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Validation of KNW atlas with publicly available mast observations (Phase 3 of KNW project)

A. Stepek, M. Savenije, H.W. van den Brink and I.L. Wijnant

De Bilt, 2015 | Technical report; TR-352

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April 2015

FINO 1 Mast and wind farm Alpha Ventus and floating LIDAR device (source: Fraunhofer IWES)

Abstract

The KNW (KNMI North Sea Wind) atlas is based on the ERA-Interim reanalyses dataset which captures 35 years (1997-2013) of meteorological measurements and generates 3D wind fields consistent with these measurements and the laws of physics. This dataset is "downscaled" using the state-of-the-art weather forecasting model, HARMONIE with a horizontal grid of 2.5 km. The result is a high resolution dataset of 35 years: the KNW dataset. In this report the KNW dataset is validated against publicly available wind measurements from three tall offshore wind masts: OWEZ, FINO1 and MMIJ (Meteorological Mast Ijmuiden). The difference between the measured wind speeds (averaged over periods when the mast measurements were undisturbed by nearby wind parks) and the KNW values is less than 0.2 m/s for all masts and all measurement heights. The ERA-HARMONIE wind speeds were tuned to match the measurements made at KNMI's 200 m tall meteorological mast at Cabauw and the same wind shear correction factor was applied uniformly throughout the whole KNW atlas area. The validation results imply that the accuracy of the long term average wind speeds of the KNW atlas is comparable to that of the measurements (cup and sonic anemometer and LIDAR). The same can be said of the estimates of the once in 10 year extreme wind speeds for heights around wind turbine hub height.

This report deals with the validation of the KNW wind atlas in the vertical dimension with measurements from three tall wind masts. In another report we validate the atlas on a horizontal plane 10 m above the North Sea (Wijnant, 2015). The reports are identical from the introduction up to and including section 1.1.3. The KNW dataset that is validated horizontally has not been corrected for the model's underestimation of the vertical shear of the horizontal wind speed (since this has little effect on the wind speed at 10 m) whereas the vertically validated dataset has been corrected. The vertically validated dataset falls just within the area bounded by 50.25-54.75 NB and 1.50-8.25 EL (publicly available from the middle of 2015) whereas the horizontally validated dataset covers the whole of the North Sea. To avoid confusion: the KNW dataset is different from the North Sea wind climatology described in KNMI TR343 (Wijnant et al, 2014). Both the KNW dataset and the climatology of TR343 are based on re-analyses model ERA-Interim, but the "downscaling" procedures used are different. The KNW dataset followed up the wind climatology of TR 343 so quickly that the TR 343 dataset was never made available to a wider public.

Acknowledgement

We want to thank the Directorate-General for Spatial Development and Water Affairs (DGRW) of the Dutch Ministry of Infrastructure and the Environment (IenM) for funding the KNW-atlas and its validation. More specifically we would like to thank Henk Merkus from DGRW for being so enthusiastic and helpful.

Content

Introduction

The KNMI North Sea Wind (KNW) atlas is based on 35 years (1979-2013) of ERA-Interim reanalyses[1] (80 by 80 km grid) and mesoscale atmospheric model HARMONIE (2.5 by 2.5 km grid, version CY37h1.1). The 6 hourly ERA-Interim reanalyses are used to initialise HARMONIE throughout its domain, so at the start of each forecast the HARMONIE values are the same as the ERA-Interim values. The resulting wind climatology consists of the + 1 hour up to and including the + 6 hour wind forecast of HARMONIE. The ERA-Interim climatology is as it were “down-scaled” to the HARMONIE 2.5 by 2.5 km grid in the course of each 6 hour forecast. This results in a three dimensional grid with a horizontal domain of 500 by 500 grid points and 60 levels along the vertical axis. For the vertical validation of the KNW atlas with publicly available wind mast measurements only part of this domain was selected and analysed (figure 0.1 left). The locations of these masts are shown in figure 0.1 (right).

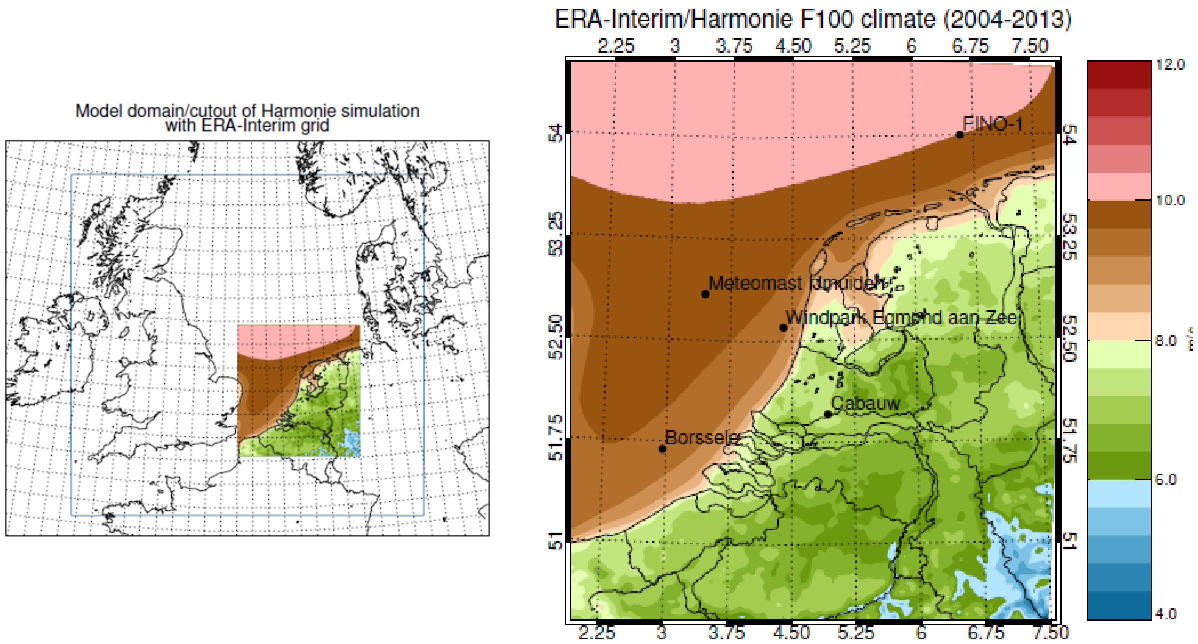


Figure 0.1
Left: Domain setup of HARMONIE (blue): 500 by 500 grid points of 2.5 km by 2.5 km with 60 vertical levels. The coloured subdomain is stored in NetCDF and used for analyses. The grid lines indicate the ERA-Interim 0.75° by 0.75° grid cells (about 80 km by 80 km).
Right: the location of the three offshore wind masts (FINO1, OWEZ and MMIJ) and the CABAUW mast used for validation, superimposed on the 10-year average wind speed at 100 m height based on ERA-Interim and HARMONIE. The Borssele Wind Farm Zone (344 km^2) is one of the areas assigned by the Dutch government for wind energy production (4 farms with a total capacity of 1400 mW) and is the one where the call for tenders will start at the end of 2015.

[1] A reanalyses is the representation of the atmospheric state that corresponds best with all available measurements in a way that is consistent with the laws of physics.

CHAPTER 1 Atmospheric models and publicly available mast measurements

1.1 Atmospheric models

1.1.1 ERA-Interim

The ERA-Interim reanalysis dataset from ECMWF (European Centre for Medium Range Weather Forecasts, www.ecmwf.int) combines one of the leading numerical weather prediction models (ECMWF model) with an advanced data-assimilation system (Baas, 2014). The resulting analysis can be considered a best-estimate, in statistical sense, of the state of the atmosphere since it is based on the very short-term model forecast adjusted to match the observations of that moment in time. ERA-Interim is available since 1979, gives full 3D analyses of the global atmosphere at a T255 spectral truncation (which corresponds to a grid size of about 80 km) and provides a 6-hourly temporal output.

The KNW-atlas is based on 35-years (1979-2013) of ERA-Interim reanalyses. This period is long enough to capture the natural long-term variability on the scale of decades of the current wind climate. The high resolution mesoscale model HARMONIE is used to enhance the spatial representation of the wind atlas which is especially beneficial in the coastal zone.

1.1.2 HARMONIE

HARMONIE (HIRLAM ALADIN Research on Mesoscale Operational NWP In Euromed), also known by the name AROME, is the numerical weather prediction model that KNMI uses operationally since 2012. It is extensively tested and continually improved by the HIRLAM-ALADIN consortium (figure 1.1). HARMONIE is a non-hydrostatic limited-area model which runs on a very high resolution grid (spacing of 2.5 km). For more details on HARMONIE /AROME, see Seity et al. (2011) and www.hirlam.org. Here, we use the CY37h1.1 version of HARMONIE that was released on 13 June 2012. More information on the HARMONIE model set-up can be found in Geertsema et al. (2014).

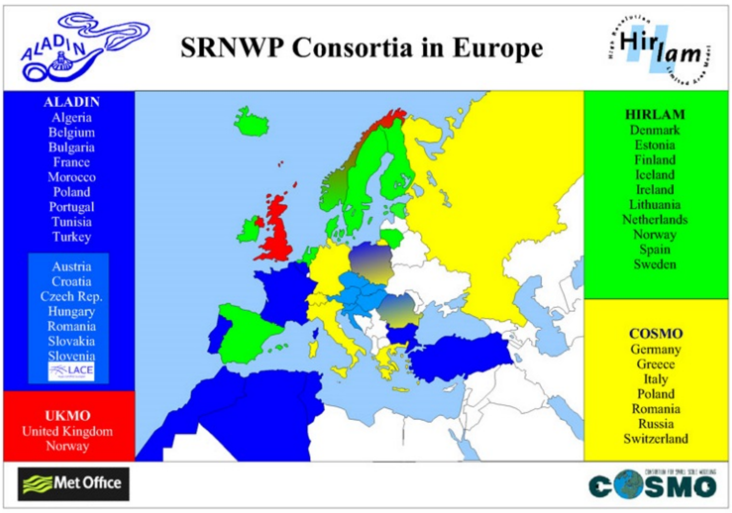


Figure 1.1 Participating countries in HIRLAM (green) and ALADIN (blue) consortium. (source: http://www.eumetnet.eu)

The HARMONIE data used are the forecasts for hours 1 up to and including 6. Every six hours ERA-interim provides a new initial state.

HARMONIE produces momentary values of wind speed for each grid box with a volume in the planetary boundary layer of 2.5 by 2.5 km and tens of meters deep. These values are volume averages of the wind speed in the grid box. Compared to anemometer measurements which average over much smaller volumes, the model values fluctuate less rapidly. Averaging the anemometer measurements over longer time periods provides wind speeds that fluctuate less rapidly too. To discover which averaging time provides the best agreement with the model's spatially averaged values, several averaging periods were applied to the 100 m height wind speed measurements of the FINO1 mast (corrected for mast effects). Figure 1.2 shows the result of this analysis. The blue values are based on hourly samples of running averages of the measurements and the red are based on all the available running averages. Sampling implies that yearly maxima are sometimes missed (so the blue line is lower than the red line). The KNW value should be compared to the blue values because the KNW values are also based on hourly samples (of the 60 momentary wind speeds per hour that HARMONIE generates). The KNW value can best be compared to the blue values based on 40-60 minute averages of the measured wind speed.

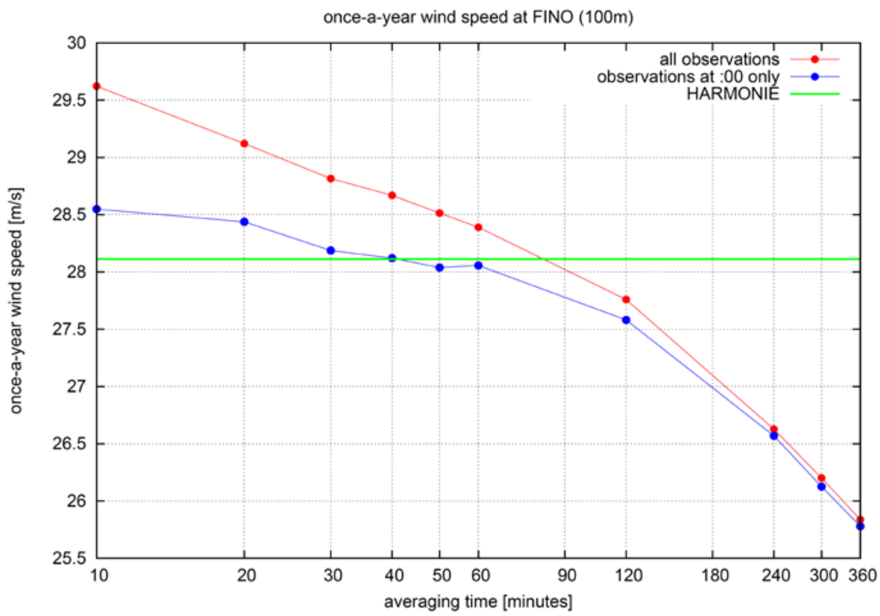


Figure 1.2: Comparison at FINO1 of the once a year return values of wind speed at 100 m from the KNW atlas (green) and from the measurements averaged over various lengths of time (blue and red).

For the comparison with measurements (which are 10 minute averages), it is assumed that the momentary model value should be compared to an hour of measurements (half an hour before to half an hour after the moment of the model value. All 6 measurements in the hour (every 10 minutes, all representing 10 min averages) are compared to this momentary HARMONIE value (figure 1.3). This may seem strange since we have shown that the HARMONIE values should be compared to hourly average anemometer measurements. However, the validation results are long term aggregates of the (HARMONIE – measurement) differences and are exactly the same as if the six 10 minute average measurements were first aggregated to hourly averages and then compared to the HARMONIE value.

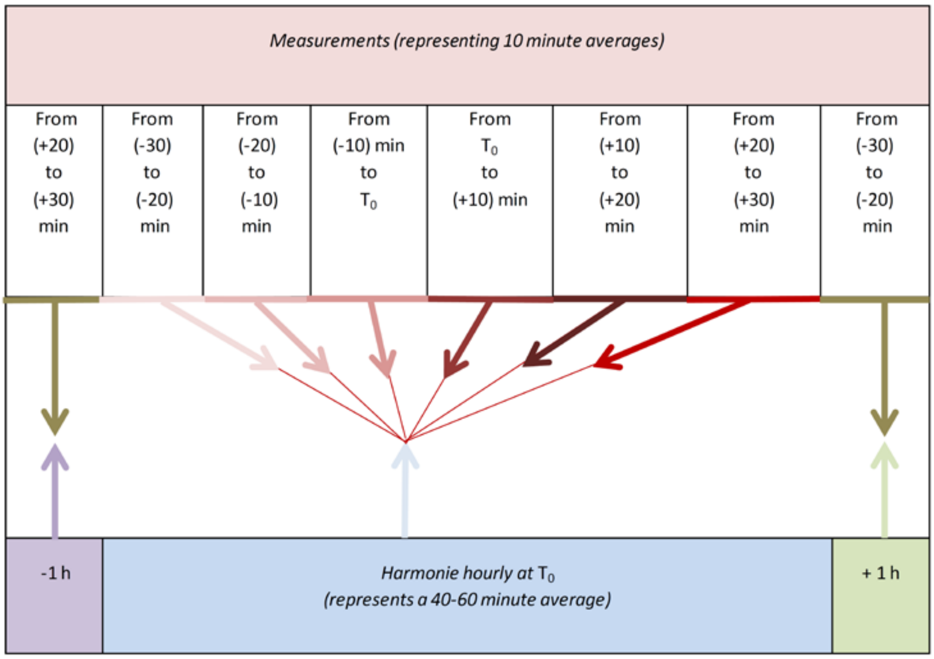


Figure 1.3 Validation scheme: for every 10 minute time step, the measurements (that represent 10 minute averages) are compared to one HARMONIE value (which represents a 40-60 minute average) i.e. the one at T_0. So for every hour 6 different measurements (here reddish arrows) are compared to the same HARMONIE value (here blue).

1.1.3 Wind shear corrected HARMONIE

Most state-of-the-art operational weather forecasting and climate models have problems with the representation of wind profiles in stable conditions because they overestimate the vertical mixing, i.e., they underestimate the increase of wind speed with height (KNMI TR342 by Wijnant et al, 2014). This is also the case for HARMONIE and more so for ERA-Interim. In a study comparing the wind speeds of HARMONIE initialised with ERA-Interim to mast measurements on the Dutch mainland for a 10-year period (2004-2013), Geertsema (2014) concluded that the model underestimates the vertical wind shear by a factor of about 15% which implies that the wind at a 100 m height is underestimated by about 5%. Fortunately, this small underestimation can be easily corrected (see Appendix A1). At all heights the HARMONIE wind speeds, corrected for the underestimation of the vertical wind shear, differ from the measured values at Cabauw by less than 0.1 m/s on average (figure 1.4). For four other tall masts at coastal sites the correction improved the validation results. At 100m height the underestimation of the wind speed was reduced by 0.3-0.4 m/s, leaving a difference of 0.1 m/s or less for three of the four masts. These validation results imply that the shear corrected HARMONIE wind speeds describe the 10 year average wind speed at nearly all locations on the mainland with an accuracy comparable to direct measurements.

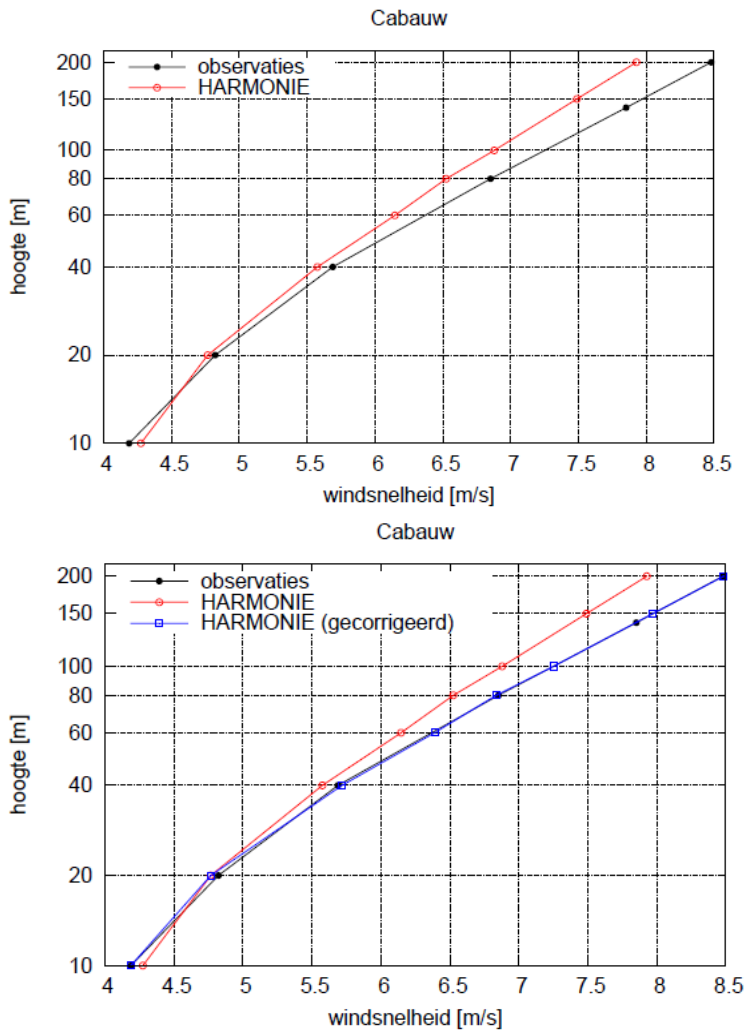


Figure 1.4 Average vertical wind profile Cabauw 2004-2013: observed (black), HARMONIE (red) and HARMONIE corrected (blue) (source: Geertsema, 2014).

Geertsema (2014) concludes that a shear correction should be generally applied to HARMONIE profiles for mainland locations. In this study we have found that this shear correction also improves validation results at wind masts on the North Sea (OWEZ, FINO, MMIJ).

The KNW dataset validated against the scatterometer 10 m wind products has not been wind shear corrected because at this height the correction is very small.

1.2 Publicly available mast measurements

The masts with publicly available wind measurements that were used for vertical validation of the KNW atlas are shown in figure 0.1 (right) as is the location of wind area Borssele where 4 wind farms (total capacity 1400 MW) are planned in the near future. Appendix A2 contains a table summarising the measurements from the tall masts used in this report.

CHAPTER 2 Standard results figures explained

Most validation results are presented in figures containing a standard set of 8 graphs and to avoid repetition they are described here. All of the graphs present wind information at a selected height with one exception: the graph showing wind speed versus height.

The top row has 2 graphs of time series with on the left the monthly mean wind speed and on the right yearly averages. HARMONIE data are not included in the validation when the measurements are missing. The black line in the monthly means graph shows the percentage of valid observations.

The second row shows the wind speed frequency distribution and the corresponding Weibull fit on the left and wind speed versus height on the right. In Appendix A3 the cumulative form of the frequency distribution can be found together with wind turbine capacity factors and Weibull fits made conform the wind energy sector standard method (Donkers, 2010). However, for the standard results graph, the Weibull fit method described by Wieringa and Rijkoord (1983, formula 5.18) was used. This is a least squares fit of the linear relationship of formula 1 and when the left hand side is plotted against the natural logarithm of the wind speed (ln U), the gradient (k) and offset (k ln a) can obtained and both Weibull parameters (k and a) can be quantified. Wind speed bins of 0.5 m/s from 4 m/s up to and including the bin containing the 99th percentile of the distribution were fitted. The graphs show 1.0 m/s bins to make them clearer.

$$(5.18) \quad \ln(-\ln[1 - F(U)]) = k(\ln U) - k \ln a \qquad (1)$$

- F(U) is the cumulative Weibull distribution function which is the chance of exceeding the wind speed U
- k is the Weibull shape parameter
- a is the Weibull scale parameter

The third row shows per 30 degree wind direction bin the frequency of occurrence of those wind directions on the left and the average wind speed per bin on the right. For the graph on the left occasions where the wind speed was 4 m/s or less are not considered because at such speeds wind vanes often do not operate correctly and wind turbines are unproductive.

The bottom row shows on the left the diurnal variation of hourly average wind speeds and on the right the seasonal variation of monthly averages. The diurnal variation graphs show is an artefact of the model caused by the initialisation of the HARMONIE weather forecasting model at 0, 06, 12 and 18 UTC with the lower ERA-Interim wind speeds. It takes a number of hours into the forecast before HARMONIE develops more realistic, smaller structures and higher wind speeds than ERA-Interim is capable of. The forecast hours included in the wind atlas dataset (hours 1-6, with 0 being the initialisation time) were chosen to optimally match measurements made at KNMI measurement sites at the meteorological standard height of 10 m. Since then however, Wijnant at al (2015) have shown that using longer forecast lead times would probably improve agreement with satellite-based measurements of the wind above the North Sea. There is obviously a limit to this because there is a limit to how far ahead you can forecast accurately.

CHAPTER 3 MMIJ

3.1 Measurement site

Measurements from the Meteo Mast IJmuiden (MMIJ) which is 75 km west of IJmuiden (figure 3.1) are available for 2012 and 2013. There is no wind farm in the neighbourhood (yet) that disturbs the measurements. There are three main levels (27, 58 and 87 m) each with three booms each supporting a cup anemometer and a wind vane. There is an anemometer at the top (92 m) and a LIDAR device is installed for measurements above 90 m.

The fact that the wind is measured at three positions makes it possible to select the sensor where the measurements are not disturbed by the mast or to combine measurements in such a way that mast effects are minimalized. The wind speed that is derived from the raw measurements is often referred to as the “true wind speed” (or derived wind speed). The MMIJ measurements used in this study are the true wind speed and directions supplied by ECN.

3.2 Comparing HARMONIE and MMIJ measurements

Figure 3.2a and b contain 8 graphs just like the standard figure described in chapter 2, but their positions in the figure are different. On the left of figure 3.2 are the results from HARMONIE without the wind shear correction factor and on the right the results for HARMONIE with shear correction. Figure 3.2a shows the 4 graphs normally on the left of the standard figure and figure 3.2b shows the 4 graphs normally on the right. Seven of the eight graphs concern the 60 m height data (with the wind vane at 58 m to be precise). The graphs show the analysis conducted for the two whole years 2012 and 2013. All of the graphs on the right hand side clearly show improved validation results compared to those on the left, except the 2 graphs on the third row of figure 3a because they show the frequency of occurrence of the wind direction and that is unaffected by the shear correction applied to the wind speed.

The bottom row of figure 3.2a shows the graphs of the diurnal variation of the hourly average wind speeds. There is no variation present in the measurements because MMIJ is far from land. The saw-tooth pattern displayed by the HARMONIE speeds is explained in chapter 2.

The second row of graphs in figure 3.2b shows the period average wind speed versus height. The HARMONIE wind speeds without wind shear correction (left) underestimate the measured wind speed and the difference increases with height. The graph on the right clearly shows that the wind shear correction eradicates almost all of the difference between model and measurement. At the 92 m measurement height the underestimation is reduced from 0.3 m/s to only 0.1 m/s. The capacity factor[2] for a Vestas V90 wind turbine calculated with the 60 m height data of the KNW atlas for 2012 and 2013 is 47.1%. This is only 0.6% lower than the 47.7% calculated using the measurements (see graph in Appendix A3).

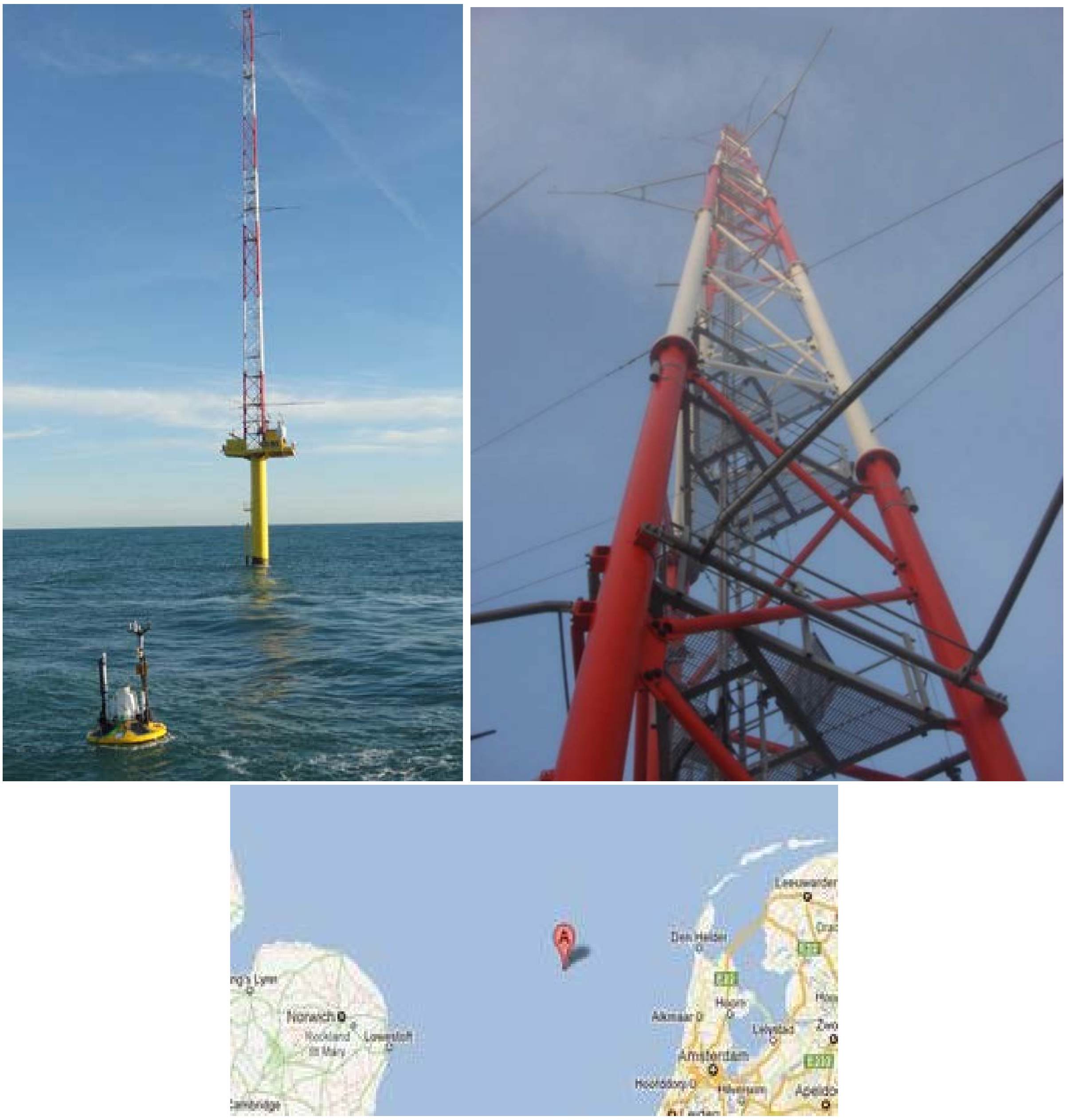


Figure 3.1 The top left panel shows Meteo Mast IJmuiden with in the foreground the met ocean buoy that was tested in the first half of 2014 (source: www.essent.nl) and the top right panel shows the mast constuction and booms (source: BILIX Consultatancy BV). The location of the mast is given in the panel below (source: ECN).

[2] The capacity factor of a wind turbine is the average power produced divided by the rated power of the wind turbine, which is the maximum power output that is only achieved at hub height wind speeds above the rated wind speed (typically 15 m/s) and below the cut-off wind speed (typically 25 m/s).

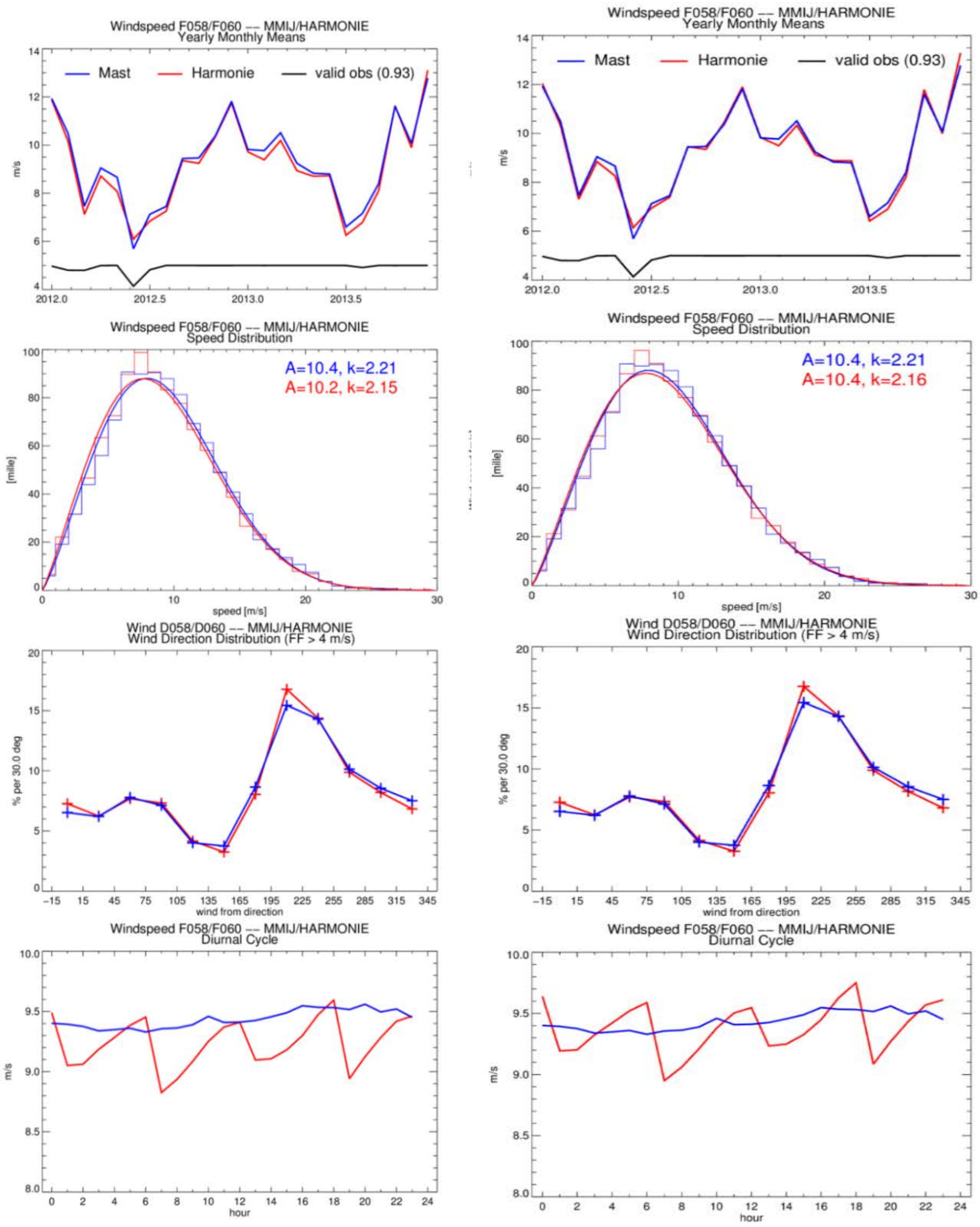


Figure 3.2a: Validation at Meteo Mast Ijmuiden for period 20120101-20131231 using anemometer (blue) , LIDAR (green) measurements and HARMONIE (red) without wind shear corrections (left) and with wind shear correction (right).

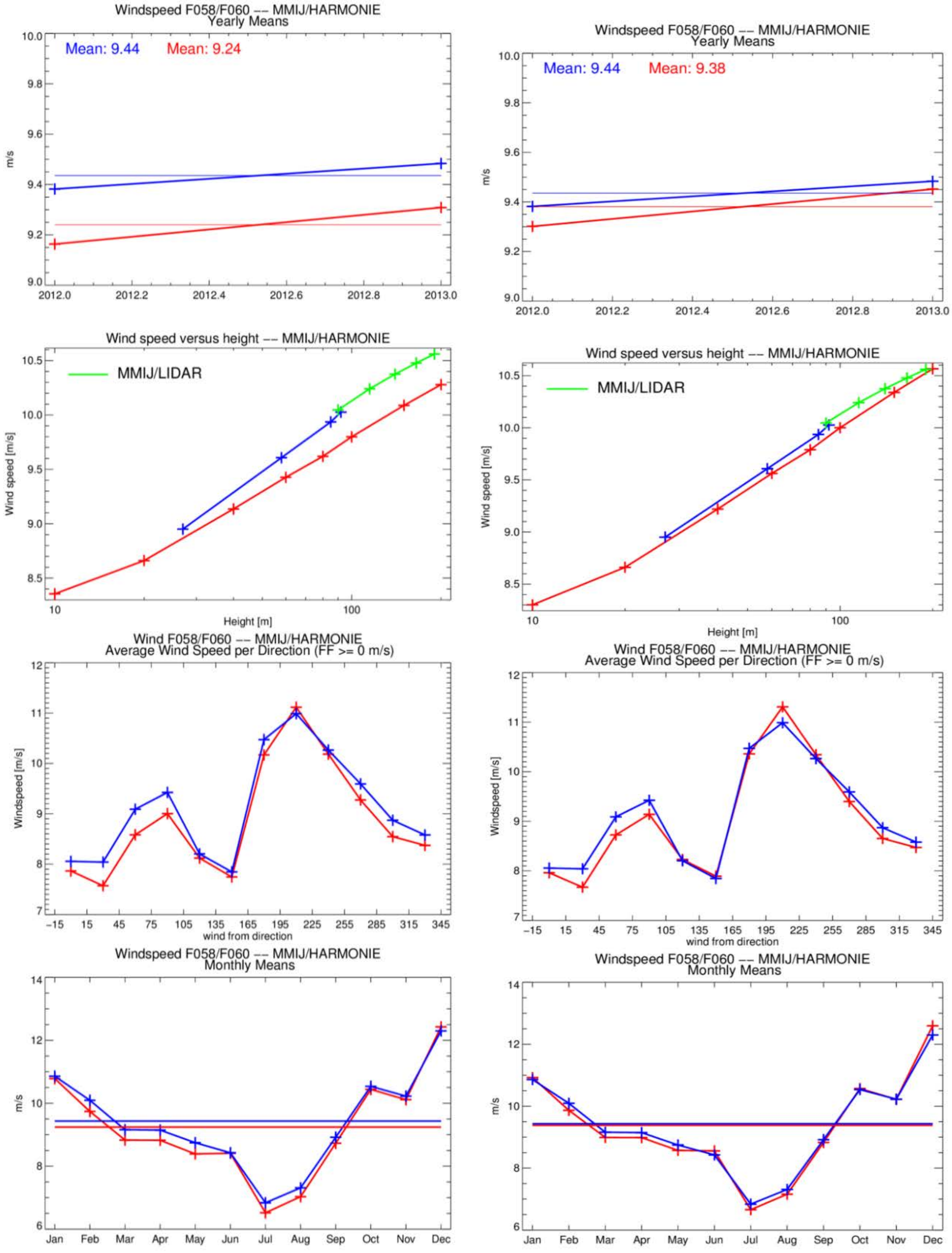


Figure 3.2b: Validation at Meteo Mast IJmuiden for period 20120101-20131231 using anemometer (blue) , LIDAR (green) measurements and HARMONIE (red) without wind shear corrections (left) and with wind shear correction (right).

CHAPTER 4 OWEZ

4.1 Measurement site

Measurements from the OWEZ mast (15 km west of Egmond aan Zee) are available from July 2005 up to and including December 2010. Construction of the Windpark Egmond aan Zee (OWEZ) began on 18 April 2006 and the wind turbines were being installed from July 2006. This means that the measurements have been undisturbed for one full year (July 2005 up to and including June 2006). After that only wind measurements from directions between 135° and 315° degrees (the southwesterly half) are undisturbed . There are three main levels (21, 70 and 116 m) each with three booms/sensors. For every measurement, one sensor is selected i.e. the one that is least disturbed by the mast: for wind directions between 0° and 120° degrees the sensor on the northeast boom, for wind directions between 120° and 240° degrees the sensor on the south boom and for wind directions between 120° and 360° degrees the sensor on the northwest boom (figure 4.1).

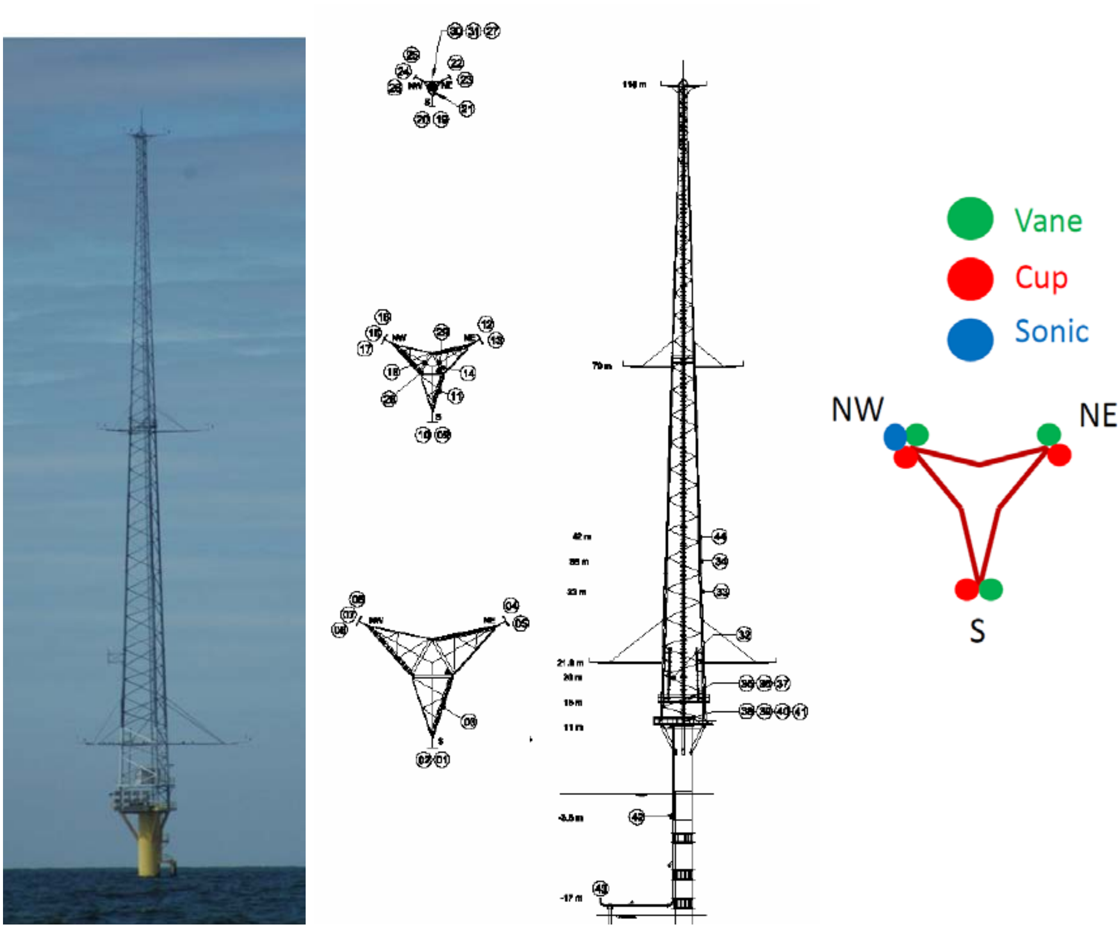


Figure 4.1: The meteorological mast at the OWEZ wind farm (left) and a schematic drawing of the meteorological mast (right) (Source: Kouwenhoven, 2007)

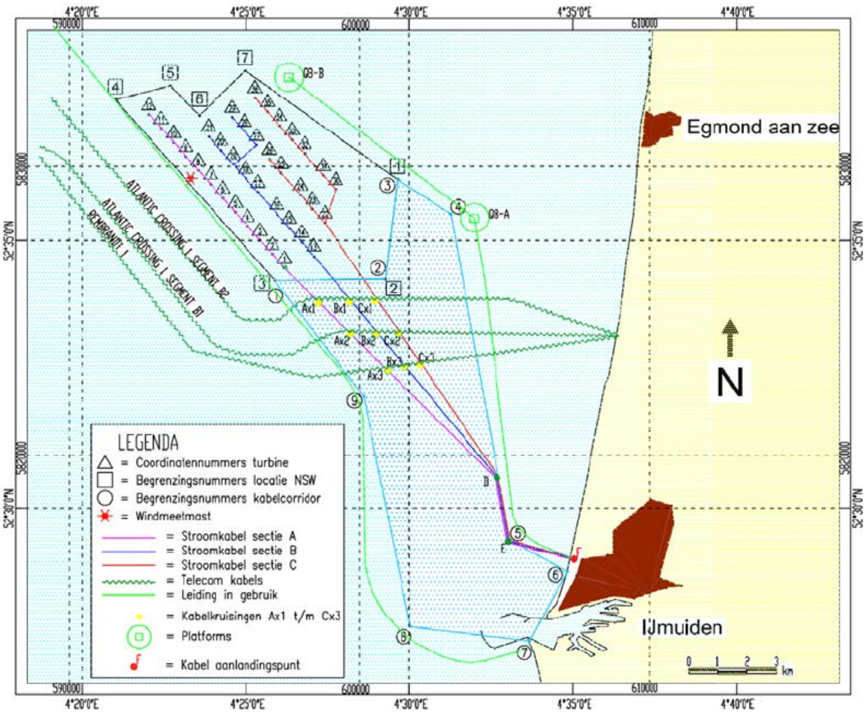


Figure 4.2: Wind mast (red asterisk) and wind turbines (black triangles) at OWEZ (Source: WEOM)

4.2 Comparing HARMONIE and OWEZ measurements

Figures 4.3-4.8 with the exception of 4.6 display the validation results in the standard format of 8 graphs as described in chapter 2. Seven of the eight graphs present wind information at the measurement height of 70 m, the exception being the graph of wind speed against height.

Figure 4.3 shows the HARMONIE validation for OWEZ for the period where the measurements were undisturbed (before construction of wind farm Egmond aan Zee: 20050701-20060630). The graph of the vertical profile of the period average wind speed (second row, on the right) shows that HARMONIE without shear correction underestimates the wind speed averaged over the undisturbed year by 0.1-0.3 m/s at all heights (figure 4.3) and the two types of measurements (sonic and cup) differ by 0.0-0.2 m/s. With shear correction (figure 4.4), HARMONIE underestimates the year average wind speed by 0.0-0.2 m/s at all heights. Appendix A3 contains a graph of the cumulative probability function of the wind speed at 70 m height for this same period and the capacity factor[3] of a Vestas V90 wind turbine based on these wind speeds. The KNW atlas distribution produces a capacity factor (41.0%) 1.9% lower than the measured distribution (42.9%). The same size of error is made by using the Weibull fit to the measurements but in this case the fit produces an overestimate of 1.9%. This means that the error introduced by using the KNW wind speeds instead of measurements is no more than that made by the standard method used in the wind energy sector of first fitting a Weibull formula, as described by Donkers (2010), to the measurements.

[3] The capacity factor of a wind turbine is the average power produced divided by the rated power of the wind turbine, which is the maximum power output that is only achieved at hub height wind speeds above the rated wind speed (typically 15 m/s) and below the cut-off wind speed (typically 25 m/s).

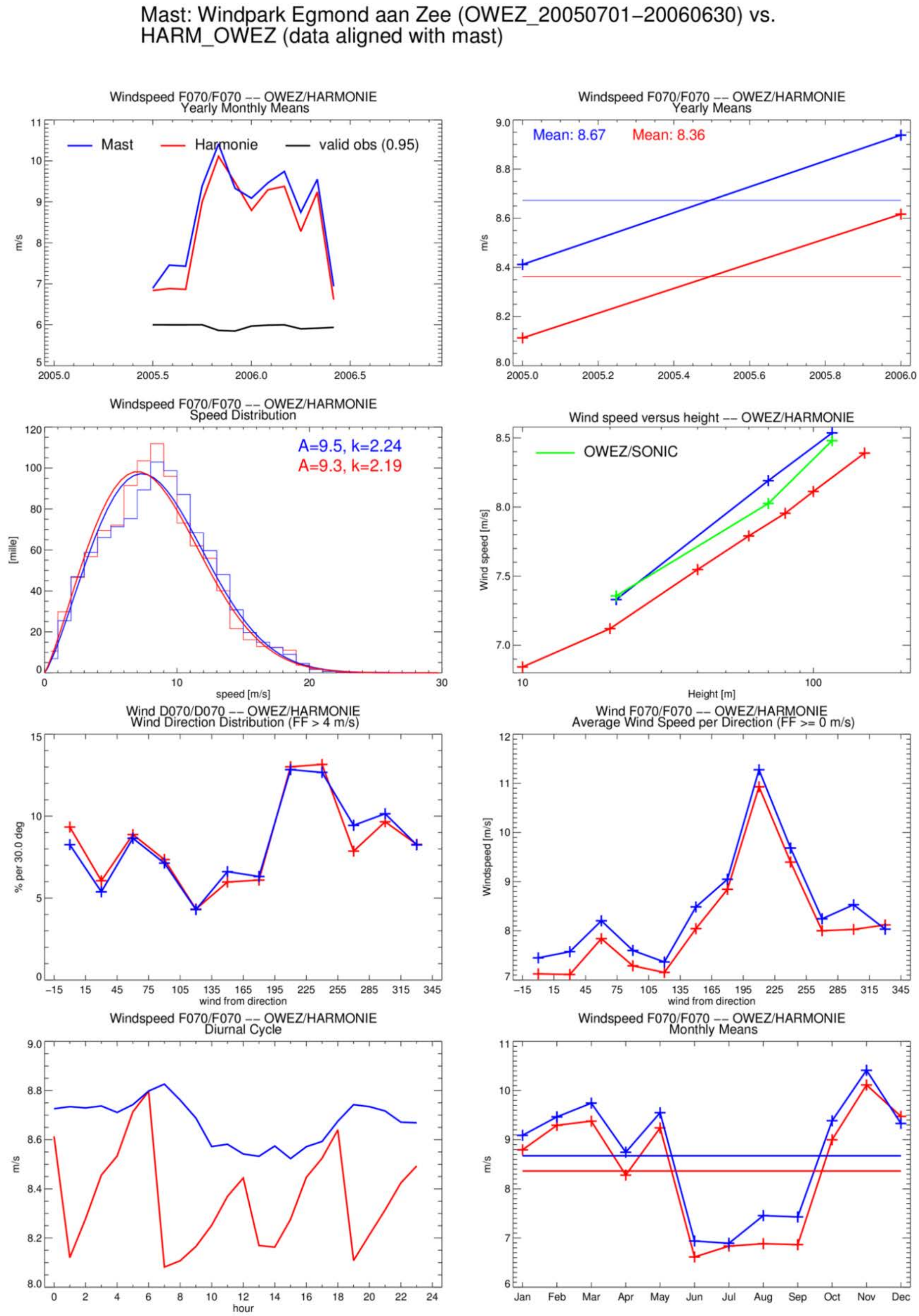


Figure 4.3 Validation at OWEZ in undisturbed period (20050701-20060630) using OWEZ measurements and HARMONIE with no shear correction. Anemometer measurements (blue) and sonic measurements (green) and HARMONIE (red)

Figure 4.4 shows the same as 4.3, but then for HARMONIE with shear correction. The bottom right graph shows the monthly average wind speed at 70 m and compared to the same graph in figure 4.3 the underestimate of the worst two months (August and September 2005) improves from 0.6 m/s to 0.5 m/s when the wind shear correction is applied. The bottom left graph shows that the measurements display a clear diurnal variation with a maximum wind speed at the end of the night and a minimum during the day. This is the opposite of what we see above land for measurements made below reversal height. This can be explained by the change is stability which occurs when the wind blows from land to sea. At night the air above land is cooled by radiative cooling of the ground which inhibits mixing of lower layers with the layers above where the wind speed is higher and so causes a minimum wind speed in the lower layers. The cool air reaches OWEZ without delay because it is close to the coast and it travels over warmer sea water which causes the air to mix vertically thus causing a maximum in the wind speed at lower levels. The opposite occurs during the day when the air warmed above land (layers well mixed) travels over the relatively cold sea water which inhibits vertical mixing and causes a minimum in the wind speed at lower levels.

Figure 4.5 shows the validation results for HARMONIE with shear correction at the OWEZ mast for the whole period where measurements were available, but only for wind directions between 135° and 315° (the southwesterly half of the compass) where wind park Egmond aan Zee does not disturb the measurements. The validation results are better than those for the shorter period before the wind park was built (figure 4.4). Does HARMONIE perform better for wind directions from the southwesterly half of the compass? The third row graph on the right of figure 4.4 shows that this is not the case because in the undisturbed year HARMONIE did not model the wind speed for wind directions from this half better than from the other. Compared to the sonic anemometer wind speed measurements and the HARMONIE wind speeds the cup anemometer wind speeds are lower in this longer period with wind direction restrictions. This is best seen by comparing the graphs of wind speed versus height on the right hand side of the second row in figures 4.4 and 4.5. It would seem that HARMONIE's improved performance in this period is due to a change in the cup anemometers' performance; possibly due to less than optimal maintenance after the important first year. In any case HARMONIE's performance during this longer period seems to be better rather than worse compared to the available measurements.

The effect of wind park Egmond aan Zee on the measurements are obvious from figure 4.6 where the validation results of HARMONIE with shear correction validation are shown for the whole period with OWEZ measurements. In the left panels all wind directions are included which means that the measurements are disturbed by the wind park from July 2006 onward which lowers the wind speed measurements so they become less than the HARMONIE wind speeds. In the panels on the right only undisturbed wind directions (between 135° and 315° degrees) are analysed and the measured wind speeds are more or less equal to the HARMONIE values. The second row shows time series of yearly average wind speed and on the left can clearly be seen that in the course of 2006 the measured wind speeds decreased compared to the HARMONIE values and never recovered. In the other rows the graphs show values averaged over the whole period and the measured values are lower than HARMONIE in the left panels due to the wind park, whereas in the right panels, without the wind park influence, the difference is much smaller.

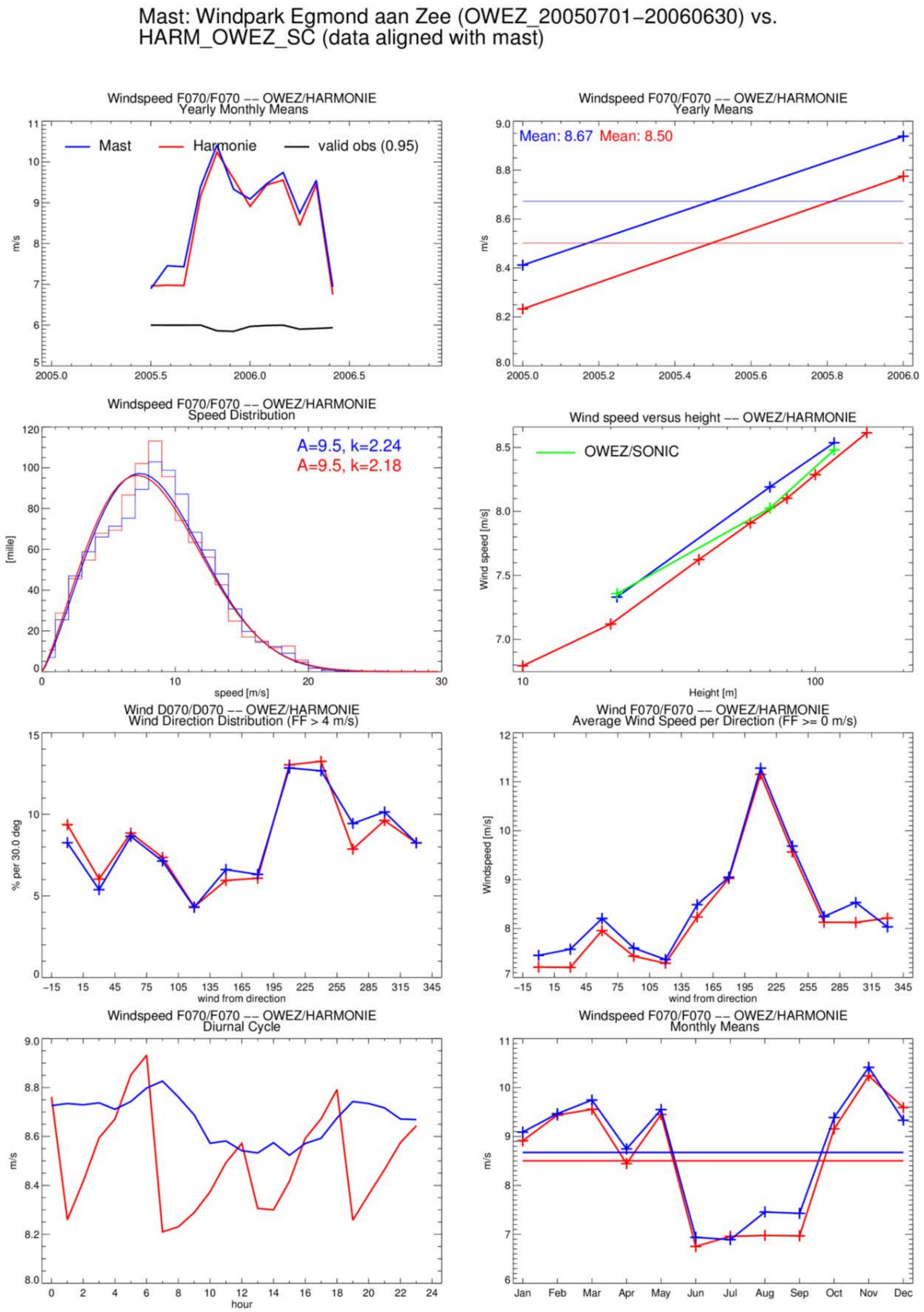


Figure 4.4 Validation at OWEZ in undisturbed period (20050701-20060630) using OWEZ measurements and HARMONIE with shear correction. Anemometer measurements (blue) and sonic measurements (green) and HARMONIE (red)

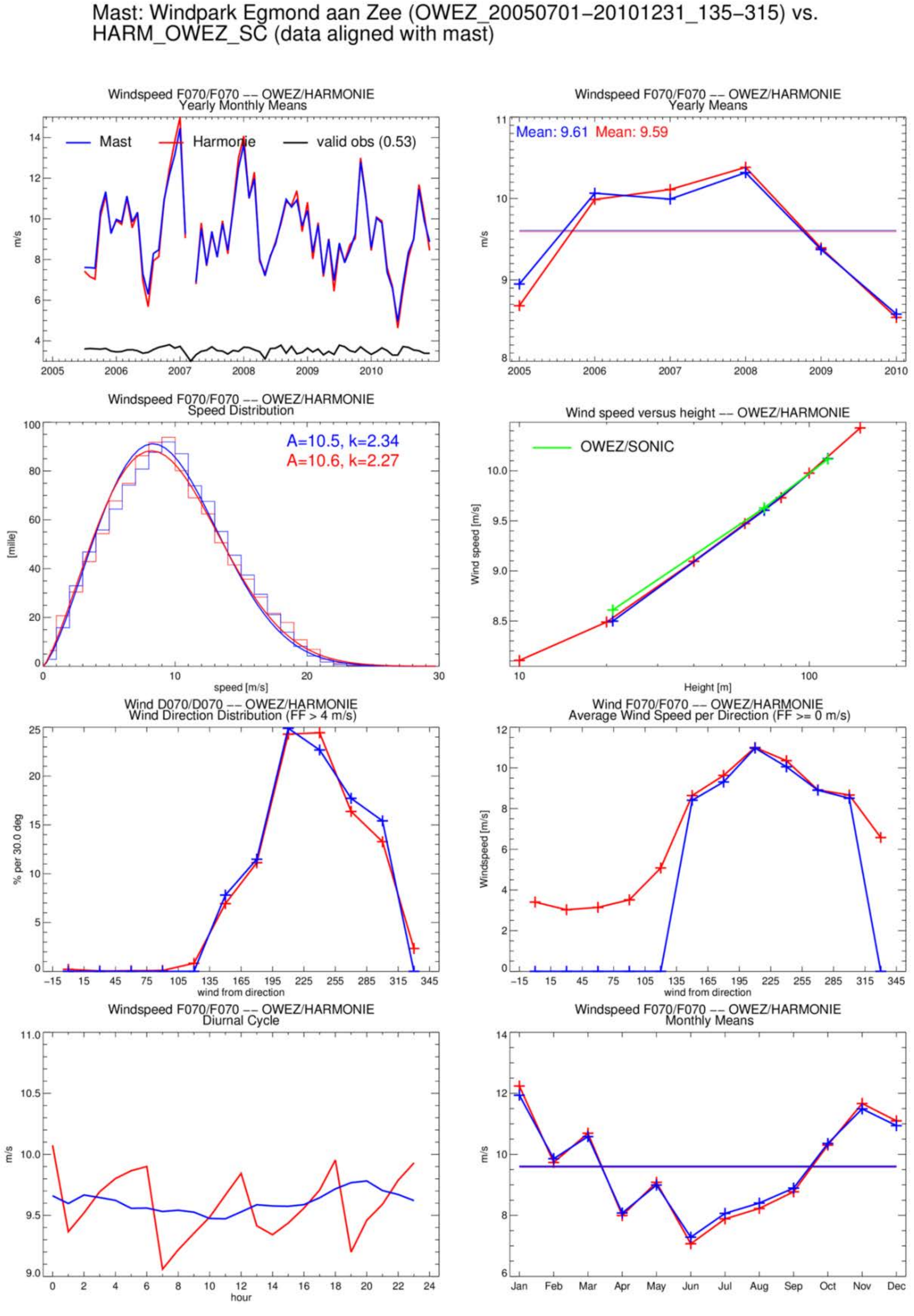


Figure 4.5 Validation at OWEZ for the whole period with OWEZ measurements (20050701-20101231) but only for wind directions between 135° and 315° (where wind farm Egmond aan Zee does not disturb the measurements) and HARMONIE with shear corrections. Anemometer measurements (blue) and sonic measurements (green) and HARMONIE (red)

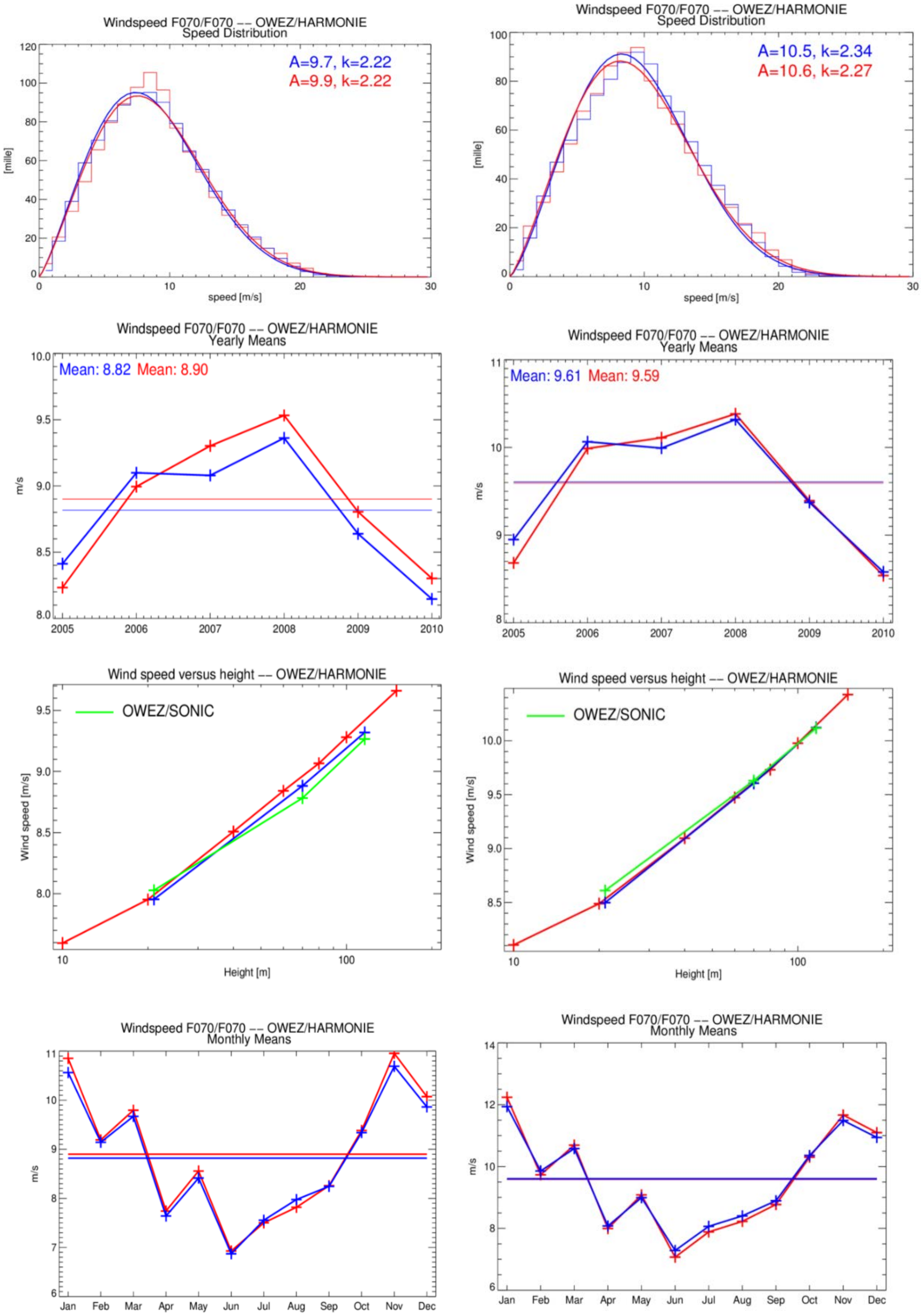


Figure 4.6 Validation at OWEZ for the whole period with OWEZ measurements (20050701-20101231) for all wind directions (left) and only for undisturbed wind directions between 135° and 315° (right) and HARMONIE with shear corrections. Anemometer measurements (blue) and sonic measurements (green) and HARMONIE (red)

ECN used OWEZ measurements for period 20050701-20091231 (only the undisturbed wind directions between 135°and 315° degrees) to validate the OWA_NEEZ wind atlas (Donkers, 2010) which is based on wind output from HARMONIE's predecessor op het KNMI, HIRLAM. In figure 4.7 the same period and wind direction restrictions were applied for the HARMONIE validation of the period average wind speed at various heights. The original OWA_NEEZ overestimated the average wind speed for this period by 0.21, 0.47 and 1.09 m/s (at respectively 116, 70 and 21 m height) while the graph on the left in figure 4.7 shows that HARMONIE without shear correction differs from the measurements by 0.2 m/s or less at all heights. An improved version of OWA_NEEZ still overestimated the wind speed but by less (respectively 0.14, 0.39 and 1.00 m/s) and HARMONIE with shear correction differs from the measurements by less than 0.1 m/s (see graph on the right of figure 4.7).

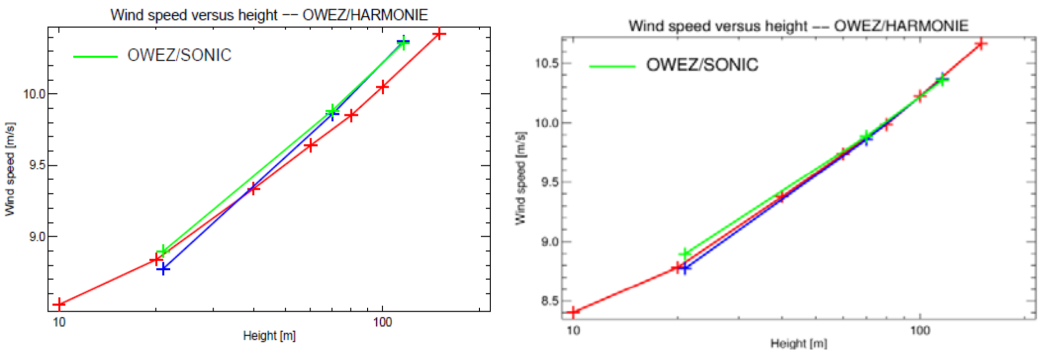


Figure 4.7 HARMONIE and measured average wind speeds at various heights for period 20050701-20091231 at OWEZ and only for undisturbed wind directions between 135° and 315° (conform ECN validation of OWA-NEEZ wind atlas). On the left HARMONIE without shear corrections and on the right with shear corrections. Anemometer measurements (blue) and sonic measurements (green) and HARMONIE (red)

CHAPTER 5 FINO1

5.1 Measurement site

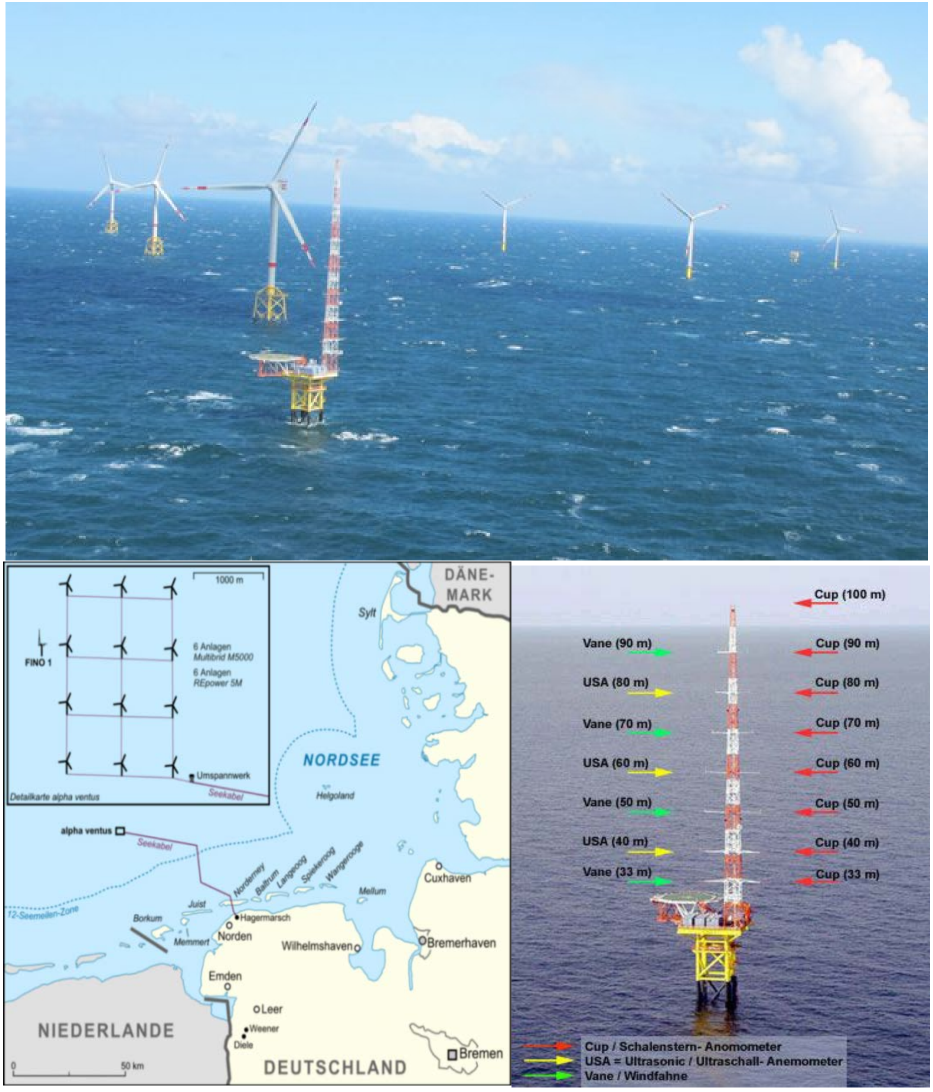


Figure 5.1 Location and configuration of FINO1 mast and wind park Alpha Ventus (source top panel and low left: www.fino1.de; source low right panel: http://imk-ifu.fzk.de/owid/)

Data from the FINO1 wind mast (45 km north of Borkum) are available since autumn 2003. The first wind turbines of wind farm Alpha Ventus were installed in November 2009 which means that measurements from wind directions between 15° to 165° (easterly winds) became disturbed. Construction of the wind farm was completed in 2010 and Alpha Ventus has been in use since then. All the anemometers (for measuring wind speed) are on booms on one side of the mast, all the wind vanes (for measuring wind direction) are on booms on the other side (figure 5.1). This implies that it is not possible to select an alternative sensor if the wind is disturbed by the mast (unlike at Cabauw, MMIJ and OWEZ where there are 3 booms per level).

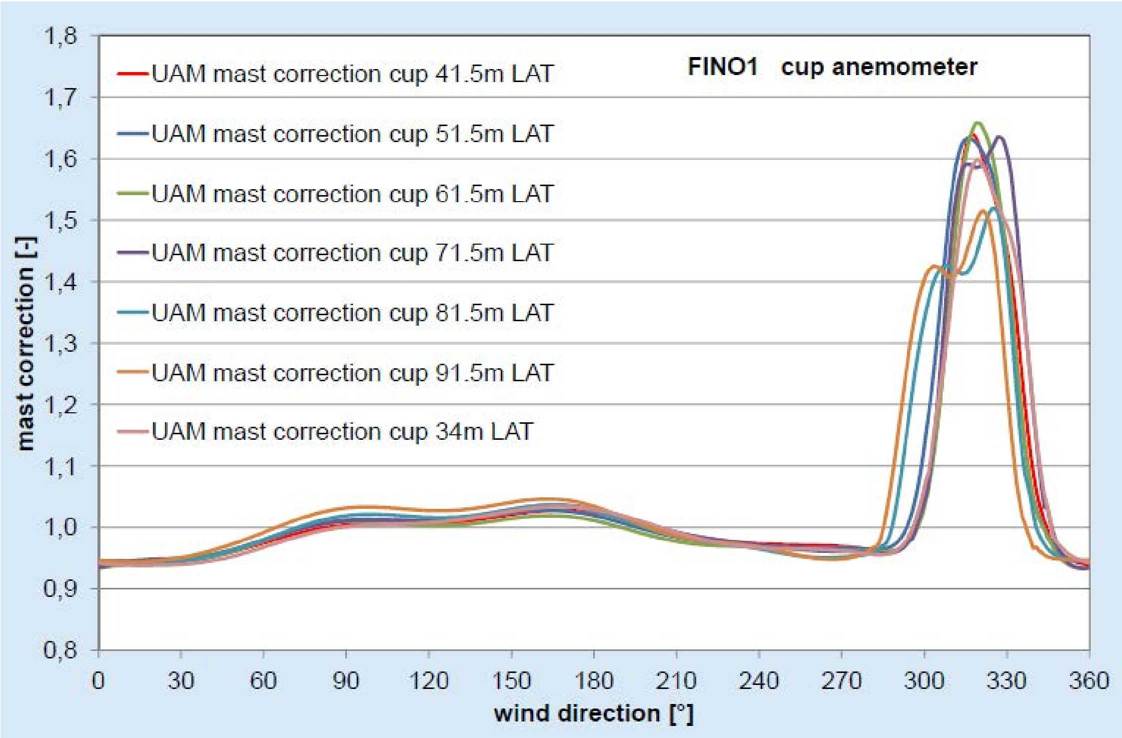
5.2 FINO1 measurements corrected for wind mast effects

Since 2007 DEWI has been developing a measurement correction scheme (only for wind speed, not for wind direction) for FINO1 in order to compensate for measurement disturbances caused by the wind mast (flow retardation upwind, wake effects downwind and lateral acceleration effects). This correction scheme is based on the assumption that vertical wind speed gradients become zero when the atmosphere is very unstable implying that an "uniform ambient flow correction" (UAM) can be applied. The UAM correction method is described in (Westerhellweg et al., 2011) and requires an undisturbed measurement of a top mounted anemometer (at FINO1 an extra anemometer was installed 1.5 m above the original top anemometer (which also gave disturbed wind speed measurements) from 15-11-2005 to 12-07-2006 and from 28-12-2008 to 29-12-2009). A LIDAR device (Leosphere Windcube WL07) was installed 10 m from the FINO1 wind mast between August 2009 until July 2010 in order to examine whether LIDAR measurements could be used for the correction of offshore mast wind measurements and in order to validate the UAM method. A comparison between UAM and LIDAR correction factors could only be made for heights above 71.5 m LAT (Lowest Astronomical Tide) because LIDAR measurements were not available below this height (the LIDAR device is mounted on the platform which is at 24.5 m LAT and does not give measurements below 40 m), but for those heights the difference between UAM and LIDAR correction factors were very small.

The UAM correction factors summarised in figure 5.2 were applied to the FINO1 measurements before using them to validate HARMONIE.

It should be noted that HARMONIE works with heights above Mean Sea Level (MSL)[4] whereas the anemometer heights are defined as heights above Lowest Astronomical Tide (LAT). The DEWI correction factors are also valid for heights above LAT. At the FINO1 site LAT is 1.27 m lower than MSL. This means that the HARMONIE wind speeds are for heights 1.27 m above the FINO1 anemometers. The average change in wind speed per meter height between 80 and 100 m is 0.008 m/s. The error incurred by taking the model heights above MSL to be the same as the anemometer heights above LAT is therefore insignificant compared to the average difference between model and measurement of about 0.2 m/s (see conclusion at the end of this section).

[4] HARMONIE calculates variables at sigma-levels instead of heights. The conversion to heights is done within the HARMONIE model and involves a very advanced technique which takes into account the state of the atmosphere at each output time.



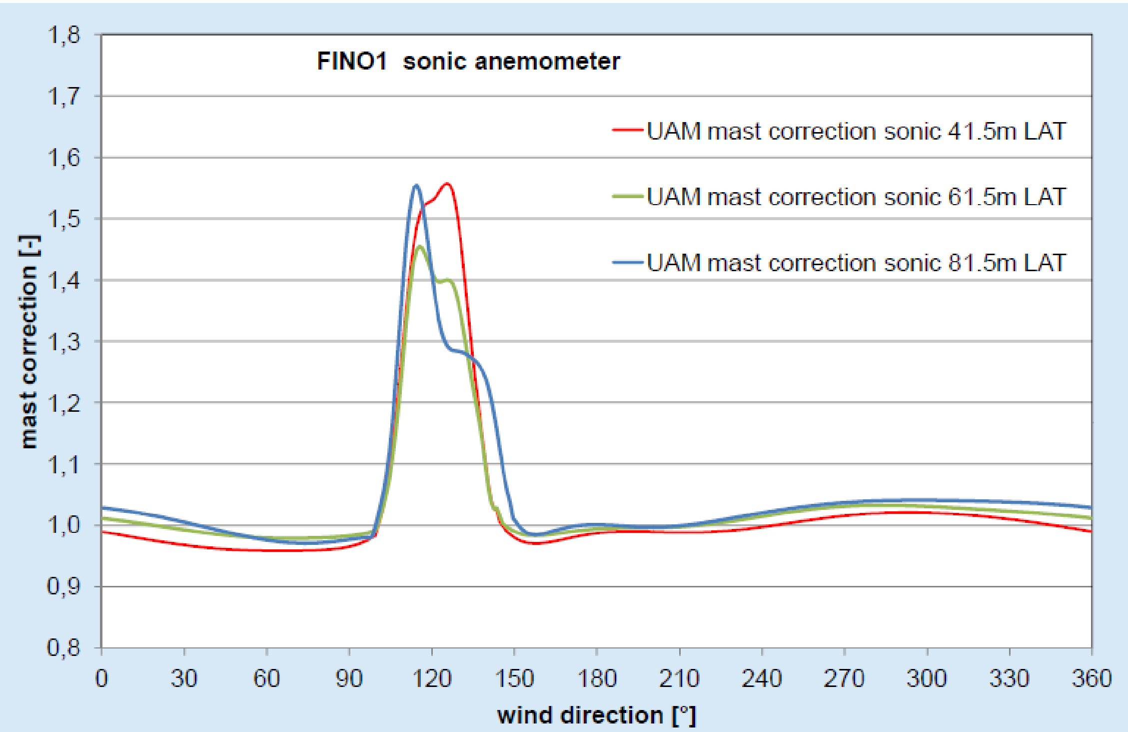


Figure 5.2 UAM mast correction for all boom mounted cup anemometers (upper) and sonic anemometers (lower) at FINO1 (source: Westerhellweg, 2012)

5.3 Comparing HARMONIE and FINO1 measurements

The general layout of the 8 graphs shown in figures 5.3, 5.7, 5.8 and 5.9 are described in chapter 2. For 7 of the 8 graphs the height of the anemometer measurements presented is 100 m and of the wind vane 90 m. The graph showing the frequency of occurrence of the wind direction (grouped in 30 degree bins; the left graph on the third row) displays a systematic error in all of the figures. The error is probably due to a misalignment of the 90 m wind vane since it is not present in the validation results of any of the other masts. If the measurements were increased by a few degrees the agreement with HARMONIE would be improved for all directions. Westerhellweg (2012) also discovered a misalignment of the 90 m anemometer when studying the power deficit caused by individual wind turbines of the Alpha Ventus wind park.

Figure 5.3 shows the HARMONIE validation with UAM corrected measurements at FINO 1 for the period where measurements were undisturbed (before construction of wind farm Alpha Ventus). The graph of the average wind speed for the whole period versus height (in the second row on the right) shows that HARMONIE differs from the measurements by less than 0.1 m/s for the lower heights. The difference is smaller than the difference between the two types of wind speed sensor used. HARMONIE underestimates the wind speed for the higher heights by at most 0.2 m/s.

The graph showing the diurnal variation of the wind speed at 100 m (lower left) shows a minimum in the measured speeds at about 10 UTC. This might be related to the minimum found at the end of the night above land at heights below the height of reversal (at Cabauw around 80 m) caused by radiative cooling at the ground which forms a stably stratified boundary layer. This prevents mixing of the lower layers with those with higher wind speeds lying above. Above the height of reversal, where the air is no longer stably stratified and able to mix with higher layers, a maximum in the wind speed is found at the end of the night. Southerly winds advect the cool near-surface air towards FINO1 over warmer sea water thus changing the stability to unstable which should result in a maximum wind speed below the height of reversal by mixing of the layers and a minimum wind speed above it. This might explain the minimum wind speed measurement shown in the graph, assuming the height of reversal at FINO1 is lower than 100 m. This assumption is supported by Wieringa (1988), who showed that the reversal near the coast is lower than that further inland. The saw-tooth pattern shown by the HARMONIE wind speeds is explained in chapter 2.

As can be seen from the upper left panel of figure 5.3 with monthly means at FINO1 at 100 m height (black line) from 20040101-20081231, measurement data were available for 93% of the time. Only at the end of 2007 a lot of data are missing, possibly due to cyclone Tilo: on 9th November 2007, a significant wave height of 10.5 metres was measured at FINO1 and the lower part of the platform was damaged (www.fino1.de).

Figure 5.4 shows that UAM-corrected FINO1 measurements and shear corrected HARMONIE data agree remarkably well. The top row graph on the right shows that the average over the whole undisturbed period of the HARMONIE 100 m wind speed now overestimates the measured average by only 0.09 m/s whereas the uncorrected HARMONIE wind speed (figure 5.3) underestimated the measurements by 0.12 m/s. Appendix A3 contains a graph of the cumulative frequency distribution of the wind speed at 100 m height for this same period and the capacity factor[5] of a Repower M5 wind turbine based on these wind speeds. The KNW atlas distribution produces a capacity factor (56.1%) 0.9% higher than the measured distribution (55.2%) and using the industry standard Weibull fit (Donkers, 2010) to the measurements gives a capacity factor which is 0.4% too low. This means that the error introduced by using the KNW wind speeds instead of measurements is of the same order of magnitude as that made by the wind energy sector standard method applied to the measurements.

However, at FINO1 the correction does not improve all of the validation results. Comparing the graph in the lower right corner of figures 5.3 and 5.4 (the seasonal variation of monthly average wind speeds) we see that the underestimation in the period February to July has been improved at the expense of the other half of the year when the wind speed is now, in figure 5.4, overestimated, whereas before it was nearly perfectly modelled. In the graph of wind speed versus height (second row on the right) we see that the measurements at the upper heights are now correctly modelled whereas they were overestimated before. However, those at the lower heights now validate less well. In the graph of average wind speed per wind direction sector bin (third row on the right) the winds from directions 225-285 are overestimated by 1-2 m/s whereas before the winds from 165-225 were underestimated by about 1.5 m/s.

Westerhellweg (2010) compared one year of FINO cup anemometer measurements (20090801-20100731) to LIDAR measurements. Table 5.1 shows the bias between the uncorrected anemometer measurements and the LIDAR measurements for the wind directions least affected by the mast (between 190° and 240°, which is approximately perpendicular to the booms; only for the top anemometer, that was added at 104.5 m from July until December 2009 and from June until August 2010, no wind direction restrictions were applied). The additional top anemometer (least disturbed by the mast) underestimates the LIDAR measurements by 0.08 m/s. Shear corrected HARMONIE overestimates the corrected 100 m anemometer wind speed for the undisturbed period (20040101-20081231) by 0.09 m/s (figure 5.4 top panel on the right) which is comparable with the difference between the two types of measurements.

Height msl [m]	R^2	Bias ($v_{lidar}-v_{cup}$) [m/s]
add top	0.998	0.08
101.5	0.999	-0.04
90	0.998	-0.15
80	0.998	-0.09
80-USA	0.997	0.06
70	0.998	-0.04

Table 5.1: Wind speed intercomparison between cup and LIDAR wind speed measurements at FINO1 (source: Westerhellweg, 2010)

[5] The capacity factor of a wind turbine is the average power produced divided by the rated power of the wind turbine, which is the maximum power output that is only achieved at hub height wind speeds above the rated wind speed (typically 15 m/s) and below the cut-off wind speed (typically 25 m/s).

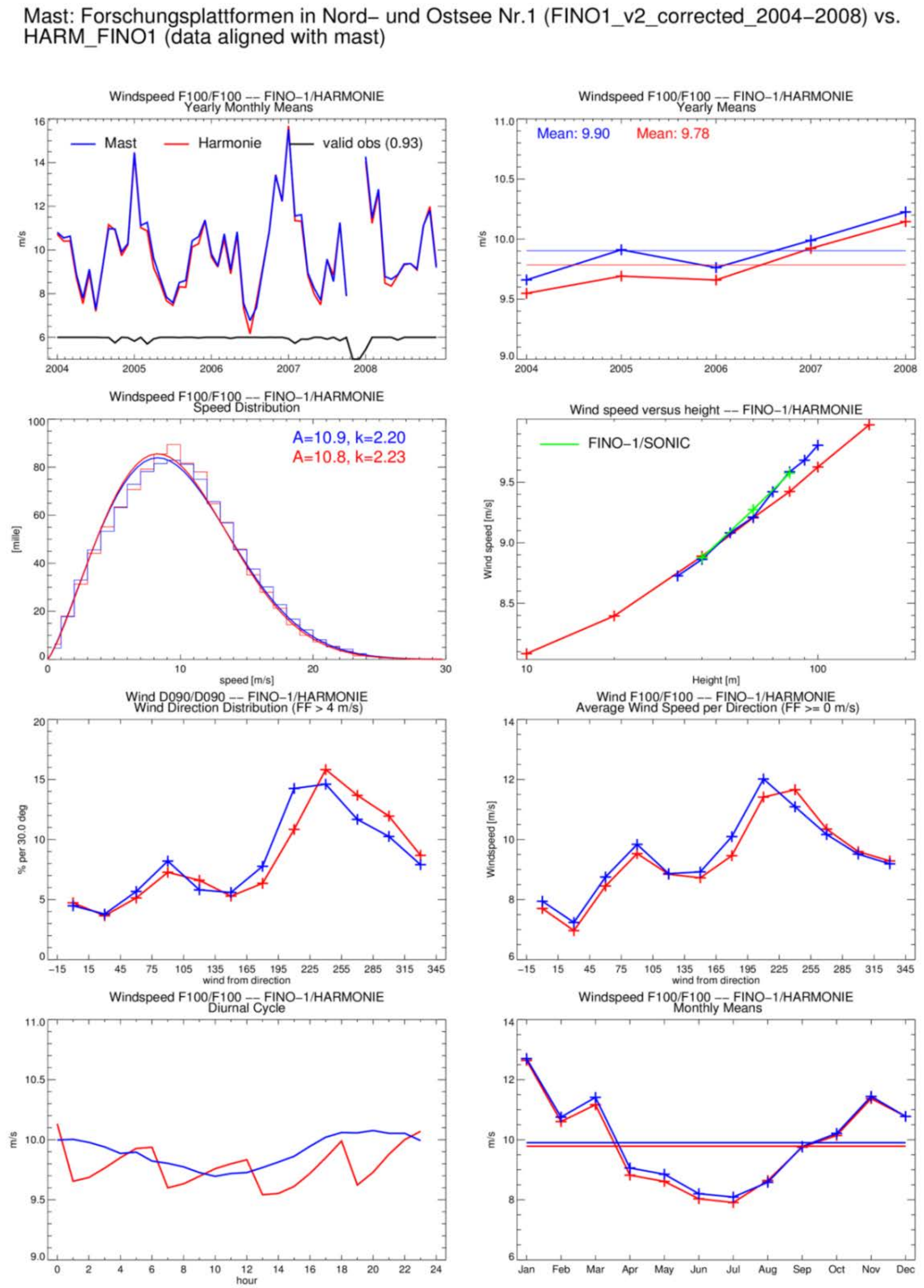


Figure 5.3 Validation of HARMONIE at FINO 1 in undisturbed period (20040101-20081231) using measurements with DEWI UAM-corrections (source: Westerhellweg, 2012). Anemometer measurements (blue) and sonic measurements (green) and HARMONIE (red)

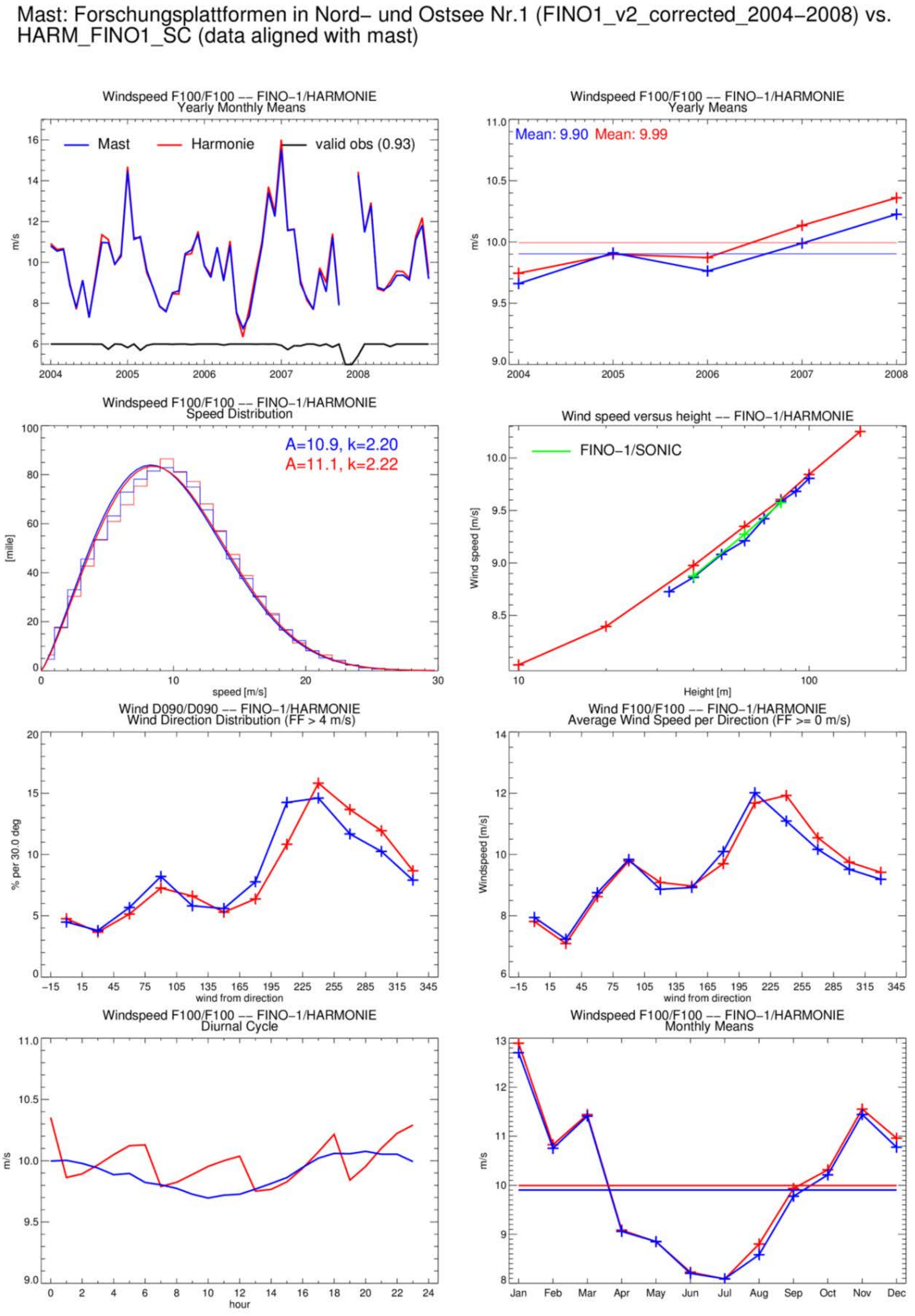


Figure 5.4 Validation at FINO 1 in undisturbed period (20040101-20081231) using measurements with DEWI UAM-corrections (source: Westerhellweg, 2012) and shear-corrected HARMONIE. Anemometer measurements (blue) and sonic measurements (green) and HARMONIE (red)

In figure 5.5 below the undisturbed measurements (2004-2008) are compared to measurements when wind farm Alpha Ventus was in operation (2010-2013).

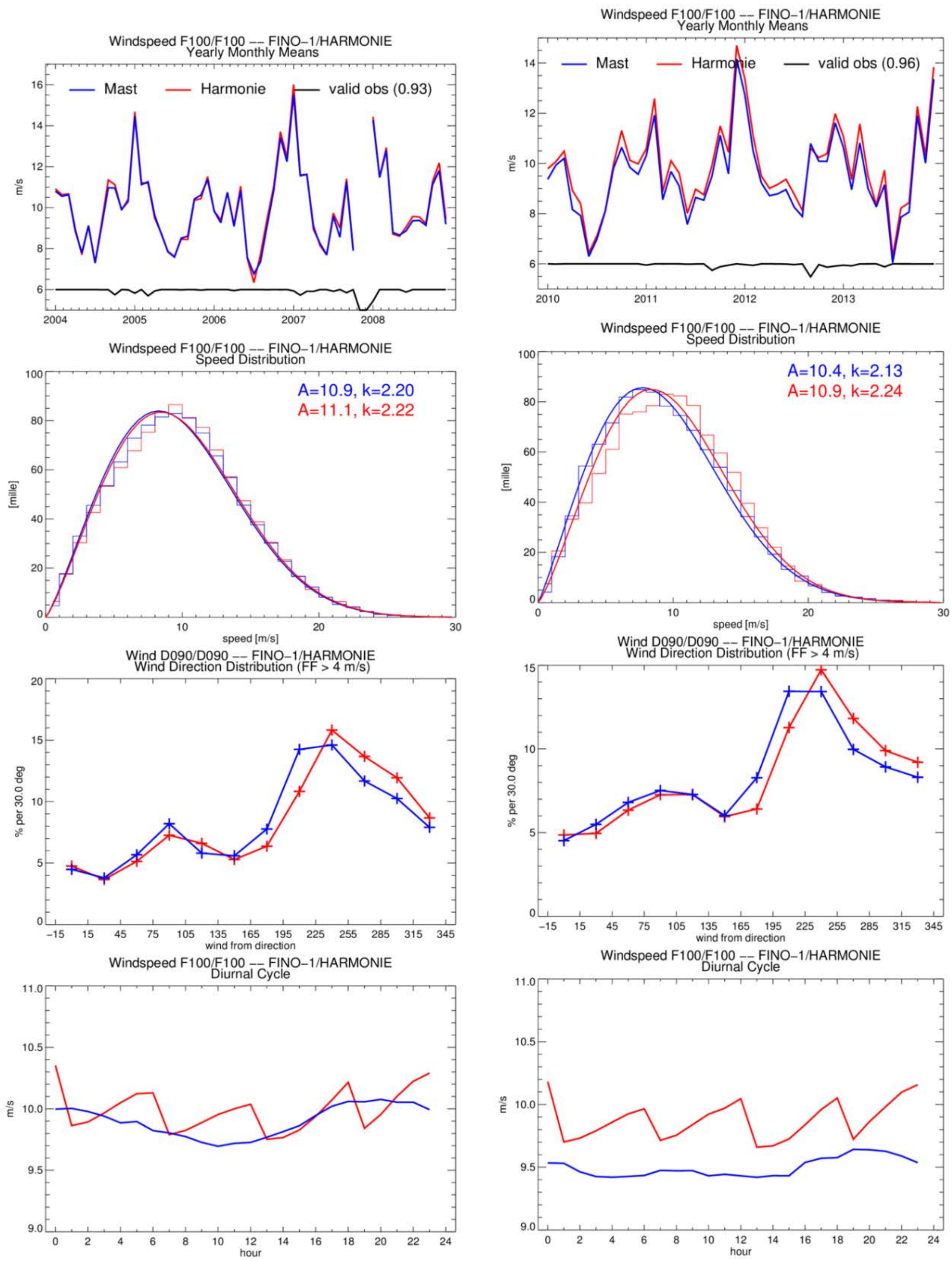


Figure 5.5a Validation at FINO 1 in undisturbed period 20040101-20081231 (left) and in the disturbed period 20100101-20131231 (right) using measurements with DEWI UAM-corrections (source: Westerhellweg, 2012) and shear-corrected HARMONIE (formula 4).
Anemometer measurements (blue) and sonic measurements (green) and HARMONIE (red)

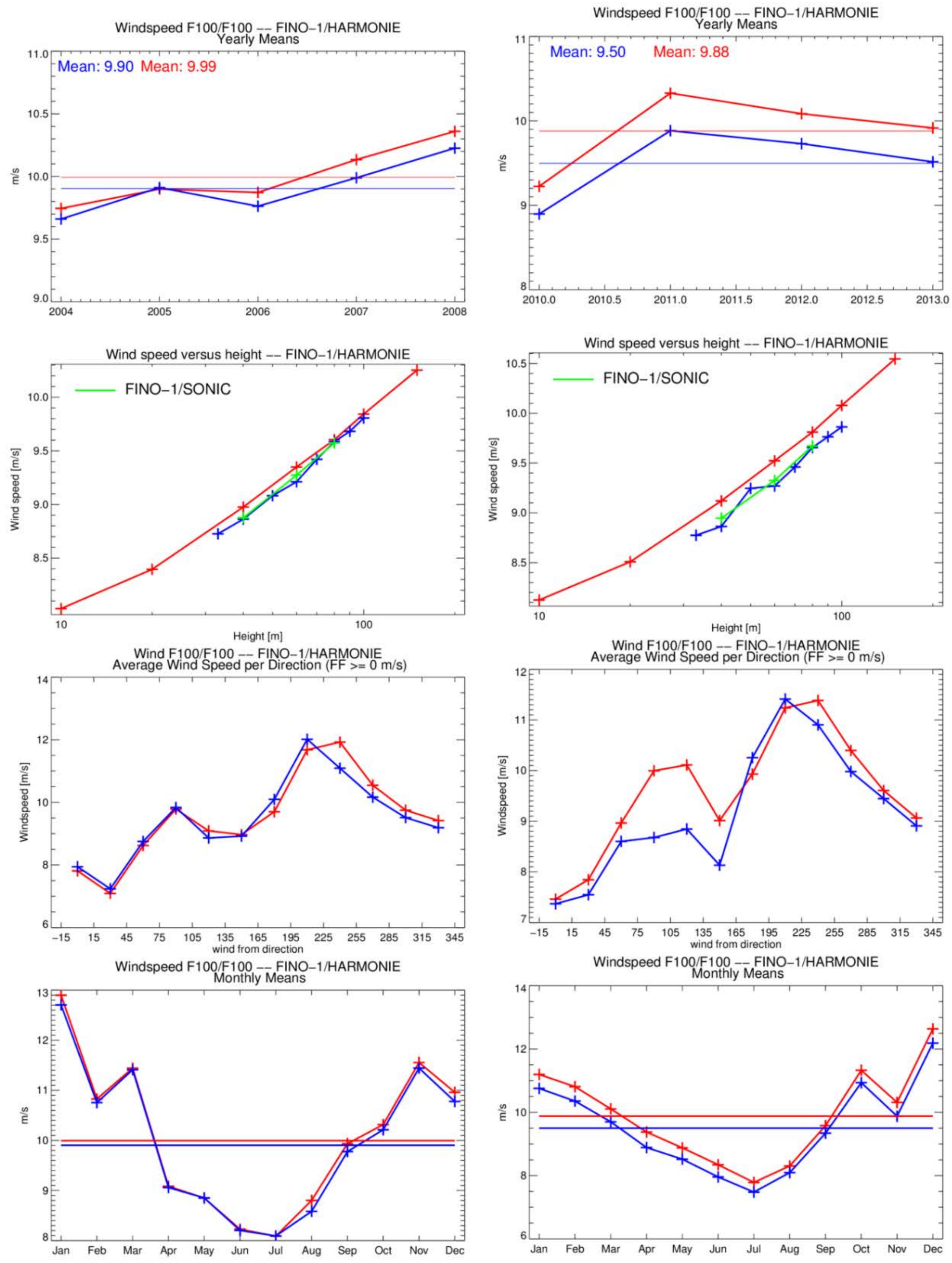


Figure 5.5b Validation at FINO1 in undisturbed period 20040101-20081231 (left) and in the disturbed period 20100101-20131231 (right) using measurements with DEWI UAM-corrections (source: Westerhellweg, 2012) and shear-corrected HARMONIE (formula 4). Anemometer measurements (blue) and sonic measurements (green) and HARMONIE (red)

Obviously there is better agreement between HARMONIE and the measurements in the undisturbed period (left). The biggest difference in the disturbed period is in the order of 1 m/s at 100 m height and this occurs for wind directions between 75° and 165° (where Alpha Ventus turbines are closest to FINO1). This can be seen in the third row of figure 5.5b, in the graph on the right. The wind turbines cause the measured wind speed to be lowered, while HARMONIE is oblivious to the presence of the wind park.

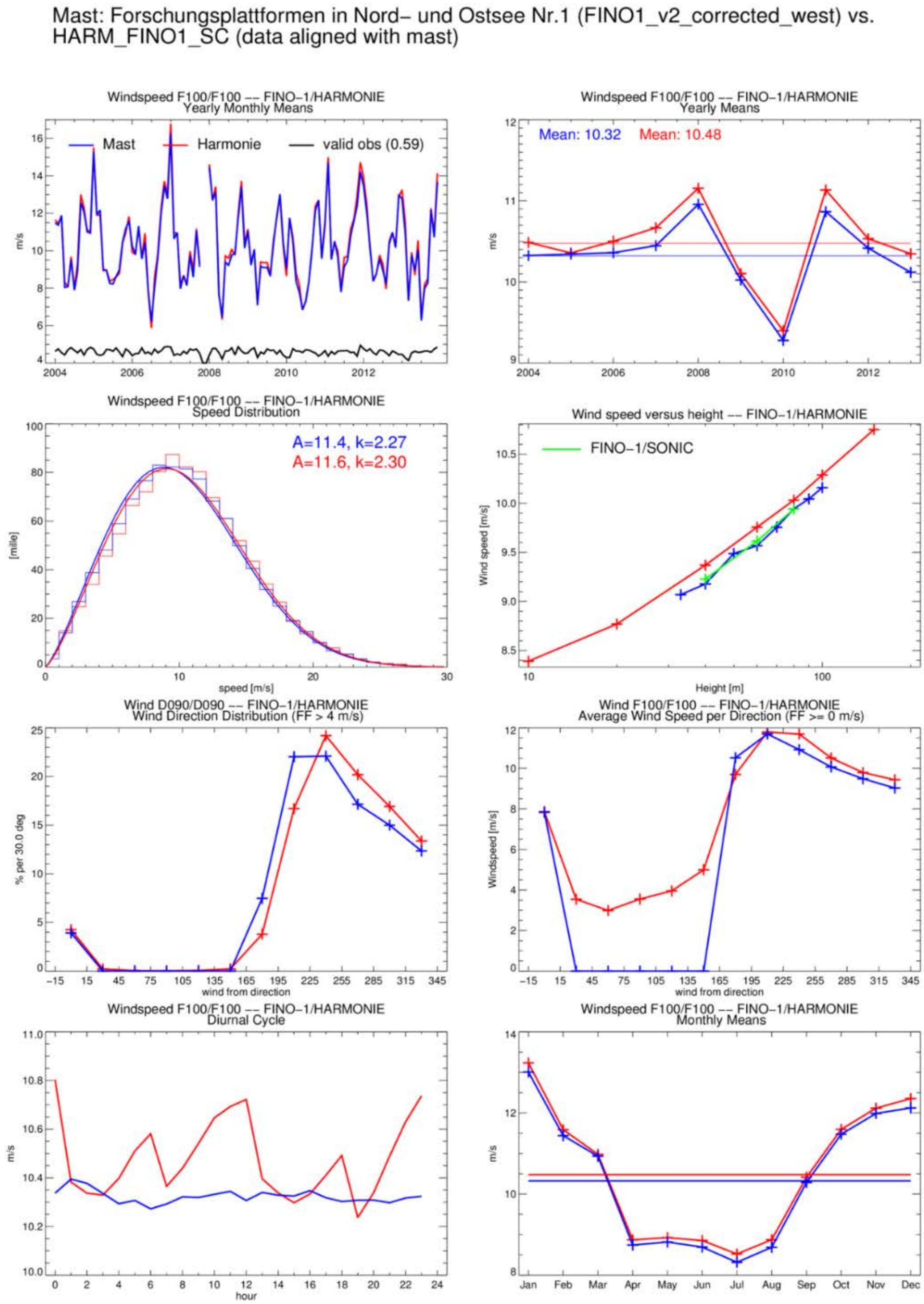


Figure 5.6 Validation at FINO1 for the whole period (20040101-20131231) but only for undisturbed westerly wind directions (between180 and 360°) using UAM-corrected FINO1 measurements and shear-corrected HARMONIE. Anemometer (blue), sonic (green) and HARMONIE (red)

If only winds from the westerly half of the compass are considered (between 180° and 360°), measurements are not disturbed by the wind farm[6] and a comparison can be made for the whole period for which measurements are available (2004-2013). Figure 5.6 shows the validation results for these undisturbed westerly winds. There is good agreement between measurements and HARMONIE with shear corrections. As the wind speed versus height graph (second row on the right) shows, the model overestimates the wind speed averaged over the whole period at all levels, but by no more than 0.2 m/s, which is within the uncertainty of the measurements. The year 2010 was a particularly calm year with a year average wind speed 10% lower than that of the whole 10 year period.

[6] The wind at FINO is undisturbed for wind directions between 165° and 15°.

CHAPTER 6 Cabauw

6.1 Measurement site

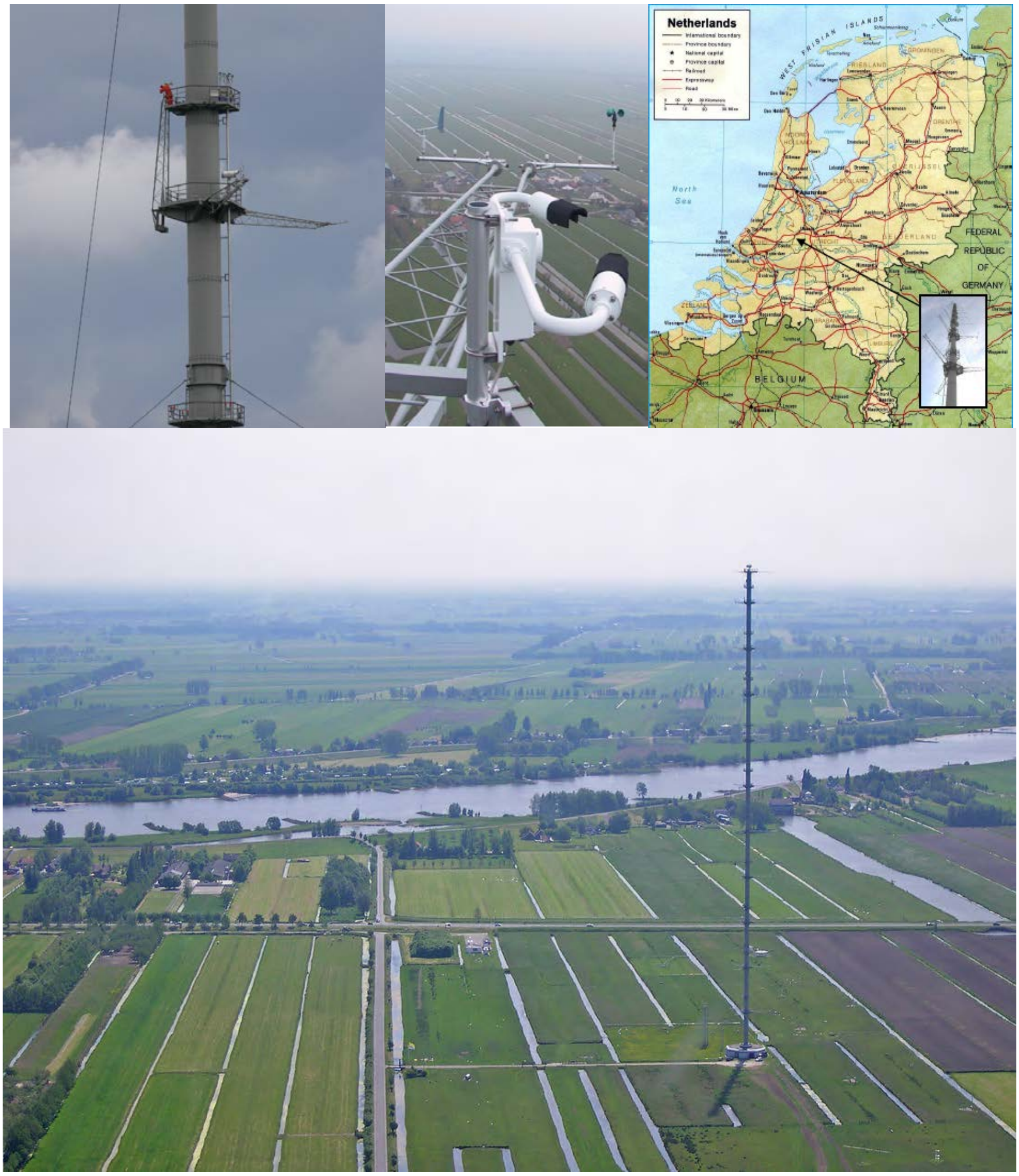


Figure 6.1 Location and configuration of the CABAUW mast (source http://www.cesar-observatory.nl/)

6.2 Comparing HARMONIE and Cabauw measurements

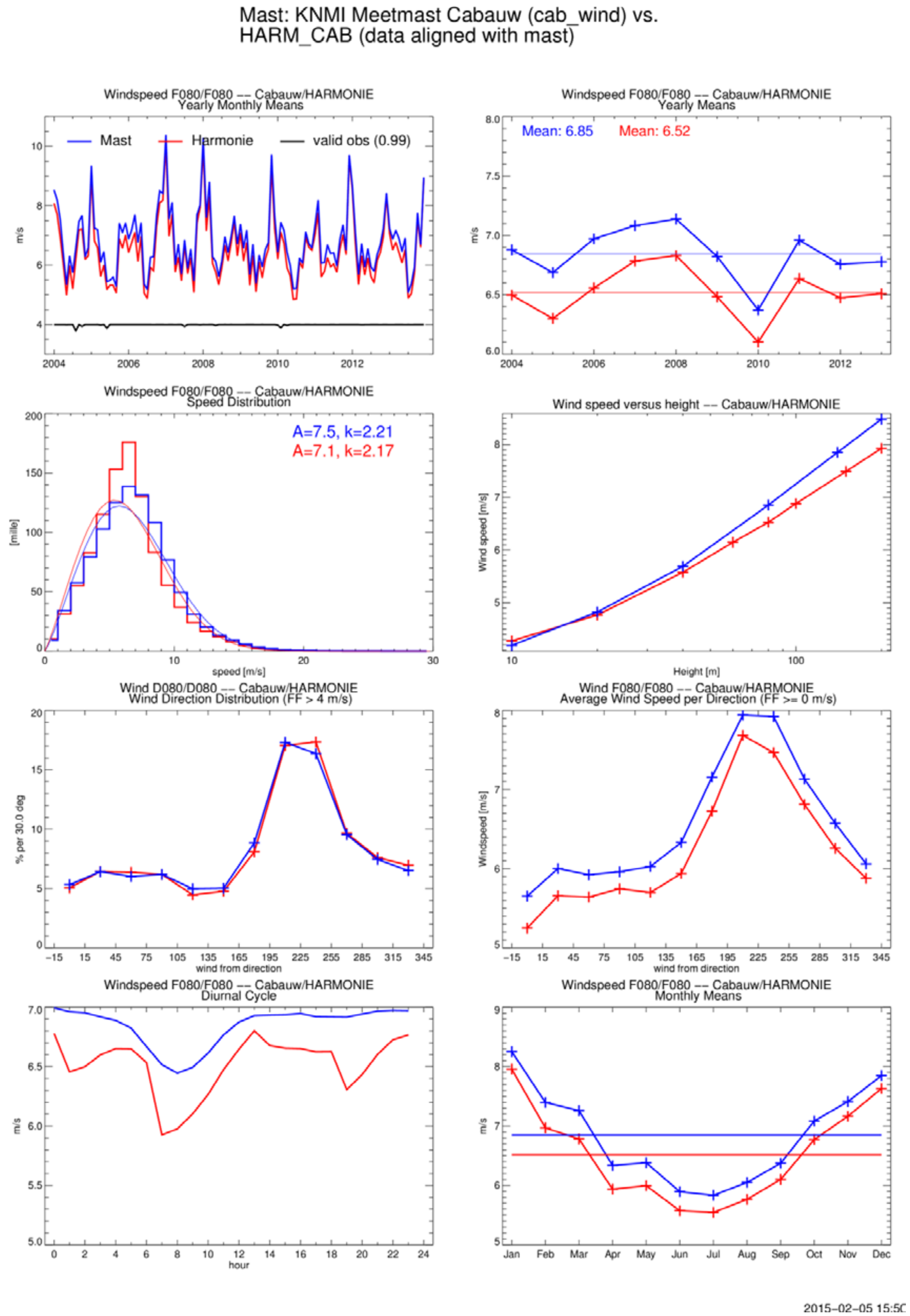


Figure 6.2 Validation at Cabauw for period 20040101-20131231 using anemometer measurements (blue) and HARMONIE without shear corrections (red).

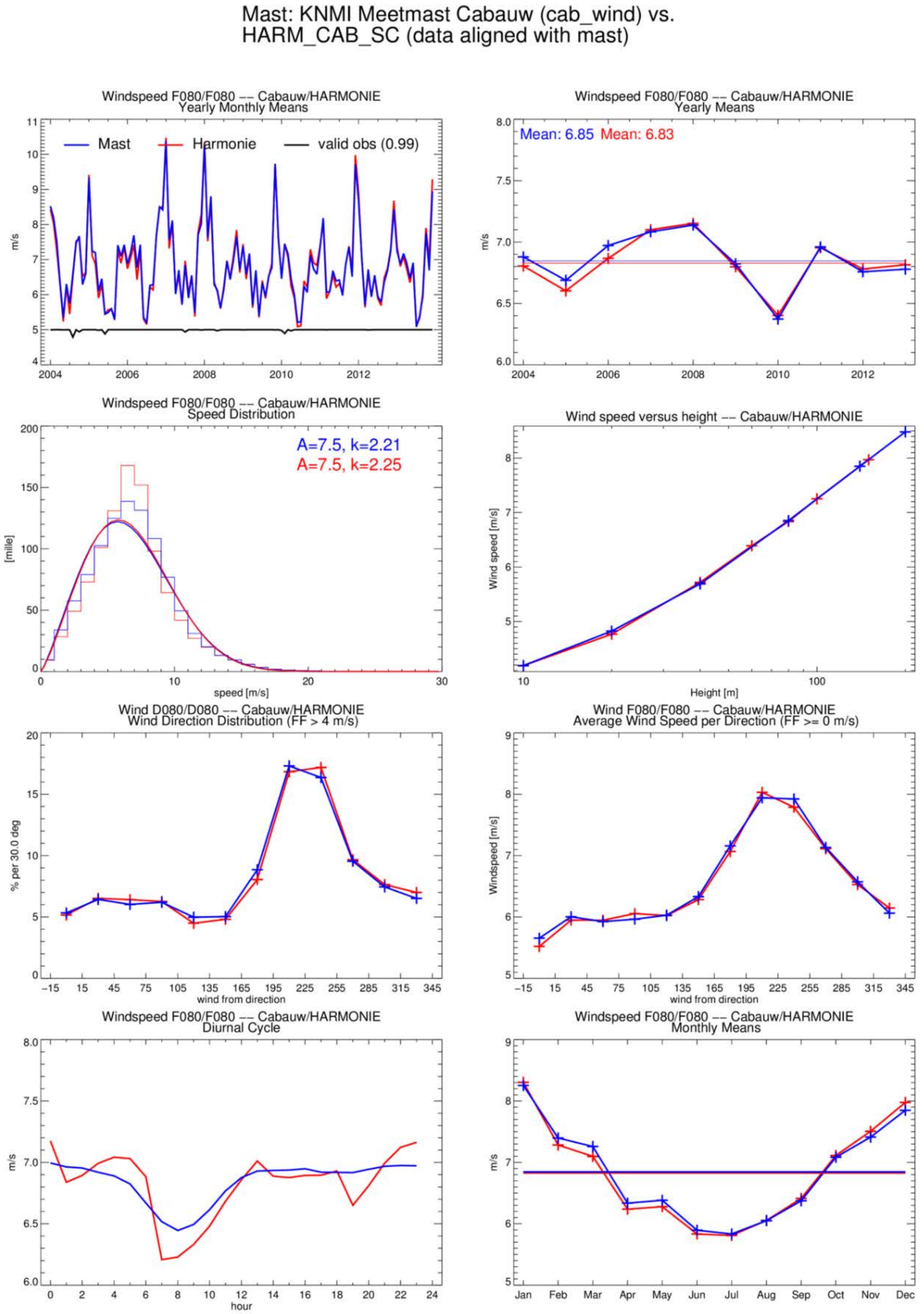


Figure 6.3 Validation at Cabauw for period 20040101-20131231 using anemometer measurements (blue) and HARMONIE with shear corrections (red).

The yearly means at Cabauw (top panel on the right in figure 6.3) validate better against the measurements from 2007 onward. There is no evidence from gustiness analyses that there have been significant roughness changes in 2007 in the vicinity of the mast affecting the wind at 10 m height (roughness changes up to 2 km from the mast have an effect on the wind measurements between 10 and 60 m height, but changes at around 600 m from the mast affect the measurements most). There may however be roughness changes further away from the mast that affect the wind at 80 m height (roughness changes up to 9 km from the mast have an effect on the wind measurements between 60 m and the top of the boundary layer, but changes at around 3 km from the mast affect the measurements most). The validation of HARMONIE against the yearly means measured at 80 m height at Cabauw was repeated exluding wind directions between 30°-60° and 30°-90° in order to find out whether the change in 2007 was a result of the construction of Wind Park Lopik (figure 6.4). The validation results remained however almost the same (not shown).

Figure 6.4. Distance from the Cabauw mast (in the bottom left corner of the figure) to Wind Park Lopik (in the top right corner of the figure) is 3.29 km. The Eneco wind park (3 turbines with hub height 120 m) was built about 3 km to the northeast of the Cabauw mast. The construction work started in 2007 and the park became operational on 26 june 2007 (google maps).

CHAPTER 7 Validating extremes

An extreme value analysis was performed on wind speeds at typical wind turbine hub height (80-100 m) from the KNW dataset, the Cabauw measurements and the ”undisturbed” measurements at MMIJ and FINO1. The ”undisturbed” period of the OWEZ mast is only one year, which is too short for reliable extreme value analysis. Storm peaks higher than the 90% percentile of the wind speed distribution and more than 24 hours apart were fitted with a GPD (General Parato Distribution). These fits (the straight lines without the “dots” in figures 7.1 to 7.3) are used to estimate the once in 10 year extremes. As can be seen from figure 7.1 to 7.3 the GPD-fit of the measurements (red line) and the GPD-fit of the KNW data (blue line) differ little and lie within each other’s fit accuracy as given by the vertical error bars (representing ± 1 standard deviation) at a return period of 10 years. This means that the once in 10 year KNW extreme wind speeds are as reliable as those based on measurements. At FINO1 the once in 10 year wind speed is the same whether one analyses the measurements or the model values and at MMIJ the difference is less than 3%.

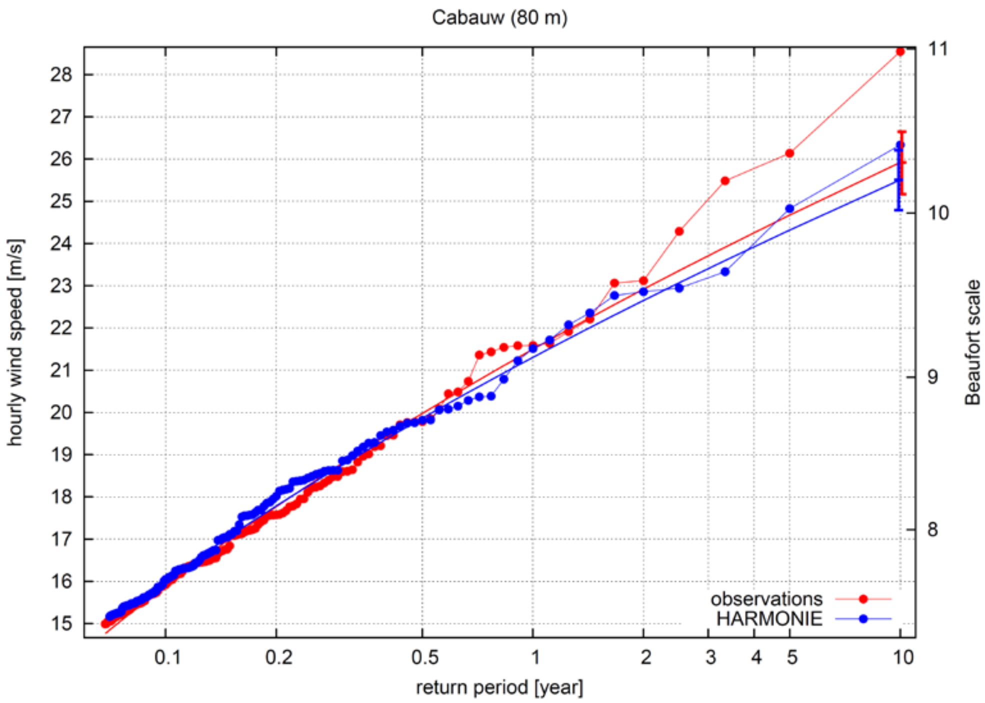


Figure 7.1. Extreme value analysis of the 80 m wind speeds measured (“observations”) at the Cabauw mast and the corresponding KNW values (“HARMONIE”) with GPD fits of the peaks above the 90% percentile threshold with at least 24 hours between the peaks

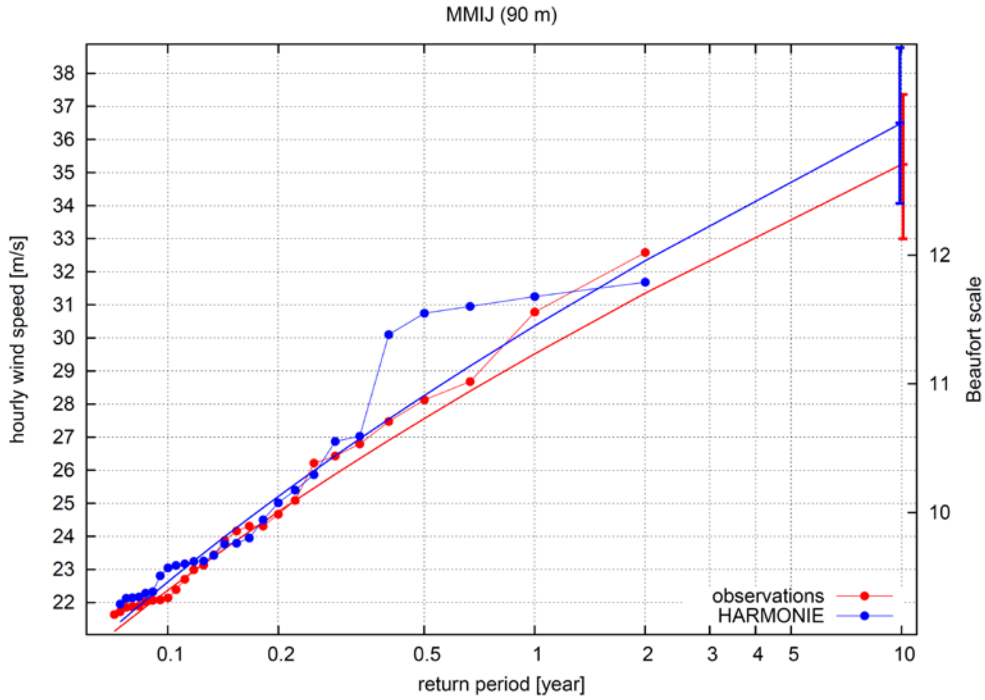


Figure 7.2. Extreme value analysis of the 90 m wind speeds measured ("observations") at the MMIJ mast and the corresponding KNW values ("HARMONIE") with GPD fits of the peaks above the 90% percentile threshold with at least 24 hours between the peaks

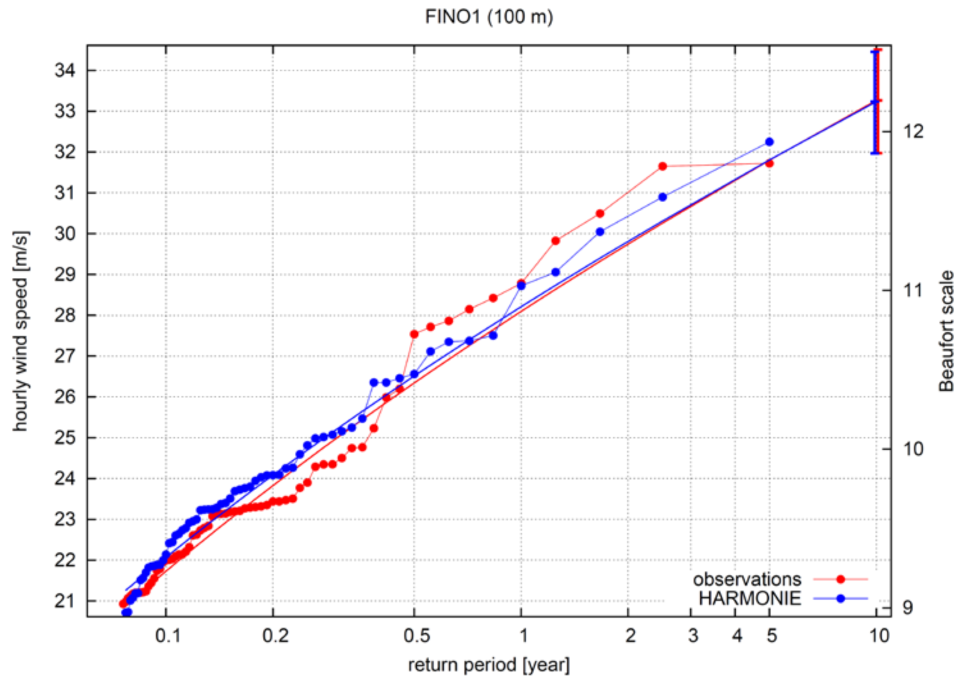


Figure 7.3. Extreme value analysis of the 100 m wind speeds measured ("observations") at the FINO1 mast and the corresponding KNW values ("HARMONIE") with GPD fits of the peaks above the 90% percentile threshold with at least 24 hours between the peaks

CHAPTER 8 Conclusions

8.1 General conclusions

- The 35 years covered by the KNW dataset ensures that the wind climatology is representative of even the natural variations on the scale of decades: the time scale relevant for wind energy installations. Shorter periods sample these decadal natural variations insufficiently to guarantee that they are well described by the resulting wind climatology.
- The wind shear correction used in the KNW atlas ensures good agreement with measurements from tall masts, not only at sea (this report) but also on land (Geertsema, 2014) when applied to the raw HARMONIE wind speeds. The same correction factor, derived using only wind speeds from KNMI's own tall mast at Cabauw, is applied uniformly throughout the HARMONIE model domain and brings the raw HARMONIE wind speeds into line with those of all the tall mast measurements irrespective of location or height.
- The difference between the measured wind speeds and the corresponding KNW values (averaged over periods when the mast measurements were undisturbed by nearby wind farms) is less than 0.2 m/s for all masts and all measurement heights.
- For these periods the wind turbine capacity factor[7] (expressed in percent) was calculated using KNW and measured wind speeds and the difference was less than 2% for all three masts. At OWEZ and MMIJ the KNW error was exactly the same size as the error incurred by the standard practice of fitting a Weibull formula to the measured wind speed frequency distribution. At FINO1 the errors were smaller: the error made by using KNW instead of measured wind speeds was 0.9%, which is of the same order of magnitude as the error made by applying a Weibull fit to the measurements before calculating the capacity factor (0.4%).
- The accuracy of the best cup anemometers is about 1% (class 0.5 according to IEC 61400-12-1), but most cup anemometers have an accuracy of about 2% (Pedersen, 2006). For wind speeds of 10 m/s (the approximate average for the southern North Sea) this implies an accuracy of 0.2 m/s which is of the same order as the shear corrected HARMONIE wind speed bias at all masts.
- If wind speeds from different sensors (cup, sonic and LIDAR) on the same mast and at the same height are compared, long average differences up to 0.2 m/s are found. This implies that the long term average wind speeds of the KNW atlas are in practice just as accurate as the measurements.

[7] The capacity factor of a wind turbine is the average power produced divided by the rated power of the wind turbine, which is the maximum power output that is only achieved at hub height wind speeds above the rated wind speed (typically 15 m/s) and below the cut-off wind speed (typically 25 m/s).

- The KNW atlas shows that the mean wind speed at different locations in an area designated for offshore wind energy can vary by a few 10ths of a m/s. Variations of this magnitude would be hugely expensive to chart using only in situ measurements and they do significantly influence the cost of the wind energy that could be produced in the designated area.
- Extreme value analysis of the KNW-atlas wind speeds around wind turbine hub height produces estimates of the once in 10 year wind speed that are as reliable as those based on measurements.
- The KNW atlas can be used for first-order estimates of the wake effect of whole wind farms by providing the undisturbed wind for comparison to be measurements in the wake.
- The KNW atlas can be used to identify systematic errors in the measurements. For example: a comparison of the measured wind direction frequency distribution at FINO1 and the KNW values identified a misalignment of the 90 m wind vane. None of the other measured distributions at different heights or from other masts showed systematic differences compared to the KNW distributions.

8.2 Detailed conclusions

1. Monthly and yearly mean wind speed time series: for all the masts used in the validation the HARMONIE wind speeds follow the measured values closely and are generally slightly lower by about 0.2 m/s and by less when the wind shear correction is applied. At Cabauw the validation results become better after 2006.
2. Wind speed frequency distribution and corresponding Weibull fit: for all the masts the KNW distributions and fits have the same form. Wind turbine capacity factors calculated using the KNW distributions are correct to an accuracy better than 2%.
3. Wind speed versus height: table 8.1 clearly shows that the KNW values are extremely good.

MMIJ 20120101-20131231 [m/s]			**OWEZ 20050701-20060630 cup/sonic [m/s]**			**OWEZ 20050701-20101231 (135°-315° degrees) cup/sonic [m/s]**		
height	**HARMONIE**	**+ SC**	**height**	**HARMONIE**	**+ SC**	**height**	**HARMONIE**	**+ SC**
27	< 0.1	< 0.1	**21**	< 0.2 / < 0.2	< 0.2 / < 0.2	**21**	< 0.1 / < 0.1	< 0.1 / < 0.1
58	< 0.2	< 0.1	**70**	< 0.3 / < 0.2	< 0.2 / < 0.1	**70**	< 0.1 / < 0.2	< 0.1 / < 0.1
87	< 0.3	< 0.1	**116**	< 0.3 / < 0.2	< 0.1 / < 0.1	**116**	< 0.1 / < 0.1	< 0.1 / < 0.1
92	< 0.3	< 0.1						
>90 (lidar)	< 0.3	< 0.1						

FINO1 20040101-20081231 cup/sonic [m/s]			FINO1 20040101-20131231 (180°-360° degrees) cup/sonic [m/s]			Cabauw [m/s]		
height	**HARMONIE**	**+ SC**	**height**	**HARMONIE**	**+ SC**	**height**	**HARMONIE**	**+ SC**
33	< 0.1	< 0.1	**33**	< 0.1	< 0.2	**10**	-0.1	< 0.1
41.5	< 0.1 / < 0.1	< 0.2 / < 0.2	**41.5**	< 0.2/ < 0.1	< 0.2/ < 0.2	**20**	0	< 0.1
51.5	< 0.1	< 0.1	**51.5**	< 0.1	< 0.1	**40**	0.1	< 0.1
61.5	< 0.1 / < 0.1	< 0.2/ < 0.1	**61.5**	< 0.1/ < 0.1	< 0.2/ < 0.2	**80**	0.3	< 0.1
71.5	< 0.1	< 0.1	**71.5**	< 0.1	< 0.2	**140**	0.5	< 0.1
81.5	< 0.2/ < 0.2	< 0.1 / < 0.1	**81.5**	< 0.2/ < 0.2	< 0.1/ < 0.1			
91.5	< 0.2	< 0.1	**91.5**	< 0.1	< 0.1			
100	< 0.2	< 0.1	**100**	< 0.2	< 0.1			

Table 8.1: Undisturbed period average wind speed difference (measured minus HARMONIE) in m/s at various measurement heights in meters ("+SC" is the KNW value which is HARMONIE with shear correction).

4. Frequency of occurrence of wind direction per 30° degree wind direction bin (hourly wind speed > 4 m/s): for all masts the modelled occurrences follow the measured ones well except those of the misaligned 90 m wind vane at FINO1.
5. Average wind speed per 30° degree wind direction bin: for all masts the modelled wind speeds underestimate the measurements by 0.3 m/s or less for most wind direction sectors and by less when the wind shear correction is applied.
6. Diurnal variation of the hourly average wind speeds: only the measurements from MMIJ show no diurnal variation because it is further from land than the other masts. However, as explained in chapter 2, the modelled wind speed of all the masts does show an artefact of the model: a strange saw-tooth pattern. For OWEZ the wind speed measurements at 70 m of the undisturbed first year of measurements display a diurnal variation with the same timing as that seen above land but with the maximum wind speed when above land (and below the reversal height) there is a minimum and with the minimum when above land there is a maximum. This can be explained by the change in atmospheric stability when air near the surface moves from land to sea. At FINO1 the diurnal pattern of the measured wind speed at 100 m has a minimum at about 10 UTC. This might be related to the minimum found at the end of the night above land at heights below the height of reversal (at Cabauw between 80 and 120 m) caused by radiative cooling at the ground which forms a stably stratified boundary layer. This prevents mixing of the lower layers with those with higher wind speeds lying above. Above the height of reversal, where the air is no longer stably stratified and able to mix with higher layers, a maximum in the wind speed is found at the end of the night. Southerly winds advect the cool near-surface air towards FINO1 over warmer sea water thus changing the stability to unstable which should result in a maximum wind speed below the height of reversal by mixing of the layers and a minimum wind speed above it. This might explain the minimum wind speed measurement shown in the graph, assuming the height of

reversal at FINO1 is lower than 100 m. This assumption is supported by Wieringa (1988), who showed that the reversal height near the coast is lower than that further inland.

7. Seasonal variation of the monthly average wind speeds: the modelled averages per month of the year follow the measured values closely and generally underestimate them by at most 0.3 m/s and by less when the wind shear correction is applied.

8.3 Comparison with OWA-NEEZ validation

Donkers (2010) used tall mast measurements to validate the OWA-NEEZ Wind Atlas (Offshore Wind Atlas of the Netherlands' Exclusive Economic Zone based on KNMI's HIRLAM model, the predecessor of HARMONIE). In this section the results of his validation are compared to the validation of the HARMONIE (initialised with ERA-interim) data.

1. OWEZ: Donkers (2010) validated the HIRLAM winds in the OWA-NEEZ Wind Atlas against OWEZ measurements for 20050701-20091231 and undisturbed winds (directions between 135° and 315°). He found that the OWA-NEEZ Wind Atlas overestimated the wind by 0.21, 0.47 and 1.09 m/s at respectively 116, 70 and 21 m height. Using a better method for estimating the local sea roughness, the HIRLAM wind speeds were recalculated and the verification for the OWEZ site improved to 0.14, 0.39 and 1.00 m/s respectively. The HARMONIE wind speed averaged over the same period and with the same wind direction restrictions differs from the measured value by 0.2 m/s or less for all heights (less than 0.1 m/s if shear correction is applied) and therefore validates better against the OWEZ measurements.
2. FINO: Donkers (2010) also used FINO measurements to validate the OWA-NEEZ wind atlas He applied the same UAM-corrections to the FINO measurements as described in section 5.2 and selected a comparable period (20040101-20091231), assuming that the effect of the wind farm on the measurements would be minimal as construction of Alpha Ventus only started in November 2009 (in this report 2009 was excluded). Donkers found that at a height of 100 m the average difference between HIRLAM and the corrected FINO measurements was -0.49 m/s which is much greater than the score achieved by its successor, HARMONIE.
3. Cabauw: Donkers (2010) validated the OWA-NEEZ Wind Atlas against Cabauw measurements (20000608-20091231) and found that it overestimated the wind measurements by 0.59, 0.51, 0.28, 0.11 and 0.41 m/s (for respectively 10, 20, 40, 80 and 140 m heights). HARMONIE without shear correction underestimates the measured wind speed by -0.1, 0.0, 0.1, 0.3 and 0.5 m/s respectively (based on a comparison for 20040101-20131231) and HARMONIE with shear correction differs by less than 0.1 m/s at all heights. So HARMONIE validates better against Cabauw measurements at heights below 80 m and HARMONIE with shear correction validates better at all heights, which is hardly surprising because the wind shear correction factor was chosen to match the HARMONIE wind speeds to those measured at Cabauw.

9 Recommendations for further research

- Run tests to see if using longer forecast lead times than the current 1-6 hours produces HARMONIE (initialized with ERA-Interim) wind speeds that better describe the diurnal variation and small scale features of the wind field, and have equivalent measurement averaging times shorter than the current 40-60 minutes.
- Run tests with HARMONIE running continuously (without the current cold start initializations every 6 hours) and only being fed information from ERA-Interim at the edges of the HARMONIE domain with the same goal as the previous recommendation.
- Run tests with HARMONIE with a horizontal resolution of 1 km instead of the current 2.5 km
- Run tests with the latest version of HARMONIE (new improved versions are released every few years). There are, for example, plans to add 10 new model heights in the lower levels of the atmosphere.
- Develop and test versions of HARMONIE optimalised for the short term forecast period of 1-18 hours ahead. This gives more freedom to model the vertical mixing in the stably stratified boundary layer more correctly since overestimating vertical mixing is currently used to improve the long term weather forecast to the detriment of the short term forecast.
- Extend the KNW dataset further back in time by using other reanalyses datasets such as ERA40 (1957-2002, 125 km grid boxes at 60 levels) or ERA-CLIM (1900-2002, 125 km grid boxes at 90 levels). These reanalyses have courser grid spacings than ERA-Interim (1979-2013, 25 km grid boxes on 60 levels) which was used in this report.
- Use the tall mast measurements to derive statistical relationships between the KNW wind speeds (40-60 minute average) at various heights and measured 10 minute average wind speeds which is the standard averaging time in the wind energy sector.
- Add other parameters of interest to the offshore wind energy sector to the KNW dataset that HARMONIE already provides but were not included in the dataset, such as the vertical wind speed, the Monin-Obukhov length (a measure of the atmospheric stability) and the turbulent kinetic energy (a measure of gustiness and turbulence intensity including all causes except deep convection).
- Identify occurrences of low level jets at the tall measurement masts and validate the KNW winds for these events and derive correction factors to apply to the whole dataset, thus creating a climatology of North Sea low level jets.
- Run tests to include wind measurements from tall measurement masts, LIDAR and SODAR (and wind turbine power production figures) in reanalysis datasets and HARMONIE data assimilation (operational weather forecast mode) to quantify the improvement that these new measurements can make to wind climate datasets and wind forecasts. The offshore wind energy sector could help provide these measurements in order to profit from the expected improvements.
- Extend the validation with measurements from other tall masts, LIDAR or SODAR in the North Sea. The offshore wind energy sector could use its own privately owned measurements to validate the KNW atlas itself or share the measurements with KNMI.

Appendix A1

The formula Geertsema (2014) used to correct for the underestimation of the wind shear is formula 1 (in which FF_{20} is the wind speed at 20 m height, FF_h is the wind speed at height h and $FF_{h,c}$ the corrected wind speed at height h)[8]. The corrected HARMONIE wind speed profile (blue) reproduces the observed profile (black) remarkably well.

$$FF_{h,c} = FF_{20} + \frac{FF_h - FF_{20}}{0.85} \qquad (1)$$

In order to determine whether shear correction formula 1 could be applied in a more general way (not only for Cabauw) two tests were performed: one to find out if the correction would be independent of the wind direction at Cabauw (which would imply independence of terrain/ surface roughness) and another to find out if the correction would also work for the Wieringermeer wind mast.

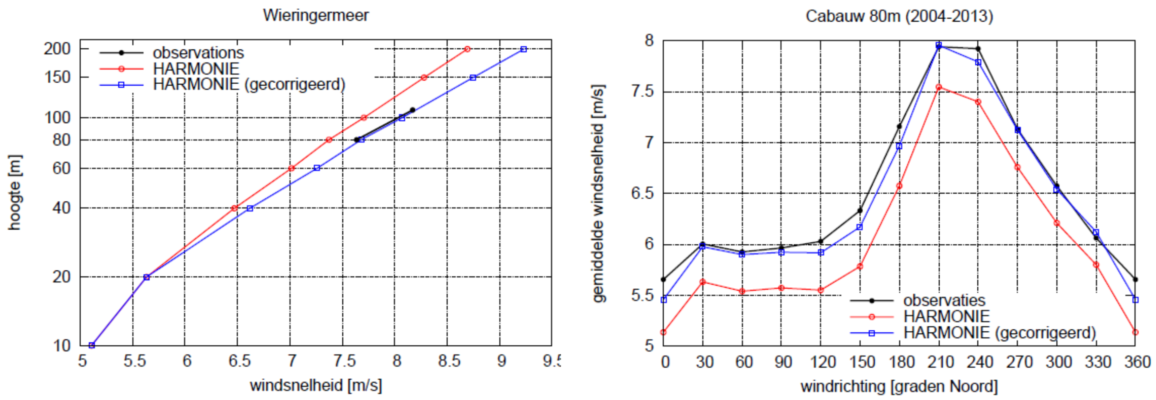


Figure 1.4 Average vertical wind profile Wieringermeer (left) and Cabauw per wind direction (right) for 2004-2013: observed (black), HARMONIE (red) and HARMONIE corrected (blue) (source: Geertsema, 2014).

Figure 1.4 shows that shear-correction formula 1 also works for the Wieringermeer wind mast (left). It also shows that the improvement of HARMONIE is almost independent of wind direction (terrain) and that measurements and HARMONIE with shear-correction are in good agreement (right). The latter implies that (at least at Cabauw) shear-correction of HARMONIE wind profiles suffices. The roughness map that HARMONIE uses, is adequate.

For the KNW-atlas the shear correction was applied to all levels (including the ones below 20 m).

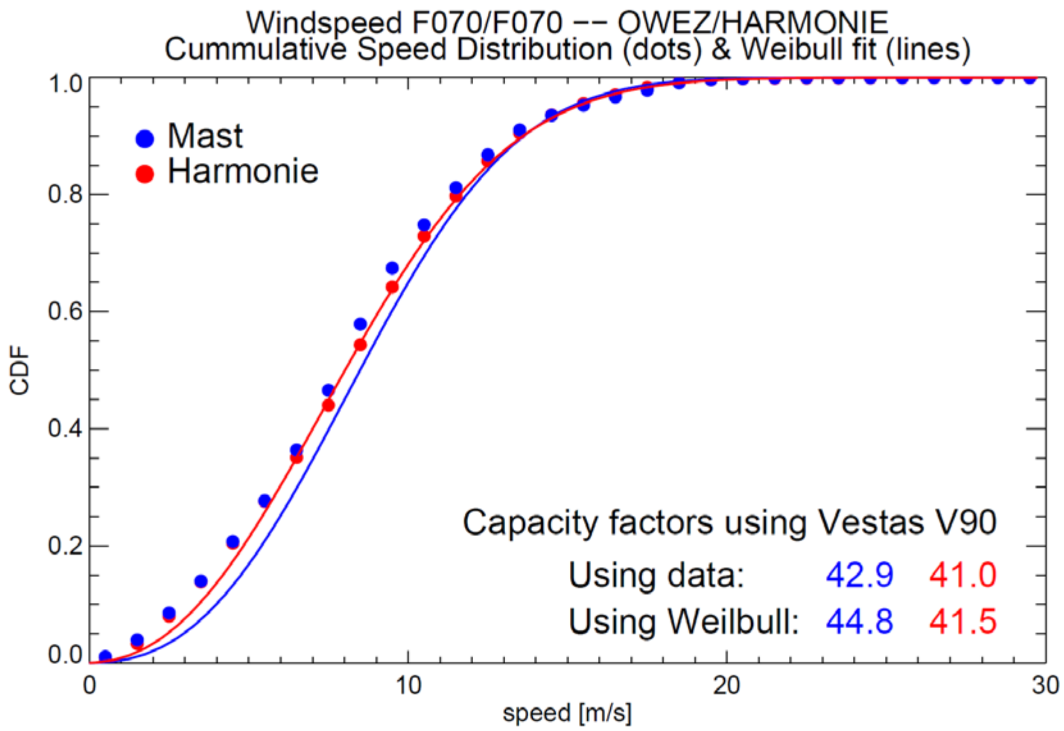
[8] In a small number of cases applying this shear correction would result in negative values for the wind speed. In those cases the shear correction was not applied. This has no effect on the wind statistics.

Appendix A2

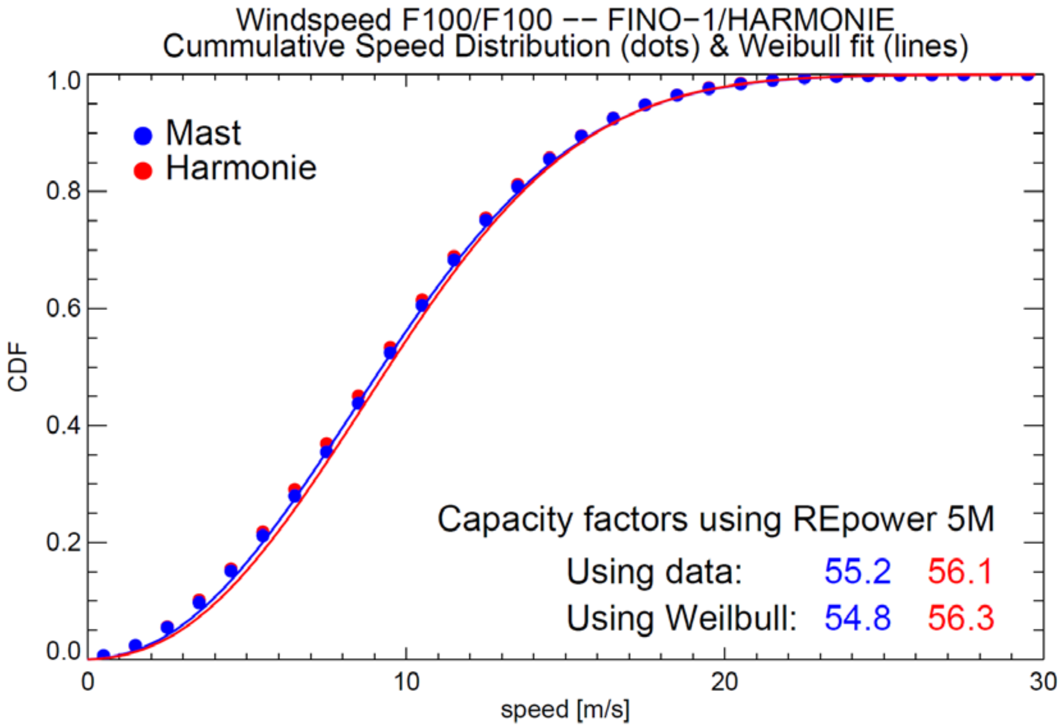
Name mast:	**Height of measurements:**	**Period**	**Lat/lon**	**Temporal resolution and more info:**
OWEZ	*Cup anemometers and vanes:* 21, 70 and 116 m (booms at 60º, 180º and 300 º) *Sonics:* 21, 70 and 116 m (only on boom at 300 º)	20050701-20101231 *Undisturbed :* 20050701-20060630 *Occasionally disturbed during construction wind farm:* 20060630-20060929 *Undisturbed in sector 316-143°*: 20060929-20101231 (Curvers, 2007)	52° 36' 22.9" N, 04° 23' 22.7" E (20 km off the coast of Egmond aan Zee)	Value available every 10 minutes (value represents a ten minute average) http://www.noordzeewind.nl/kennis/rapporten-data/
FINO-1	*Cup anemometers:* 101.0 m (top) 91.5 m (135º) 81.5 m (139º) 71.5 m (143º) 61,5 m (142º) 51.5 m (140º) 41.5 m (142º) 34.0 m (143º) *Sonics:* 81.5 m (311º) 61.5 m (308º) 41.5 m (308º) *Vanes:* 91.5 m (315º) 71.5 m (307º) 51.5 m (310º) 34.0 m (307º)	20040101-20131231 *Undisturbed :* 20040101-20081231 *Undisturbed in sector 165-15°*: 20090101-20131231	54° 00' 53.5" N, 06°35' 15.5" E (45 km north of Borkum)	Cup and vane: measuring interval 1 Hz and log interval 1 min (implies that every minute an average of 60 values is stored) Sonic: Measuring interval 50 Hz and log interval 10 Hz (implies that 10 times a second an average of 5 values is stored) http://www.bsh.de/de/Meeresdaten/Projekte/FINO/index.jsp
Cabauw	10, 20, 40, 80, 140, 200 m (booms at 10º, 130º and 250 º)	20010101-20131231 *(undisturbed)*	51.971° N, 4.927° E (51° 58' 9" N 4° 55' 33" E)	Value available every 10 minutes (value represents a ten minute average) http://www.cesar-database.nl/
MMIJ (IJmuiden Buiten or Tromp-binnen)	Boom height: 25.5 m (286.5º), 57.0 (166.5 º) and 86.5 (46.5º). Top: 92 m (sonic: only wind speed) Cup anemometers measures 1.5 m above and vanes 0.7 m above boom height, sonic 1.5 m below. LIDAR: 90, 115, 140, 165, 190, 215, 240, 265, 290 and 315 m	20120101-20131231 *(undisturbed)*	52° 50.89' N 3° 26.14' E (75 km off the coast of IJmuiden)	Value available every 10 minutes (value represents a 10 minute average) ECN supplied: • Daily csv-files of 4 Hz raw measurements 4Hz. • Monthly csv-files with 10 min averages (all measurements including LIDAR) • True winds (10 minute averages of measurements from 3 booms combined in such a way that mast effects are minimalised). • Invalid observations are not included http://www.meteomastijmuiden.nl/

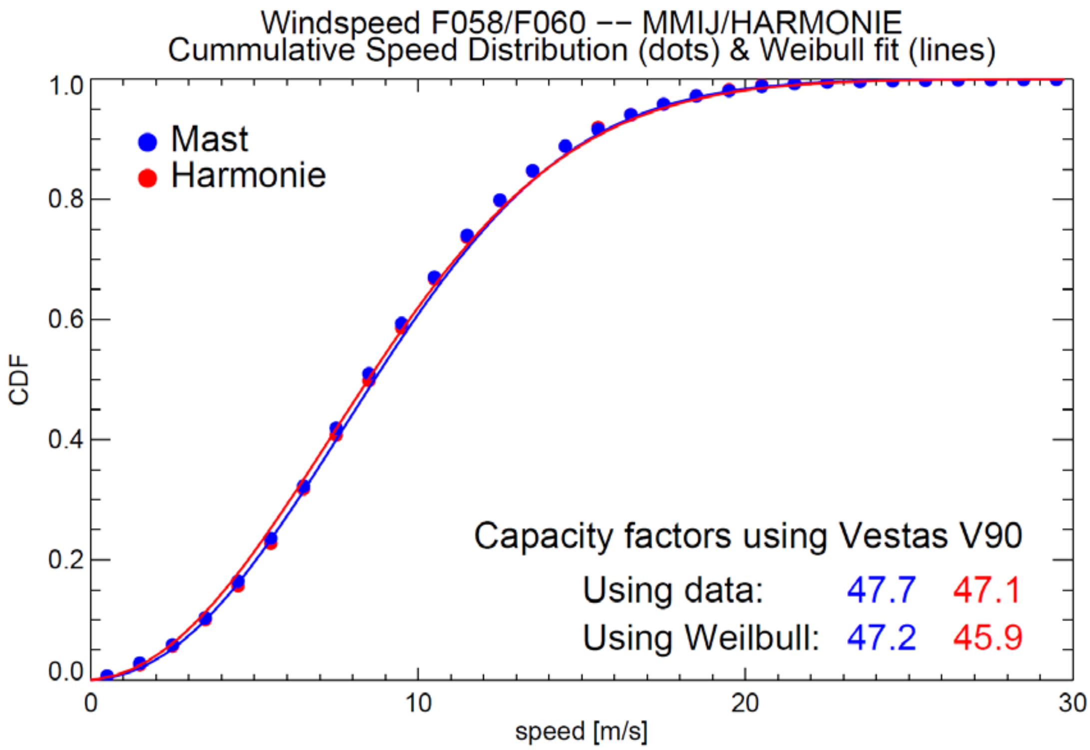
Appendix A3

These three graphs of the cumulative wind speed distribution also show the Weibull fits to the data performed conform the wind energy industry standard method as described by Donkers (2010). The capacity factor[9] of a Vestas V90 wind turbine is also shown on the OWEZ and MMIJ graphs (wind speeds at respectively 70 and 60 m) and of a Repower 5M on the FINO1 graph (100 m). On each graph four capacity factors are shown: two calculated directly from the data and two based on the best fit Weibull formula. At OWEZ and MMIJ the error (respectively 1.9 and 0.6%) made by using KNW data instead of measurements is equal to that made by following the industry standard method involving the Weibull fit (to the measured wind speeds). At FINO1 using the KNW data gives an overestimate of the capacity factor of 0.9% and the Weibull fit, an underestimate of 0.4%.



[9] The capacity factor of a wind turbine is the average power produced divided by the rated power of the wind turbine, which is the maximum power output that is only achieved at hub height wind speeds above the rated wind speed (typically 15 m/s) and below the cut-off wind speed (typically 25 m/s).


Windspeed F100/F100 -- FINO-1/HARMONIE
Cummulative Speed Distribution (dots) & Weibull fit (lines)
CDF
speed [m/s]
Mast
Harmonie
Capacity factors using REpower 5M
Using data: 55.2 56.1
Using Weilbull: 54.8 56.3


Windspeed F058/F060 -- MMIJ/HARMONIE
Cummulative Speed Distribution (dots) & Weibull fit (lines)
CDF
speed [m/s]
Mast
Harmonie
Capacity factors using Vestas V90
Using data: 47.7 47.1
Using Weilbull: 47.2 45.9

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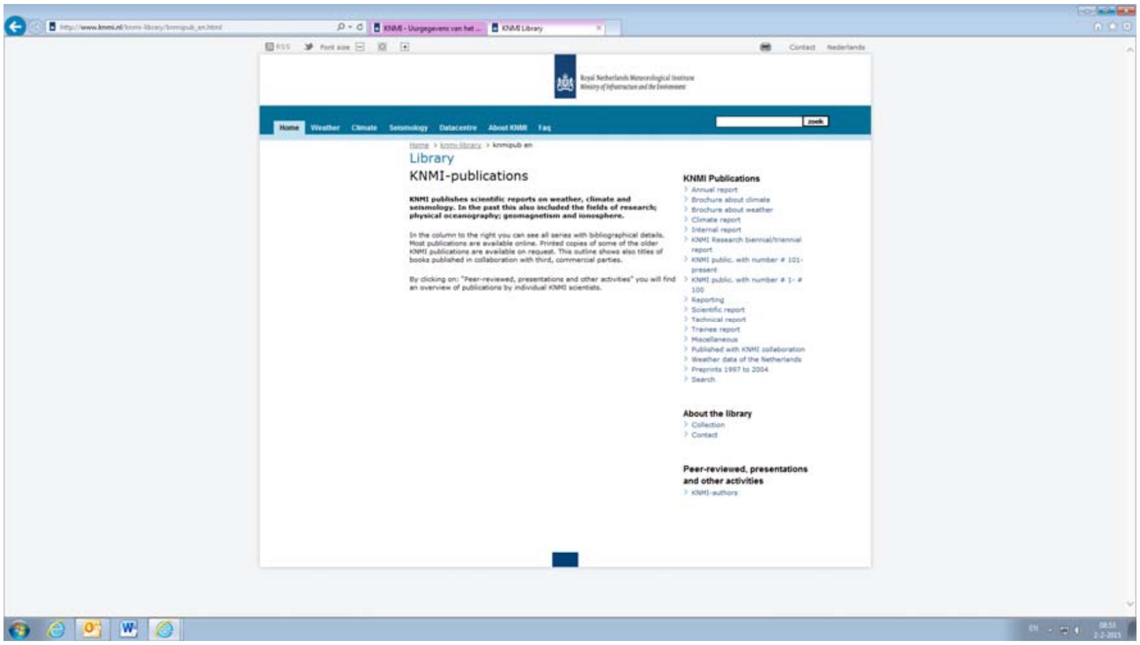

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