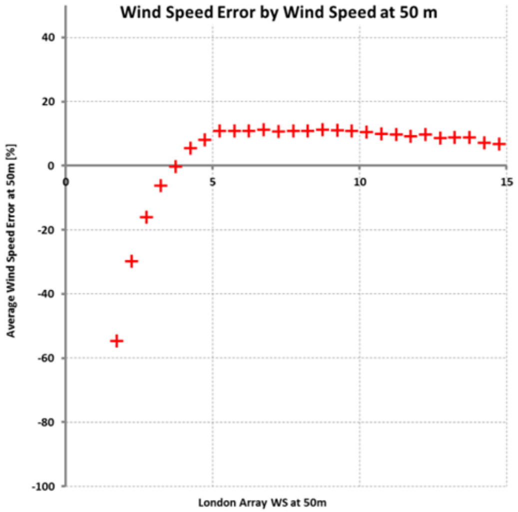

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
Shell Flats 1 Late at a height of 81 [m/s]
RSQ: 0.99

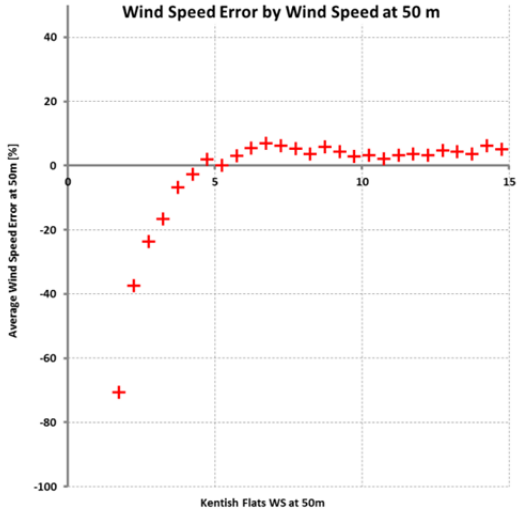

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
Shell Flats 2 Early at a height of 51 [m/s]
RSQ: 0.92

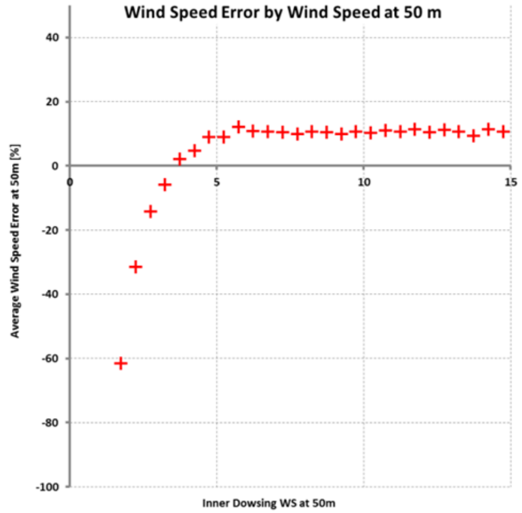

Monthly Correlation with MERRA
MERRA at a height of 50m [m/s]
Shell Flats 2 Late at a height of 51 [m/s]
RSQ: 0.98

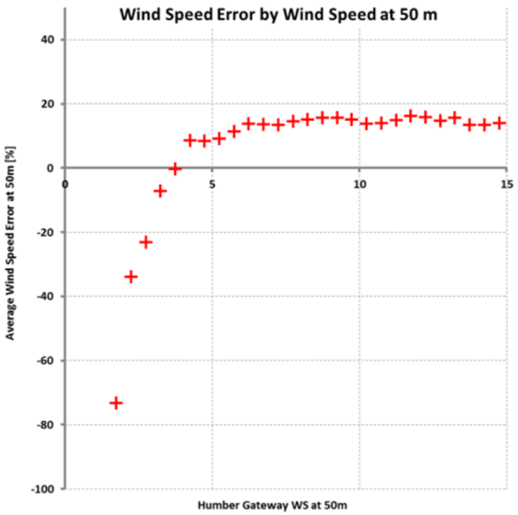
Appendix D – MERRA Wind Speed Error by Wind Speed

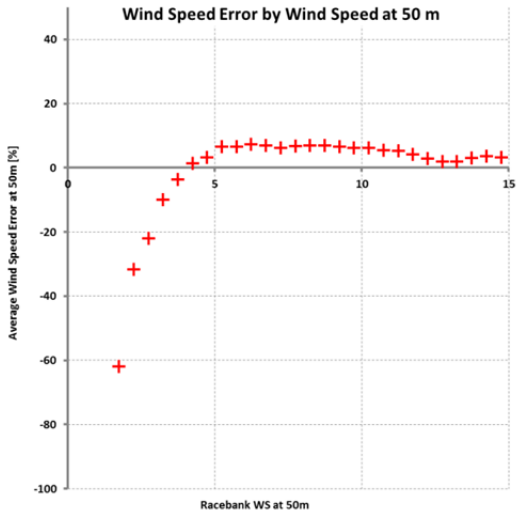


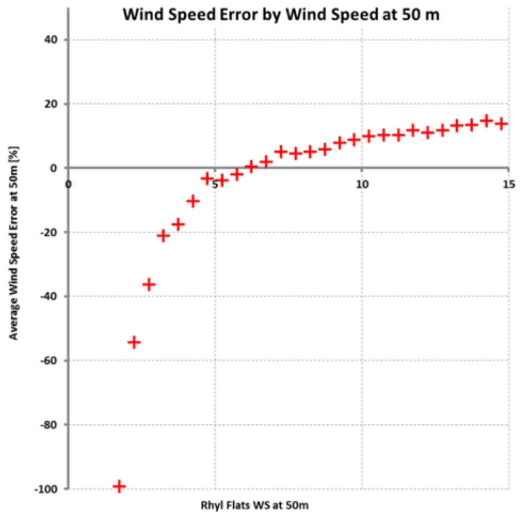


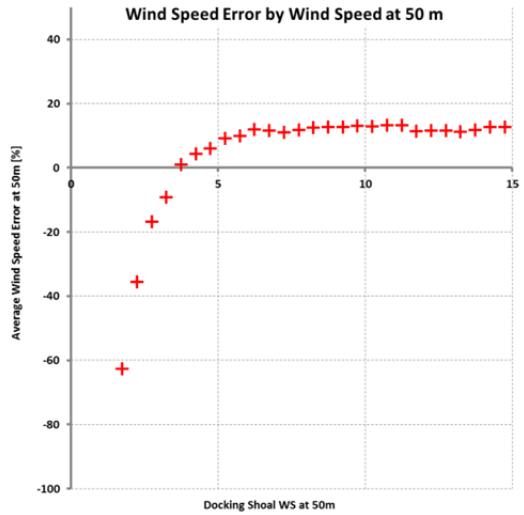


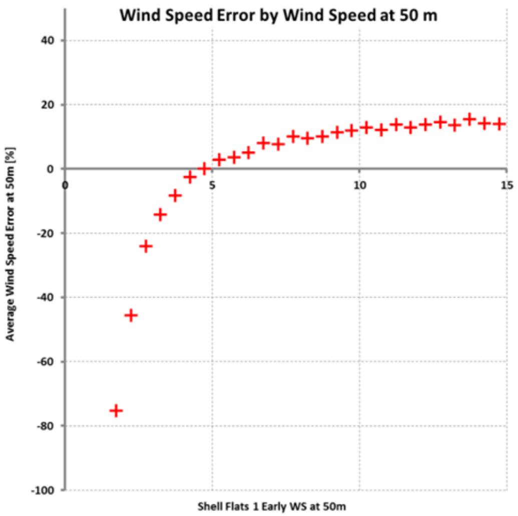


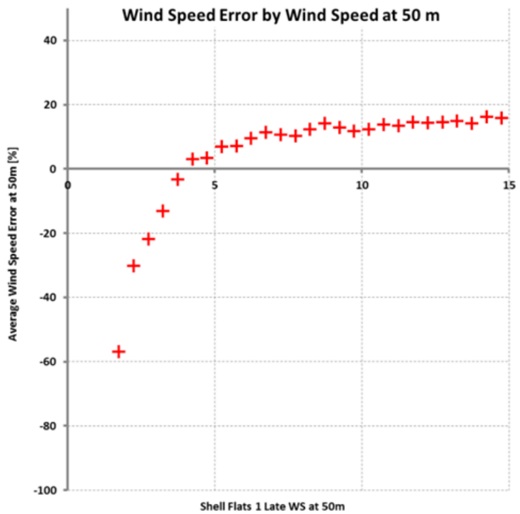


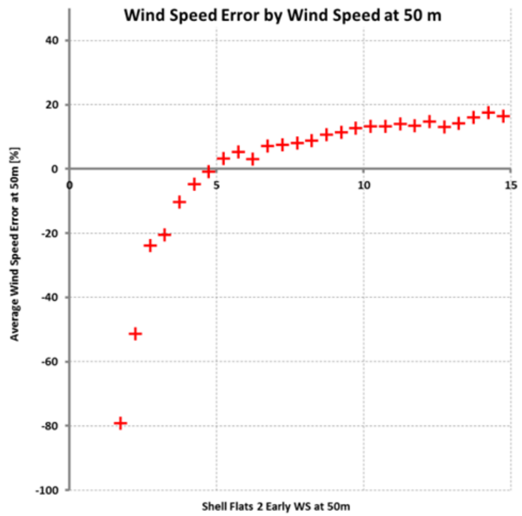


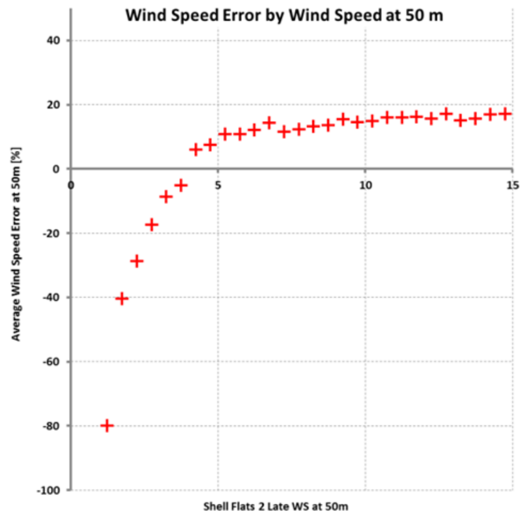


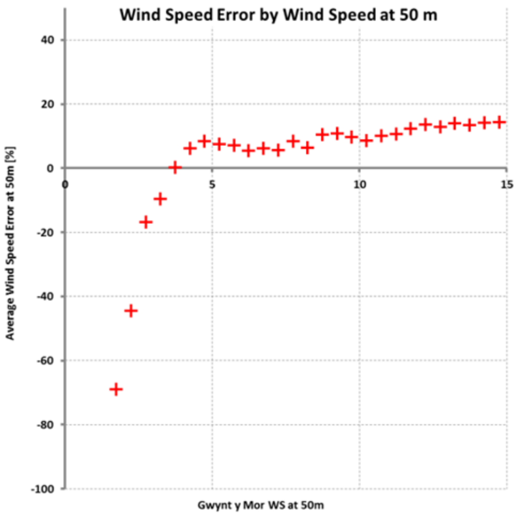


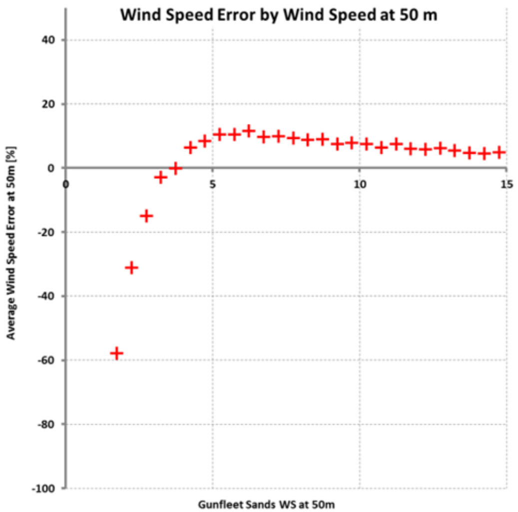

Wind Speed Error by Wind Speed at 50 m
Average Wind Speed Error at 50m [%]
40
20
0
-20
-40
-60
-80
-100
0
5
10
15
Shell Flats 1 Early WS at 50m

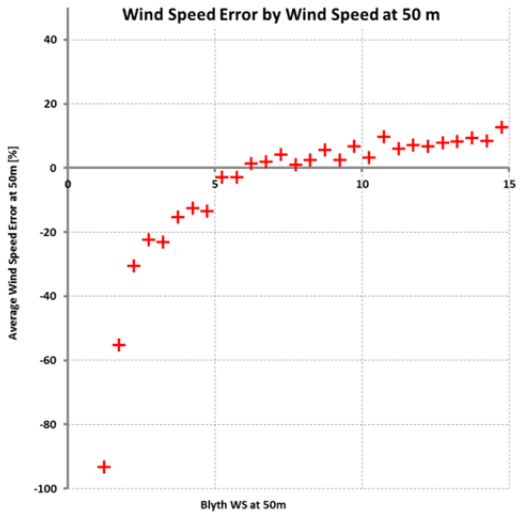

Wind Speed Error by Wind Speed at 50 m
Average Wind Speed Error at 50m [%]
40
20
0
-20
-40
-60
-80
-100
0
5
10
15
Shell Flats 1 Late WS at 50m

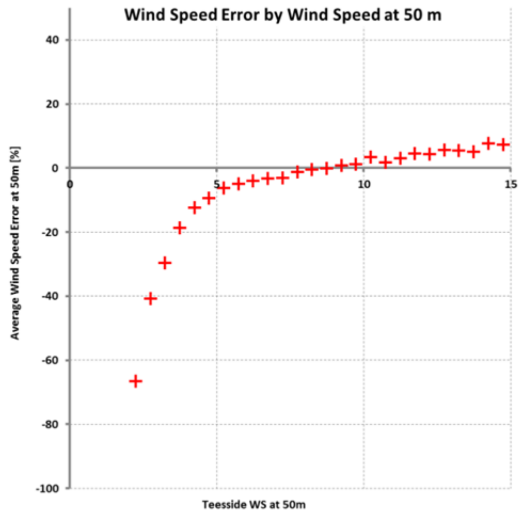

Wind Speed Error by Wind Speed at 50 m
Average Wind Speed Error at 50m [%]
40
20
0
-20
-40
-60
-80
-100
0
5
10
15
Shell Flats 2 Early WS at 50m

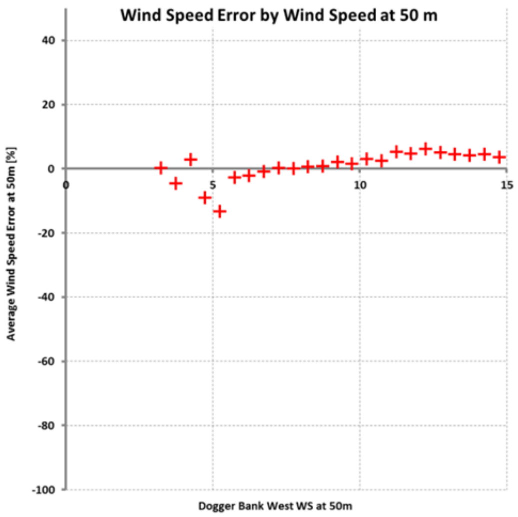

Wind Speed Error by Wind Speed at 50 m
Average Wind Speed Error at 50m [%]
40
20
0
-20
-40
-60
-80
-100
0
5
10
15
Shell Flats 2 Late WS at 50m

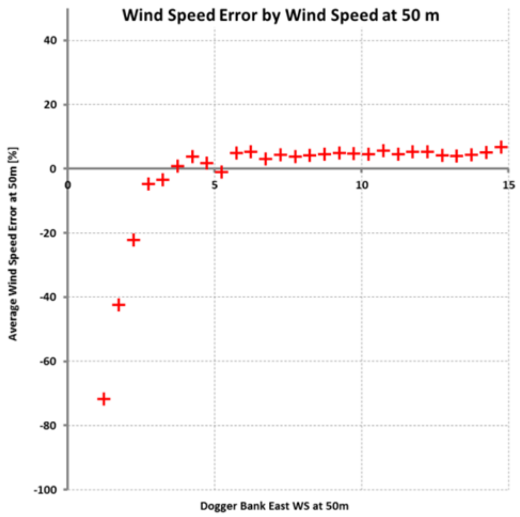

Wind Speed Error by Wind Speed at 50 m
Average Wind Speed Error at 50m [%]
40
20
0
-20
-40
-60
-80
-100
0
5
10
15
Gwynt y Mor WS at 50m


Wind Speed Error by Wind Speed at 50 m
Average Wind Speed Error at 50m [%]
40
20
0
-20
-40
-60
-80
-100
0
5
10
15
Gunfleet Sands WS at 50m

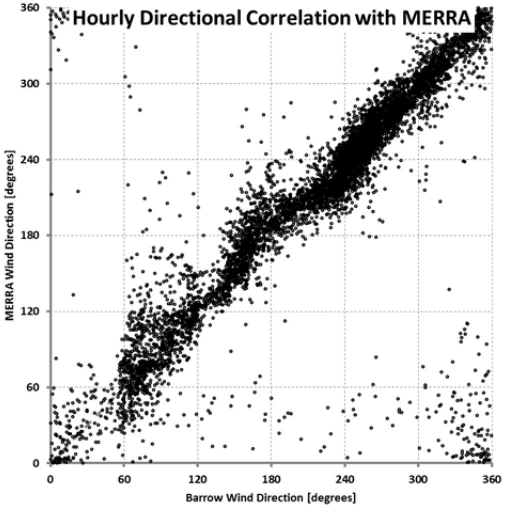

Wind Speed Error by Wind Speed at 50 m
Average Wind Speed Error at 50m [%]
40
20
0
-20
-40
-60
-80
-100
0
5
10
15
Blyth WS at 50m

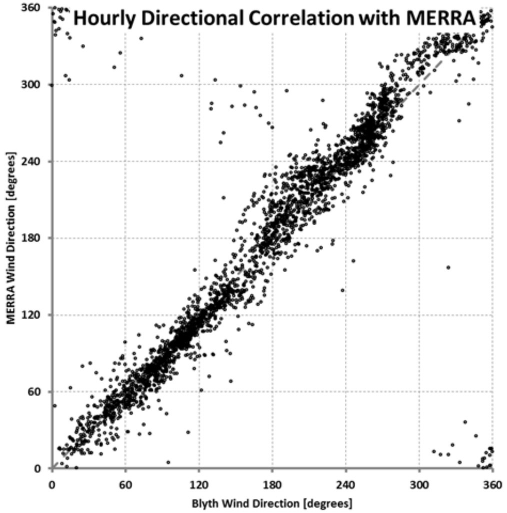

Wind Speed Error by Wind Speed at 50 m
Average Wind Speed Error at 50m [%]
40
20
0
-20
-40
-60
-80
-100
0
5
10
15
Teesside WS at 50m

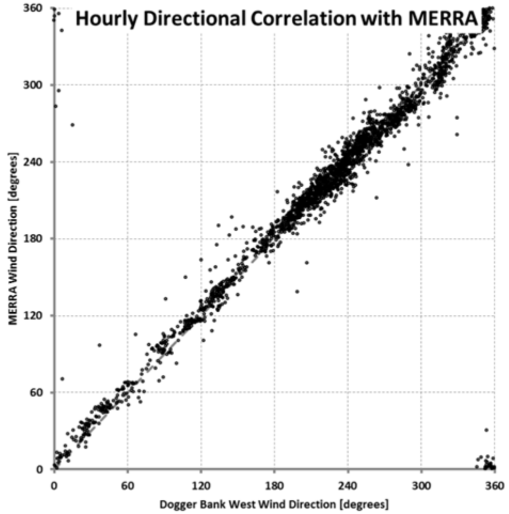

Wind Speed Error by Wind Speed at 50 m
Average Wind Speed Error at 50m [%]
Dogger Bank West WS at 50m

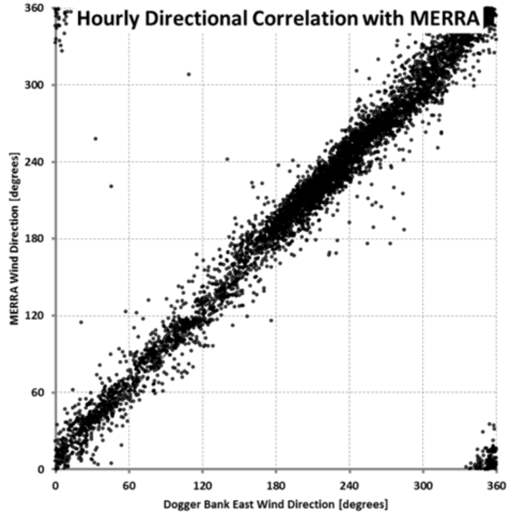

Wind Speed Error by Wind Speed at 50 m
Average Wind Speed Error at 50m [%]
Dogger Bank East WS at 50m

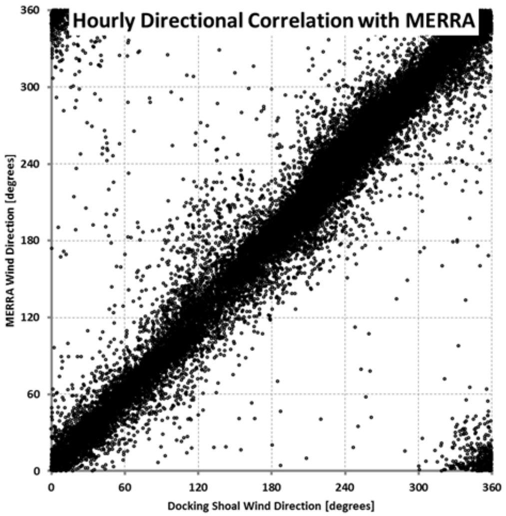
Appendix E – Hourly Directional Correlations with Mast Data

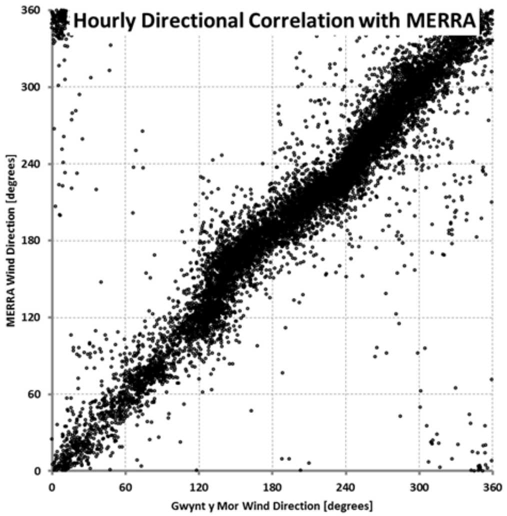


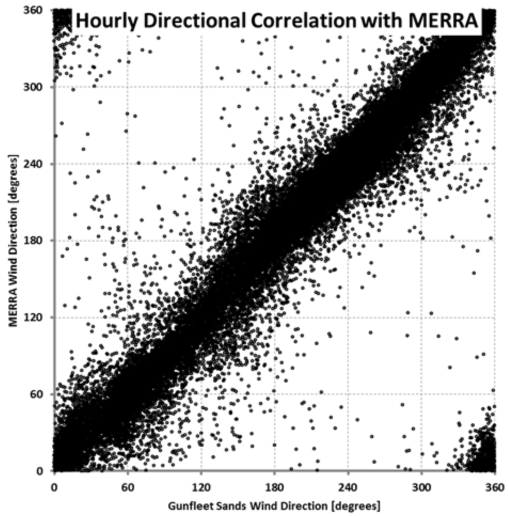


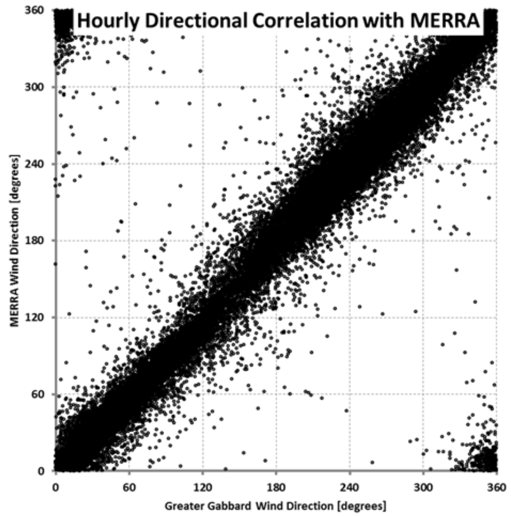


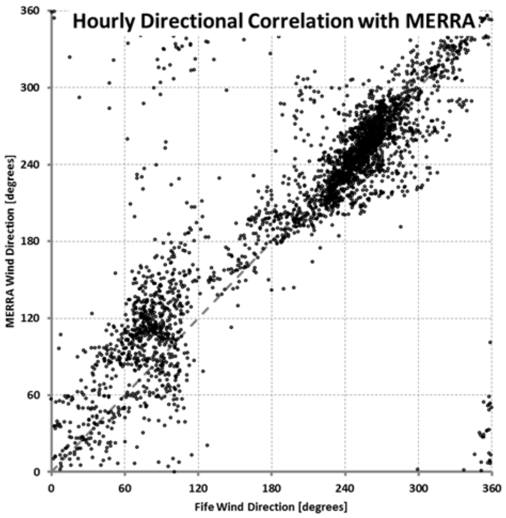


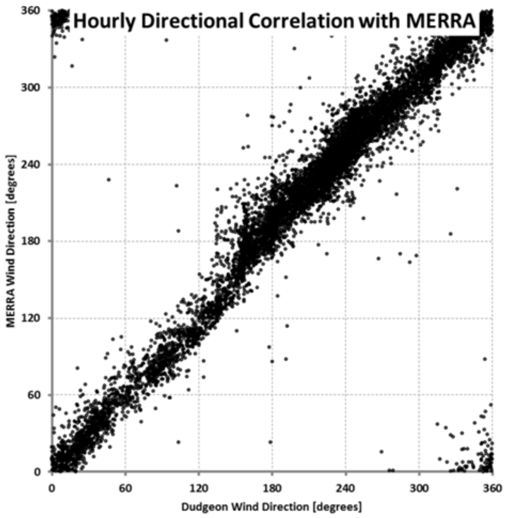


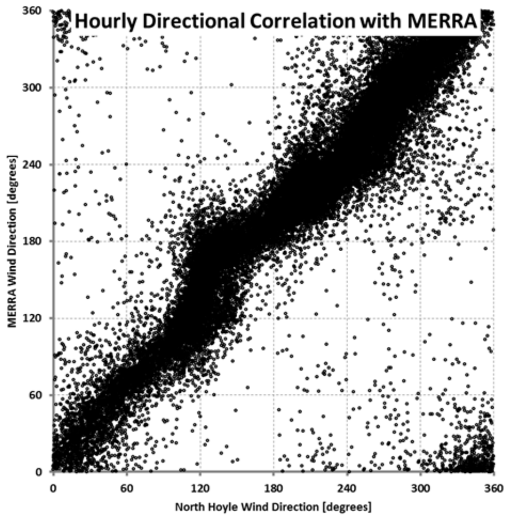


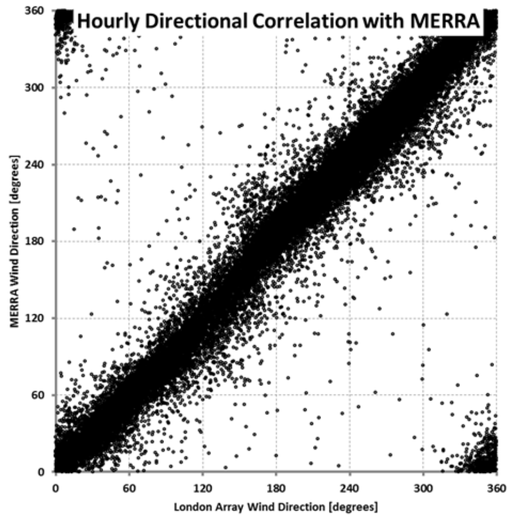


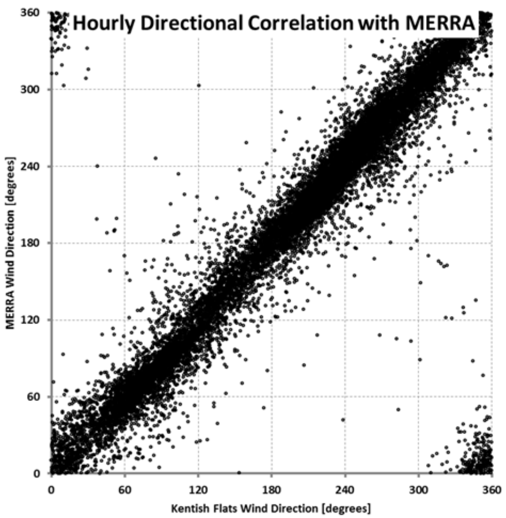


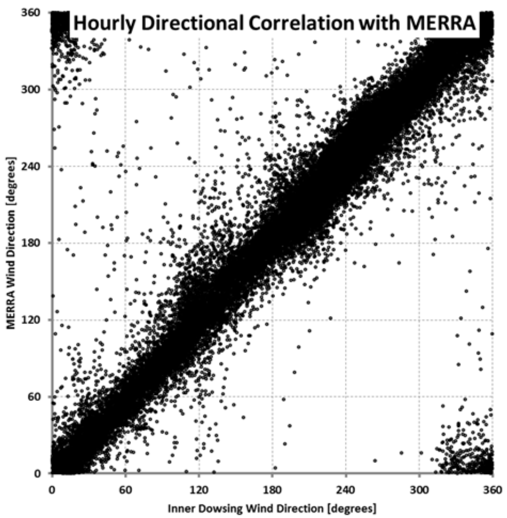

Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0 60 120 180 240 300 360
Fife Wind Direction [degrees]

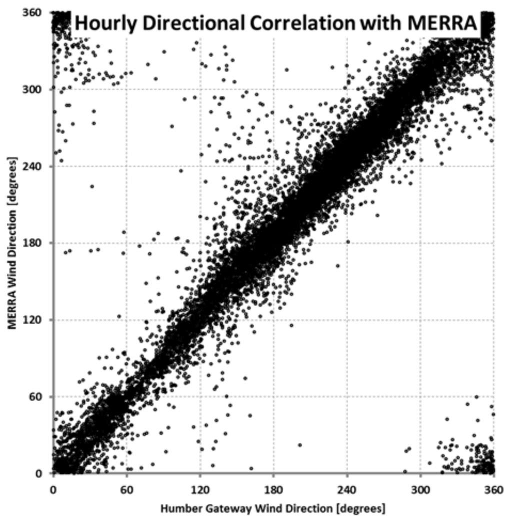

Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0 60 120 180 240 300 360
Dudgeon Wind Direction [degrees]

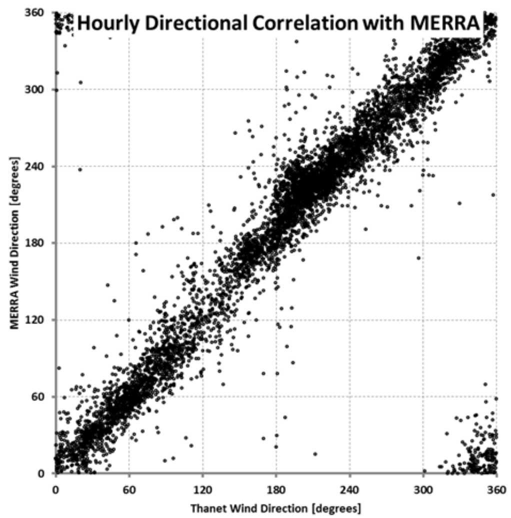

Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0 60 120 180 240 300 360
North Hoyle Wind Direction [degrees]

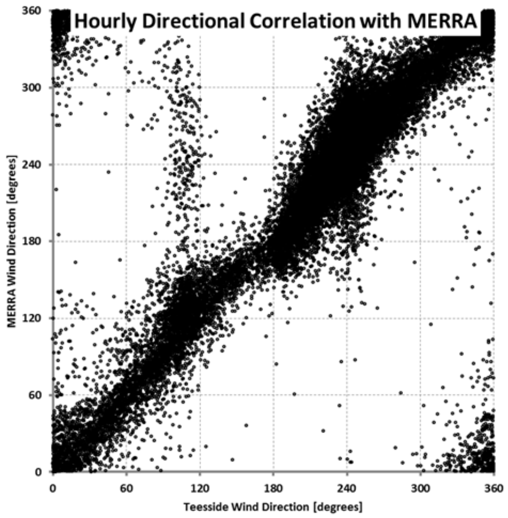

Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0 60 120 180 240 300 360
London Array Wind Direction [degrees]

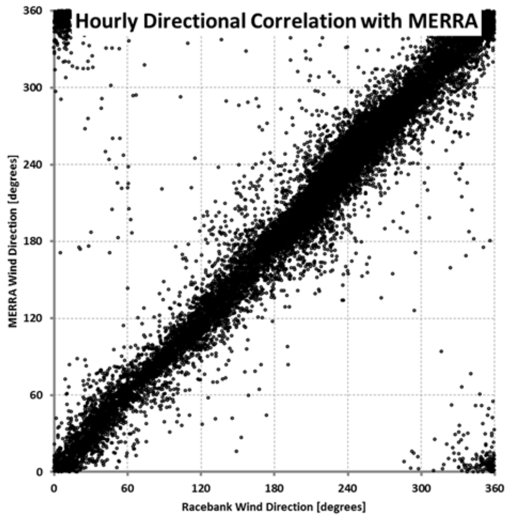

Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0 60 120 180 240 300 360
Kentish Flats Wind Direction [degrees]

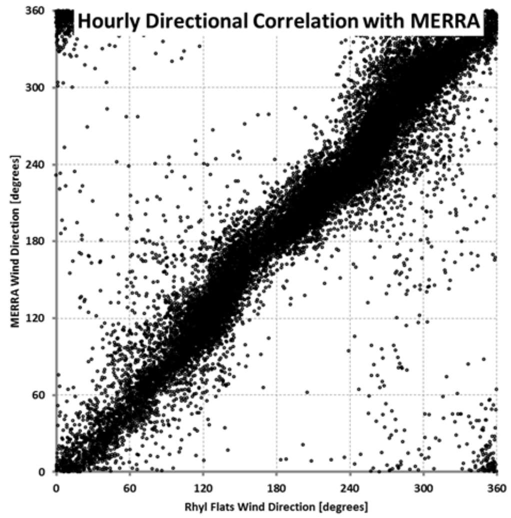

Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0 60 120 180 240 300 360
Inner Dowsing Wind Direction [degrees]

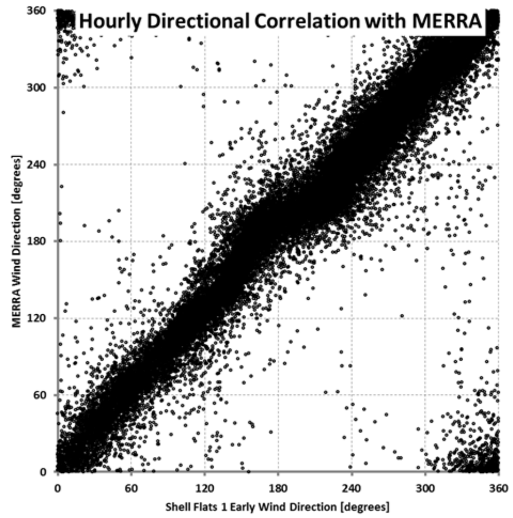

Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0 60 120 180 240 300 360
Humber Gateway Wind Direction [degrees]

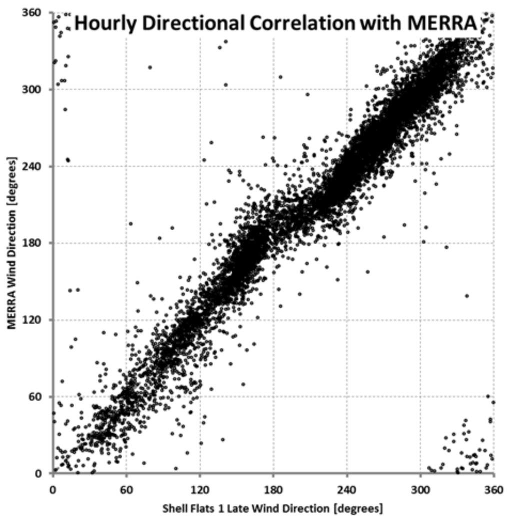

Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0 60 120 180 240 300 360
Thanet Wind Direction [degrees]

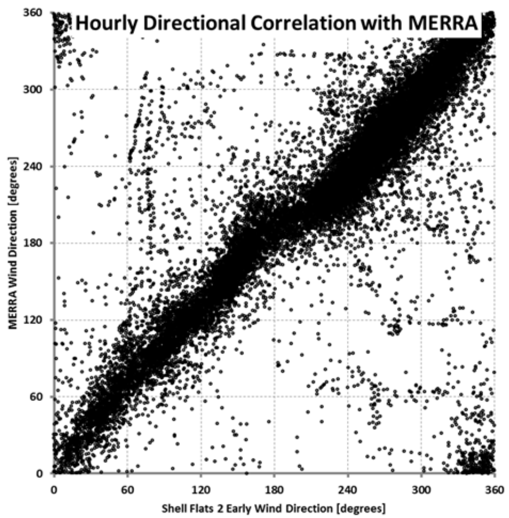

Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0
60
120
180
240
300
360
Teesside Wind Direction [degrees]

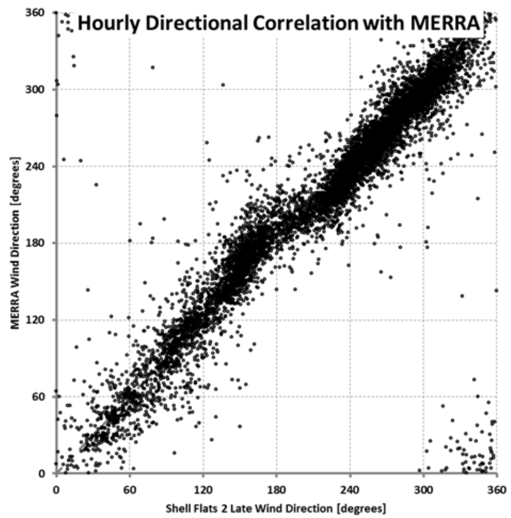

Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0
60
120
180
240
300
360
Racebank Wind Direction [degrees]


Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0
60
120
180
240
300
360
Rhyl Flats Wind Direction [degrees]


Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0
60
120
180
240
300
360
Shell Flats 1 Early Wind Direction [degrees]


Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0
60
120
180
240
300
360
Shell Flats 1 Late Wind Direction [degrees]


Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0
60
120
180
240
300
360
Shell Flats 2 Early Wind Direction [degrees]


Hourly Directional Correlation with MERRA
MERRA Wind Direction [degrees]
0
60
120
180
240
300
360
Shell Flats 2 Late Wind Direction [degrees]

Appendix F – Mast Photos

Dudgeon

Fife Energy Park

Greater Gabbard

Gwynt Y Mor

Inner Dowsing

London Array

North Hoyle

Rhyl Flats

Teesside