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DOWA validation against coastal wind lidar measurements

S. Knoop and I.L. Wijnant

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Steven Knoop and Ine Wijnant

Royal Netherlands Meteorological Institute (KNMI), P.O. Box 201, 3730 AE De Bilt, The Netherlands

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Abstract

The creation of the Dutch Offshore Wind Atlas (DOWA) is 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 aims to provide the developers of offshore wind power in the Netherlands with knowledge on wind conditions additional to the information in the KNMI North Sea Wind (KNW) atlas.

In this report, the DOWA is validated against wind lidar measurements from a Dutch coastal location (Tweede Maasvlakte) of a period of 13 months, and compared to the KNW-atlas. We find for DOWA a mean bias in the wind speed of -0.2 m/s (i. e. DOWA overestimates the wind speed), with a standard deviation of 1.2 m/s, which for KNW are -0.1 m/s and 1.5 m/s, respectively. DOWA captures the diurnal cycle much better than KNW (which suffers from huge jumps in the hourly mean wind every six hours due to the cold starts) and seasonal patterns in the diurnal cycle are also nicely reproduced. A linear regression analysis of DOWA compared to the measurements gives values for the slope of around 0.99 and for R^2 of about 0.92, which are better than KNW (0.97 and 0.88, respectively). Thus, DOWA provides an improvement in the hourly correlation. The mean bias in the wind direction is -7° and -6° with a standard deviation of 25° and 28° for DOWA and KNW, respectively, which show both strong dependence on the wind direction, while only the standard deviation is sensitive to the considered range of wind speeds. The validation analysis is also done separately for land wind and sea wind, which reveal quite some differences in the validation results, in particular in the hourly correlation of the wind speed and the wind direction bias.

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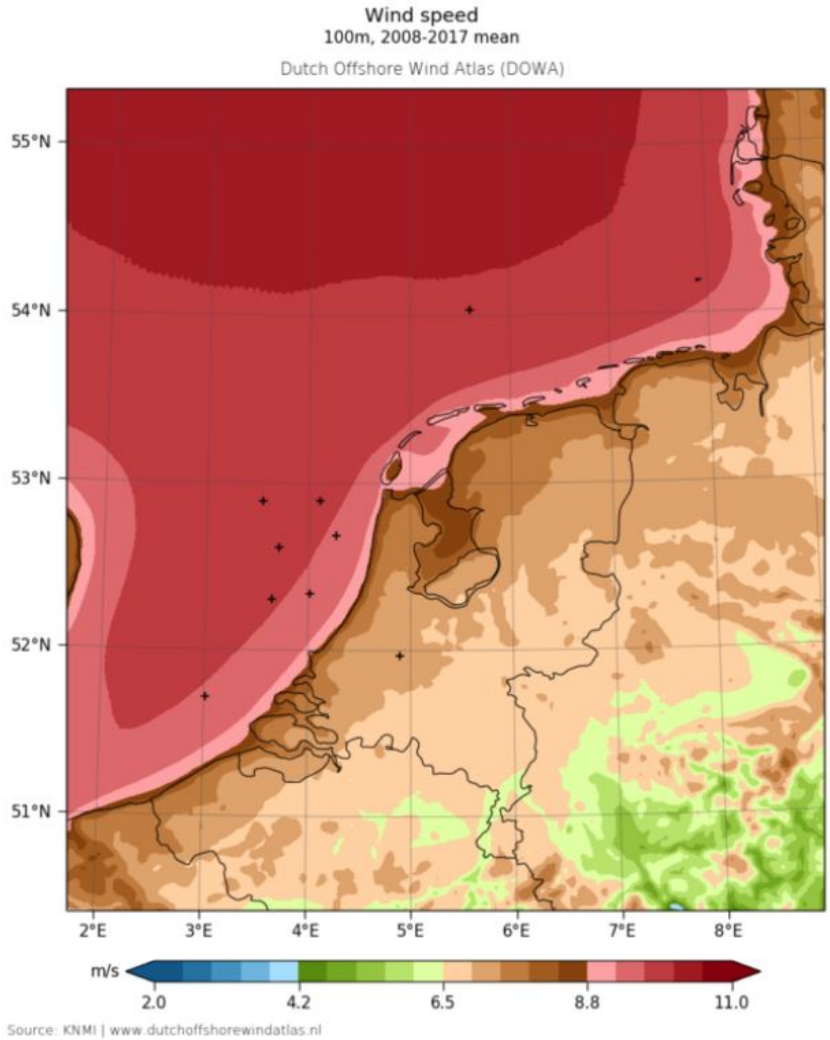


Figure 1: Sample picture from the DOWA website [1], showing the 10-year (2008-2017) average wind speed at a height of 100 m. The "+"-symbols are the locations of Cabauw and wind farm zones Borssele, Hollands Kust Zuid, Zuidwest, Noord, Noordwest and West, Ijmuiden Ver and Ten Noorden van de Wadden.

1 Introduction

The Dutch part of the North Sea is expected to see a significant growth in wind energy production over the next decade. By 2023, this area 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 energy requires a thorough understanding of the offshore wind conditions. While offshore wind measurements exist, they are limited in space and time. However, by using mesoscale atmospheric models to increase the spatial and temporal resolution of global reanalysis datasets, wind atlases can be developed to depict the offshore wind climatology at various locations and heights.

In 2013 the Royal Netherlands Meteorological Institute (KNMI) launched the KNMI North Sea Wind (KNW) atlas [2] to depict offshore wind conditions across the North Sea. The KNW-atlas is based on the global reanalysis ERA-Interim and was downscaled using atmospheric model HARMONIE, providing a long-term wind atlas from 1979 onwards. This KNW-atlas is validated against offshore and Cabauw mast [3] and scatterometer [4] wind measurements. Results demonstrated the ability of the KNW-atlas to accurately depict the wind speed climatology (long-term averages and extremes) with the comparable accuracy of a standard cup or sonic anemometer. Because the KNW-atlas was made with six-hourly 'cold starts' and a coarse global reanalysis, the KNW-atlas did not exhibit a strong correlation with the hourly wind measurements. In addition, the KNW atlas required the application of a uniform wind shear correction to compensate the underestimation of the increase of wind with height by HARMONIE.

In January 2019, the Dutch Offshore Wind Atlas (DOWA) [1] was made public, which was part of a joined project of ECN part of TNO, Whiffle, and KNMI, supported by the Topsector Energy subsidy from the Ministry of Economic Affairs and Climate Policy (SDE+ Hernieuwbare Energie Call). The DOWA is a wind atlas based on a 10-year reanalysis (2008-2017)[1]. Compared to KNW, the DOWA is made using global reanalysis ERA5, a newer version of HARMONIE and newer methods, in order to improve

[1]More recently the DOWA dataset was extended to include 2018, which is used in this validition report.

Figure 2: Map of part of the Dutch coast, indicating the location of the wind lidar measurements at the Tweede Maasvlakte. (Google maps)

the hourly correlation, the representation of the average diurnal cycle and the vertical wind shear [5]. A sample picture of the average wind speed at a height of 100 m is shown in Fig. 1. As part of the DOWA project, the KNW-atlas was extended using the same model-setup to guarantee a homogeneous dataset.

To prove and quantify the quality of DOWA, and to make a comparison with the KNW-atlas, validation studies have been performed, against offshore satellite wind measurements (ASCAT) [6], offshore meteo mast and wind lidar measurements [7] and mast wind measurements at Cabauw [8]. In this report we present results from a validation of DOWA against wind lidar measurements on the Dutch coast, namely at the Tweede Maasvlakte (see Fig. 2), consisting of wind profiles up to a height of 200 m.

The structure of this report is as follows. In Sect. 2 the wind lidar instrument is introduced. In Sect. 3 the coastal site and the corresponding wind lidar measurements are described, including data availability and auxiliary mast wind measurements. In Sect. 4 the methodology of the validation is discussed, and in Sect. 5 the main results of the validation study are presented. The discussions on the validation results and conclusions are given in Sect. 6 and Sect. 7 respectively.

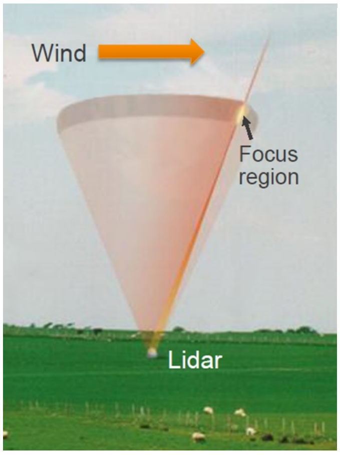
2 Wind lidar

Wind lidars are laser-based remote sensing instruments that measure wind speed and wind direction aloft by measuring the Doppler-shift of the backscattered laser light, typically by aerosols in the moving air. The measurements used in this validation report are obtained with a ZephIR 300 vertical profiling wind lidar (ZX Lidars, previously ZephIR Lidar, UK [9]).

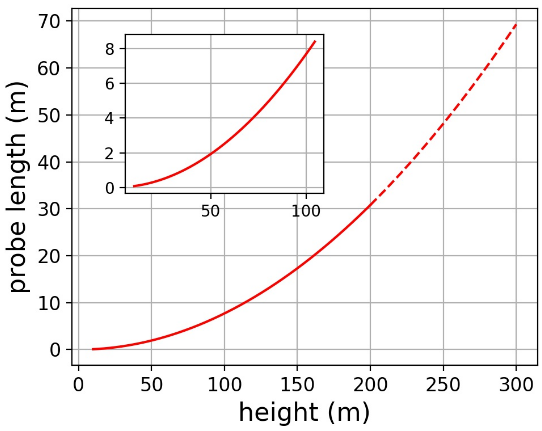
The ZephIR 300 is a homodyne, continuous-wave (CW) focusing wind lidar, in which the laser beam performs a so-called velocity azimuth display (VAD) scan, in order to be sensitive to the horizontal wind speed (see Fig. 3(a)). The scanning cone angle is 30°, meaning that at a measuring height of 100 m, the probed volume has a diameter of 115 m. For each height one complete VAD scan takes 1 s from which the 3D wind vector is reconstructed (i. e. horizontal and vertical wind speed, horizontal wind direction). The different heights are measured sequentially by changing the focus of the laser beam after each VAD scan. The manufacturer specifies the wind speed and wind direction accuracies as <0.1 m/s and <0.5°, respectively, and the height range is 10-200 m above the instrument.

Being a CW focusing wind lidar, the probe length increases quadratically with height: at 10 m height above the instrument the probe length is 0.07 m, whereas at 200 m it is 30 m (see Fig. 3(b)). Thus, one has to keep in mind that besides the horizontal spatial averaging, because of the conical scan, there is also a height dependent vertical spatial averaging through the finite focus region. Of course, for the sake of DOWA or KNW validation this is not important because these length scales are still much smaller than the size of the model grid boxes.

As a result of the homodyne detection, meaning that only the absolute value of the Doppler-shift is measured, there is a 180° ambiguity in the measured wind direction. To solve this issue the ZephIR 300 includes an attached meteo station, which contains a sonic anemometer to measure the wind direction just above the instrument and provides an estimate for the remotely measured wind direction. Still, a few percent of incorrectly assigned wind direction events is possible, which can be (partly) corrected by an additional source of wind measurements, e. g. a nearby mast [10] or model output. Note that these wind direction errors do not impact the measured wind speed. Also related to the homodyne detection, the minimum reported wind speed value in the considered data here is about 0.6 m/s, and lower wind speeds



(a) CW wind lidar



(b) probe length

Figure 3: (a) Conical scan of a CW wind lidar in order to measure the horizontal wind, ranging by focusing the laser beam at a particular height. (b) Probe (or focus) length of the ZephIR 300 wind lidar as function of height.

are not recorded. For more information about CW wind lidars, in particular the ZephIR, see Ref. [11].

The instrument outputs quality controlled 10-minutes averaged data, including horizontal and vertical wind speed, horizontal wind direction, minimum, maximum and standard deviation of the horizontal wind speed, and turbulence intensity. For the DOWA validation only the 10-minutes averaged data of horizontal wind speed and wind direction is considered. The overall data availability is about 98% or better (see Sect. 3.1), mostly limited by fog or low clouds. No additional quality control or filtering is applied to the wind lidar data. A recent comparison of this particular instrument with the Cabauw mast in situ measurements is given in Ref. [10].

3 Coastal site: Tweede Maasvlakte

3.1 Wind lidar measurements

The Tweede Maasvlakte (or Maasvlakte 2) is very recently (2008-2013) reclaimed land of approximately 2000 hectares adjoining the (Eerste) Maasvlakte. In 2017-2018 Ventolines has performed a wind measurement campaign and wind study at the Tweede Maasvlakte, commissioned by Rijkswaterstaat (RWS) [12]. In this campaign a ZephIR 300 wind lidar was installed on the outer ring of the area (GPS coordinates: 51.97834, 3.97740 or 51°58'42.0"N 3°58'38.6"E), see Fig. 4. Measurements were taken from April 6, 2017 until May 15, 2018. The wind lidar was installed on a dike, which has an altitude of +11.75 m NAP and which is the highest part of the area, see Fig. 5. The wind lidar was configured to measure at the following heights (above NAP, so including the height of the dike): 23, 43, 51, 78, 93,

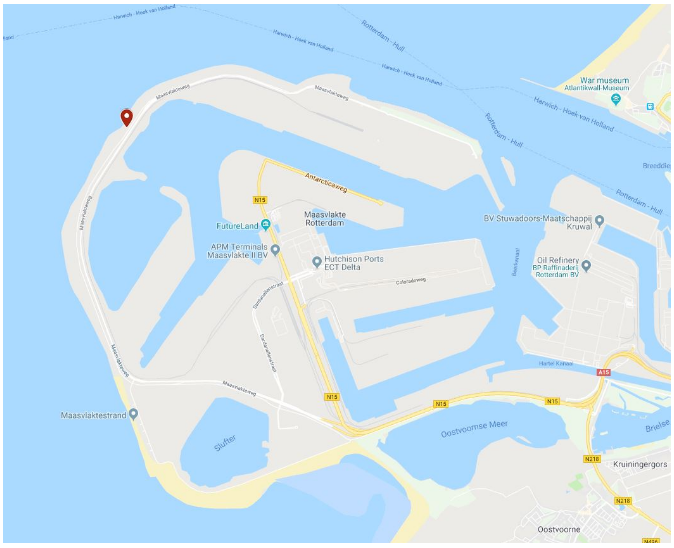


Figure 4: Zoom in of Tweede Maasvlakte, indicating the location of the wind lidar with the red dot. (Google maps)

Figure 5: Photo of the wind lidar ("Lidar ZP598") at the outer ring dike of the Tweede Maasvlakte, including the wind mast ("Windsnelheidsmeter") and visibility sensor ("Zichtbaarheidsmeter). Taken from Ref. [12].

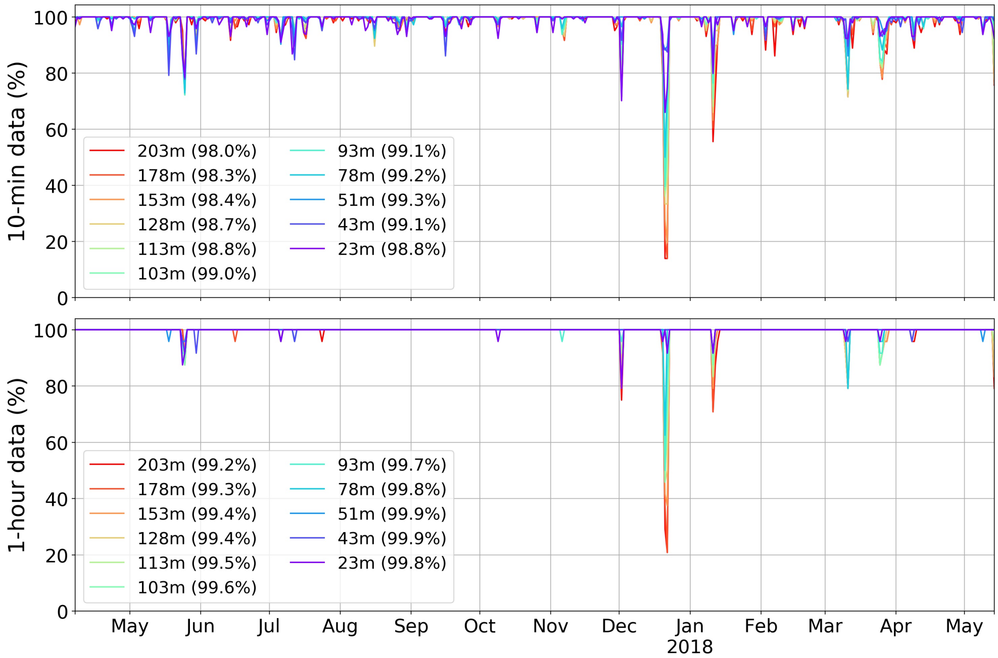


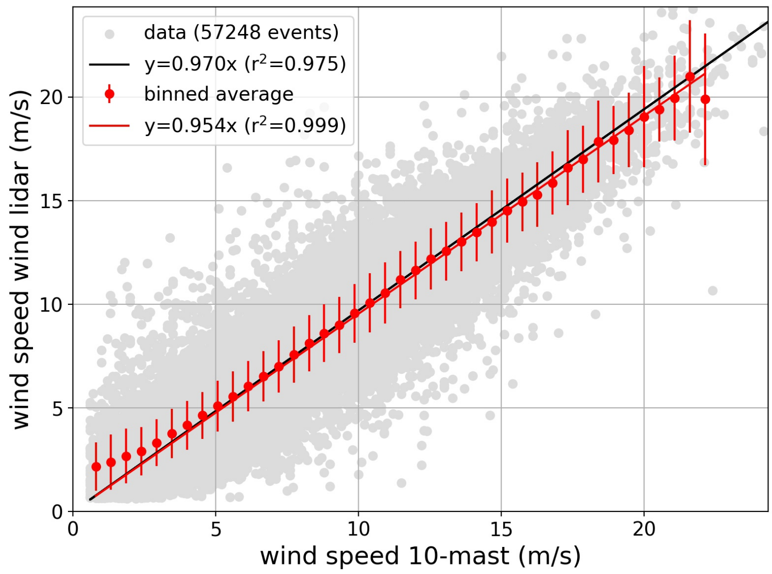
Figure 6: Daily data availability of the 10-minute (upper panel) and 1-hourly (lower panel) averaged data at the Tweede Maasvlakte. In the legends the overall data availability per height for the whole period is given (April 6, 2017 to May 15, 2018). Data availability is defined as the percentage of daily valid 10-minute or hourly wind lidar values, in which a valid hourly data requires only one valid 10-minute data.

103, 113, 128, 153, 178, 203 m.

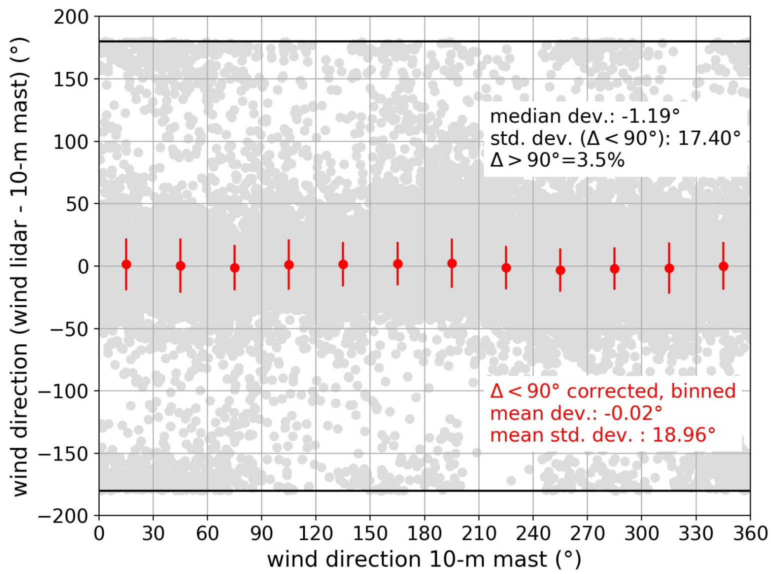
The daily data availability of the wind lidar is shown in Fig. 6. The overall 10-minute data availability is 98% or better, and the 1-hour data availability, requiring at least one valid 10-minute output each hour, is above 99%. The strongest dips, on December 21-22 and January 11, are due to thick fog.

The wind lidar was installed directly next to a 10-m wind mast of RWS (see Fig. 5), equipped with cup anemometer and wind vane. The wind mast data can be used to validate the wind lidar of the lowest measuring height, check for the correct alignment of the wind lidar, and (at least partially) correct for possible 180° errors in the wind lidar wind direction data. In Fig. 7 scatterplots of the wind speed and wind direction are shown, comparing the (10 minute averaged) wind mast measurements and the lowest measuring height of the wind lidar. above the dike). For wind speed an overall good agreement and strong correlation is observed, despite the small height mismatch of 1 m (the lowest measuring height of the wind lidar is 11 m above the dike), and only for the very low wind speeds some difference is seen. For wind direction the very small median deviation suggests correct alignment of the wind lidar (assuming the wind vane of the wind mast is correctly installed). Part of the data in the scatterplot is clustered around $\pm 180°$, due to the 180° issue in the wind lidar (see Sect. 2). We quantify this effect by considering the number of events for which the absolute value of the deviation is larger than 90°, indicated as "$\Delta > 90°$". We find (for wind speed larger than 0.5 m/s) $\Delta > 90°$=3.5%, which is comparable with other studies [10, 13]. In Fig. 8 a histogram of the 10-mast wind speeds is shown, together with the $\Delta > 90°$ events, indicating that those errors are correlated with low wind speeds.

With the wind direction information from the 10-m mast we apply a correction to the wind lidar



(a) wind speed



(b) wind direction

Figure 7: (a) Wind speed and (b) wind direction comparison between the lowest measuring height of the wind lidar (11 m above the dike) and the collocated 10-m mast at the Tweede Maasvlakte, in which the results of statistical analysis of unbinned (gray) and binned (red) data are shown. The error bars indicate the standard deviation. Events for which the mast reported wind speeds below 0.5 m/s are filtered out.

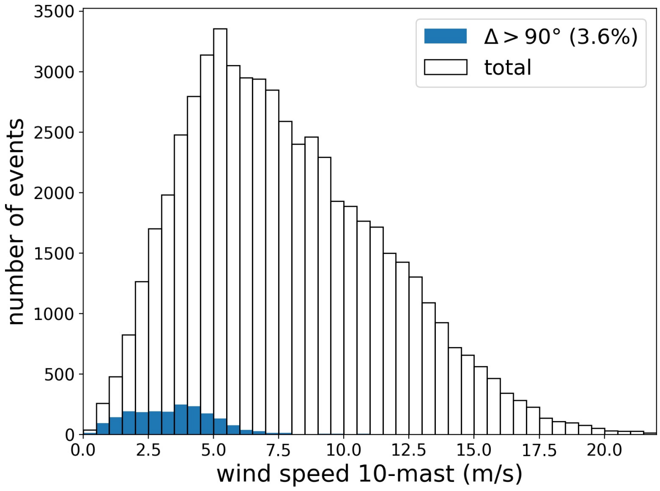


Figure 8: Histogram of the reported wind speeds (bin size 0.5 m/s) of the 10-m mast at Tweede Maasvlakte, indicating that the $\Delta > 90°$ events (in blue) occur almost exclusively with low wind conditions.

data by changing the wind direction by 180° (for all heights) for each 10-minute timestamp at which $\Delta > 90°$ occur. By definition, this gives a perfect correction for the lowest measuring height of the wind lidar, and a partial (but significant) correction for the other heights, where the percentage of remaining 180° error events will increase with height, but will probably stay below 2% [10]. The corrected wind lidar measurements are used for the DOWA validation. Again, the wind direction correction has no impact on the wind speed measurements.

Regarding the measurement location, the wind lidar is installed on a 12 m high dike, which will influence the wind flow, in particular when the wind direction is perpendicular to the orientation of the dike (either from sea or from land). This effect can be observed in the vertical wind speed measured by the wind lidar. In Fig. 9(a) histograms of the vertical wind speed for different heights are shown. Typically, the vertical wind speed distribution are centered around zero, with a width on the order of a few 0.1 m/s. However, for the lower levels, asymmetric distributions shifted towards positive vertical wind speeds (upward motion) are observed. This is also highlighted in Fig. 9(b), in which a height profile of the mean vertical wind speed is shown. Here we observe that the effect of the dike on the vertical wind speed decreases rapidly with height. A quantitative analysis on the impact of the dike on the horizontal wind speed is beyond the scope of this validation report. However, for the comparison of the wind lidar measurements and the models (in which the dike is not present) a possible bias at the lower height due to the dike should be considered.

For this validation study it is interesting to make a distinction whether wind is coming from sea or from land. We define the sea wind sector between wind directions 215° and 30° (as measured by the wind lidar), following the orientation of the dike (Fig. 4), and all the other wind directions define the land wind sector. Note that within the land wind sector there is also a lot of water, inside and around the Tweede Maasvlakte. The wind direction distribution is shown in Fig. 10 as wind roses for the lowest and highest measuring height. In Table 1 the percentages of hourly data in the land and sea wind sector are given for each measuring height, showing a small increase (decrease) of data in the sea (land) wind sector with increasing height.

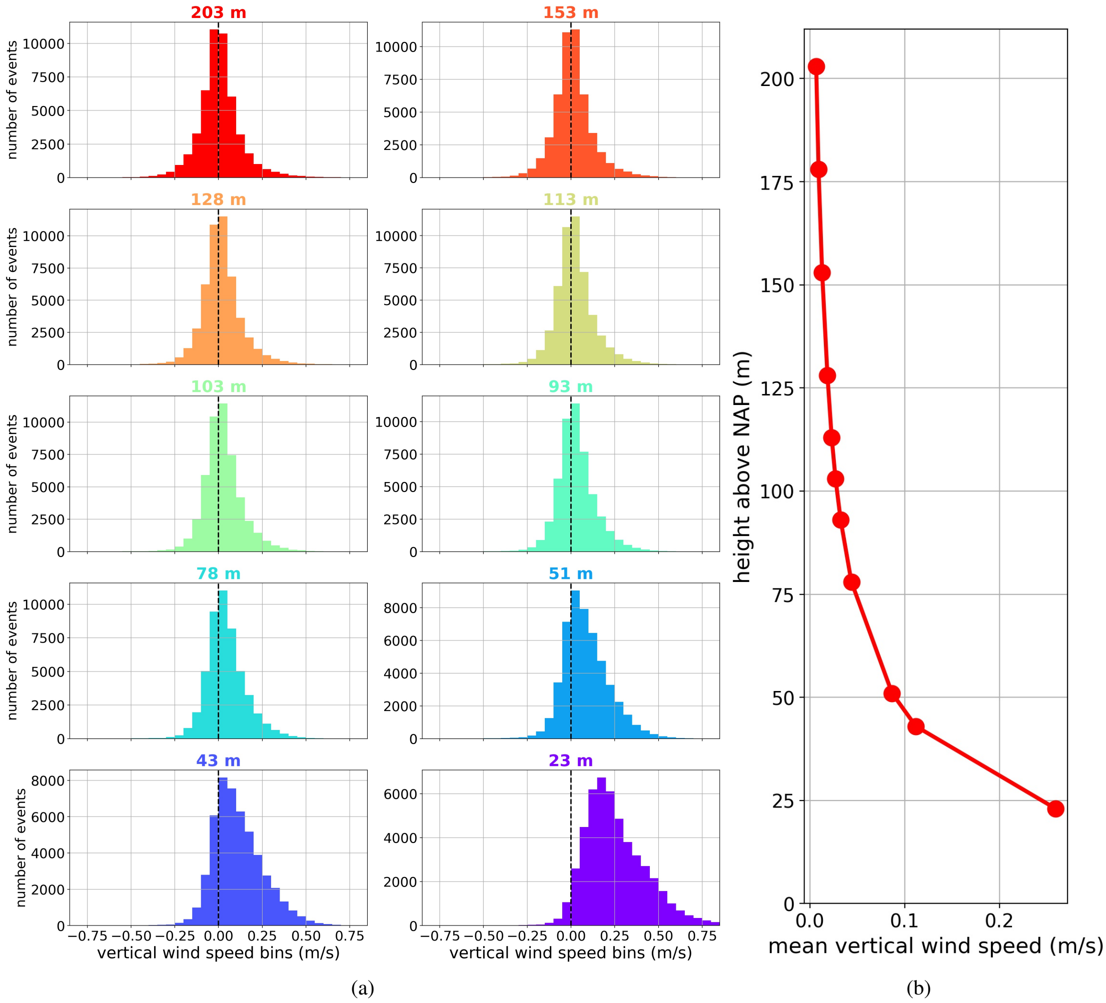
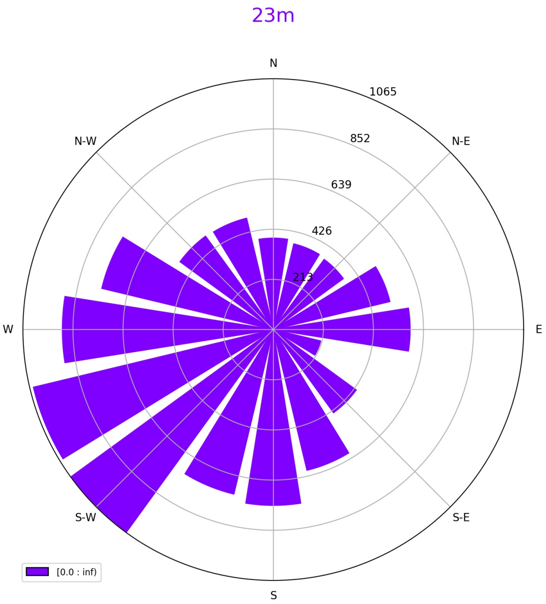
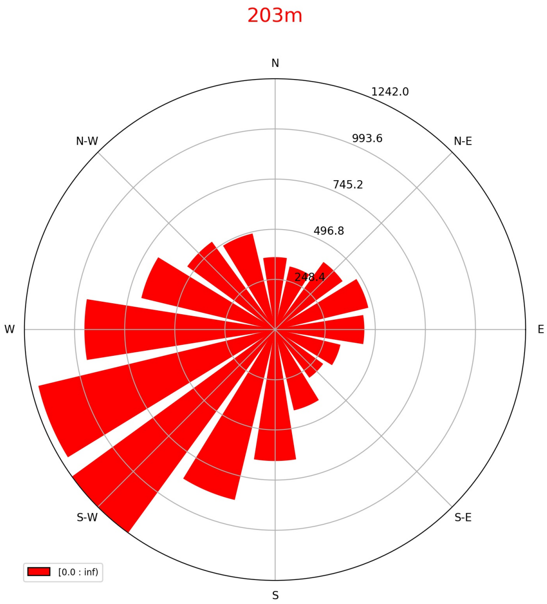


Figure 9: Vertical wind speed (10-minute averaged) measured by the wind lidar: (a) Histograms of the different heights (bin size 0.05 m/s), (b) height profile of the mean vertical wind speed. Positive vertical wind speeds corresponds to an upward motion.



(a) 23m



(b) 203m

Figure 10: Wind roses (bin size 22.5°) of the wind lidar measurements (hourly averaged) for (a) the lowest height 23 m and (b) the highest height of 203 m.

height (m)	land (%)	sea (%)
23	44.2	55.8
43	43.9	56.1
51	43.7	56.3
78	43.4	56.6
93	43.3	56.7
103	43.1	56.9
113	43.0	57.0
128	42.7	57.3
153	42.2	57.8
178	41.8	58.2
203	41.2	58.8

Table 1: Percentages of land and sea wind (from hourly average wind lidar measurements).

3.2 Wind atlases

The DOWA and KNW wind atlases are extensively described in the report on the DOWA dataset [5] and previous validation reports (see e. g. Ref. [8]). In short, the KNW-atlas and the DOWA are based on ECMWF (European Centre for Medium-Range Weather Forecasts) ERA-Interim and ERA5 reanalyses, respectively, which are downscaled using different versions of the atmospheric weather model HARMONIE. In contrast to KNW, in DOWA additional measurements (ASCAT-satellite surface winds and MODE-S-EHS aircraft wind profiles) are assimilated in HARMONIE and no (six-hourly) cold starts were used, which should both result in a better hourly correlation with measurements and a better representation of the average diurnal cycle. The horizontal grid spacing of KNW and DOWA is 2.5 by 2.5 km, and the published output heights are 10, 20, 40, 60, 80, 100, 150 and 200 m (KNW) and 10, 20, 40, 60, 80, 100, 120, 140, 150, 160, 180, 200, 220, 250, 300, 500 and 600 m (DOWA).

The GPS coordinates of the nearest DOWA and KNW grid point to the measurement location are (51.979,3.987) and (51.983,3.970), respectively, both about 0.7 km away, but either towards east (DOWA) or west (KNW) (see Appendix A). In Fig. 11 land-sea-mask maps of KNW and DOWA are shown, providing information to what extend the model grid boxes are considered as sea or land. Some differences between KNW and DOWA are visible, which might reflect how well the models match the measurements, especially for the lower levels, where for which the local roughness has a large effect on the wind.

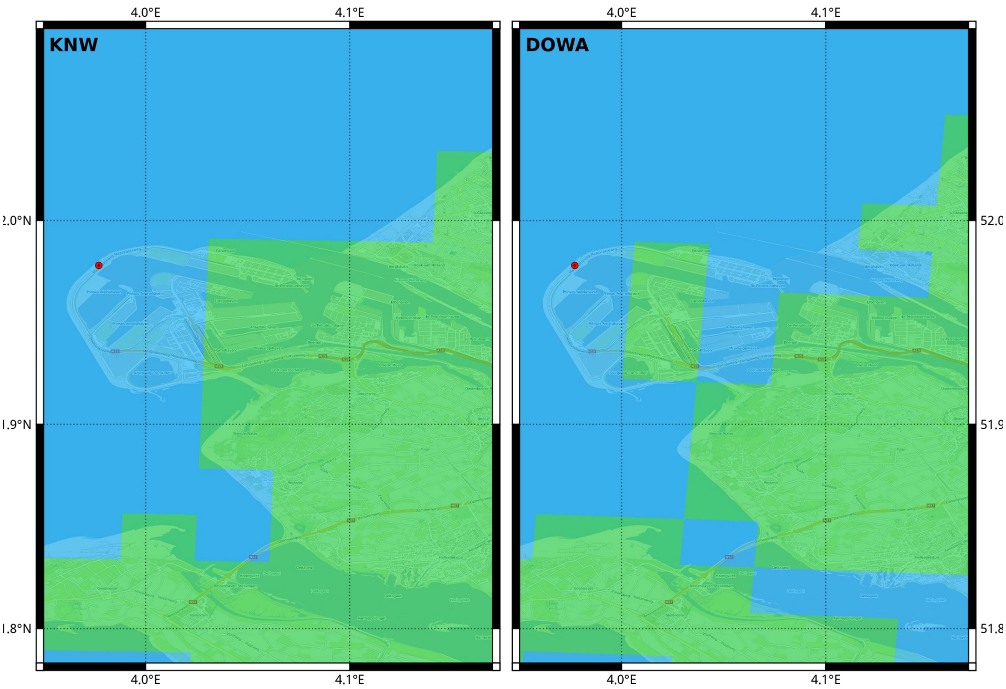


Figure 11: Land-sea-mask map of KNW (left) and DOWA (right), showing the model grid boxes in blue (green) if more than 50% is considered water (land). Wind lidar located indicated with the red dot. (provided by Bert van Ulft)

4 Validation methodology

For the preparation the different datasets (measurements and wind atlases) in order to make comparable collocated datasets several steps are taken or considerations are made:

- The wind atlases have an hourly output that represents the state of the atmosphere at the full hour. The wind lidar measurements used are 10-minute averages. To validate DOWA and KNW, one hour of measurements are averaged, i. e. six 10-minute averaged data values are taken, namely those belonging to the half hour before and the half hour after the full hour. This 60 minute average was compared to the hourly DOWA/KNW output (that represents a 2.5 by 2.5 km grid box average).
- The validation is conducted for all measuring heights of the wind lidars. A cubic-spline interpolation scheme was used to interpolate the model data to those heights. The highest wind lidar height of 203 m exceeds the range of KNW. Here the 200 m KNW output values are taken, which is justified because at this height the probe length is much larger than this difference (see Fig. 3(b)).
- For temporal averaging and height interpolation "scalar averaging" of wind speed and wind direction is applied. This means that the wind speed and wind direction are averaged independently (in contrast to "vector averaging" in which the wind vector is averaged and therefore the wind direction is weighted with the corresponding wind speed).
- We only consider hourly wind atlas information for which there is a valid wind lidar measurement. Thus, timestamps for which wind lidar measurements are missing are filtered out, which is less than 1% of the data, see Figs. 6).
- For DOWA and KNW no spatial interpolation of the wind atlas data has been performed. We simply took the nearest grid point to the wind lidar location, as described in Sect. 3.2. In Appendix A a comparison is made with the westerly neighboring (more sea like) grid points of DOWA and KNW, indicating that the choice of grid point has only a very small effect on the validation results.
- The model variance is used to assess the significance of the differences between the atlasses and the measurements (i. e. the bias). The model variance is estimated by calculating the standard deviation of the mean, taking into account an equivalent sample size (ESS) based on an autoregression of order 1 model (see Appendix B). We apply (and show) the uncertainty estimates solely on the bias (measurements - model) to avoid seasonal effects, and only on the model part, not taking into account the measurement uncertainty (which is described in Sect. 2).

  Compared to the DOWA Cabauw meteomast validation [8] the model variance in this report is much larger, due to the much shorter dataset (13 months compared to 10 years).

5 Validation results

In this section the validation results are presented. Bias is defined as the difference between measurement and atlas (referred to as "model"), meaning that a negative (positive) bias means that the model overestimates (underestimates) the measurements. Model variance is indicated in the bias plots as the shaded areas. The results are discussed in Section 6.

5.1 Mean wind speed

5.1.1 Monthly mean wind speed

As a first overview of the comparison between the wind lidar measurements and the models the monthly mean wind speed at a height of 103 m is shown in Fig. 12: the upper panel the wind speed measured by the wind lidar and from DOWA and KNW, the lower panel the mean bias between the wind lidar measurements and the models. The results of all heights are shown in Appendix C. The monthly mean wind speed shows a seasonal pattern with higher wind speeds in the winter and lower in the summer. DOWA shows a more constant bias around -0.2 m/s, whereas KNW shows a larger variation.

5.1.2 Mean wind speed and bias profiles

In Fig. 13 the height profiles of the mean wind speed (left panel), the mean bias (middle panel) and the standard deviation of the bias (right panel) for the full measurement period are shown, the latter two are also given in Table 2. The profiles show an increase of the mean wind speed with height. DOWA has a constant bias of -0.2 m/s from a height of 40 m upwards, and a bias of -0.1 m/s at 23 m. KNW has a smaller bias around -0.1 m/s, and nearly 0 m/s at 23 m.

For DOWA the standard deviation of the bias ranges from 1.2 to 1.3 m/s, while those KNW are slightly larger, ranging from 1.5 to 1.6 m/s. Thus, DOWA has a smaller standard deviation than KNW,

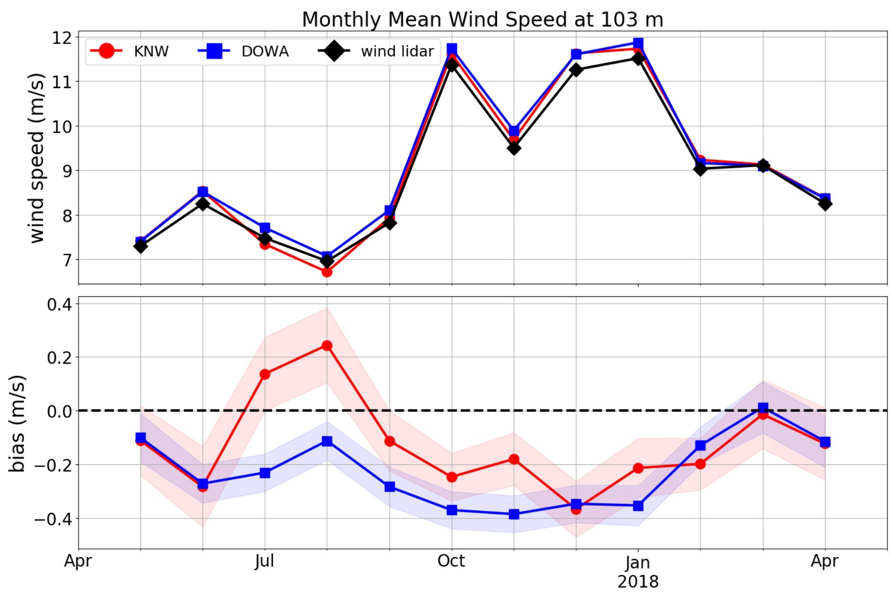


Figure 12: Monthly mean wind speed at a height of 103 m, showing wind lidar measurements (black), DOWA (blue) and KNW atlas (red).

which already indicates a better correlation between the model output and measurements, which will be further discussed below (Sect. 5.1.3 and 5.2).

In Fig. 14 the height profiles of the mean wind speed (left panel), the mean bias (middle panel) and the standard deviation of the bias (right panel) are shown again, but now making a distinction between land and sea wind. There is a clear difference in the mean wind speed, where the mean wind speed from sea is significantly larger than from land. For DOWA the mean bias for land wind is smaller (less negative) than sea wind, whereas for KNW the opposite is the case. The difference between DOWA and KNW sea wind speed bias is quite significant. In the standard deviation of the bias there is hardly a difference between land and sea wind.

The mean bias in the wind speeds can be further investigated by considering narrower wind sectors;

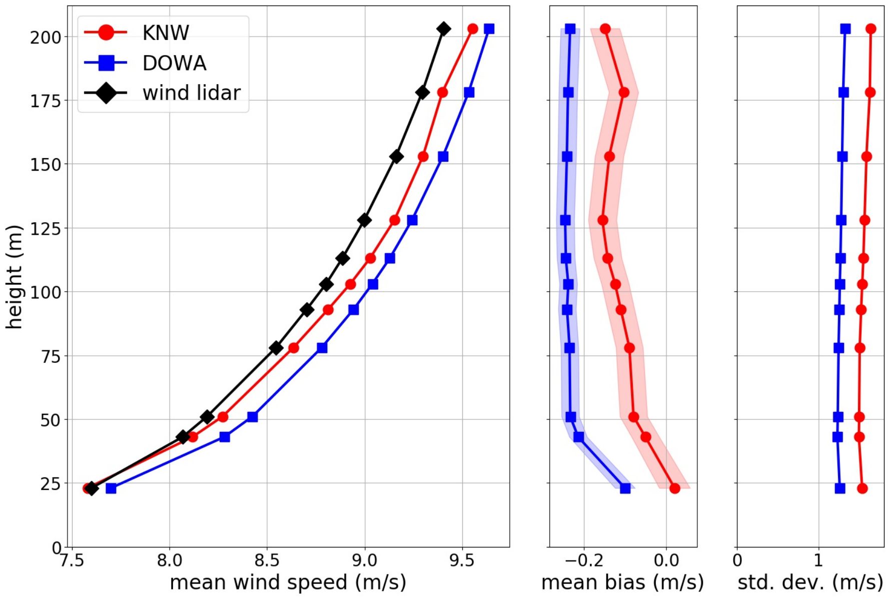


Figure 13: Height profiles of the mean wind speed (left), mean bias (middle) and standard deviation of the bias (right), showing wind lidar measurements (black), DOWA (blue) and KNW atlas (red).

height (m)	bias (m/s)		std. dev. (m/s)	
	DOWA	KNW	DOWA	KNW
23	-0.10	0.02	1.26	1.53
43	-0.21	-0.05	1.23	1.50
51	-0.23	-0.8	1.24	1.50
78	-0.23	-0.09	1.25	1.50
93	-0.24	-0.11	1.26	1.52
103	-0.24	-0.12	1.26	1.54
113	-0.24	-0.14	1.27	1.55
128	-0.24	-0.15	1.28	1.56
153	-0.24	-0.14	1.29	1.59
178	-0.24	-0.10	1.30	1.63
203	-0.23	-0.15	1.33	1.64

Table 2: Mean wind speed bias and standard deviation of the bias for DOWA and KNW.

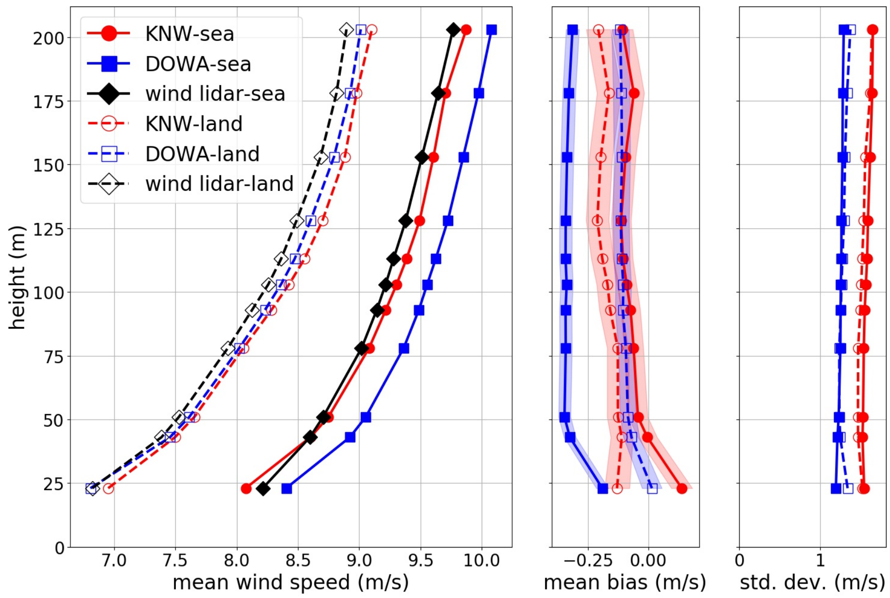


Figure 14: Same as Fig. 13, but making a distinction between land (dashed line, open symbols) and sea wind (solid line, closed symbols).

results are shown in Appendix D.

5.1.3 Hourly mean wind speed

In Fig. 15 the hourly mean wind speed at a height of 103 m is shown: the upper panel the wind speed of wind lidar measurements and both models, the lower panel the mean bias between the wind lidar measurements and the models. The results of all heights are shown in Appendix E. One notices that KNW shows strong non-physical "jumps" every 6 hours, which are absence for DOWA. The KNW "jumps" correspond with the use of cold starts with ERA-Interim every 6 hours. The height-dependence of the diurnal cycle is much weaker than typical observed for a "pure" onshore location [8], and only for the higher levels one can recognize a maximum during nighttime and minimum during daytime, while the opposite effect at the lower levels is not visible. This behavior is well captured by DOWA.

In Fig. 16 the hourly mean wind lidar measurements and DOWA data are displayed separately for the four seasons, showing clear differences between the seasons. We see that DOWA does an excellent job of capturing the diurnal dynamics in all seasons over the whole profile.

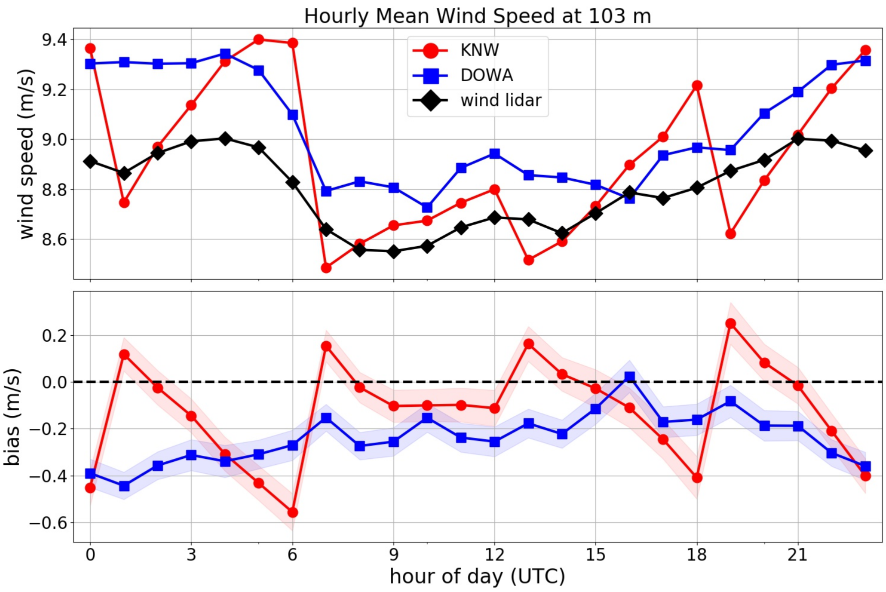


Figure 15: Hourly mean wind speed at 103 m, showing wind lidar measurements (black), DOWA (blue) and KNW atlas (red). The upper panel shows the wind speed of wind lidar measurements and models, the lower panel the mean bias between the wind lidar measurements and the models.

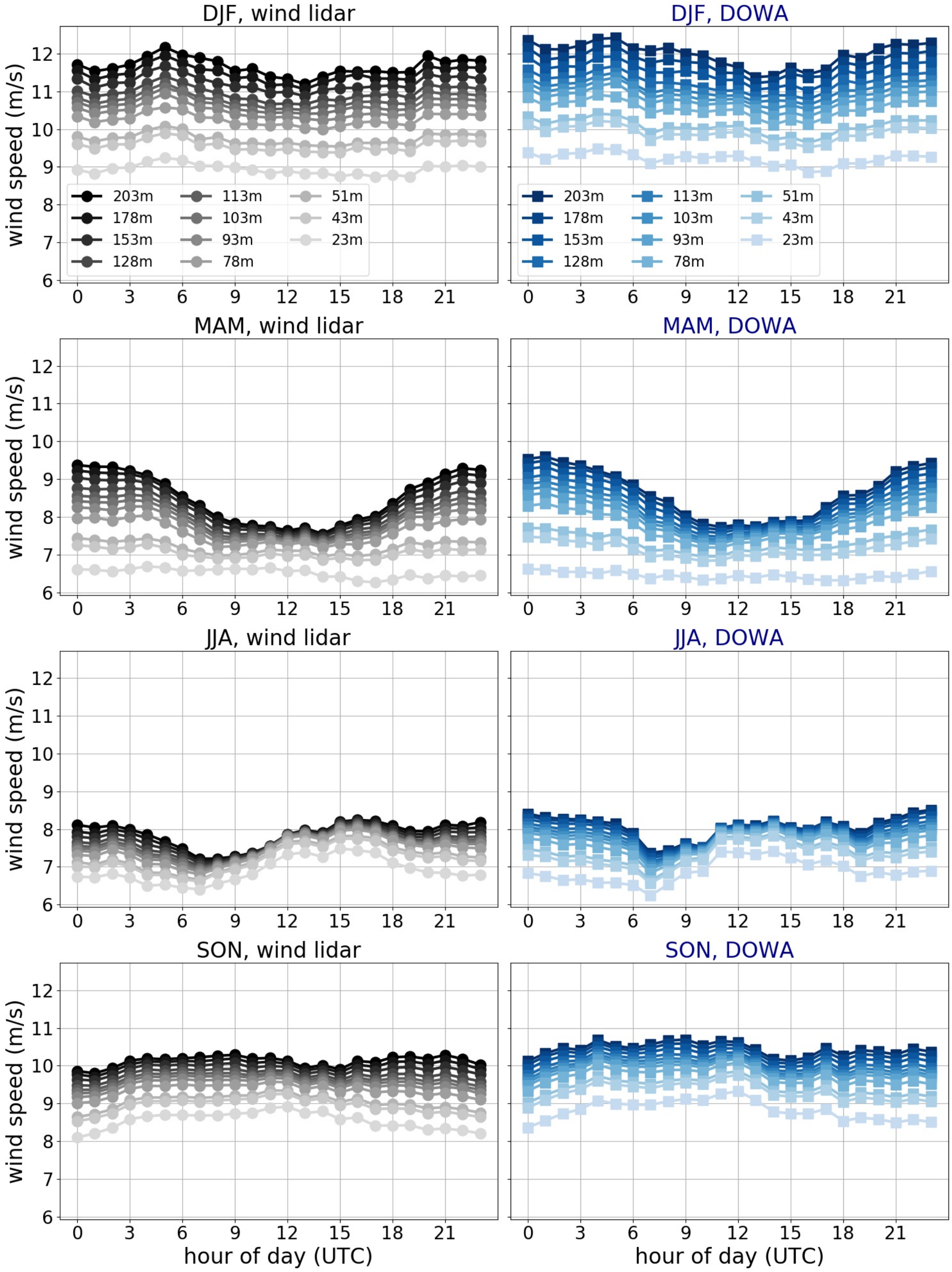


Figure 16: Hourly mean wind speed for the wind lidar measurements (left) and DOWA (right), separated into the four season: winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November).

5.2 Hourly wind speed correlation

The most direct validation of the models is to consider the hourly correlation between the model output and the wind lidar measurements. In Fig. 17 the DOWA wind speeds are plotted against the wind lidar wind speeds for a height of 103 m. The results of all heights are shown in Appendix F. Linear regression is performed to quantify the correlation between the models and the measurements: the expression $y = ax + b$ is fitted to the data and the coefficient of determination R^2 is determined. A perfect correlation would result in a slope $a = 1$, an intercept or offset $b = 0$, and a coefficient of determination R^2 of 1.

The fit results of all heights are shown as a height profile of the slope, offset and R^2 in Fig. 18 and Table 3, for the DOWA and KNW-atlas. For DOWA the slope ranges from 0.99 to 1.00, and is always closer to 1 than KNW, which ranges from 0.96 to 0.98. For DOWA the offset ranges from 0.2 to 0.3 m/s, while for KNW the offset ranges from 0.2 to 0.5 m/s. For DOWA R^2 ranges from 0.89 to 0.93, and is always closer to 1 than KNW, for which R^2 ranges from 0.84 to 0.88. Overall, these results indicate that DOWA provides an improvement in the correlation compared to KNW.

In Fig. 19 the fit results are shown again, making a distinction between land and sea wind. Regarding the slope, DOWA performs similar for land and sea wind, only the lowest height shows a clear difference. For KNW, the slope for land wind changes gradually with height, with slopes larger than one for the lower levels. In the offset similar behavior is visible. For R^2 better results are seen for the sea wind compared to the land wind, for DOWA and KNW.

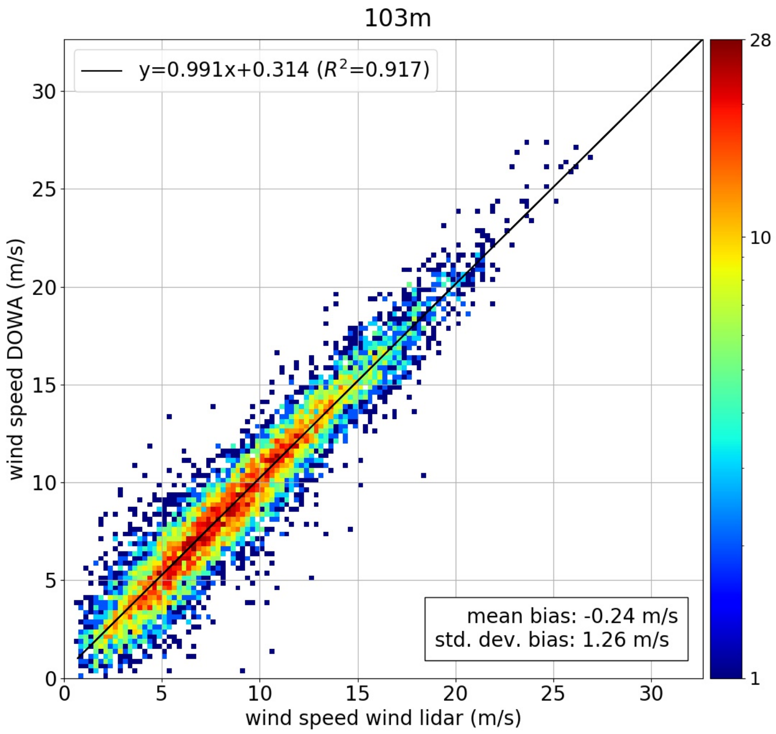


Figure 17: Scatterplot of the DOWA and wind lidar wind speed measurements (visualized as a density plot with logarithmic color scale), showing the result of a linear regression (slope, intersect and R^2) and the mean bias and standard deviation of the bias.

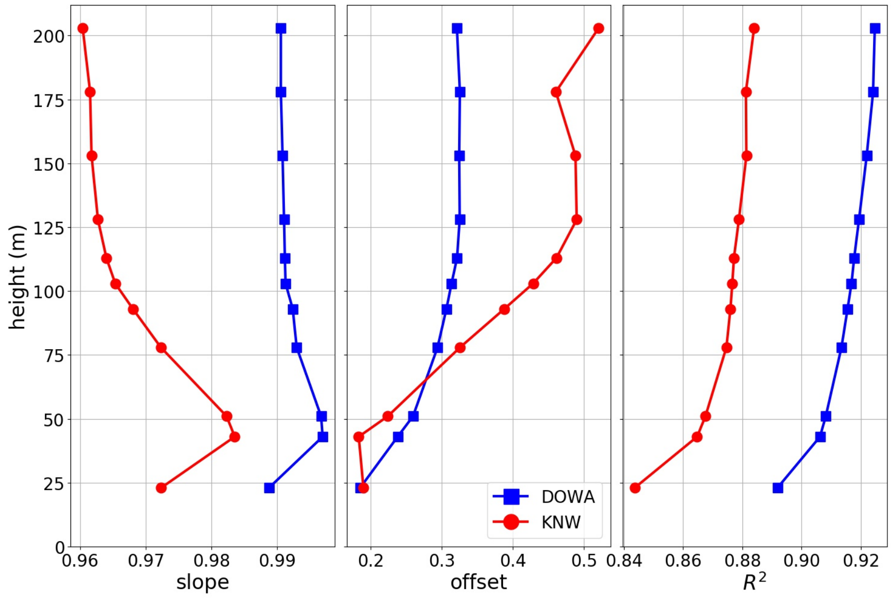


Figure 18: Height profile of the results of the linear regression (slope, offset and R^2) of the wind speed data, comparing the DOWA (blue) and KNW atlas (red).

height (m)	slope		offset (m/s)		R^2	
	DOWA	KNW	DOWA	KNW	DOWA	KNW
23	0.989	0.972	0.18	0.19	0.89	0.84
43	0.997	0.984	0.24	0.18	0.91	0.86
51	0.997	0.982	0.26	0.22	0.91	0.87
78	0.993	0.972	0.29	0.33	0.92	0.87
93	0.992	0.968	0.31	0.39	0.92	0.88
103	0.991	0.965	0.31	0.43	0.92	0.88
113	0.991	0.964	0.32	0.46	0.92	0.88
128	0.991	0.963	0.33	0.49	0.92	0.88
153	0.991	0.962	0.32	0.49	0.92	0.88
178	0.991	0.962	0.33	0.46	0.92	0.88
203	0.991	0.960	0.32	0.52	0.93	0.88

Table 3: Results of the linear regression fit in terms of the slope, offset and R^2 parameters, comparing DOWA and KNW.

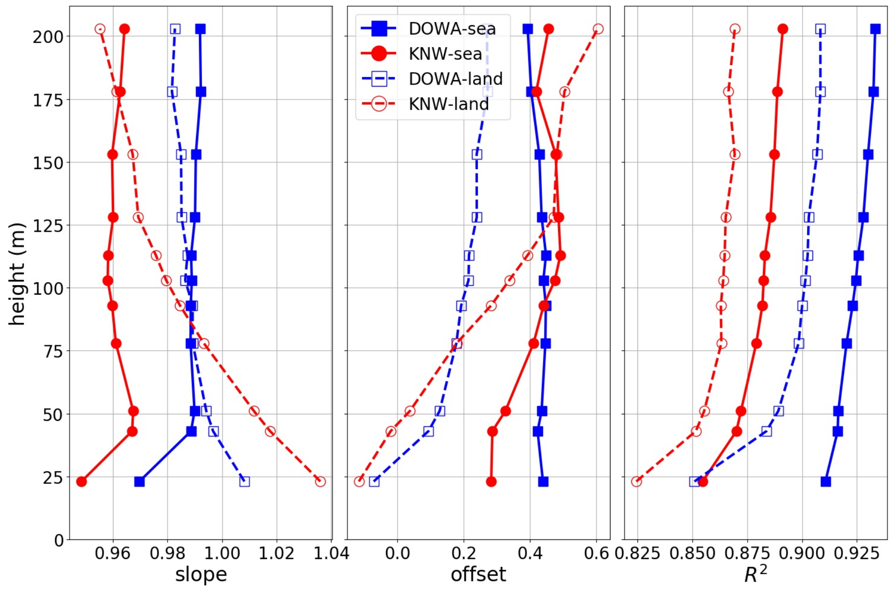


Figure 19: Same as Fig. 18, but making a distinction between land (dashed line, open symbols) and sea wind (solid line, closed symbols).

5.3 Hourly wind direction correlation and mean bias profiles

In Fig. 20 the DOWA wind directions are plotted against the wind lidar wind directions for a height of 103 m. The results of all heights are shown in Appendix G. From these plots the (directional) mean bias and standard deviation of the bias can be derived[2]. Height profiles of the mean bias and standard deviation of the bias for DOWA and KNW are shown in Fig. 21. For DOWA the mean bias is around -7°, for KNW around -6°. For DOWA the standard deviation of the bias is about 25°, for KNW 28°. The standard deviation in the wind direction bias is very sensitive to the selected wind speed range. In Fig. 21 also results are shown for wind speed above 4 m/s (dashed lines): the mean bias hardly changes but the standard deviation reduces significantly.

Height profiles of the mean bias and standard deviation of the bias for DOWA and KNW are shown again in Fig. 22, in which a distinction is made between land and sea wind. For DOWA and KNW, the mean bias for sea wind is clearly smaller (less negative) than for land wind, and also the standard deviation of the bias is smaller for sea wind than for land wind. The mean bias in the wind direction can be further investigated by considering narrower wind sectors; results are shown in Appendix H.

[2]A linear regression should not be applied to the wind direction data because the wind direction is not a continuous variable.

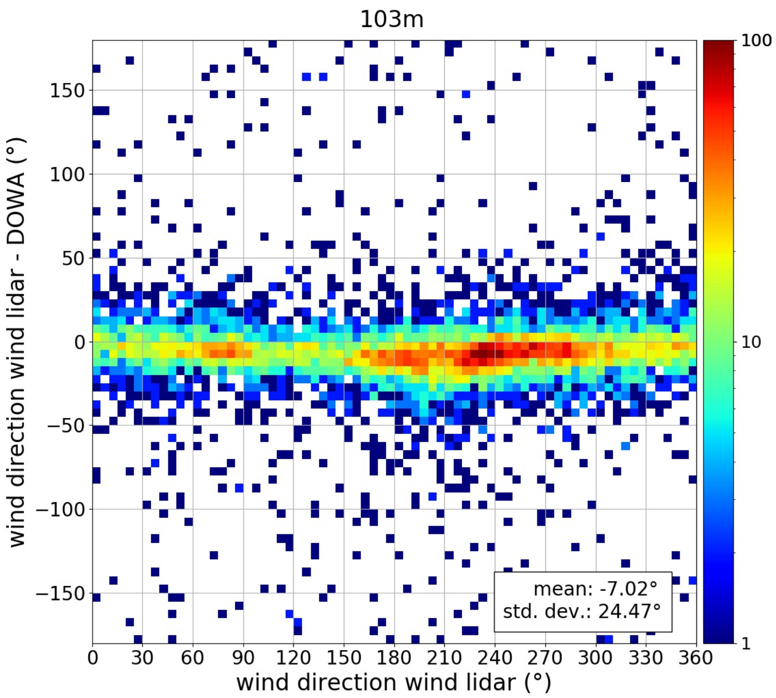


Figure 20: Scatterplot of the DOWA and wind lidar wind direction measurements at 103 m (visualized as a density plot with logarithmic color scale), showing the mean bias and standard deviation of the bias.

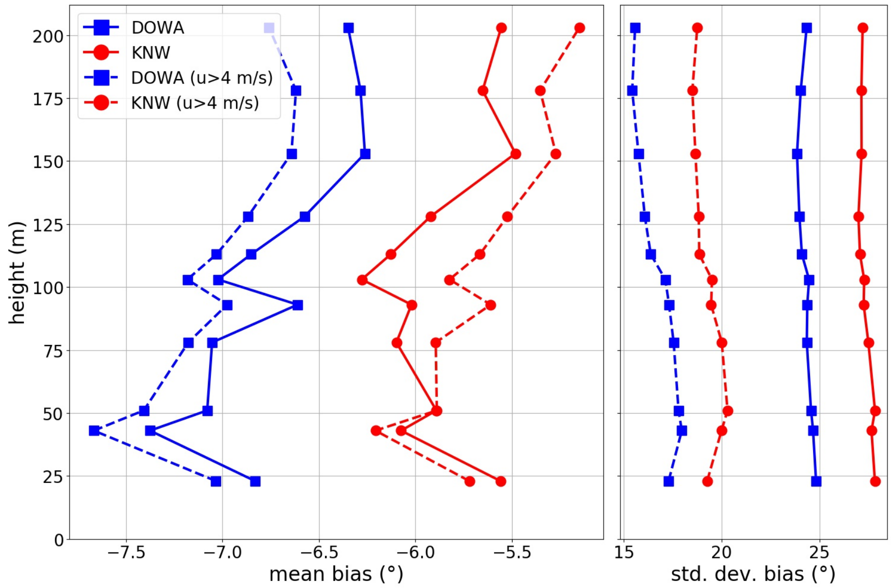


Figure 21: Height profiles of the mean bias (left) and standard deviation of the bias (right), showing DOWA (blue) and KNW atlas (red). Solid lines are all data, dashed lines only data with wind speed larger than 4 m/s.

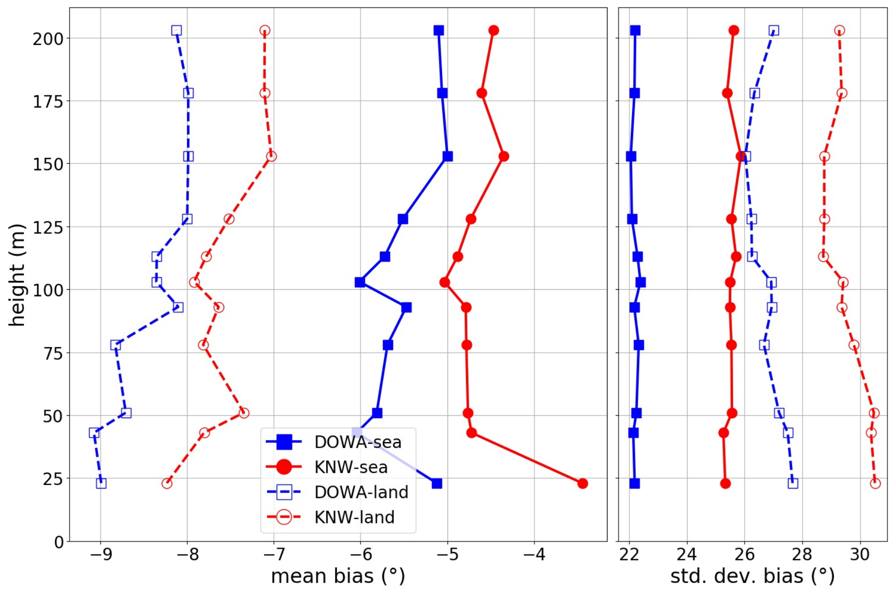


Figure 22: Same as Fig. 21, but making a distinction between land (dashed line, open symbols) and sea wind (solid line, closed symbols).

6 Discussion

A general issue for these kind of validation studies is that of representativeness of the models with respect to the measurements, i. e. whether local conditions (roughness) around the measurement point are well represented by the characterization of the grid boxes of the models. This issue mostly impacts the wind comparison at the lower levels, which are much more sensitive the local environment in the vicinity of the measurement site than the wind at higher levels. For a coastal location the land-sea-mask of the underlying model is very crucial, as the sea roughness is much smaller than any land roughness. The choice of land-sea-mask will affect the model wind, particularly at lower levels, and therefore the validation result.

As discussed in Sect. 3.1, the presence of the dike might influence the horizontal wind speed. By considering the vertical wind speed a rapid decrease of the dike effect with height is seen, and for the higher levels the presence of the dike should not impact the validation results. However, for the lower levels the horizontal wind speed might be disturbed, which could introduce an additional bias in the comparison with the models. Indeed, the height profiles of the mean wind speed bias (Fig. 13), in particular for sea wind (Fig. 14), show a small "kink" for the lowest level, which corresponds to a larger measured wind speed compared to the models, for DOWA and KNW. However, it is also at these lower levels that comparison between measurements and models is most challenging due to the representativeness of the models, and therefore firm conclusions cannot be drawn.

7 Conclusions

DOWA has been validated against wind lidar measurements from the Tweede Maasvlakte of a period of 13 months, and compared to the KNW-atlas. We find for DOWA a mean bias in the wind speed of -0.2 m/s (i. e. DOWA overestimates the wind speed), with a standard deviation of 1.2 m/s, which for KNW are -0.1 m/s and 1.5 m/s respectively. DOWA captures the diurnal cycle much better than KNW (which suffers from huge jumps in the hourly mean wind every six hours due to the cold starts) and seasonal patterns in the diurnal cycle are also nicely reproduced. A linear regression analysis of DOWA compared to the measurements gives values for the slope of around 0.99 and for R^2 of about 0.92, which are better than KNW (0.97 and 0.88 respectively). Thus, DOWA provides an improvement in the hourly correlation. The mean bias in the wind direction is -7° and -6° with a standard deviation of 25° and 28° for DOWA and KNW respectively, which show both strong dependence on the wind direction, while only the standard deviation is sensitive to the considered range of wind speeds. The validation analysis is also done separately for land wind and sea wind, which reveals quite some differences in the validation results, in particular in the hourly correlation of the wind speed and the wind direction bias. Overall, DOWA performs equally well or better than KNW.

These coastal validation results can be compared with the *offshore* meteo mast and wind lidar measurements [7] and *onshore* mast wind measurements at Cabauw [8]. Regarding the mean wind speed similar results are observed among the three validation studies, in which the DOWA and KNW biases are similar (within 0.1 m/s), but the DOWA standard deviation is a few 0.1 m/s smaller. For the correlation in the wind speed, in particular the slope and R^2, offshore the highest correlation between the models and the measurements is observed, and onshore the lowest, with the coastal validation in between these results. Regarding the wind direction the mean bias and standard deviation, the present results are similar to the onshore case for the lower levels, but while onshore the mean bias and standard deviation become smaller with height, for the coastal situation these values changes little with height. Therefore at the higher levels the comparison between measurements and models are better for onshore compared to coastal (these values are not reported for the offshore validation).

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Acknowledgment

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A Grid point selection

The coordinates of the wind lidar measurement location are 51.97834° N, 3.97740° E. For DOWA and KNW the nearest grid point is taken:

- DOWA:
  - grid point indices x=73, y=73;
  - 51.979° N, 3.987° E;
- KNW:
  - grid point indices x=69, y=71;
  - 51.983° N, 3.970° E;

The grid point locations of DOWA and KNW, with respects to the wind lidar location, are displayed in Fig. 23 (see Fig. 4 or Fig. 11 for the map). The results of the validation study can be very sensitive to the precise land-sea-map of the models, and therefore impact the comparison between DOWA and KNW. Therefore we have also considered the grid points more towards sea, namely (72,73) for DOWA and (68,71) for KNW, and compared the mean wind speed for sea wind with the nearest grid points. Results are shown in Fig. 24. Although small differences in the mean wind speed bias can be observed, the particular choice of grid points cannot explain the differences observed between DOWA and KNW.

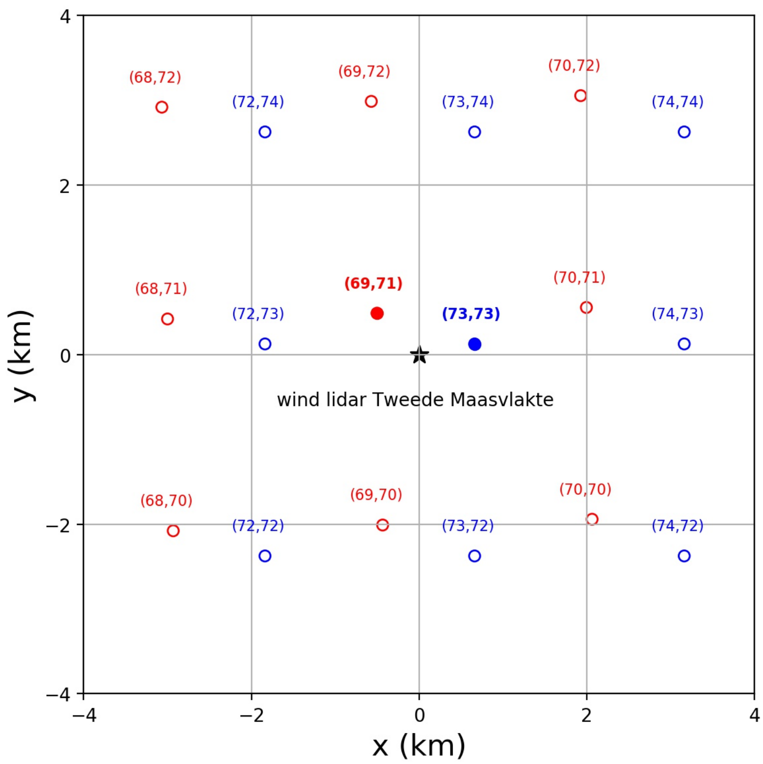


Figure 23: Grid points of DOWA (blue) and KNW (red).

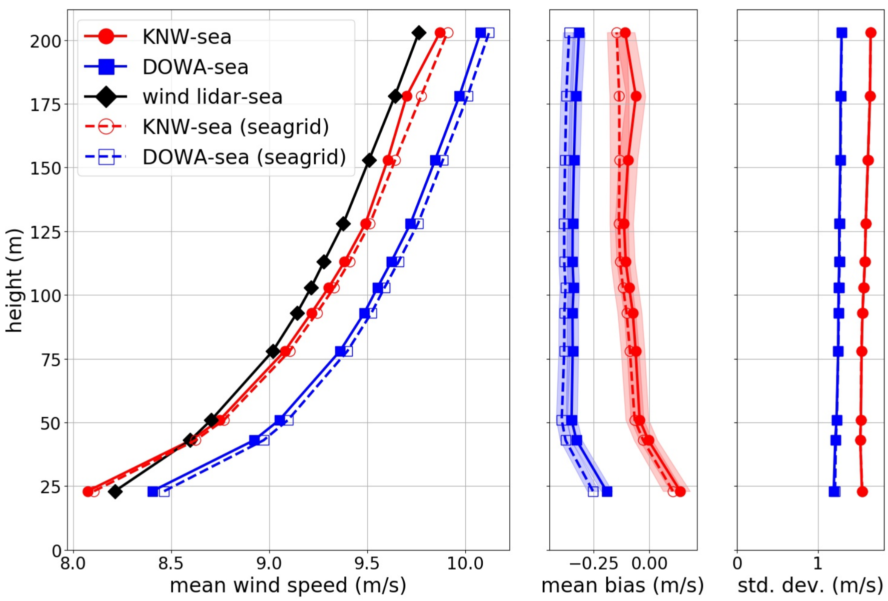


Figure 24: Height profiles of the mean wind speed (left), mean bias (middle) and standard deviation of the bias (right), showing wind lidar measurements (black), DOWA (blue) and KNW atlas (red), all for sea wind, comparing the nearest grid points ((73,73) for DOWA and (69,71) for KNW) with the more westerly grid points ((72,73) for DOWA and (68,71) for KNW, denoted "seagrid").

B Model uncertainty estimates

Here we briefly outline the method to estimate the uncertainty on the model mean statistics. For an uncorrelated data set the standard deviation of the mean is $\sigma_{\mathrm{mean}} = \sigma/\sqrt{N}$, where is σ is the standard deviation of the data set and the N the (independent) number of points. The variance is the square of the standard deviation: σ^2_{mean}. However, if data has a dependency (the data points are not independent), one needs to estimate an equivalent sample size (ESS), defined as $N' = N/\tau_D$, which will be smaller than N, leading to a larger σ_{mean}. A rough estimate of τ_D can be made based on an autoregression of order 1 model AR(1) [14] (as a more simple alternative to bootstrap methods) on data of the form:

$$x_{k+1} = \alpha x_k + \varepsilon_k \tag{1}$$

with $x_1, \varepsilon_1, ..., \varepsilon_{n-1}$ independent random variables. Here k are the timestamps. The estimator is:

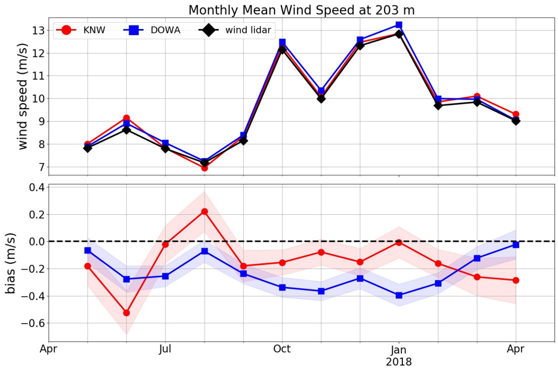
$$\hat{\tau}_D = \frac{1+\hat{\alpha}}{1-\hat{\alpha}} \tag{2}$$

with $\hat{\alpha}$ the estimate of α. With $\tilde{x}_k \equiv x_k - \mu$ and μ the mean of x_k:

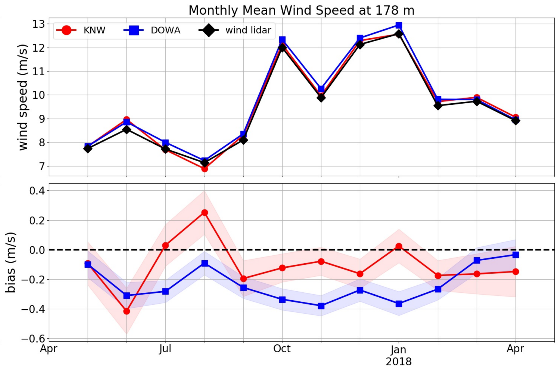
$$\hat{\alpha} = \frac{\sum_{k=1}^{n-1} \tilde{x}_k \tilde{x}_{k+1}}{\sum_{k=1}^{n-1} |\tilde{x}_k|^2}. \tag{3}$$

Eq. 3 is applied to the timeseries of the bias to calculate σ_{mean} to derive standard deviation of yearly, yearly monthly, monthly mean and mean of the full period. For directional mean Eq. 3 is applied to the full period, and it is assumed that $\hat{\tau}_D$ is independent of wind direction. For the hourly mean an uncorrelated data set is assumed.

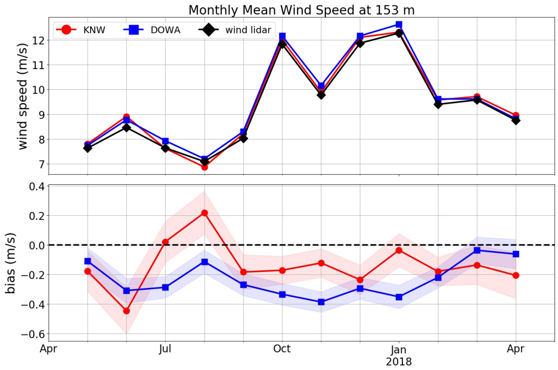
C Monthly mean wind speed



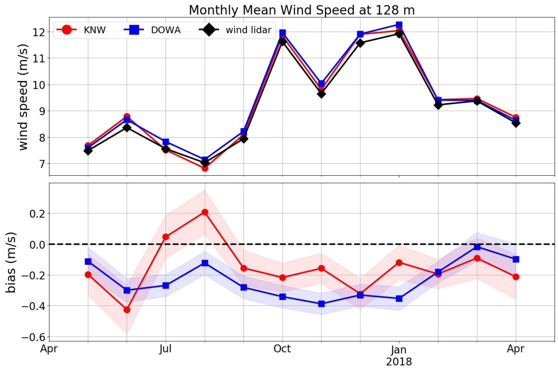
(a) 203m



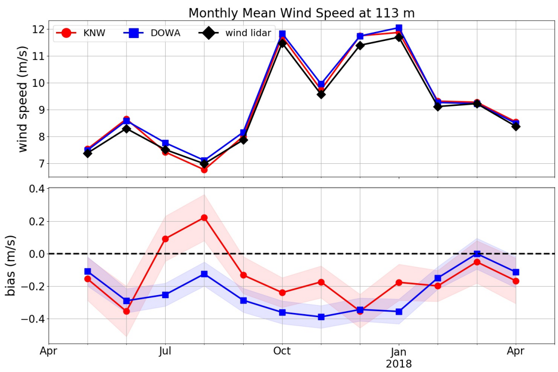
(b) 178m



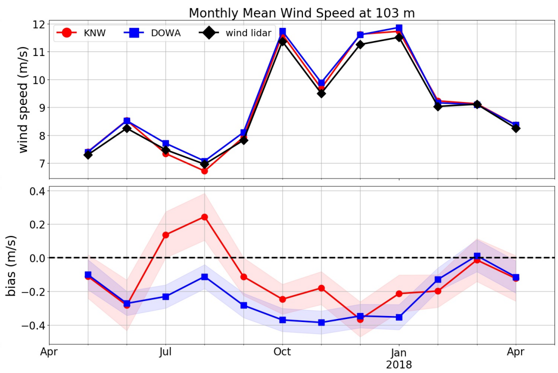
(c) 153m



(d) 128m

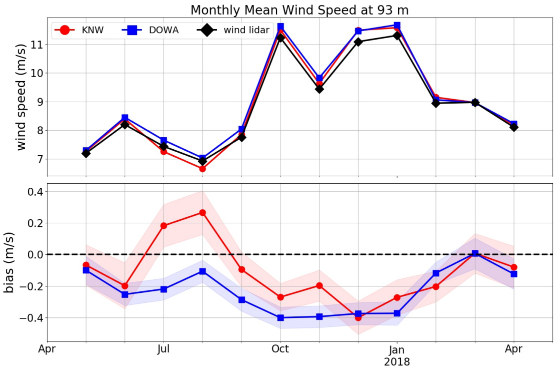


(e) 113m

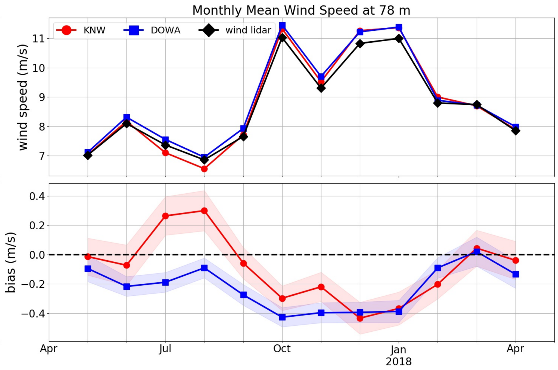


(f) 103m

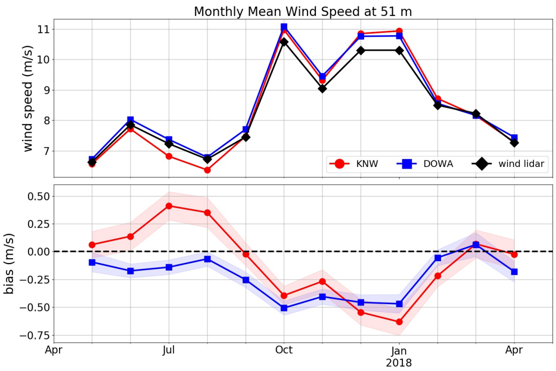
Figure 25: Monthly mean wind speed, showing wind lidar measurements (black), DOWA (blue), KNW atlas (red).



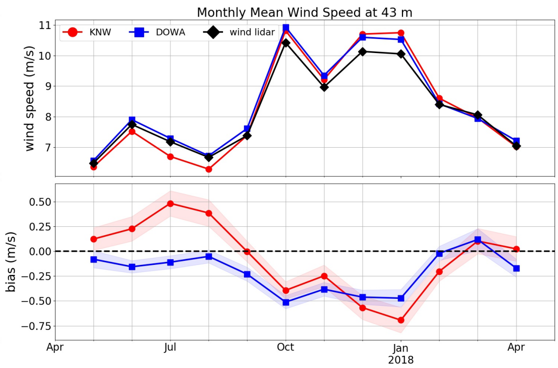
(a) 93m



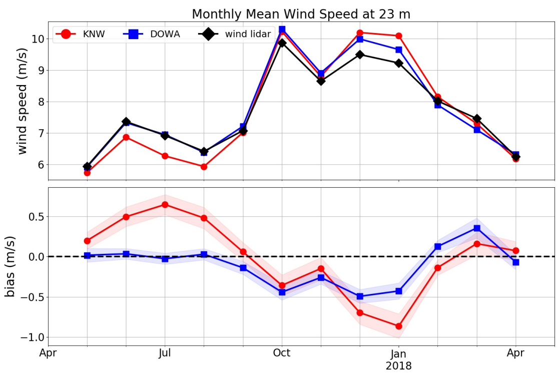
(b) 78m



(c) 51m



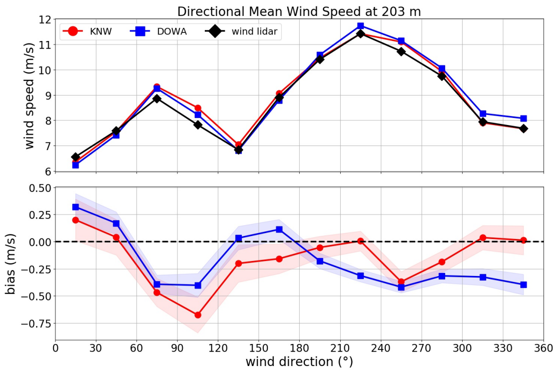
(d) 43m



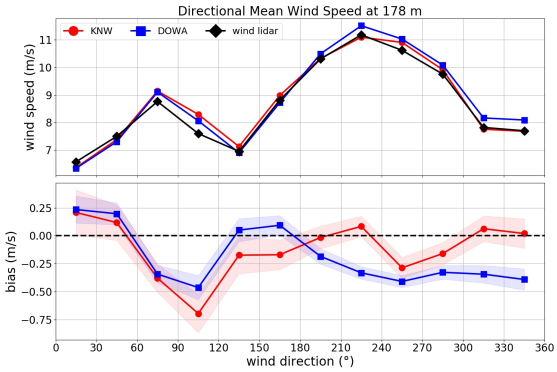
(e) 23m

Figure 26: Continuation of Fig. 25

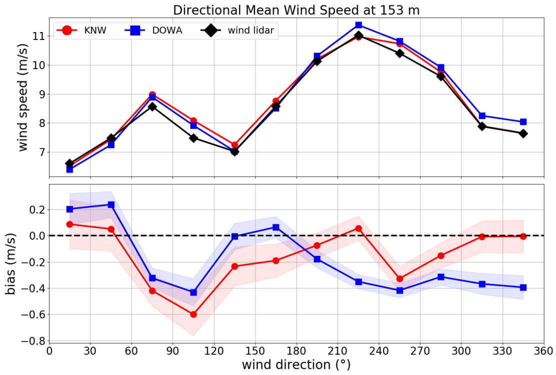
D Wind speed directional bias



(a) 203m



(b) 178m



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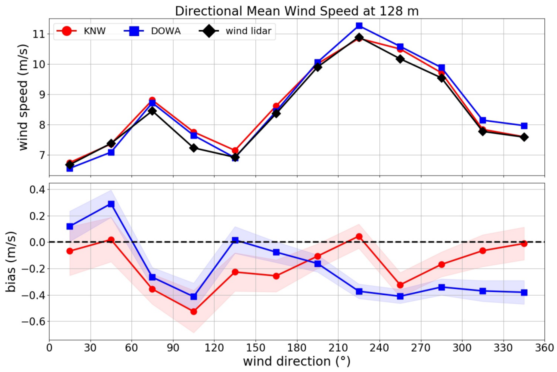

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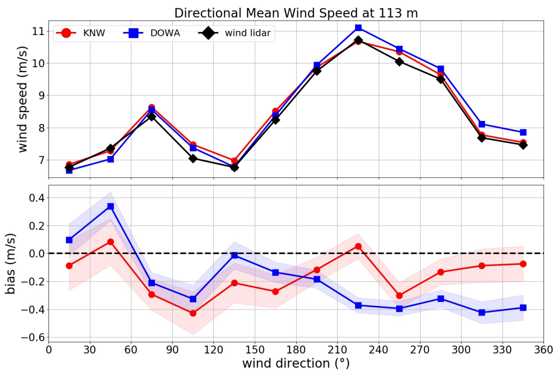

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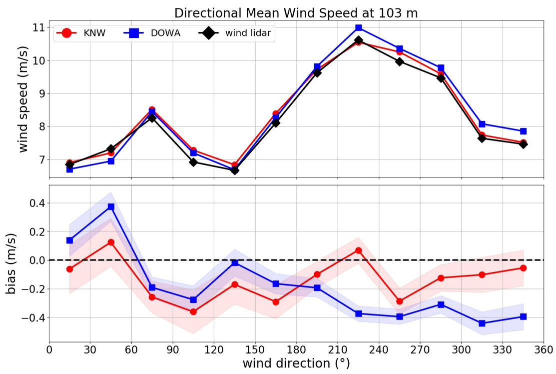
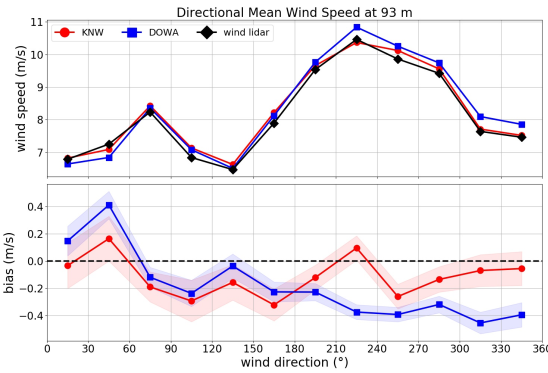
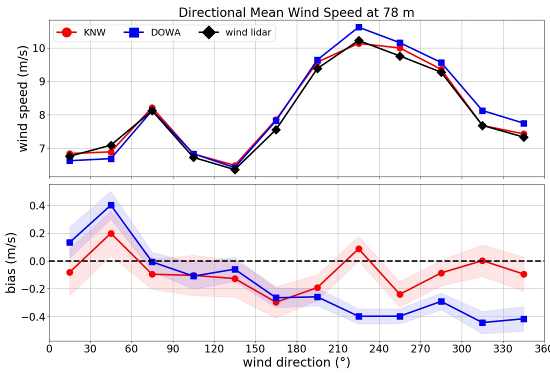


(f) 103m

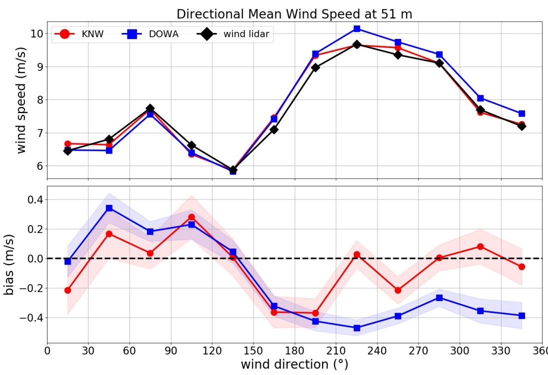
Figure 27: Directional wind speed bias, with sector width of 30°, showing DOWA (blue) and KNW atlas (red). Note the different scales on the *y*-axis.



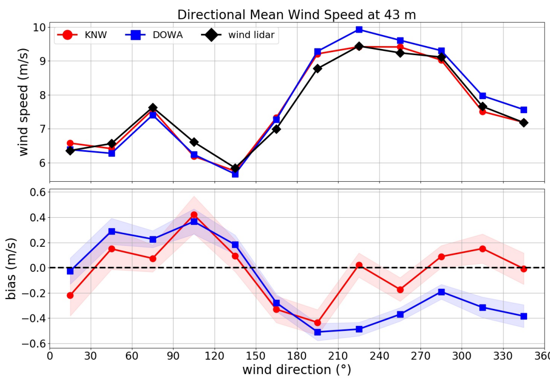
(a) 93m



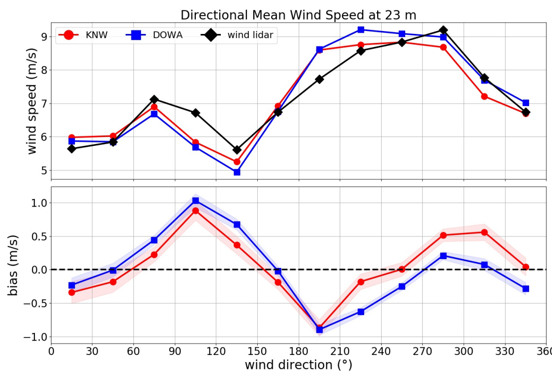
(b) 78m



(c) 51m



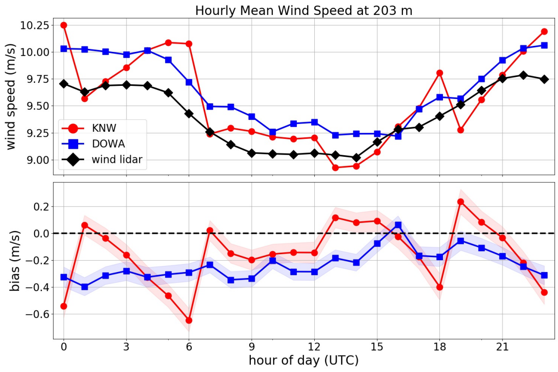
(d) 43m



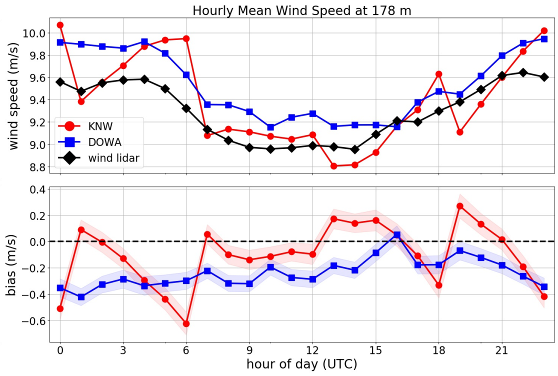
(e) 23m

Figure 28: Continuation of Fig. 28.

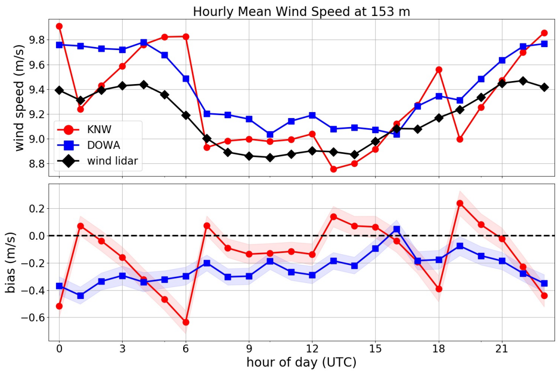
E Hourly mean wind speed



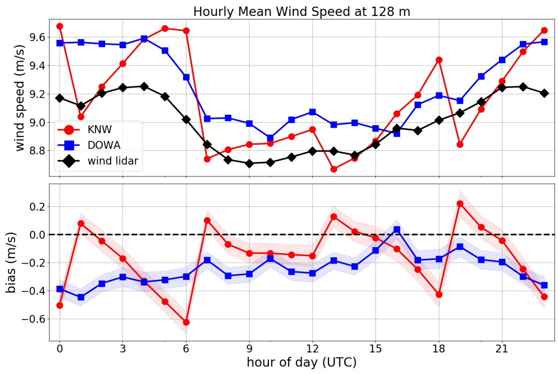
(a) 203m



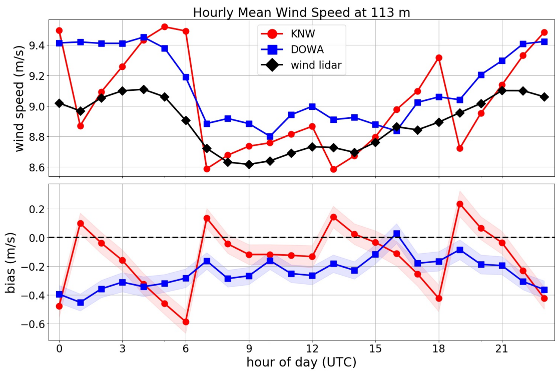
(b) 178m



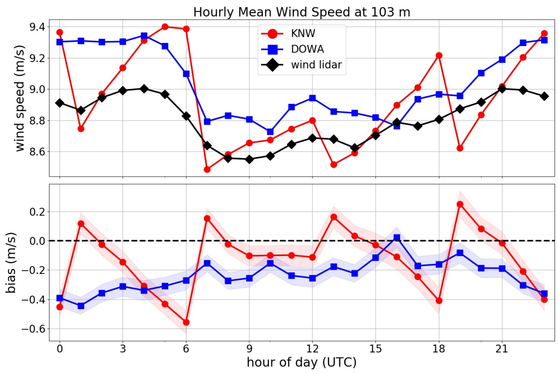
(c) 153m



(d) 128m

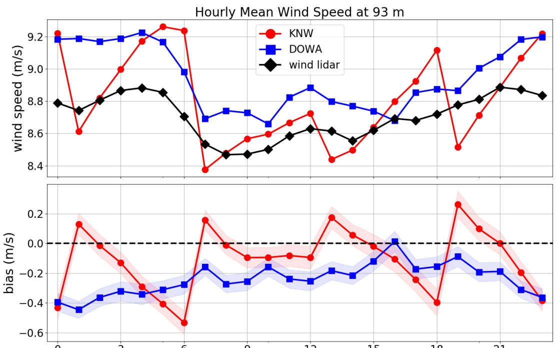


(e) 113m

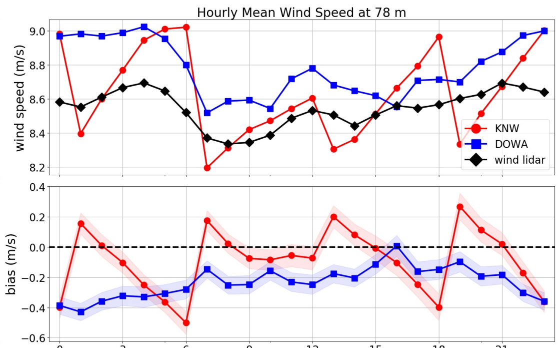


(f) 103m

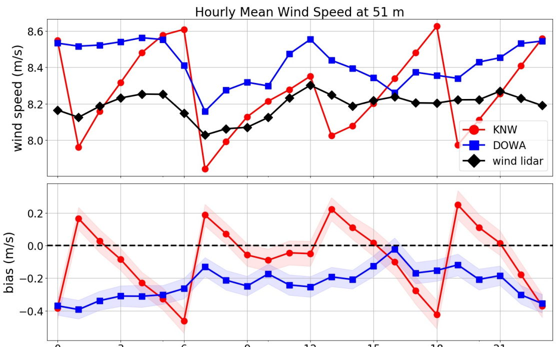
Figure 29: Hourly mean wind speed, showing wind lidar measurements (black), DOWA (blue) and KNW atlas (red). The upper panel shows the wind speed of wind lidar measurements and models, the lower panel the mean bias between the wind lidar measurements and the models.



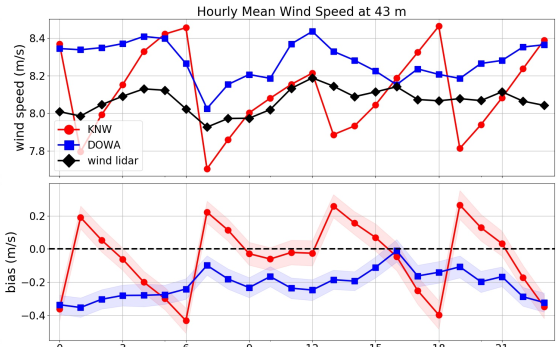
(a) 93m



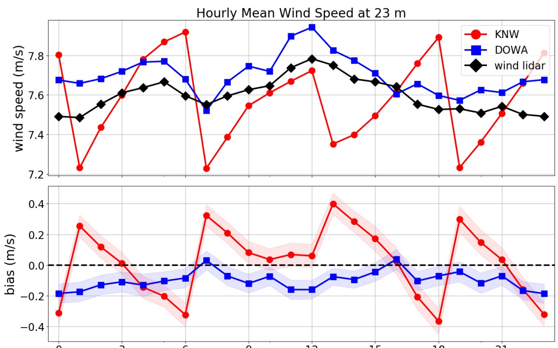
(b) 78m



(c) 51m



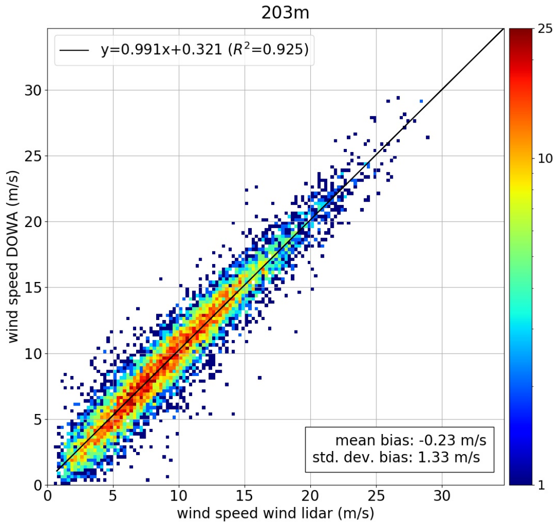
(d) 43m



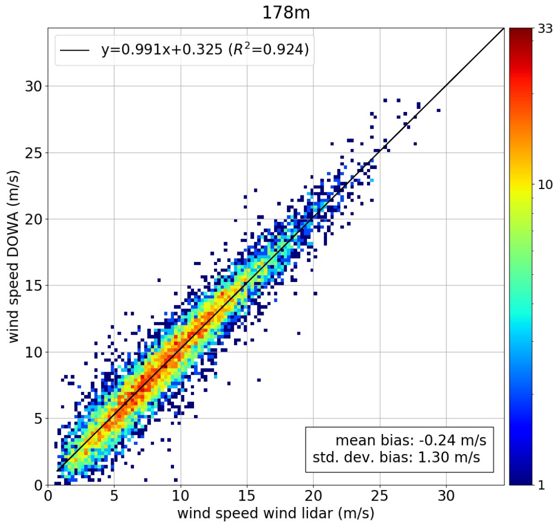
(e) 23m

Figure 30: Continuation of Fig. 29.

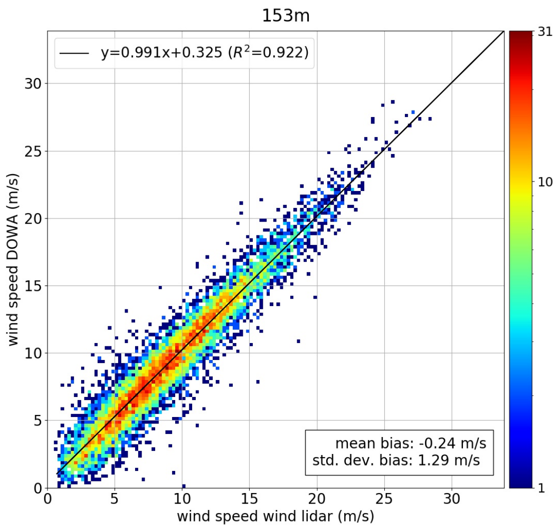
F Hourly wind speed correlation



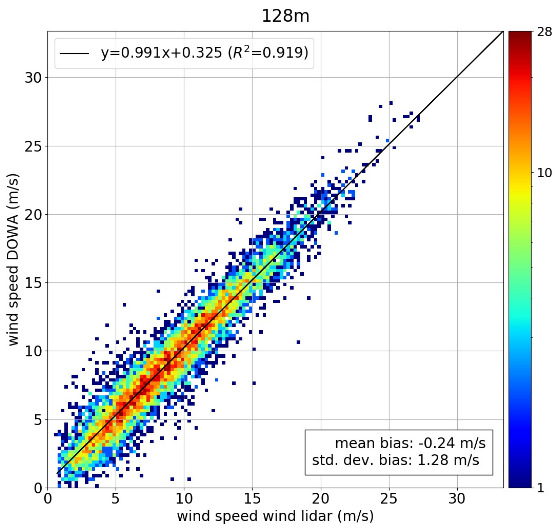
(a) 203m



(b) 178m

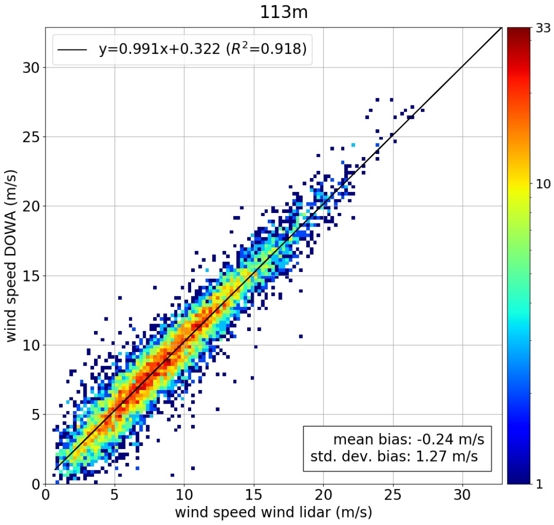


(c) 153m

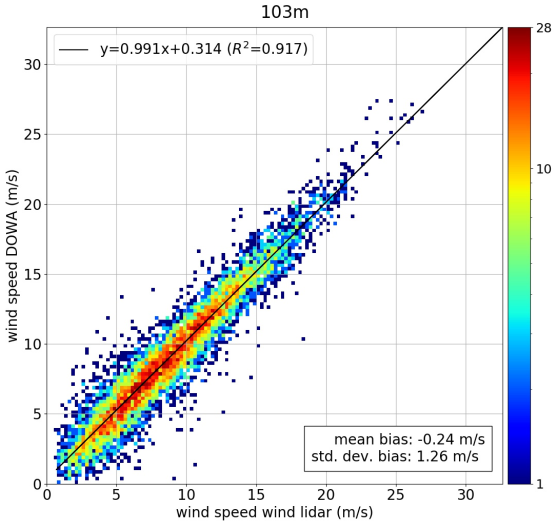


(d) 128m

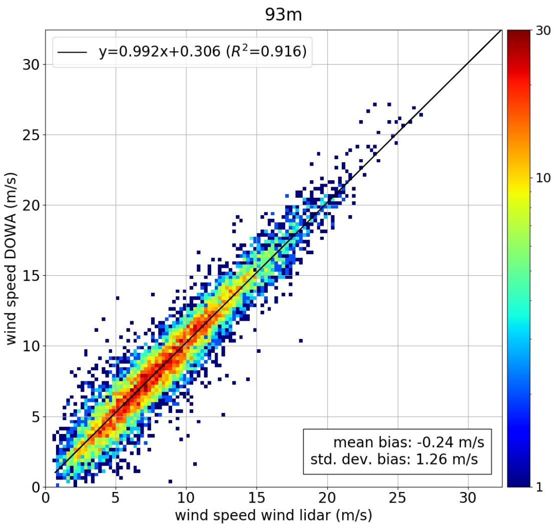
Figure 31: Scatterplot of the DOWA and wind lidar wind direction measurements (visualized as a density plot with logarithmic color scale), showing the mean and standard deviation of the difference between the wind lidar measurements and DOWA.



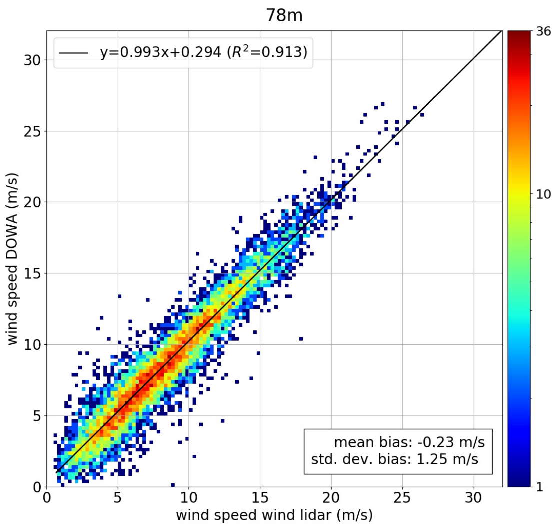
(a) 113m



(b) 103m

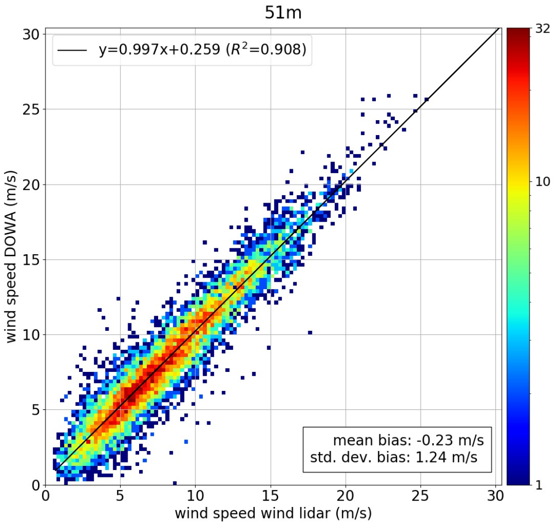


(c) 93m

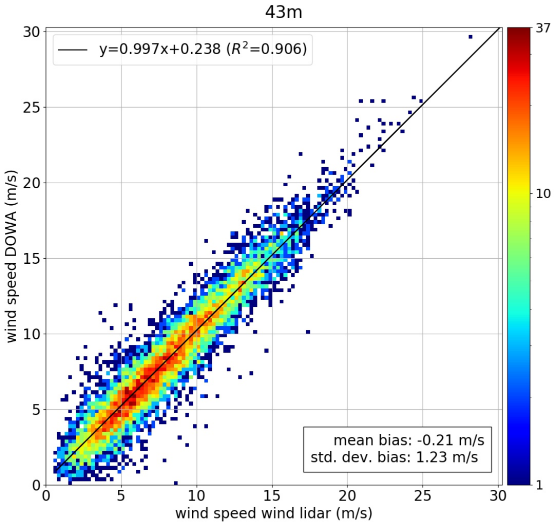


(d) 78m

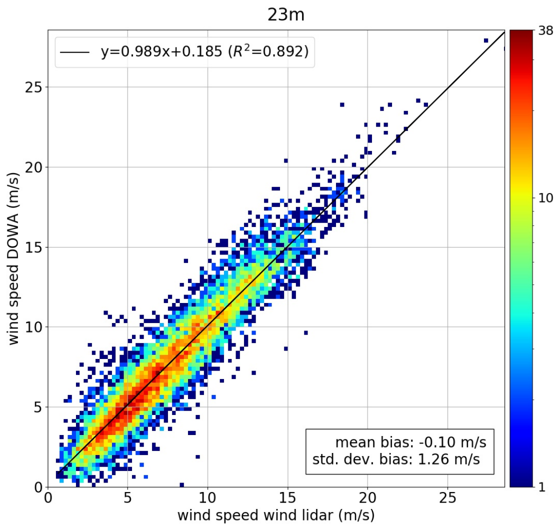
Figure 32: Continuation of Fig. 31.



(a) 51m



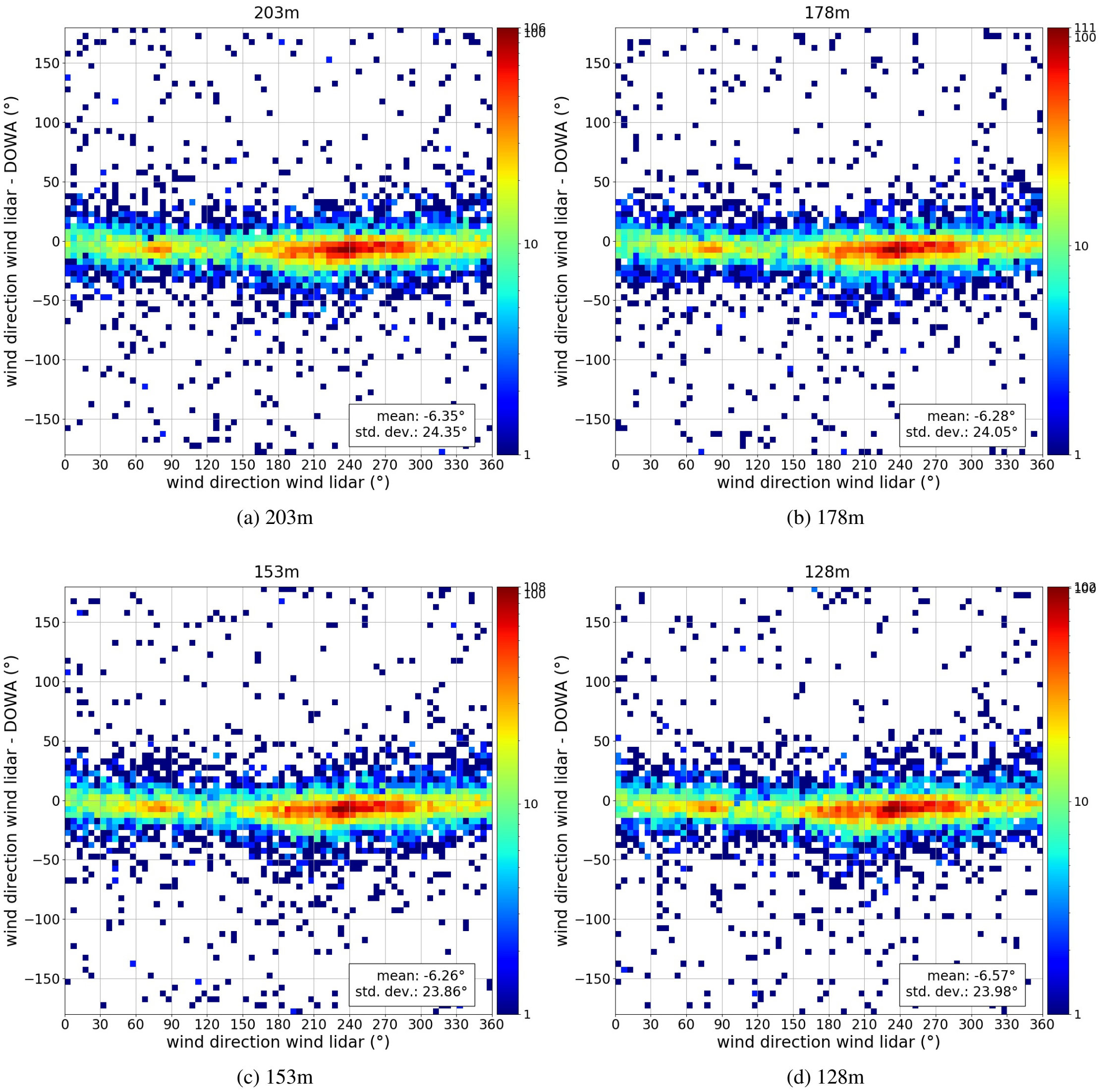
(b) 43m



(c) 23m

Figure 33: Continuation of Fig. 32.

G Hourly wind direction correlation



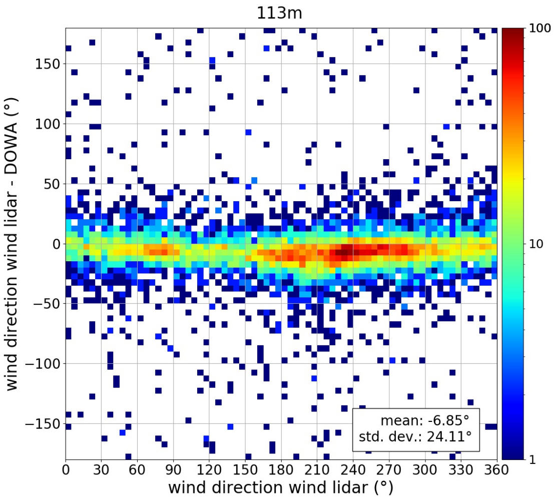
(a) 203m

(b) 178m

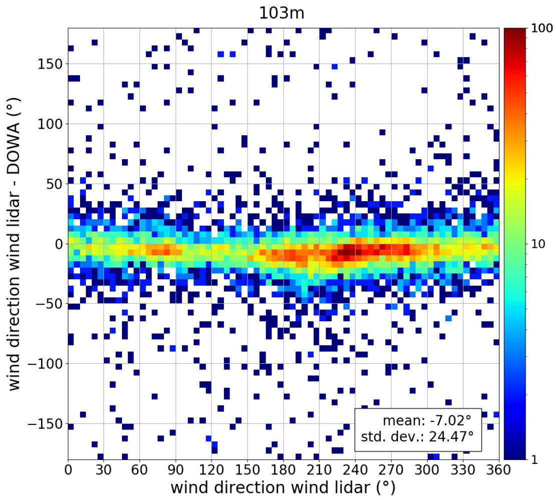
(c) 153m

(d) 128m

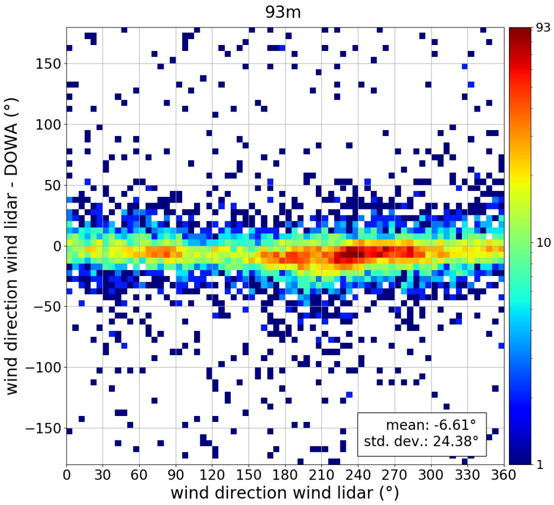
Figure 34: Scatterplot of the DOWA and wind lidar wind direction measurements (visualized as a density plot with logarithmic color scale), showing the mean and standard deviation of the difference between the wind lidar measurements and DOWA.



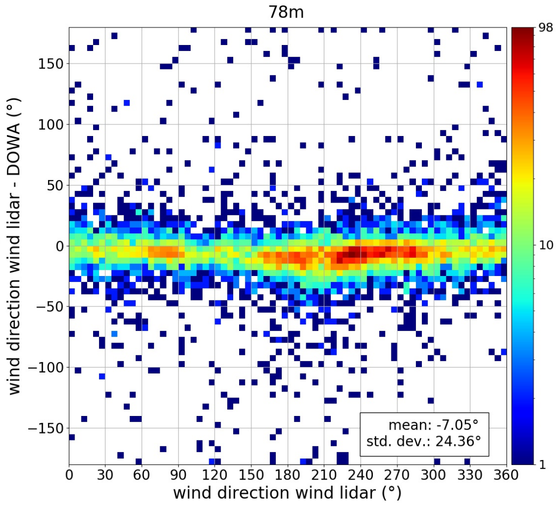
(a) 113m



(b) 103m

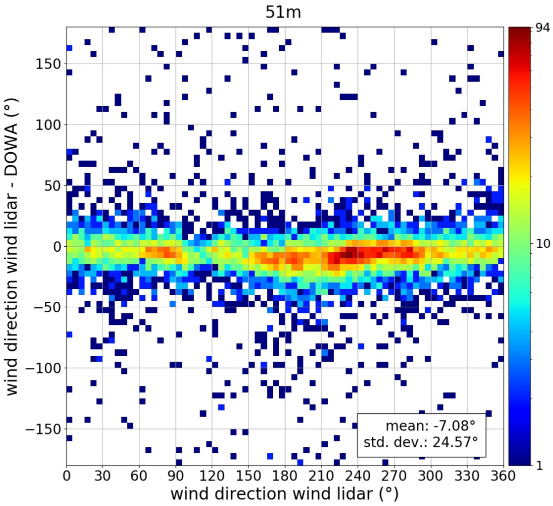


(c) 93m

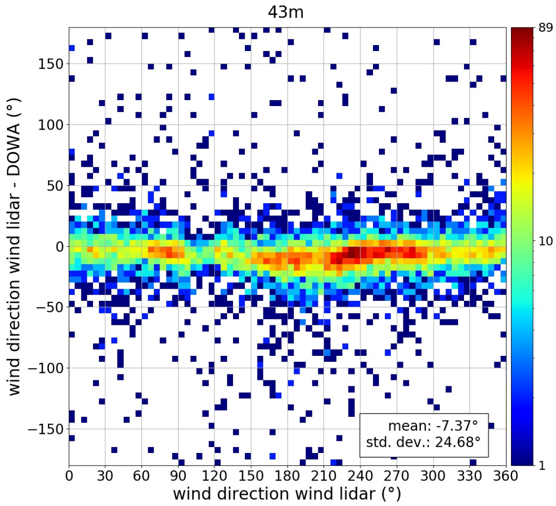


(d) 78m

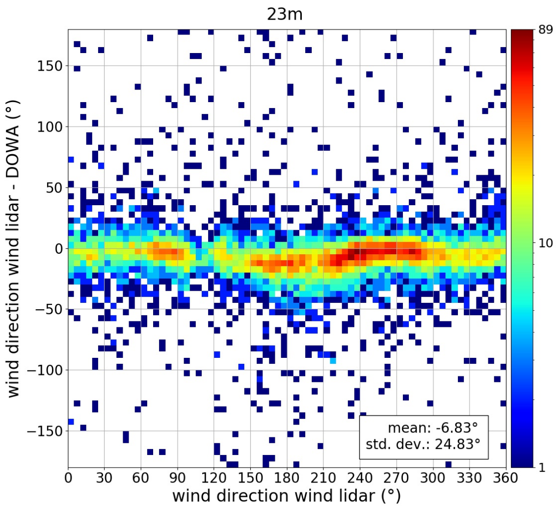
Figure 35: Continuation of Fig. 34.



(a) 51m



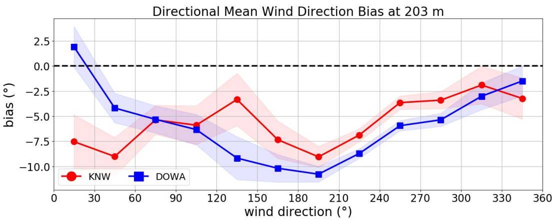
(b) 43m



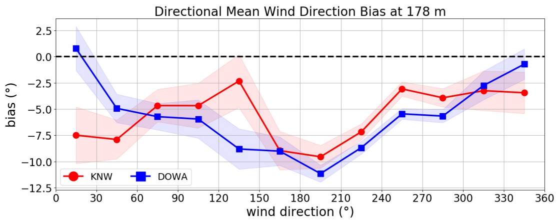
(c) 23m

Figure 36: Continuation of Fig. 35.

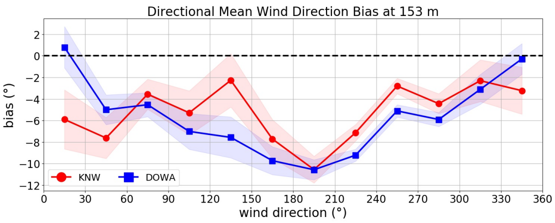
H Wind direction directional bias



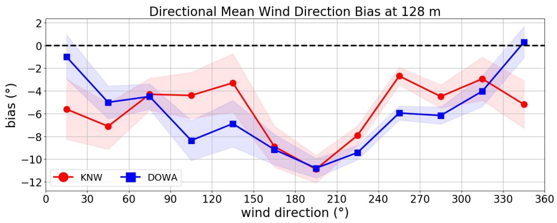
(a) 203m



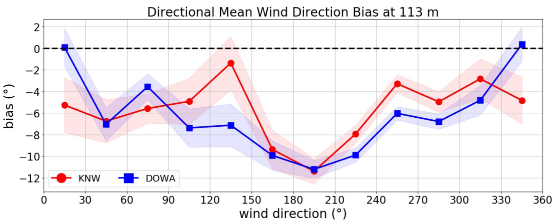
(b) 178m



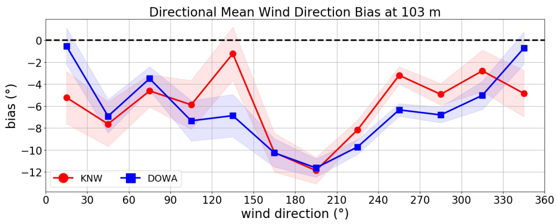
(c) 153m



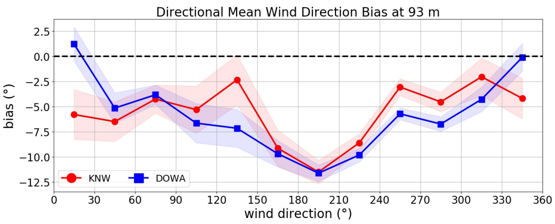
(d) 128m



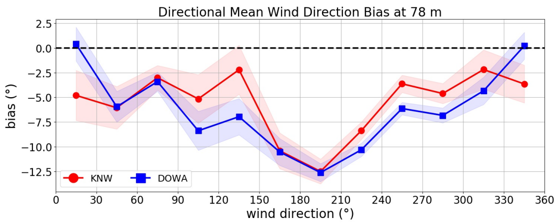
(e) 113m



(f) 103m

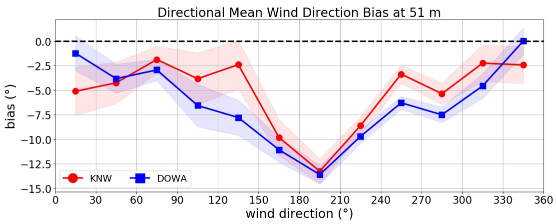


(g) 93m

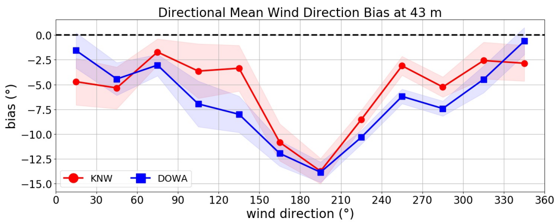


(h) 78m

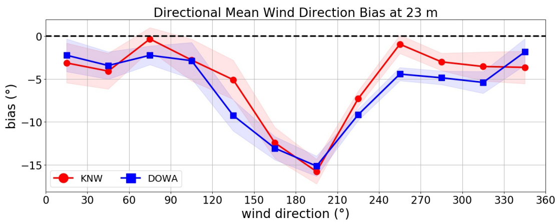
Figure 37: Directional wind direction bias, with sector width of 30°, showing DOWA (blue) and KNW atlas (red). Note the different scales on the *y*-axis.



(a) 51m



(b) 43m



(c) 23m

Figure 38: Continuation of Fig. 37.

Royal Netherlands Meteorological Institute

PO Box 201 | NL-3730 AE De Bilt
Netherlands | www.knmi.nl