Westerduinweg 3
1755 LE Petten
P.O. Box 15
1755 ZG Petten
The Netherlands

www.tno.nl

T +31 88 866 50 65

TNO report 2019 R10427

Representation of North Sea Wind Conditions in the DOWA and the EMD-ConWx European Mesoscale Dataset

Date	7 June 2019
Author(s)	J. B. Duncan
Copy no	
No. of copies	
Number of pages	22 (incl. appendices)
Number of appendices	1
Sponsor	Supported with Topsector Energy Subsidy from the Ministry of Economic Affairs and Climate Policy
Contributing Project Parner	Koninklijk Nederlands Meteorologisch Instituut (KNMI)**
Project name	Dutch Offshore Wind Atlas (DOWA)
Project number	060.33810

Since April 1st ECN and TNO have joined forces.

Summary

The creation of the Dutch Offshore Wind Atlas (DOWA) was part of a joint project with ECN part of TNO, Whiffle, and KNMI. The DOWA is a wind atlas based on a 10-year reanalysis, which is an hourly description of the state of the atmosphere using measurements and atmospheric (weather) models. The DOWA attempts to improve upon the ability of the KNW-atlas (previously released by KNMI in 2013) to accurately depict hourly wind field variability (i.e. correlation). In order to improve upon the KNW-atlas, the DOWA uses an updated version of the global ECMWF reanalysis (ERA5), as well as an updated version of the HARMONIE numerical weather model (Cycle 40h1.2.tg2). Furthermore, the method that was used to make the atlas was changed—there were no 'cold starts' within the global reanalysis and at three-hour intervals additional aircraft and satellite measurements were assimilated. Within this report, the performance of the DOWA in representing North Sea wind conditions is compared to the EMD-ConWx European mesoscale dataset that were modeled in-house in collaboration between EMD and ConWx. The performance of the two datasets is defined relative to light-detection and ranging (LiDAR) measurements at three offshore measurement sites (IJmuiden, Lichteiland Goeree, and the Europlatform). The most significant conclusion from this report is that the DOWA provides improved hourly wind speed correlation compared to the EMD-ConWx European mesoscale dataset.

Contents

1 Introduction

The Dutch Part of the North Sea is expected to see significant growth in wind energy production over the next decade. By 2023, the Dutch Part of the North Sea should have a total installed capacity of 4.5 GW and by 2030 an installed capacity of 11.5 GW. Efficient development of offshore wind requires a thorough understanding of the offshore wind conditions. While offshore wind measurements exist, they are limited both in space and time. However, by using mesoscale atmospheric models to increase the spatial and temporal resolution of global reanalyses, wind atlases can be developed to derive the offshore wind climatology at various locations and heights.

ECN published its first Offshore Wind Atlas (OWA1) in 2004 (Brand et al. 2004), which is a numerical wind atlas based on data from the Koninklijk Nederlands Meteorologisch Instituut (KNMI) HiRLAM (High Resolution Limited-area Atmospheric Model). In vertical direction the lower levels of the model were employed, i.e. in the atlas four fixed heights were considered (60m, 90m, 120m and 150m amsl; almost the same as LAT in the part of the North Sea that was considered.). OWA1 is based on the numerical data of the years 2000-2003, and was validated using data of offshore and coastal wind stations measured in the same period. A second version OWA2 (Donkers et al. 2011), an update of OWA1, was issued in 2011. Again it was based on atmospheric data from the HiRLAM, but now a longer period was considered. In addition sea depths originating from the Hydrographic Service of the Royal Netherlands Navy were used in order to estimate the wave height (sea surface roughness). The lowest levels in the vertical were used, but now three fixed heights were considered (40m, 90m and 140m amsl).

Within the past decade, KNMI has produced two wind atlases—the KNMI North Sea Wind (KNW) atlas and the Dutch Offshore Wind Atlas (DOWA)—to depict offshore wind conditions across the North Sea. Because of the method that was used to make the KNW-atlas (i.e. six-hourly ‘cold starts’ with the much coarser global reanalysis model ERA-Interim), the KNW-atlas did not exhibit a strong correlation with the hourly wind measurements (Stepek et al. 2015). Therefore, new models and methods were used in the DOWA to improve hourly correlation compared to the KNW-atlas; namely, the DOWA uses an updated version of the global ECMWF reanalysis (ERA5) and an updated version of the HARMONIE numerical weather model (Cycle 40h1.2.tg2). Validation of the DOWA against wind measurements by Advanced SCATterometer (ASCAT) (Duncan et al. 2019), and light-detection and ranging (LiDAR) and instrumented meteorological masts (Duncan et al. 2019) demonstrated that the DOWA: (1) improves hourly wind speed correlation, (2) is able to adequately represent vertical wind shear without any empirical correction factors, and (3) is able to depict monthly and annual average wind speeds with similar accuracy to the KNW-atlas.

The above mentioned atlases are not the only source for this type of wind information. ConWx in collaboration with EMD (EMD-ConWX) produces a European mesoscale dataset (available via a subscription) using the in-house mesoscale model of ConWX and ERA-Interim as the global boundary dataset. The EMD-ConWX European dataset is updated monthly with a three-month delay to real time. Ecofys previously performed a wind resource assessment of the Borssele Wind Farm Zone and found that the KNW-atlas demonstrated better correlation with measurements (Crockford et al. 2015). These results have motivated the current study that aims to document the improvement of the DOWA (a publicly available resource) to the subscription-based EMD-ConWX European mesoscale dataset at three locations across the North Sea. Emphasis will be placed on hourly wind speed correlation given its importance to wind resource assessment.

This report is structured as follows: section two provides details of the measurements and models used, section three compares the representation of North Sea wind speeds in the DOWA and the EMD-ConWx European mesoscale dataset, and section four provides a brief summary of the results.

2 Atmospheric models and measurements

2.1 Reanalysis, wind atlas, and mesoscale model information

Both the DOWA and the EMD-ConWX European mesoscale dataset are based on a global ECMWF reanalysis. The DOWA is downscaled using the atmospheric weather model HARMONIE, and the EMD-ConWX European mesoscale dataset uses an in-house mesoscale model for downscaling. More information on the respective models is provided below.

2.1.1 Reanalysis

Making a reanalysis involves fitting a state-of-the-art atmospheric model to historical weather measurements to obtain a spatially and temporally consistent long-term dataset that depicts the time-varying state of the atmosphere. The global ERA-Interim reanalysis was used to produce the KNW-atlas and the global ERA5 reanalysis was used to produce the DOWA. Both of these reanalysis datasets were produced by the European Center for Medium-range Weather Forecasts (ECMWF; www.ecmwf.int). More information on ERA-Interim and ERA5 is provided below.

2.1.1.1 ERA-Interim

The ERA-Interim reanalysis that was used as the global boundary dataset in the EMD-ConWx mesoscale model combines one of the leading numerical weather prediction models (ECMWF model) with an advanced data-assimilation system (Baas 2014). The resulting analysis is considered a statistical 'best-estimate' of the state of the atmosphere at the model scales since it is based on very short-term model forecasts that have been adjusted to match observations. ERA-Interim starts in 1979 and provides three-dimensional analysis of the global atmosphere at a T255 spectral truncation (i.e. corresponding to a grid size of about 80 km). The archived reanalysis dataset provides six-hourly temporal output.

2.1.1.2 ERA5

ERA5 is the fifth generation of ECMWF atmospheric reanalysis of the global climate and is used to make the DOWA. ERA5 will (once completely available) eventually replace ERA-Interim. The main differences between ERA-Interim and ERA5 are:

- ERA5 will eventually be available from 1950 to now (ERA-Interim 1979 to now).
- ERA5 will provide hourly data as opposed to the six-hour data produced by ERA-Interim.
- ERA5 exhibits a horizontal grid spacing of 31 km (improved relative to the ERA-Interim 80-km horizontal resolution).
- ERA5 depicts atmospheric troposphere and lower stratosphere conditions at 137 vertical levels up to about 80 km (ERA-Interim only provides 60 levels).
- ERA5 employs an updated model version of the ECMWF model (see https://confluence.ecmwf.int//pages/viewpage.action?pageId=74764925).

2.1.2 The DOWA

Creating the DOWA[1] was part of a joint project with ECN part of TNO, Whiffle, and KNMI. The DOWA is a wind atlas based on a 10-year (2008-2017) reanalysis (ERA5) that was downscaled to a 789 by 789 grid that is centered on the KNMI meteomast Cabauw using the atmospheric weather model HARMONIE. HARMONIE (HIRLAM ALADIN Research on Mesoscale Operational NWP In Euromed), also known by the name AROME, is the numerical weather prediction model used operationally by KNMI since 2012. It is continually being improved and tested by the HIRLAM-ALADIN consortium (Figure 1). HARMONIE is a non-hydrostatic limited-area model that runs on a high-resolution grid spacing of 2.5 km and outputs hourly data. More details regarding HARMONIE /AROME can be found in Seity et al. (2011) and online (www.hirlam.org). HARMONIE model set-up can be found in Toros et al. (2014). The HARMONIE version CY40h1.2.tg2 that was used to produce the DOWA incorporates an improved turbulence parameterization (HARATU) that enables enhanced estimates of wind speed (De Rooy 2017).

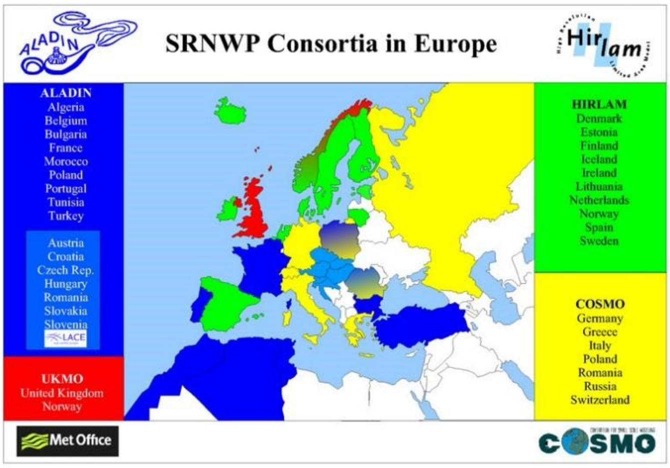

Figure 1 Participating countries in the HIRLAM (green) and ALADIN (blue) consortiums (source: http://www.eumetnet.eu).

The following new methodologies were also implemented within the DOWA.

- **Assimilation of measurements:**
  - For the DOWA, the full potential of HARMONIE as a weather forecasting model was leveraged by assimilating additional measurements (both conventional and innovative) that were not used in ERA5. Innovative measurements included high-resolution satellite surface wind fields (Advanced Scatterometer [ASCAT]) and aircraft wind profile measurements (MODE-S EHS). The 3DVAR assimilation technique was used to assimilate these measurements at three-hour intervals at the beginning of each HARMONIE forecast cycle (see 'cold start' discussion below). Using these additional measurements is expected to improve the quality of the time series and provide a more detailed depiction of the diurnal cycle.

[2] The DOWA-project is financed by the Ministry of Economic Affairs and Climate Policy (SDE+ Hernieuwbare Energie Call)

- **Cold start:**
  - Except at the beginning of each parallel stream[2], no cold starts were used in the DOWA. The DOWA is comprised +1 hr, +2 hr, and +3 hr HARMONIE forecasts. At each hour, the boundaries of the DOWA domain (North, South, East, and West at all model levels) are fed with ERA5 reanalysis data, and each three-hour forecast cycle is initialized using the latest HARMONIE forecast of the previous cycle (i.e. no cold starts with ERA5 data) and data-assimilated measurements.

Additional DOWA details can be found online (http://www.dutchoffshorewindatlas.nl/).

2.1.3 *EMD-ConWx European mesoscale model*

Because the mesoscale model that was used to produce the EMD-ConWx European mesoscale dataset was developed in-house by ConWx in collaboration with EMD, no extensive documentation of this model can be found. However, in Thiesen and Ristic (2011), it is stated that the mesoscale model used for downscaling is an extension of the National Meteorological Center's step-mountain Eta coordinate model. A description of the latest NMC Eta coordinal model version can be found in Mesinger et al. (2012).

2.2 Validation measurement information

Ten-minute average wind data provided by platform-mounted LiDAR at IJmuiden (MMIJ), Lichteiland Goeree (LEG), and the Europlatform (EPL) were used in this study to compare the representation of North Sea wind conditions in the DOWA and the EMD-ConWx European mesoscale dataset (Figure 2). A Zephir 300s continuous-wave (CW) LiDAR was deployed at the MMIJ and EPL measurement sites and the WINDCUBE v2 pulsed LiDAR was deployed at LEG. A summary of the LiDAR measurements at each site—including LiDAR type, measurement heights, and the data collection period—is provided in Table 1. The measurement heights at MMIJ are defined relative to the lowest-astronomic tide, while the measurement heights at EPL and LEG are defined relative to the mean sea level. Because the lowest-astronomic tide is on average only 1.06 m below the mean sea level, this difference is not expected to significantly impact the results presented. LiDAR data quality control procedures are documented in Appendix A and furthermore it should be noted that none of the LiDAR measurement locations were impacted by the presence of any neighbouring wind farms.

Information on the specific offshore measurement platforms and their installation details can be found online at www.windopzee.net and in Section 2.2 of the ECN part of TNO report titled 'Understanding of the Offshore Wind Resource up to High Altitudes (≤315 m)' (Duncan et al. 2018). The latter report also contains information on data availability.

As stated in Duncan et al. (2019), all fixed LiDARs used in this report were verified prior to their specific installation offshore. Specific references on these verifications are provided in Duncan et al. (2019) as well.

[2] Stream A (2010-2012), stream B (2013-2014), stream C (2008-2009) and stream D (2015-2017) were run simultaneously to speed up calculations (it takes about 1 month to calculate 4 months) and then glued.

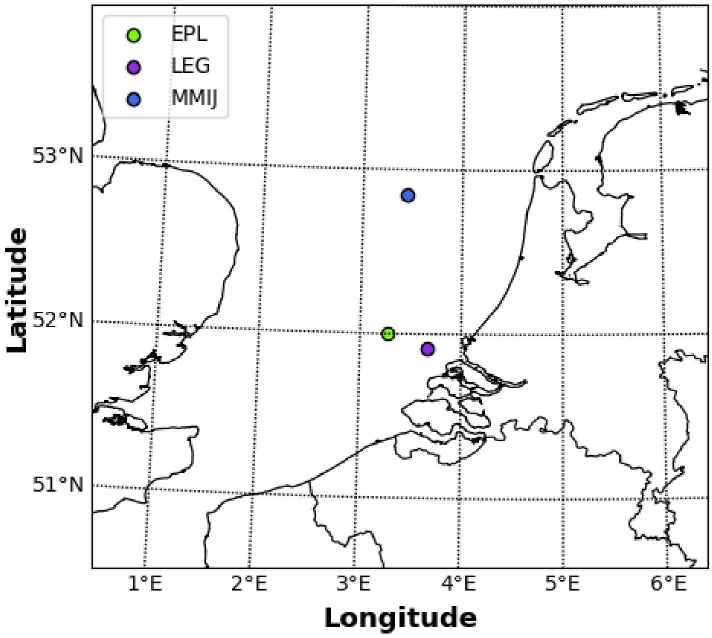

Figure 2 Location of the three measurement sites used to compare the representation of North Sea winds in the DOWA and the EMD-ConWx European mesoscale dataset.

Table 1 Measurement site LiDAR description. Measurement heights are indicated by HGT_{min}:$HGT_{interval}$:HGT_{max} and any other measurement heights.

Measurement Location Identifier	LiDAR Type	Measurement Heights (m)	Data Collection Period
MMIJ	ZephIR 300s	90:25:315	01-Nov-2011 — 09-Mar-2016
EPL	ZephIR 300s	91:25:291 and 63	30-May-2016 — 31-Dec-2017
LEG	WINDCUBEv2	91:25:291 and 63	17-Nov-2014 — 31-Dec-2017

2.3 Development of comparable collocated datasets

Fundamental differences exist (temporal and spatial) between the LiDAR measurements and the hindcast data (i.e. the DOWA and the EMD-ConWx European mesoscale dataset). The hindcast data are provided at one-hour intervals (i.e. 00:00 UTC, 01:00 UTC, etc.) and it represent a best estimate of the wind conditions at that hour for the grid-cell area (2.5 km by 2.5 km grid box in the DOWA and a 3 km by 3 km grid box in the EMD-ConWX European mesoscale dataset). The hindcast data are therefore instantaneous volume averages, whereas the LiDAR measurement data are 10-min temporal averages at the measurement location. It has been previously argued that the instantaneous volume-averaged KNW-atlas values should be each compared to an hourly averaged measurement value (Stepek et al. 2015). Therefore, measurements from a half-hour before and a half-hour after the hindcast hour (i.e. six total 10-min mean measurements) were averaged (scaler averages as opposed to vector averages) to produce an hourly measurement value for comparison to the hindcast hourly values. An analogous ‘one-hour’ measurement value was derived as long as there was at least one valid measurement (i.e. the measurement passed the quality control measures described in Appendix A) within the one-hour period.

Adjustments were also made to account for height differences between the hindcast data and measurements. A cubic-spline interpolation scheme was used to interpolate both the DOWA data (available at: 10, 20, 40, 60, 80, 100, 120, 140, 150, 160, 180, 200, 220, 250, and 300 m) and the EMD-ConWx European mesoscale data (available at: 10, 25, 50, 75, 100, 150, 200 m) to the site-specific measurement heights. Furthermore, LiDAR wind data were compared to wind data derived from the nearest hindcast grid cell.

3 Wind Speed Performance Comparison of the DOWA and EMD-ConWX European Mesoscale Dataset

The performance of the DOWA and the EMD-ConWx European mesoscale dataset in their representation of North Sea wind speeds is examined. North Sea wind speed representation as resolved by the LiDAR, the DOWA, and the EMD-ConWx European mesoscale data is first examined in Section 3.1 by comparing the Weibull distribution fits, Section 3.2 examines the ability of the DOWA and the EMD-ConWx European mesoscale dataset to accurately depict the vertical profile of wind speed, and Section 3.3 examines both hourly wind speed correlation and the representation of the diurnal wind speed cycle. Bias is defined as the measurement wind speed minus the hindcast wind speed (i.e. $WS_{LiDAR} - WS_{hindcast}$). Therefore, a positive bias indicates hindcast wind speed underestimation while a negative bias indicates hindcast wind speed overestimation. The results presented herein are derived from collocated datasets (i.e. a hindcast value was only considered when an hourly measurement value was also defined).

3.1 Weibull distribution

A two-parameter Weibull distribution can be used to reasonably depict variations in wind speed (i.e. the wind speed distribution) at a location (Burton et al. 2011; Rehman et al. 2012; Genc et al. 2005). Methods established by Wieringa and Rijkoord (1983) and previously used to validate the KNW-atlas (Stepek et al. 2015) were used to determine the Weibull fit using a wind speed bin size of 0.5 m/s at both the LiDAR measurement height nearest 100 m and 200 m. The Weibull parameters are defined by,

$$\ln(-\ln[1 - F(U)]) = k(\ln U) - k \ln A,$$

where $F(U)$ is the cumulative Weibull distribution function (i.e. the chance of exceeding wind speed U), k is the Weibull shape parameter, and A is the Weibull scale parameter. The parameter A is proportional to the mean wind speed of the distribution and the parameter k depicts the shape of the distribution. The value of *k* is inversely proportional to the spread of the wind speed distribution. Therefore, large *k* values indicate less wind variability.

The two-parameter Weibull distribution at the LiDAR measurement height nearest 100 m as defined by the LiDAR, the DOWA, and the EMD-ConWx European mesoscale dataset is provided in the left column of Figure 3 for MMIJ, the left column of Figure 4 for EPL, and the left column of Figure 5 for LEG. The right column of Figures 3 through 5 demonstrates differences in the representation of *A* and *k* with height by the DOWA and the EMD-ConWx European mesoscale dataset. The values of *A* and *k* at the LiDAR measurement height nearest both 100 m and 200 m are provided in Tables 2 and 3 for each LiDAR measurement location.

The DOWA performed slightly better than the EMD-ConWx European mesoscale dataset in depicting the value of *A*. At the LiDAR measurement height nearest 100 m, the DOWA overestimates the value of *A* by an average value of 0.092 m/s, while the EMD-ConWx European mesoscale dataset underestimate the value of *A* by an average value of 0.10 m/s. At the LiDAR measurement height nearest 200 m, the bias in *A* in the EMD-ConWx European mesoscale dataset was positive at MMIJ and LEG and negative at EPL, while in the DOWA the bias in *A* was negative at each LiDAR measurement location. The mean absolute bias was therefore used to quantify the performance of the hindcasts at the LiDAR measurement height nearest 200 m. The mean absolute bias was 0.061 m/s in the DOWA and 0.089 m/s in the EMD-ConWx European mesoscale dataset. The DOWA also more accurately depicts the decrease in *k* with height offshore. At LEG for example, the value of *k* in the EMD-ConWx European mesoscale dataset initially increases with height when it should decrease with height as accurately depicted by the DOWA.

Table 2 The value of *A* in m/s at the LiDAR measurement height nearest 100 m and 200 m.

Measurement Location Identifier	**Weibull Scale Parameter Nearest 100 m (LiDAR | DOWA | EMD-ConWx)**			**Weibull Scale Parameter Nearest 200 m (LiDAR | DOWA | EMD-ConWx)**		
MMIJ	11.38	11.41	11.24	12.10	12.10	11.95
EPL	9.99	10.07	9.89	10.50	10.61	10.51
LEG	11.05	11.21	10.97	12.15	12.21	12.04

Table 3 The value of *k* at the LiDAR measurement height nearest 100 m and 200 m.

Measurement Location Identifier	**Weibull Shape Parameter Nearest 100 m (LiDAR | DOWA | EMD-ConWx)**			**Weibull Shape Parameter Nearest 200 m (LiDAR | DOWA | EMD-ConWx)**		
MMIJ	2.19	2.15	2.20	2.06	2.03	2.09
EPL	2.19	2.16	2.25	2.05	2.05	2.11
LEG	2.27	2.21	2.29	2.15	2.13	2.22

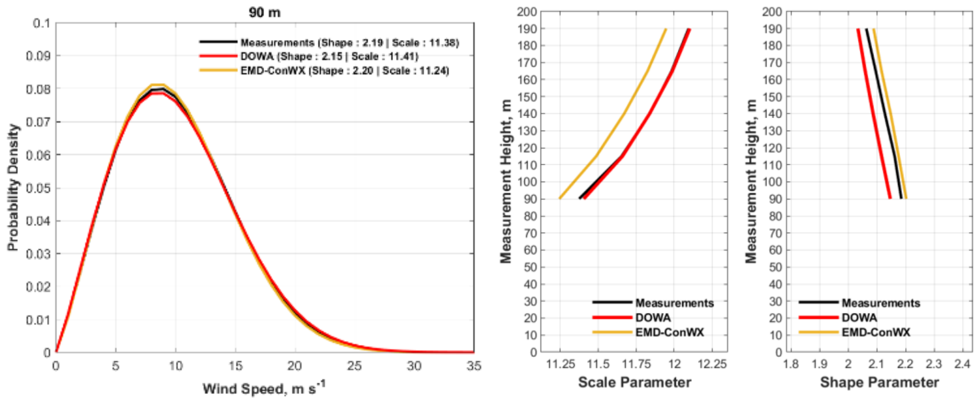

Figure 3 (Left column) The Weibull fit at the LiDAR measurement height nearest 100 m at MMIJ. (Right column) The vertical profile of the Weibull scale (*A*) in m/s and shape (*k*) parameters.

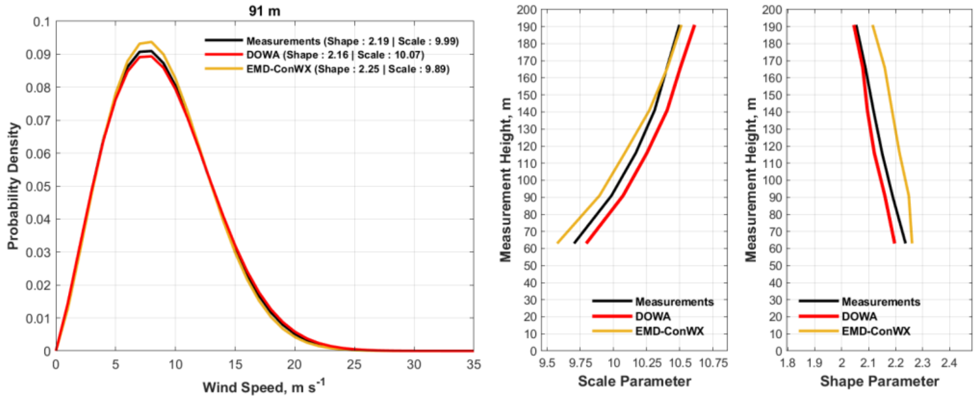

Figure 4 Same as Figure 3 except at the EPL LiDAR measurement location.

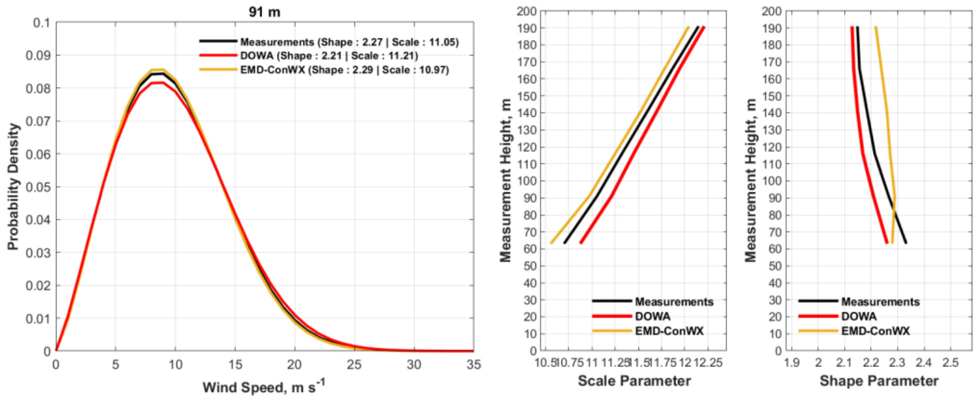

Figure 5 Same as Figure 3 except at the LEG LiDAR measurement location.

3.2 Representation of the vertical profile in wind speed

The vertical profile of wind speed as defined by LiDAR, the DOWA, and the EMD-ConWx European mesoscale dataset is provided in Figure 6 for MMIJ, Figure 7 for EPL, and Figure 8 for LEG. Vertical profiles of the mean (μ) and the standard deviation (σ) of the wind speed bias are also provided in these Figures. At each LiDAR measurement location and measurement height, the value of μ was slightly negative in the DOWA, indicating a slight overestimation of the wind speed. However, within the EMD-ConWx European mesoscale dataset, there is a much larger variation in the value of μ between measurement sites and measurement heights. Considering all LiDAR measurement sites and measurement heights, the value of μ ranged between -0.031 m/s and 0.17 m/s (i.e. a range of 0.20 m/s) in the EMD-ConWx European mesoscale dataset and the value of μ ranged between -0.14 m/s and -0.010 m/s (i.e. a range of 0.13 m/s) in the DOWA. Reduced variation in the value of μ between LiDAR measurement sites and measurement heights indicates that the DOWA is a more useful resource than the EMD-ConWx European mesoscale dataset, partially because a single mean-bias-error correction would be more effective within the DOWA. Also, the value of σ at each LiDAR measurement site and measurement height was smaller in the DOWA than in the EMD-ConWx European mesoscale dataset. On average, the value of σ at a given height and measurement location was reduced by 0.49 m/s (26.92 %) from a mean value of 1.82 m/s within the EMD-ConWx European mesoscale dataset to a mean value of 1.33 m/s within the DOWA.

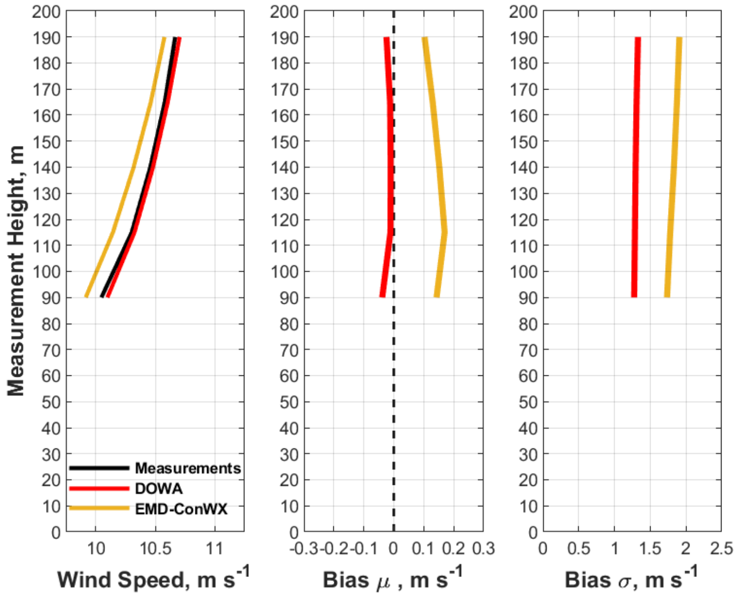

Figure 6 (Left column) Vertical profile of wind speed as defined by the LiDAR, the DOWA, and the EMD-ConWx European mesoscale wind data at MMIJ. The mean (μ) (middle column) and standard deviation (σ) (right column) of the wind speed bias.

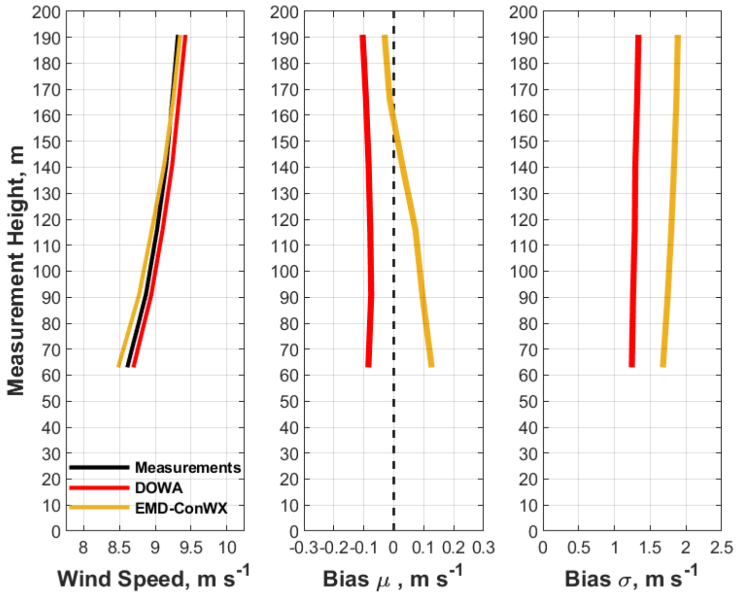

Figure 7 Same as Figure 6 except at the EPL LiDAR measurement location.

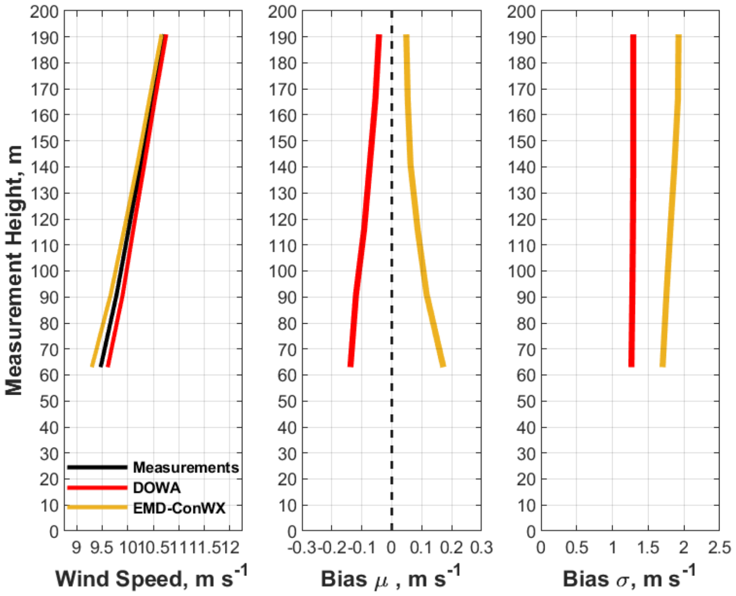

Figure 7 Same as Figure 6 except at the LEG LiDAR measurement location.

3.3 Hourly correlation and representation of the diurnal cycle in wind speed

Hourly correlation between the LiDAR and the hindcast wind speeds was examined using linear least-squares regression. Linear least-squares regression defines the linear relationship between two variables (i.e. x and y) as $y = mx + b$, where m is the slope of the line and b is its y-intercept. Within the presented analyses, x is the LiDAR wind speed and y is the hindcast (i.e. the DOWA or the EMD-ConWx European mesoscale dataset) wind speed (i.e. $WS_{Hindcast} = slope * WS_{LiDAR} + y_{intercept}$). Given a slope value of one, which indicates that a unit change in the measured wind speed corresponds on average to a unit change in the hindcast wind speed, the y-intercept value gives an indication of the mean bias. The value of R^2 denotes the clustering (i.e. precision) of the data about the fitted linear regression line, and the square root of R^2 (i.e. R) is the correlation coefficient. Therefore, superior hindcast performance would be indicated by: (1) an R^2 value closer to one (i.e. $R^2 \rightarrow 1$), a (2) a slope value closer to one (i.e. $slope \rightarrow 1$), and (3) an intercept value closer to zero (i.e. $intercept \rightarrow 0$).

Hourly correlation of the hindcast data to the LiDAR wind speeds at the measurement height nearest 100 m is examined in Figure 8 for MMIJ, Figure 9 for EPL, and Figure 10 for LEG. The slope, y-intercept, and coefficient of determination (R^2) of the linear least-squares regression fits are provided in Table 4. All statistics examined demonstrate superior hourly wind speed correlation within the DOWA compared to that within the EMD-ConWx European mesoscale dataset. The mean slope value considering all three LiDAR measurement location was 0.99 within the DOWA and 0.90 within the EMD-ConWx European mesoscale dataset, while the mean R^2 value was 0.93 within the DOWA and 0.86 within the EMD-ConWx European mesoscale dataset. The ability of the DOWA and the EMD-ConWx European mesoscale dataset to resolve diurnal average wind speeds is also provided in the bottom subplots of Figures 8 through 10. At each LiDAR measurement location and hindcast hour (e.g. 00:00 UTC, 01:00 UTC, etc.), the σ value of the hourly wind speed bias was less in the DOWA than it was in the EMD-ConWx European mesoscale dataset, indicating that the representation of the diurnal cycle was better in the DOWA. On average, the σ value of the hourly wind speed bias was reduced by 0.46 m/s (26.59 %) from a mean value of 1.73 m/s within the EMD-ConWx European mesoscale dataset to a mean value of 1.27 m/s within the DOWA.

Table 4 The slope, y-intercept, and R^2 values derived from performing linear least-squares regression between the hindcast and LiDAR wind speeds.

Measurement Location Identifier (hgt)	**Slope Value (KNW | DOWA)**		**Y-Intercept Value (KNW | DOWA)**		**R^2 Value (KNW | DOWA)**	
MMIJ (90 m)	0.92	0.98	0.71	0.20	0.87	0.93
EPL (91 m)	0.89	0.98	0.90	0.27	0.84	0.92
LEG (91 m)	0.91	1.00	0.79	0.15	0.86	0.93

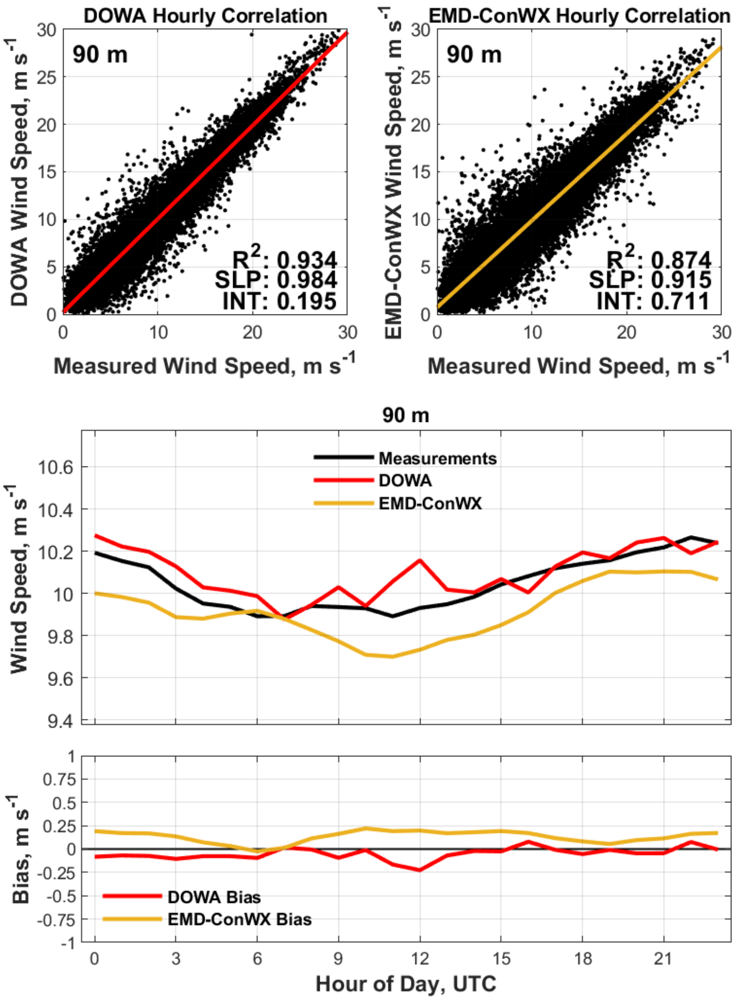

Figure 8 (Upper-Left Subplot) Scatterplot of the DOWA versus the LiDAR wind speeds at MMIJ. (Upper-Right Subplot) Scatterplot of the EMD-ConWx European mesoscale dataset versus LiDAR wind speeds at MMIJ. (Bottom Subplot) Hourly mean (i.e. diurnal) hindcast and LiDAR wind speeds at MMIJ along with the corresponding hourly bias values.

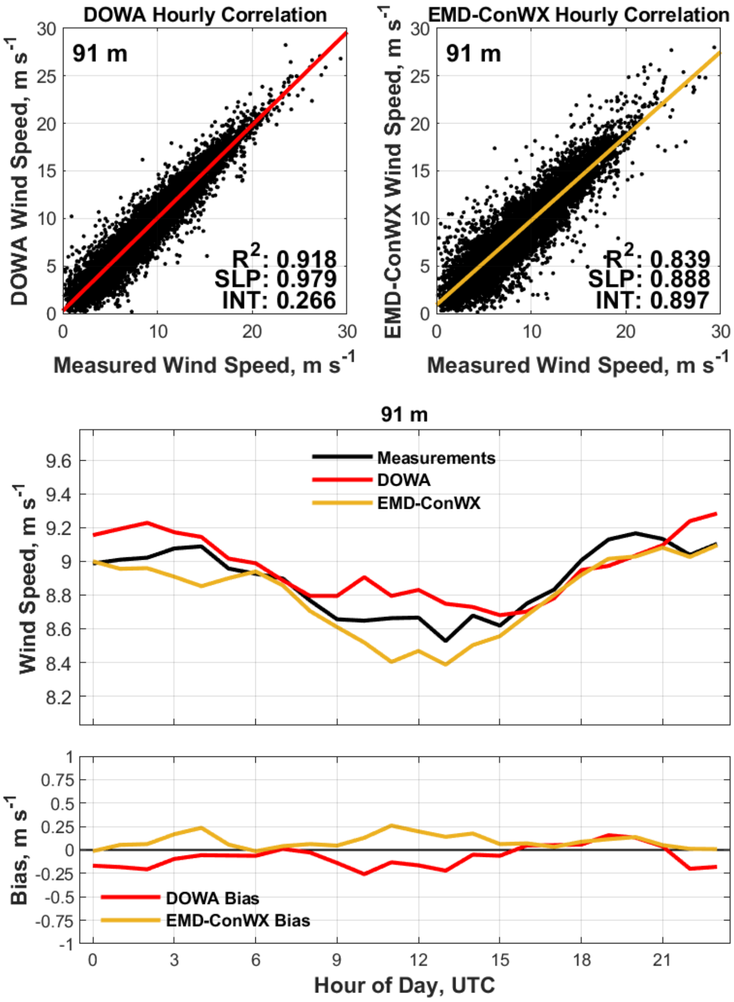

Figure 9 Same as Figure 8 except at the EPL LiDAR measurement location.

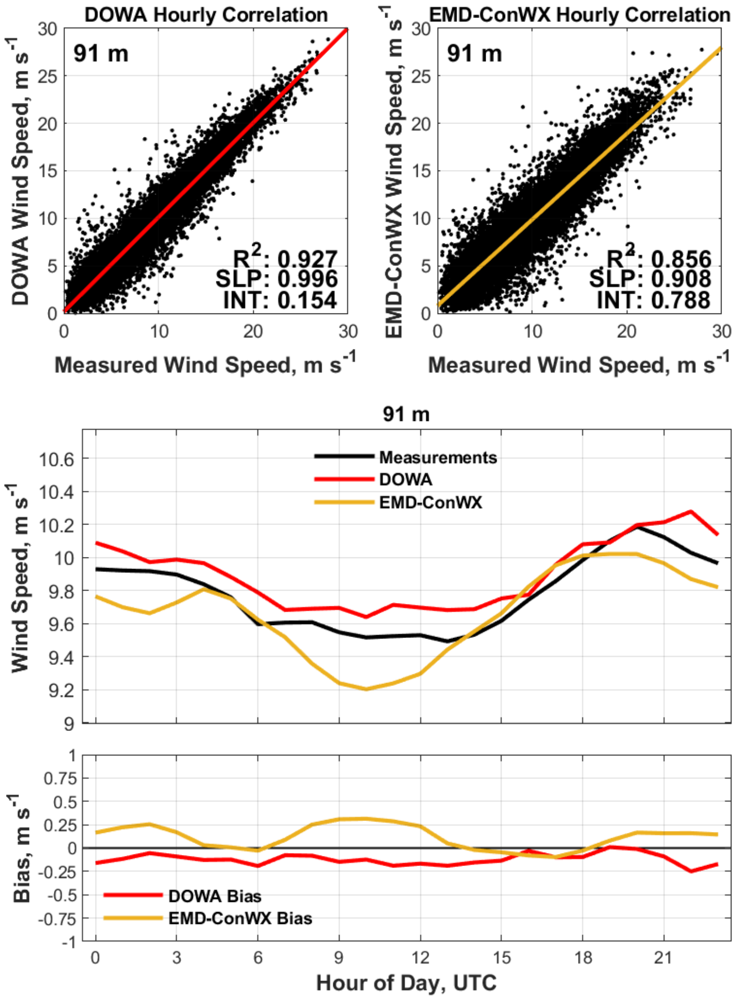

Figure 10 Same as Figure 8 except at LEG.

4 Summary of results

Conclusions that were derived from comparing the DOWA and the EMD-ConWx European mesoscale dataset to LiDAR wind speeds at MMIJ, LEG, and EPL are provided below.

- The DOWA performed slightly better than the EMD-ConWx European mesoscale dataset in depicting vertical differences in the Weibull parameters *A* and *k* with height.

- The mean wind speed bias varied less between measurement sites and heights in the DOWA than in the EMD-ConWx European mesoscale dataset. This indicates that the DOWA is a more useful resource than the EMD-ConWx European mesoscale dataset. Also, the value of σ at each measurement site and measurement height was smaller in the DOWA than in the EMD-ConWx European mesoscale dataset.

- Linear least-squares regression between the hindcast data and the LiDAR wind speeds indicates that the DOWA exhibits enhanced hourly wind speed correlation compared to the EMD-ConWx European mesoscale dataset.

  - The mean slope value considering all three LiDAR measurement locations was 0.99 within the DOWA and 0.90 within the EMD-ConWx European mesoscale dataset, while the mean R^2 value was 0.93 within the DOWA and 0.86 within the EMD-ConWx European mesoscale dataset.

  - At each LiDAR measurement location and hindcast hour (e.g. 00:00 UTC, 01:00 UTC, etc.), the σ value of the hourly wind speed bias was less in the DOWA than it was in the EMD-ConWx European mesoscale dataset, indicating that the representation of the diurnal cycle was better in the DOWA.

5 Acknowledgement

The activities for which the results are described in this report are carried within the framework of the DOWA project, i.e. a joint project with ECN.TNO, Whiffle and KNMI, which is financed by the Ministry of Economic Affairs and Climate Policy (SDE+ Hernieuwbare Energie Call).

6 References

Baas, P., 2014: Final report of WP1 of the WTI2017-HB Wind Modelling project. Scientific Report, WR 2014-02, De Bilt: KNMI.

Brand, A.J., and T. Hegberg, 2004: Wind resource in the Dutch part of the North Sea, ECN-RX—04-132. Presented at the European Wind Energy Conference 2004, London.

Burton, T., N. Jenkins, D. Sharpe, and E. Bossanyi, 2011: Wind energy handbook. John Wiley & Sons, Ltd. Chichester, UK.

Crockford, A., H. Pater, and E. Holtslag, 2015: Borssele Offshore Wind Farm Zone wind resource assessment. ECOFYS Report (WIENL 15778).

De Rooy, W. C., and H. de Vries, 2017: Harmonie verification and evaluation. HIRLAM Technical Report (V70), 79 pp.

Donkers, J.A.J., A.J. Brand, and P.J. Eecen, 2011: Offshore Wind Atlas of the Dutch Part of the North Sea, ECN-M—11-031. Presented at the European Wind Energy Association conference 2011, Brussels.

Duncan, J. B., G. J. Marseille, and I. L. Wijnant, 2019: DOWA validation against ASCAT satellite winds. TNO Technical Report (TNO 2018 R11649).

Duncan, J.B., P.A. van der Werff, and E.T.G. Bot, 2018: Understanding of the offshore wind resource up to high altitudes (≤315 m). TNO Technical Report (TNO 2018 R11592).

Duncan, J. B., I. L. Wijnant, and S. Knoop, 2019: DOWA validation against offshore mast and LiDAR measurements. TNO Technical Report (TNO 2019 R10062).

Genc, A., M. Erisoglu, A. Pekgor, G. Oturanc, A. Hepbasli, and K. Ulgen, 2005: Estimation of wind power potential using Weibull distribution. *Energy Sources*, **9**, 809-822.

Mesinger, F., and Coauthors, 2012: An upgraded version of the Eta model. *Meteorology and Atmospheric Physics*, **116**, 63-79.

Peña, A., C. B. Hasager, S.-E. Gryning, M. Courtney, I. Antoniou, and T. Mikkelsen, 2009: Offshore wind profiling using light detection and ranging measurements. *Wind Energy*, **12**, 105-124.

Rehman, S., A. M. Mahbub Alam, J. P. Meyer, and L. M. Al-Hadhrami, 2012: Wind speed characteristics and resource assessment using Weibull parameters. *International Journal of Green Energy*, **9**, 800-814.

Seity, Y., P. Brousseau, S. Malardel, G. Hello, P. Bénard, F. Bouttier, C. Lac, and V Masson, 2011: The AROME-France convective-scale operational model. *Monthly Weather Review*¸**139**, 976-991.

Stepek, A., M. Savenije, H. W. van den Brink, and I. L. Wijnant, 2015: Validation of KNW-atlas with publicly available mast observations (Phase 3 of KNW project). KNMI Technical Report (TR-352).

Thiesen, J., and I. Ristic, 2011: Short-term wind power prediction. *5th Atmospheric Science Symposium*, Istanbul, TR.

Toros, H., G. Geertsema, G. Cats, 2014: Evaluation of the Hirlam and Harmonie Numerical Weather Prediction Models during air pollution episode over Greater Istanbul Area. CLEAR – Soil, Air, Water, **42**, 863-870.

Wieringa, J., and P. J. Rijkoord, 1983: Windklimaat van Nederland. Staatsuitgeverij Den Haag.

A Data quality control

The other quality control measures performed by ECN part of TNO on the LiDAR measurements are detailed below.

A.1 Plausible value checks

Plausible value checks were imposed on the wind data. Any 10-min value that satisfied the following criteria were removed from the data record and were not used for the DOWA validation.

- The mean wind speed was either greater than the period maximum wind speed or less than the period minimum wind speed.
- The mean wind speed was less than 0.05 m/s.
- Turbulence intensity (TI) for the period fell below 0.10 % (i.e. 0.001).
- At the measurement height, the value of TI was 10 standard deviations (σ_{TI}) greater than the mean (μ_{TI}) TI value (i.e. $TI \geq \mu_{TI} + 10\sigma_{TI}$); μ_{TI} and σ_{TI} were defined as the height-respective value for the entire data collection period. Because TI typically decreases with mean wind speed, this threshold was only imposed if the 10-min mean wind speed exceeded 4 m/s.

A.2 Quality control specific to LiDAR type

Quality control measures specific to the LiDAR (i.e. ZephIR 300s versus the WINDCUBEv2) data were also applied. Any 10-min observation that satisfied the following criteria were removed from the data record.

- A LiDAR error code (e.g. 9998 or 9999) was reported.
- A carrier-to-noise ratio (CNR) (i.e. a measure of signal quality) less than -22. CNR information was only outputted with the WINDCUBEv2 LiDAR data.
- Backscatter magnitude less than $1e^{-5}$ or greater than 100. Backscatter served as a proxy for CNR for the ZephIR 300s wind LiDAR data wherein CNR information was not available.
- Data availability within the 10-min period less than 80 %.

The ZephIR 300s wind LiDAR uses a compact met station equipped with a sonic anemometer to determine the sign of the wind direction. The use of this sonic anemometer can sometimes lead to a 180º wind direction error (Peña et al. 2009), especially at low wind speeds. Analysis performed by ECN part of TNO of LiDAR wind data at MMIJ collected across a two-year period indicated that this flow-reversal error was evident in approximately 3.6 % of the data record (Poveda and Wouters 2014). This flow-reversal can be identified and mitigated by comparing the LiDAR wind directions to an independent wind direction source (e.g. a meteorological mast). However, an independent measurement source was not available at each of the measurement locations. Therefore, instead of using collocated mast measurements to mitigate this error, wind direction data from the DOWA was used. If the absolute difference between the DOWA and LiDAR wind directions was between 160º and 200º (i.e. $\pm$20º from 180º), then the wind direction measurement was not considered in the presented analyses. Because wind directions can vary significantly at lower wind speeds, this difference was only examined when the LiDAR wind speed was greater than 4 m s^{-1}. These 180º wind direction errors do not impact the quality of the measured wind speeds.