DOWA validation against Cabauw meteomast wind measurements

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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 order to improve upon the KNW-atlas, the DOWA uses an updated version of the global ECMWF reanalysis, as well as an updated version of the HARMONIE numerical weather model that was used to transform the global reanalysis into a regional wind atlas. The method that was used to make the atlas was changed as follows: the 'cold starts' within the global reanalysis used in KNW were removed and at three-hour intervals aircraft and satellite measurements were assimilated.

The DOWA is validated against wind speed and direction measurements from the Cabauw meteorological mast, for the 10-year period of DOWA and at heights between 10 m and 200 m. The validation results are compared to the KNW-atlas. It is found that the average difference (bias) between DOWA wind speeds and those measured at Cabauw varies between -0.1 m/s to 0.3 m/s for the different heights. Significant differences between DOWA and KNW are only found at 10 and 20 m altitude, where KNW performs better. For heights above 20 m there is no significant difference between DOWA and KNW regarding 10-year averaged wind speed bias. The diurnal cycles is better captured by DOWA compared to KNW, and the correlation is slightly improved in DOWA.

In addition, a comparison with the global ECMWF ERA-Interim and ERA5 reanalyses, used for KNW and DOWA respectively, is made, in particular highlighting the added skill provided by downscaling those global datasets with HARMONIE.

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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 only symbol inland indicates the location of Cabauw (51.97°N, 4.93°E).

Figure 2: The 213-m tall Cabauw meteorological mast (photo by Ruben Jorksveld, KNMI).

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, 5] 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). Compared to KNW, the DOWA is made using global reanalysis ERA5, a newer version of HARMONIE and newer methods, in order to improve the hourly correlation (diurnal cycle) and the representation of the vertical wind shear. 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.

In this validation study the DOWA is compared to wind measurements from the Cabauw meteomast (Fig. 2), in terms of the hourly correlation, hourly, monthly and yearly average wind speed statistics, and wind speed and wind direction distributions, for the full DOWA period (2008-2017) and up to a height of 200 m. The results are compared to those of the KNW-atlas, demonstrating the improvements made within the DOWA project. In addition, comparisons are made with the KNW-atlas without the uniform wind shear correction and the global reanalysis datasets of ERA-Interim and ERA5.

This report is structured as follows. In Sect. 2 an overview of the relevant atmospheric models is given and the KNW and DOWA wind atlases are described. In Sect. 3 the wind measurements of the Cabauw meteorological mast are discussed. 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.

5

2 Atmospheric models

The KNW-atlas and the DOWA are based on different global ECMWF (European Centre for Medium-Range Weather Forecasts) reanalyses, which are downscaled using different versions of the atmospheric weather model HARMONIE. 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 is used to produce the KNW-atlas, the global ERA5 reanalysis for the DOWA.

2.1 ECMWF reanalysis models: ERA-Interim and ERA5

The ERA-Interim reanalysis combines one of the leading numerical weather prediction models (ECMWF model) with an advanced data-assimilation system. 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 a three-dimensional analysis of the global atmosphere at a grid size of about 80 km. The archived reanalysis dataset provides six-hourly outputs (at 00, 06, 12, 18 hour).

ERA5 is the fifth generation of the ECMWF atmospheric reanalysis of the global climate. ERA5 will eventually replace ERA-Interim. The main improvements are:

- ERA5 employs an updated model version of the ECMWF model.

- ERA5 will eventually contain data from 1950 to the present (ERA-Interim 1979 to now).

- ERA5 provides hourly data as opposed to the six-hourly 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 contains atmospheric troposphere and lower stratosphere conditions at 137 vertical levels up to about 80 km (ERA-Interim only provides 60 levels).

2.2 HARMONIE

The numerical weather prediction model HARMONIE (HIRLAM ALADIN Research on Mesoscale Operational NWP In Euromed) is used operationally by KNMI since 2012. It is extensively tested and continually improved by the HIRLAM-ALADIN consortium (see Fig. 3). HARMONIE is a non-hydrostatic limited-area model that runs on a high-resolution grid spacing of 2.5 by 2.5 km. More details regarding HARMONIE/AROME can be found in Ref. [6] and online (www.hirlam.org). HARMONIE model set-up can be found in Ref. [7]. HARMONIE version 37h1.1 was used to produce the KNW-atlas and HARMONIE version 40h1.2.tg2 was used to make the DOWA. Compared to 37h1.1, 40h1.2.tg2 incorporates an improved turbulence parametrization (HARATU) that enables enhanced estimates of wind speed [8]. Another difference is the used ECOCLIMAP databases to characterize the surface (land/sea, land use), and thereby the roughness: 37h1.1 ECOCLIMAP-I [9] and 40h1.2.tg2 ECOCLIMAP-II [10].

2.3 Wind atlases

2.3.1 KNW-atlas

The KNW-atlas [2] was the first atlas that was based on a period that was long enough to capture the variability in the Dutch wind climate. The KNW-atlas released in 2013 captured 35 years of atmospheric variability from 1979 to 2013. As part of the DOWA project, the KNW-atlas was extended using the
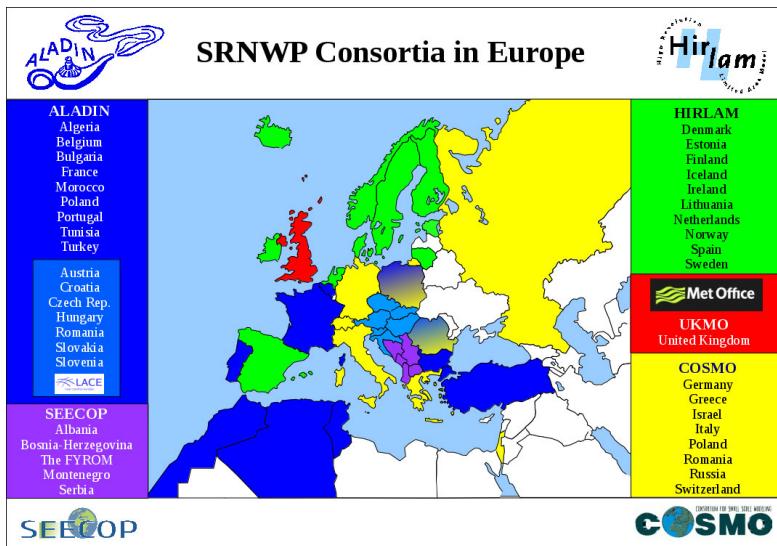
Figure 3: Short Range Numerical Weather Prediction (SRNWP) consortia in Europa, showing the participating countries in the HIRLAM (green) and ALADIN (blue) consortia (source: http://www.eumetnet.eu).

same model-setup to guarantee a homogeneous dataset. The KNW-atlas encompasses more than 40 years (i. e. 1979 – August 31, 2019). The downscaling of ERA-Interim using HARMONIE version 37h1.1 results in hourly data at a horizontal grid spacing of 2.5 by 2.5 km. There are eight published height levels: 10, 20, 40, 60, 80, 100, 150 and 200 m. It was found that the wind speeds require a shear-correction term [11, 3]. This shear-correction term is tuned to match wind measurements made at the Cabauw meteomast (2004-2013) and is uniformly applied (i. e. the same for all heights and locations) throughout the KNW domain:

$$U_{\text{KNW}}(h) = U_{\text{KNW–wowsc}}(20) + \frac{U_{\text{KNW–wowsc}}(h) - U_{\text{KNW–wowsc}}(20)}{0.85}, \tag{1}$$

where $U_{\text{KNW}}(h)$ and $U_{\text{KNW–wowsc}}(h)$ are the corrected (KNW) and uncorrected (KNW without wind shear correction) wind speed at height h, respectively. Note that $U_{\text{KNW}}(20m) = U_{\text{KNW–wowsc}}(20m)$ and $U_{\text{KNW}}(h) > U_{\text{KNW–wowsc}}(h)$ for $h > 20$ m.

Previous validation studies of the KNW-atlas demonstrate a climatological (long-term average) accuracy of better than 0.5 m/s at a height of 10 m, and an accuracy of better than 0.2 m/s at higher levels, and also the ability to represent the climatological extremes [3, 4].

2.3.2 DOWA

Creating the DOWA [1] was part of a project with ECN part of TNO, Whiffle, and KNMI. The DOWA is a wind atlas based on a 10-year (2008-2017) reanalysis. Due to the limited time span of the DOWA, it cannot adequately capture North Sea wind climate variability like the KNW-atlas. Therefore, the DOWA is not expected to provide any significant improvements to the climatological accuracy of the KNW-atlas. However, the DOWA is expected to improve hourly wind correlation and the representation of vertical wind shear. There are 17 height levels: 10, 20, 40, 60, 80, 100, 120, 140, 150, 160, 180, 200, 220, 250, 300, 500 and 600 m, extending the height range of KNW.
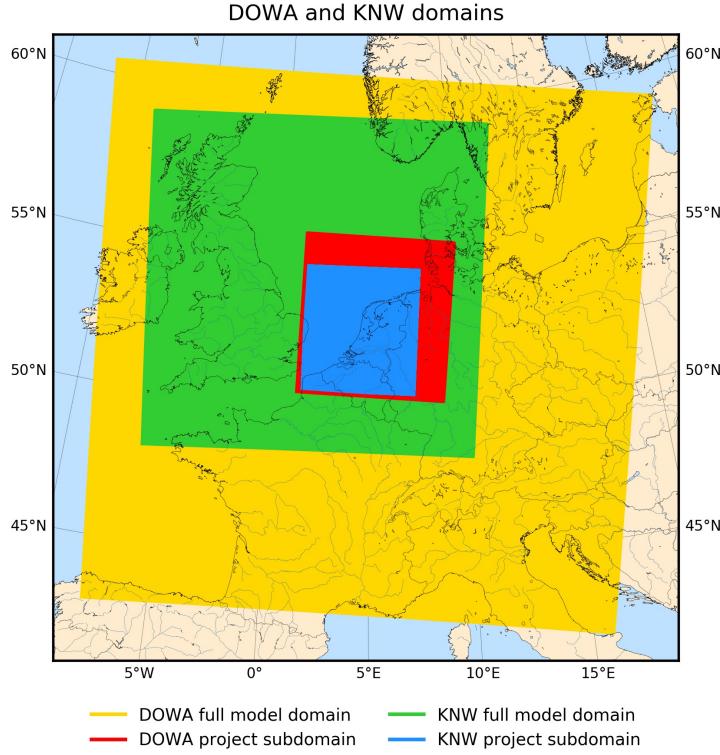
Figure 4: ERA5-HARMONIE domain (yellow) of 789x789 points and DOWA-subdomain of 217x234 points (red). ERA-Interim-HARMONIE domain of 500x500 points (green) and KNW-subdomain of 170x188 points (blue).

DOWA contains not only wind climatology, but also information required for further downscaling with a Large Eddy Simulation (LES) models. This means that it is possible to downscale the information in DOWA locally from hourly to 10 seconds and from 2.5 km to 100 m horizontally. The DOWA domain is also larger than that of the KNW-atlas, even including areas where German wind farms are being planned and built (see Fig. 4).

In addition to using new models (i.e. ERA5 instead of ERA-Interim and HARMONIE version 40h1.2.tg2 instead of 37h1.1), new methodologies were implemented within the DOWA. These are detailed in the bullets below.

- Assimilation of measurements

  – For the KNW-atlas, no additional measurements were assimilated into HARMONIE during the process of downscaling (i.e. the only measurements used were the ones assimilated in the ERA-Interim reanalysis).

  – 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. 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). Innovative measurements included high-resolution satellite surface wind fields (Advanced Scatterometer [ASCAT]) and aircraft wind profile measurements (MODE-S EHS). Using these additional measurements is expected to improve the quality of the time series and provide a more detailed depiction of the diurnal cycle.

- Cold start:

  - For the KNW-atlas, each six-hour forecast period started with the ERA-Interim reanalysis (cold start). Subsequently, HARMONIE (using no additional data assimilation) was used to produce the +1 hour up to the +6 hour forecast.

  - No cold starts were used in the DOWA, except at the beginning of each parallel stream[1]. The DOWA is comprised of +1 hour, +2 hour, and +3 hour 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.

Relevant differences between the KNW-atlas and the DOWA are summarized in Table 1.

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[1]For the computation of DOWA several "streams" were run simultaneously: stream A (2010-2012), stream B (2013-2014), stream C (2008-2009) and stream D (2015-2017), to speed up the calculations.

	KNMI North Sea Wind (KNW) Atlas	Dutch Offshore Wind Atlas (DOWA)
Timespan	1-1-1979 until 31-8-2019[a] (40+ years)	1-1-2008 until 31-12-2018 (11 years)[b]
Variability of the North Sea wind climate	Captures the variability of the North Sea wind climate	Does not capture the variability of the North Sea wind climate
Used models	Based ERA-Interim reanalysis and the mesoscale weather model HARMONIE version 37h1.1 (1979-2013) and version 37h1.2.bugfix (2013-2019), the latter tested and adapted to guarantee a homogeneous dataset (similar results versions 37h1.1 and 37h1.2.bugfix)	Based on ERA5 reanalysis (follow-up of ERA-Interim with higher spatial and temporal resolution) and the mesoscale weather model HARMONIE version 40h1.2.tg2 (improved wind information because turbulence is modeled better)
Method	HARMONIE only used as downscaling tool only (data assimilation of measurements in ERA-Interim)	Additional HARMONIE data assimilation (ASCAT-satellite surface wind measurements and MODE-S-EHS aircraft wind profile measurements)
Climatological information height	up to and including a height of 200 m	up to and including a height of 600 m
LES-downscaling	Lacks the information required for further LES-downscaling	Includes the information required for further LES-downscaling
Cold starts	Cold starts: limited quality of hourly correlation with measurements (e.g. diurnal cycle)	No cold starts: better hourly correlation with measurements and representation of the diurnal cycle
Wind shear correction	Uniform wind shear correction applied	No wind shear correction required

Table 1: Summary of the main differences between KNW and DOWA.

[a] ERA-Interim no longer available after 31-8-2019.

[b] The year 2018 was created as an extra year (the original DOWA-proposal included only 10 years 2008-2017) and is not included in this validation report.

3 Cabauw meteorological mast wind measurements

In Cabauw (51.971° N, 4.927° E), near Lopik in Utrecht, KNMI has a mast of a height of 213 m (see Fig. 2), part of the CESAR (Cabauw Experimental Site for Atmospheric Research) Observatory [12]. The mast is used for meteorological measurements in the lowest few hundred meters of the atmosphere. Its instrumentation and siting, in particular in the context of wind measurements, have been extensively described [13, 14]. Wind speed and wind direction are measured with KNMI cup anemometers and wind vanes, respectively, at six levels: 10, 20, 40, 80, 140 and 200 m.

Precautions are taken to avoid large flow obstruction from the 213-m tall mast ("A-mast") and the main building at the bottom of it:

- At the levels 40, 80, 140, and 200 m of the A-mast the wind direction is measured at three booms and wind speed is measured at two booms; the selection between the booms depends on the wind direction

- At the levels 10 and 20 m the wind direction and wind speed are measured at two separate, smaller masts south ("B-mast", 30 m SE from A-mast) and north (two "C-masts", 70 m and 140 m NE from A-mast for 20 m and 10 m level, respectively) of the main building; the selection between these two masts depends on the wind direction.

Careful calibration procedures and applications of corrections assures an accuracy of the KNMI cup anemometer of 1% (or 0.1 m/s for low wind speeds), and KNMI wind vane of 0.5° [15, 16, 17]. Calibration periods for the cup anemometer and wind vane are 14 and 26 months, respectively. During operation, the accuracy of the cup anemometers is monitored to stay within 1% by comparing the two available instruments at the same height, provided that wind direction allows for proper wind measurements for both. The starting threshold for the cup anemometer is 0.2 m/s [18], which might increase up to 0.3 m/s within the calibration period. Therefore, a low wind speed filtering is applied in this validation study (see below). Response length, which is approximately the passage of wind (in meters) required for the output of a wind-speed sensor to indicate 63% of a step-function change of the input speed, is about 3 m [18]. The corresponding response time is the response length divided by the wind speed.

The wind measurements are corrected for flow distortions from the mast and are quality controlled. 10 minute averaged data and statistics (minimum, maximum and standard deviation within the 10-minute period) of wind speed and wind direction are available from the CESAR Database (CDS) [19], either unvalidated, validated, or validated and gap-filled. Here we have used the validated (non-gap-filled) data. For this validation study hourly averaged data have been constructed from these 10 minute averaged data (see Sect. 4).

The monthly data availability of the mast measurements are shown in Fig. 5 and Fig. 6, for wind speed and wind direction, respectively. In this validation study a minimum wind speed of 0.5 m/s is taken for both wind speed and wind direction measurements, and the data availability after discarding measurements with less than 0.5 m/s is also shown. The legends give the overall data availability per height for the whole period (2008-2017). Without the low wind speed filtering the data availability is at least 99.6%. Reasons for absence of measurements are mostly operational, like failures in data communication or transfer, or power failures (which can be recognized by simultaneous data outage for all heights and both cup and vane). With low wind speed filtering, the data availability of the 10-minute averaged data decreases, most noticeable for the lower levels (98.8% at 10 m). However, the effect of low wind speed filtering on the hourly averaged data, which is of relevance for the validation, is very small.
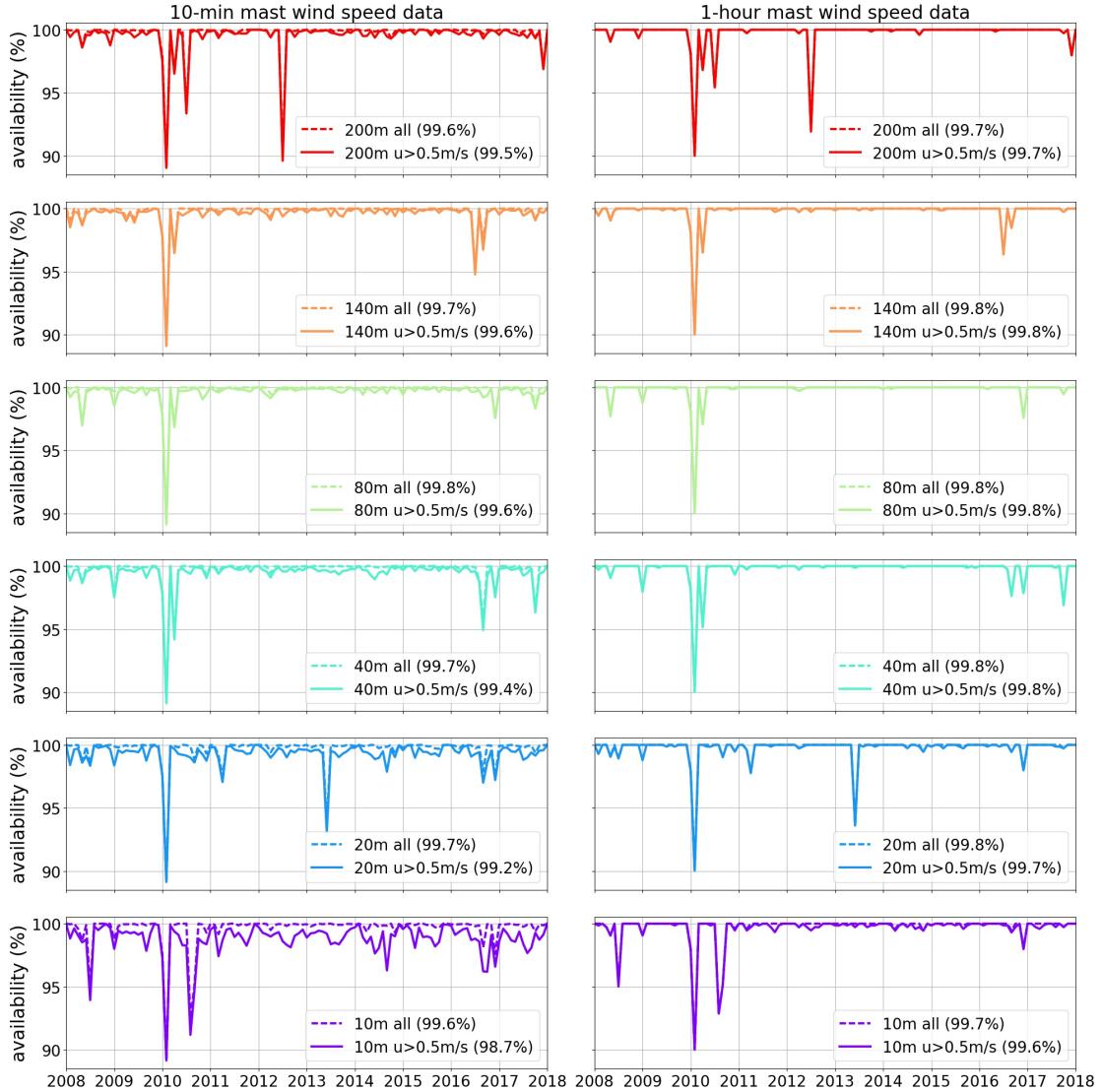
Figure 5: Monthly data availability of the 10-minute (left panel) and 1-hourly (right panel) wind speed measurements from the Cabauw meteomast, all data (dashed lines) and data for which the wind speed is larger than 0.5 m/s (solid lines). In the legends the overall data availability per height for the whole period is given. Data availability is defined as the percentage of monthly valid 10-minute or hourly data, in which a valid hourly data requires only one valid 10-minute data.
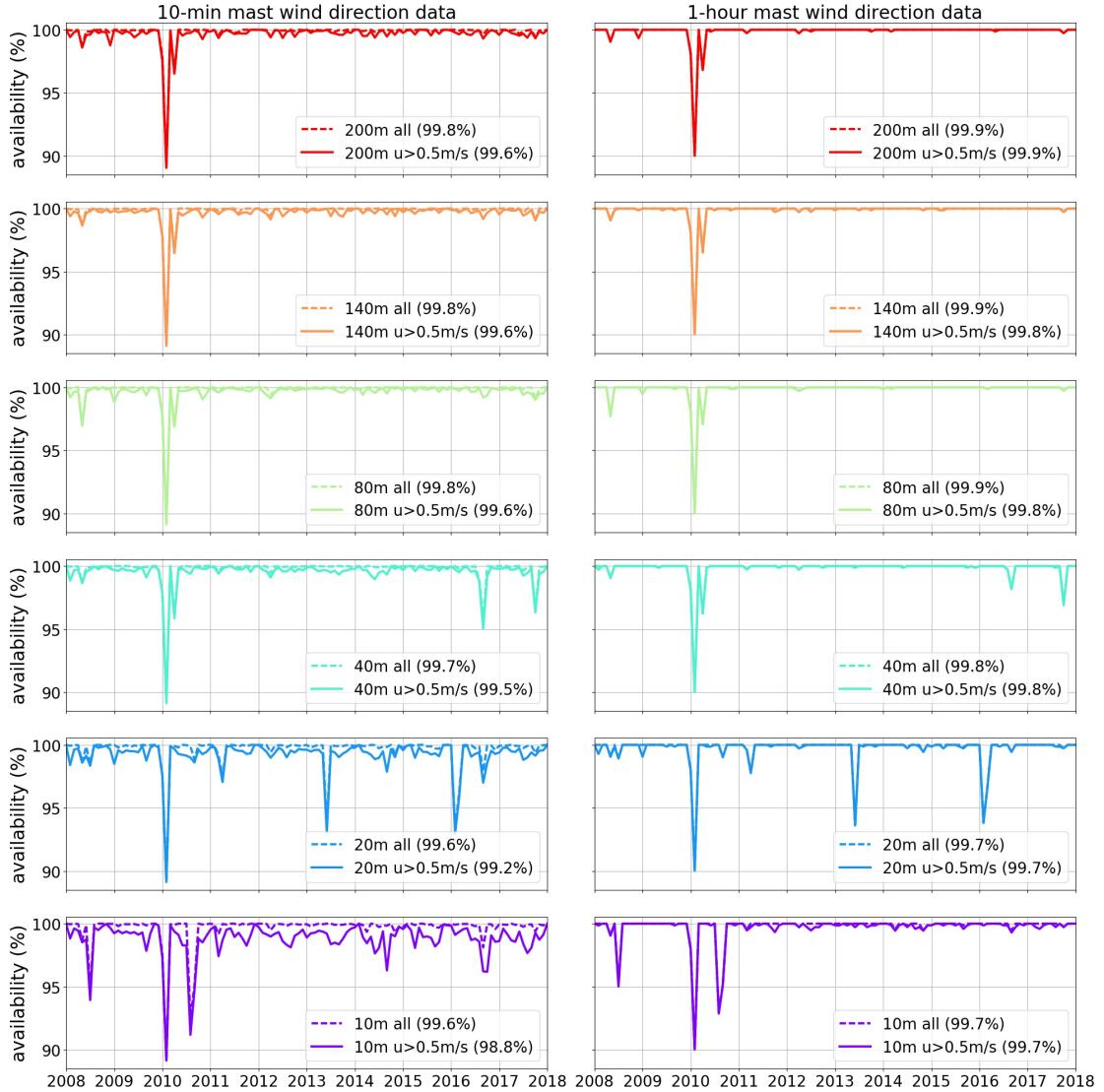
Figure 6: Monthly data availability of the 10-minute (left panel) and 1-hourly (right panel) wind direction measurements from the Cabauw meteomast, all data (dashed lines) and data for which the wind speed is larger than 0.5 m/s (solid lines). In the legends the overall data availability per height for the whole period is given. Data availability is defined as the percentage of monthly valid 10-minute or hourly data, in which a valid hourly data requires only one valid 10-minute data.

4 Methodology

The strategy adopted for this validation study is based on the previous KNW validation report [3], which details the performance of the KNW atlas against offshore and Cabauw mast measurements. Hence, a similar study of the temporal averages (i.e. yearly monthly mean, yearly mean, monthly mean, hourly mean etc.) is conducted along with measurement-of-accuracy statistics (bias, standard deviation and root mean squared error). In addition, the hourly correlations between the measurements and the wind atlases have been calculated.

Besides the DOWA and KNW atlases, we have also included KNW without wind shear correction (KNW-wowsc) in our validation study. The KNW-atlas is "tuned" via the wind shear correction to the 10-year averaged Cabauw meteomast measurements for the years 2004-2013, which overlaps with the validation period considered here. Therefore it is hard to improve KNW regarding the average wind speed in this particular validation study. By directly comparing DOWA and KNW-wowsc the improvements made by using the newer HARMONIE version (in particular the HARATU turbulence scheme) become more visible.

We have also included the global reanalysis datasets of ERA-Interim and ERA5 in our validation study to assess whether downscaling with HARMONIE adds skill, and to investigate whether differences between DOWA and KNW can be traced back to their host reanalysis model.

The time period of all datasets are from 1st January 2008 up to and including 31st December 2017. Computations are performed and graphs are generated with Python scripts (and using the Pandas module).

For the preparation of 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 (except ERA-Interim, which is 6-hourly) that represents the state of the atmosphere at the full hour. The Cabauw meteomast measurements used are 10-minute averages. To validate DOWA with Cabauw measurements, one hour of Cabauw 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 output (that represents a 2.5 by 2.5 km grid box average). The method to compare the wind atlases with the Cabauw measurements is conform the one used to validate the KNW-atlas [3]. In Appendix A results based on shorter averaging times are shown.

- The validation is conducted for all measuring heights of the Cabauw meteomast: 10 m, 20 m, 40 m, 80 m, 140 m, and 200 m. These levels are all present within the DOWA; for the KNW-atlas a cubic-spline interpolation scheme was used to interpolate the model data to 140 m.

  The sigma levels from ERA-Interim and ERA5 are converted into heights. A constant height for each level is taken, based on the averages over the 10-year period. For both ERA-Interim and ERA5 the lowest 15 levels are taken into account. For ERA-Interim those correspond to 9.9, 35, 71, 123, 193, 285, 400 m, ... , 2.3 km; for ERA5 to 10, 31, 54, 79, 107, 137, 170, 205, 245, 288 m, ... , 566 m. A cubic-spline interpolation scheme was used to interpolate the model data to the measuring heights.

- For both 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).

- For the Cabauw meteomast measurements we filter out wind speed and wind direction data for which the wind speed is less than 0.5 m/s.

- We only consider hourly wind atlas information for which there is a valid Cabauw meteomast measurement. Thus, timestamps for which Cabauw meteomast measurements are missing, or the measured wind speed is too low for a reliable measurement, are filtered out, which is at most only 0.4% of the data (see Sect. 3).

- We have derived KNW-wowsc by applying the inverse of Eq. 1 to the KNW output data:

$$U_{\text{KNW}-\text{wowsc}}(h) = 0.85 U_{\text{KNW}}(h) + 0.15 U_{\text{KNW}}(20), \tag{2}$$

  where U is the wind speed and h is the height.

- For DOWA and KNW no spatial interpolation of the wind atlas data has been performed. We simply took the nearest grid point to the Cabauw meteomast. Details on the coordinates and chosen grid points, and a sensitivity study on the neighboring grid points are given in Appendix B. For ERA-Interim and ERA5 four grid points close to Cabauw were obtained from ECMWF (with a spacing of $0.125°$, see also Appendix B) and further interpolated to the location of the Cabauw meteomast.

- 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 C). 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. 3).

5   Validation results

In this section the validation results are presented. The focus is on the comparison between DOWA and KNW atlas. 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 (which in some cases are too narrow to be visible). Measurement uncertainty is not included, but with a measurement accuracy of 0.1 m/s or 1% one can state that (for wind speeds below 20 m/s) a bias below 0.2 m/s is not significant. The results are discussed in Section 6.

The following statistics are shown and discussed:

- Yearly monthly mean wind speed (Sect. 5.1.1);

- Yearly mean wind speed (Sect. 5.1.2);

- Monthly mean wind speed (Sect. 5.1.3);

- Directional mean wind speed (Sect. 5.1.4);

- Hourly mean wind speed (diurnal cycle) (Sect. 5.1.5);

- Mean wind speed and mean bias profiles (Sect. 5.1.6);

- Weibull parameter profiles (Sect. 5.2);

- Hourly wind speed correlation (Sect. 5.3);

- Mean wind direction bias profiles (Sect. 5.4);

- Extreme values analysis (Sect. 5.5).

Additional graphs are shown in the Appendices:

- Wind direction distributions (Appendix D);

- Wind speed distributions and Weibull fits (Appendix E);

- Wind direction hourly correlation (Appendix F).

5.1 Mean wind speed

The following subsections validation results of the mean wind speed are presented. In Figs. 7-11 the mean wind speed shown for the different heights, with two panels for each height: in the upper panel the wind speed of mast measurements and models, in the lower panel the bias between the mast measurements and the models. Model variance is indicated in the bias plot (which in some cases are too narrow to be visible).

5.1.1 Yearly monthly mean wind speed

In Fig. 7 the yearly monthly mean wind speed is shown. The yearly monthly mean wind speed shows varies significantly and a seasonal pattern with higher wind speeds in the winter and lower in the summer is visible. DOWA and KNW show a very similar bias, varying between -0.5 m/s and +0.5 m/s, for the higher levels (down to 40 m). For the lowest levels (10 and 20 m), DOWA shows a larger bias than KNW, and mostly positive, meaning that DOWA underestimates the wind speed at those heights.

ERA-Interim and ERA5 show a similar positive bias of around 0.5 m/s at 200 m, which remain of similar size and sign for ERA5 for the other heights, where for ERA-Interim the bias drops, to become mostly negative from 40 m downwards.

5.1.2 Yearly mean wind speed

In Fig. 8 the yearly mean wind speed is shown. Here the inter-annual variability (IAV) becomes visible, with 2008 and 2015 years with a relatively high mean wind speed, and a low mean wind speed in 2010. IAV is captured by all models, but DOWA and KNW capture the IAV much better than ERA5. For the higher levels (down to 40 m) DOWA and KNW show biases between -0.2 m/s and 0.1 m/s, and the differences between DOWA and KNW are less than 0.2 m/s. For lower levels differences between DOWA and KNW are larger: for 20 m height DOWA has a large positive bias of about 0.3 m/s, while KNW has a small bias below 0.1 m/s, whereas at 10 m DOWA has a positive bias up to 0.2 m/s, while KNW has a small negative bias below 0.1 m/s. The decreasing trend observed in the bias (about 0.1 m/s) is probably not significant.

Again, ERA-Interim and ERA5 show a similar positive bias around 0.5 m/s at 200 m, which remain of similar size and sign for ERA5 for the other heights, where for ERA-Interim the bias drops, to become -0.2 m/s from 40 m downwards.

5.1.3 Monthly mean wind speed

In Fig. 9 the monthly mean wind speed is shown. The seasonal behavior of the mean wind speed is captured well by all models, showing a larger mean wind speed in the winter than in the summer. For the three highest levels (80, 140 and 200 m) DOWA and KNW are very similar, with biases between -0.2 m/s and +0.1 m/s, and with differences between DOWA and KNW well below 0.2 m/s. For the three lowest levels (10, 20 and 40 m) difference between DOWA and KNW up to 0.5 m/s appear in the winter months, where DOWA shows a positive bias and KNW a negative one. In the summer months the difference between DOWA and KNW is less than 0.1 m/s. Thus, the differences observed between DOWA and KNW at the lower levels in yearly (monthly) means are mainly due to differences in the winter.

Again, ERA-Interim and ERA5 show a similar constant, positive bias of around 0.5 m/s at 200 m. For the lowest levels a small seasonal dependence is visible, where ERA5 shows the largest (positive) bias in the winter months and where ERA-Interim performs very well, except for August until October, when the bias is negative.
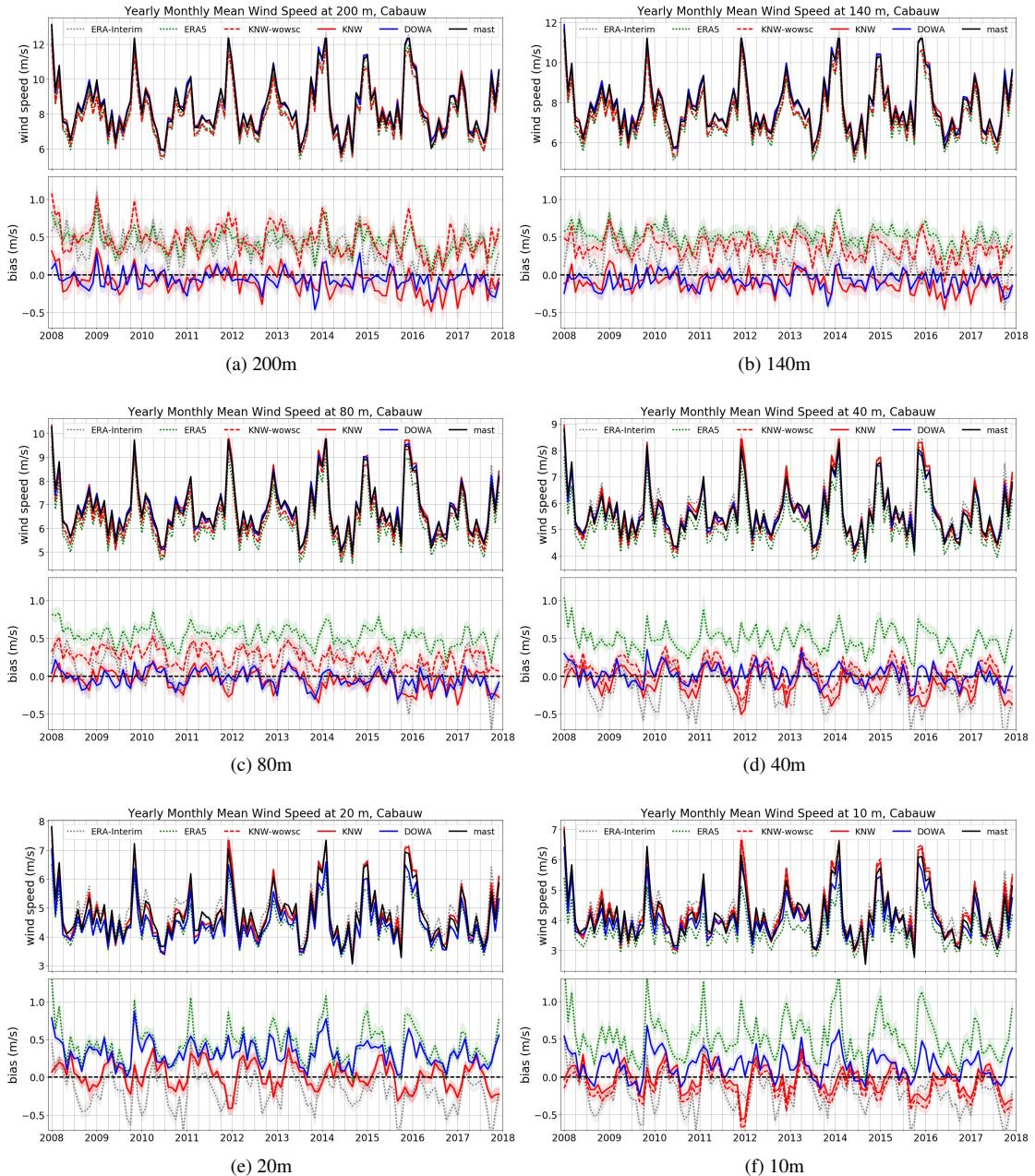
Figure 7: Yearly monthly mean wind speed, showing mast measurements (black), DOWA (blue), KNW atlas (red), KNW atlas without wind shear correction (red, dashed), ERA5 (green, dotted) and ERA-Interim (gray, dotted). Model variance is indicated by the shaded areas in the bias plots.
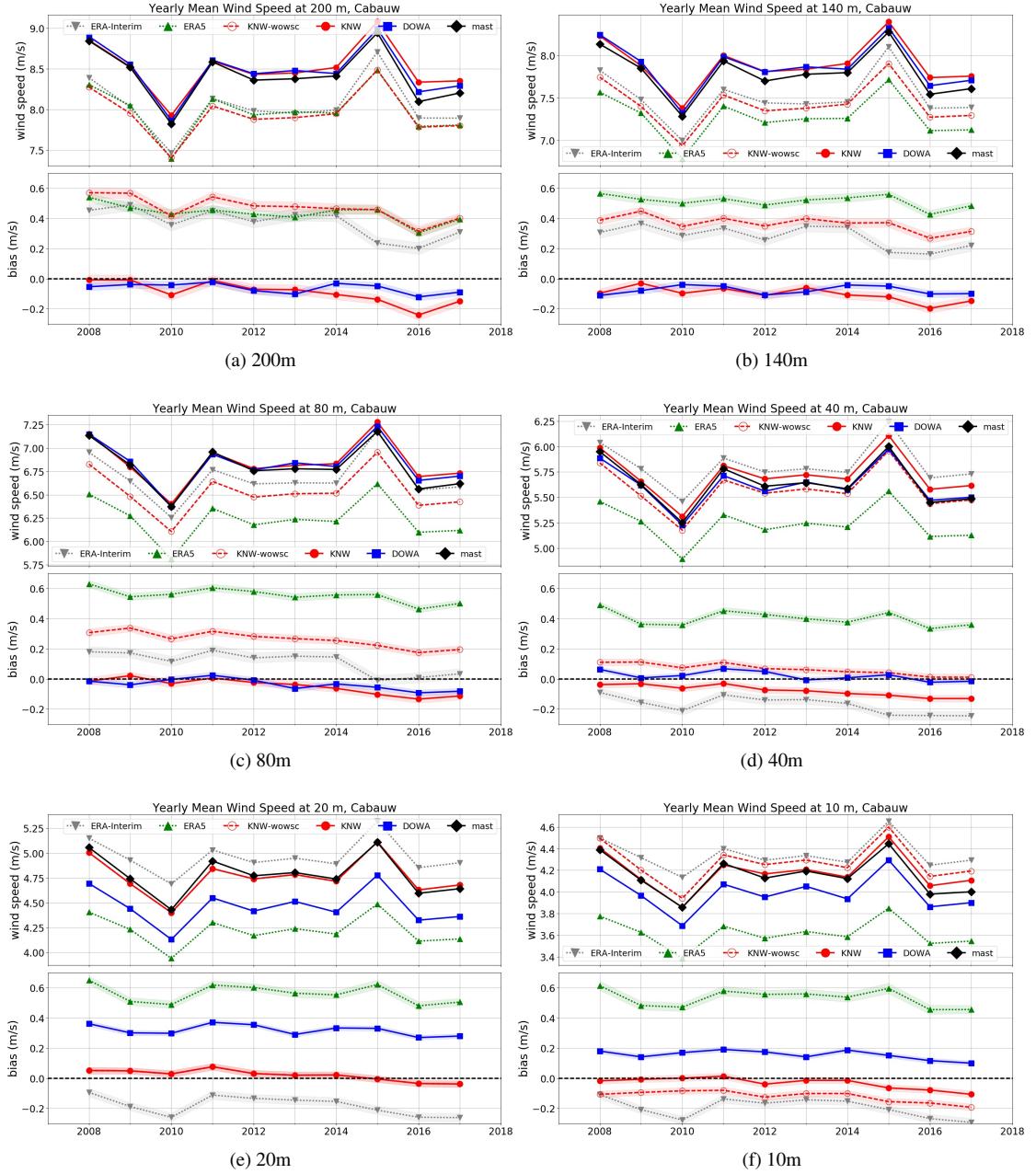
Figure 8: Yearly mean wind speed, showing mast measurements (black), DOWA (blue), KNW atlas (red), KNW atlas without wind shear correction (red, dashed), ERA5 (green, dotted) and ERA-Interim (gray, dotted). The upper panel shows the wind speed of both mast measurements and models, the lower panel the bias between the mast measurements and the models. Model variance is indicated by the shaded areas in the bias plots.
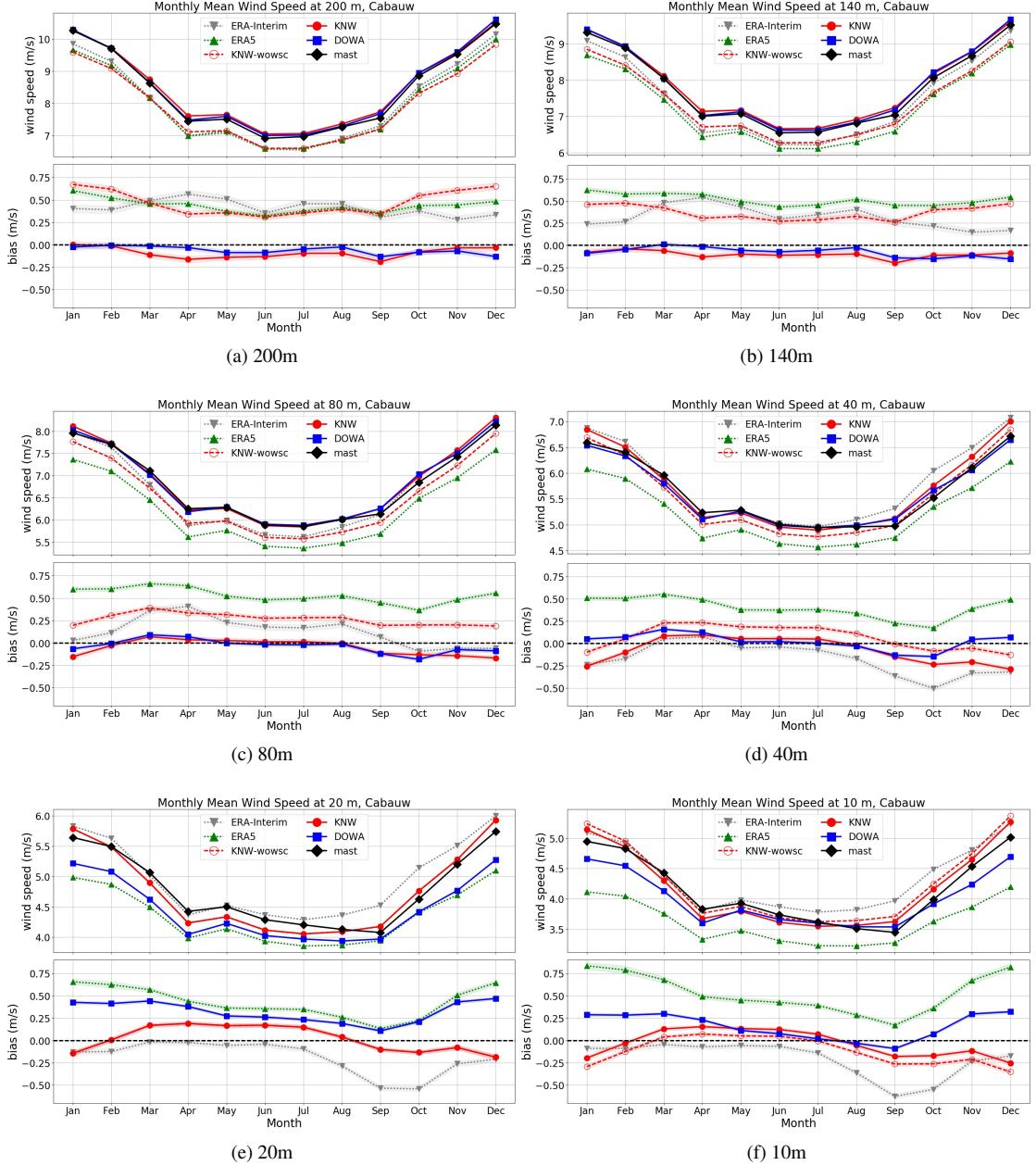
Figure 9: Monthly mean wind speed, showing mast measurements (black), DOWA (blue), KNW atlas (red), KNW atlas without wind shear correction (red, dashed), ERA5 (green, dotted) and ERA-Interim (gray, dotted). The upper panel shows the wind speed of both mast measurements and models, the lower panel the bias between the mast measurements and the models. Model variance is indicated by the shaded areas in the bias plots.

5.1.4 Directional mean wind speed

In Fig. 10 the directional mean wind speed is shown. The sector width is 30 °, resulting in 12 sectors. The shape of the directional mean wind speed is reproduced by all models, showing that the 210°-240° sector represents the sector with the highest mean wind speed. For the three highest levels (80, 140 and 200 m) DOWA shows a pronounced bias feature (with an amplitude up to 0.6 m/s) for the 120°-150° wind sector, not present in KNW; outside this feature DOWA and KNW are similar. Here it should be noted that wind directions between 120° and 150° occur least often (wind direction distributions are shown in Appendix D), which means that the impact of this feature on the mean wind speed is less dramatic as Fig. 10 suggests. At lower levels the differences between DOWA and KNW are about 0.2 m/s, and again DOWA has a positive bias.

ERA-Interim and ERA5 also show a pronounced bias feature for the 120°-150° wind sector at the highest levels. ERA5 shows a large positive bias of 1 m/s for the 210°-240° wind sector at the lowest levels.

5.1.5 Hourly mean wind speed

In Fig. 11 the hourly mean wind speed is shown. The validation of the hourly mean wind speed shows how well the models capture the diurnal cycle. It can be seen that the diurnal cycle depends strongly on height: at lower levels wind speed is maximum during daytime and minimum during nighttime, while at higher levels it is the other way around. This behavior is captured by both DOWA and KNW. When considering the biases one notices that KNW shows strong non-physical "jumps" every 6 hours, whereas DOWA shows weaker "jumps" for the higher levels every 3 hours. The KNW "jumps" correspond with the use of cold starts every 6 hours, while the DOWA features are due to the data assimilation. Difference between night and day can be explained by the fact that the assimilated Mode-S EHS observations are only available during the day (when there is aviation). Again, for the lower levels DOWA has a large positive bias, especially for 20 m, which is fairly independent on the hour of day.

The diurnal cycle is not only height-dependent, but also strongly dependent on the season. Daytime solar radiation is much stronger in the summer than in winter. As a result there is more mixing in the boundary layer and wind will change less with height. In Fig. 12 the hourly mean mast measurements and DOWA data are displayed separately for the four seasons, indeed 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.
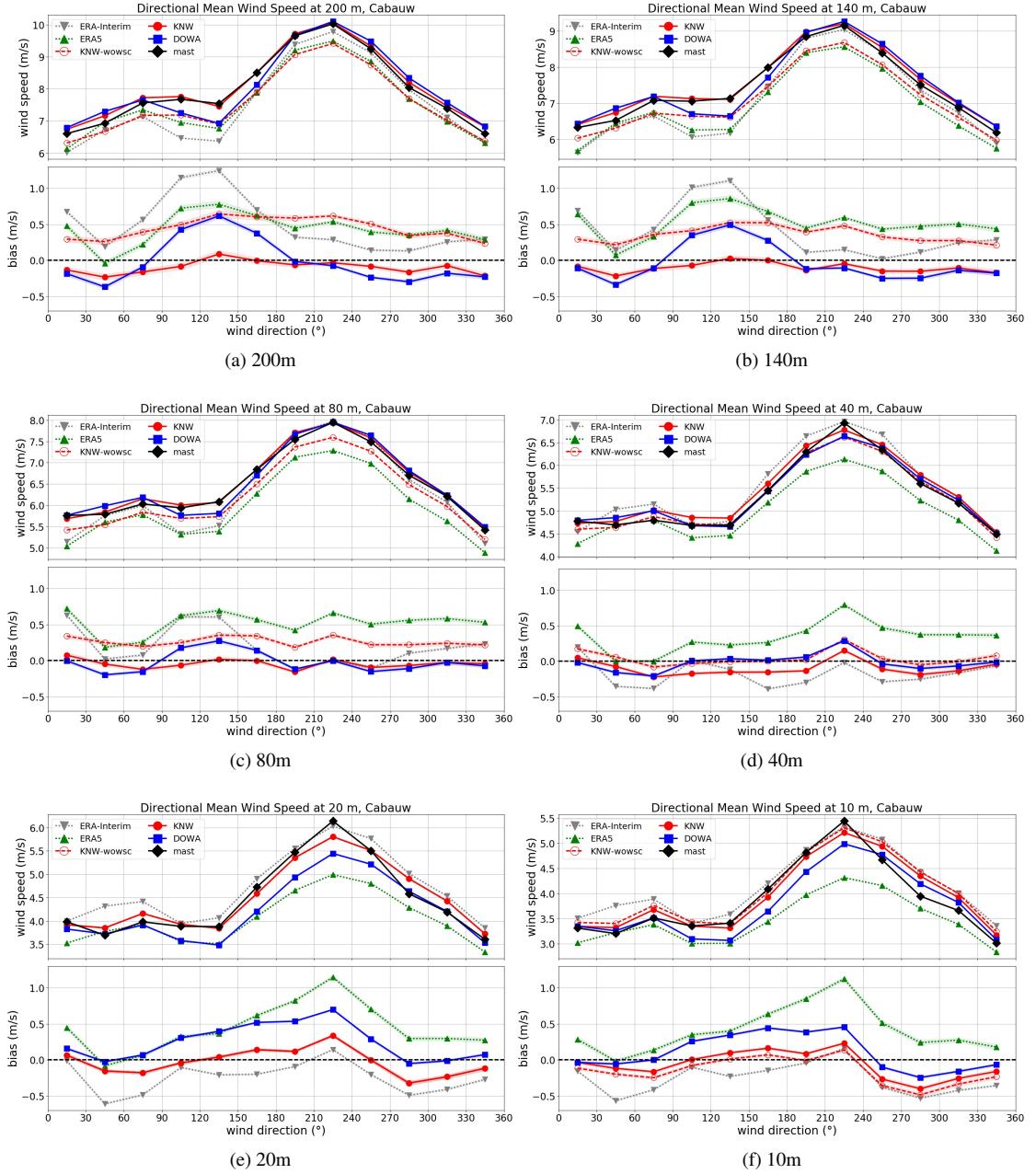
Figure 10: Directional mean wind speed, showing mast measurements (black), DOWA (blue), KNW atlas (red), KNW atlas without wind shear correction (red, dashed), ERA5 (green, dotted) and ERA-Interim (gray, dotted). The upper panel shows the wind speed of both mast measurements and models, the lower panel the bias between the mast measurements and the models. Model variance is indicated by the shaded areas in the bias plots.

(a) 200m   (b) 140m

(c) 80m   (d) 40m

(e) 20m   (f) 10m
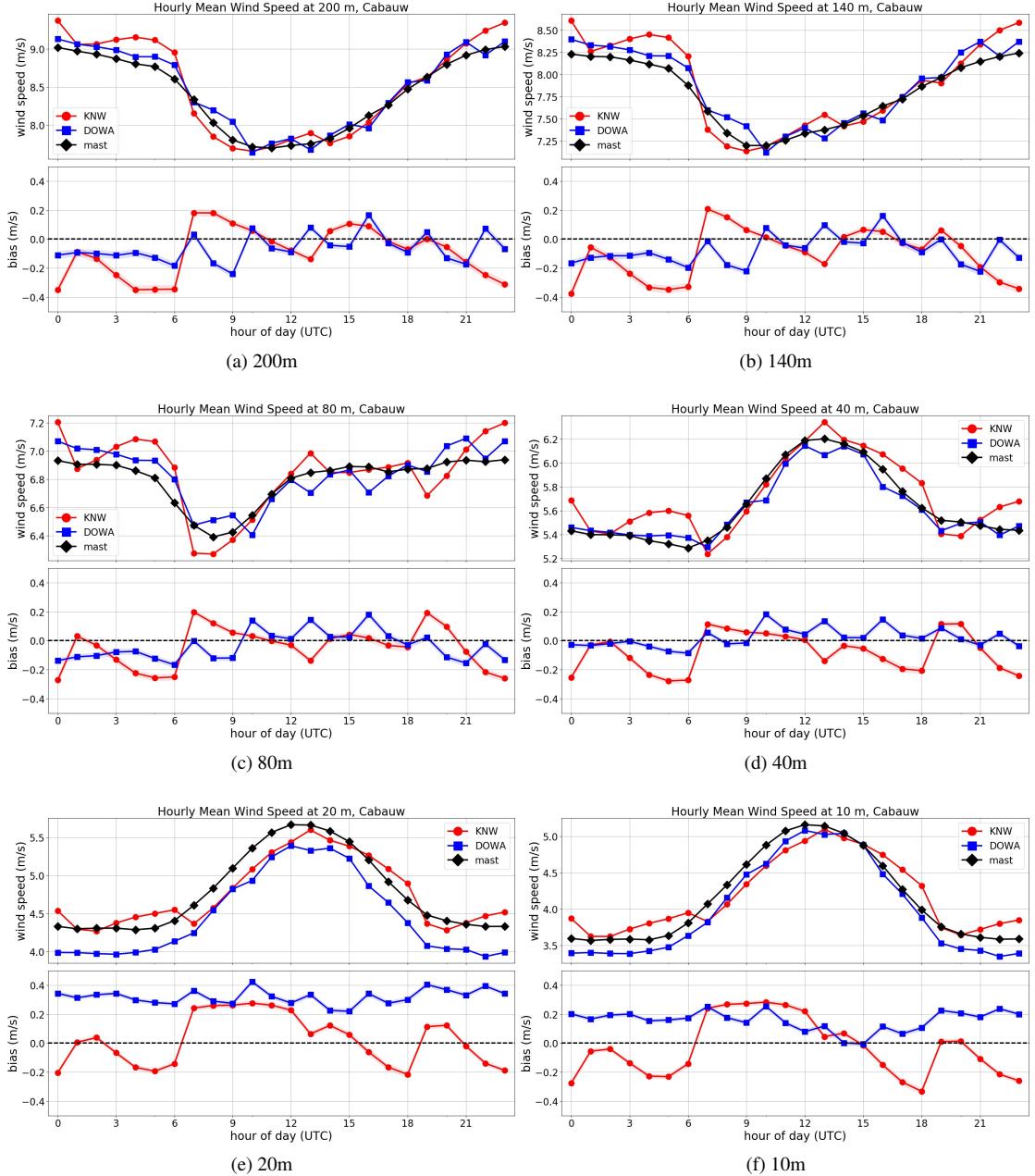
Figure 11: Hourly mean wind speed, showing mast measurements (black), DOWA (blue) and KNW atlas (red). The upper panel shows the wind speed of both mast measurements and models, the lower panel the bias between the mast measurements and the models.
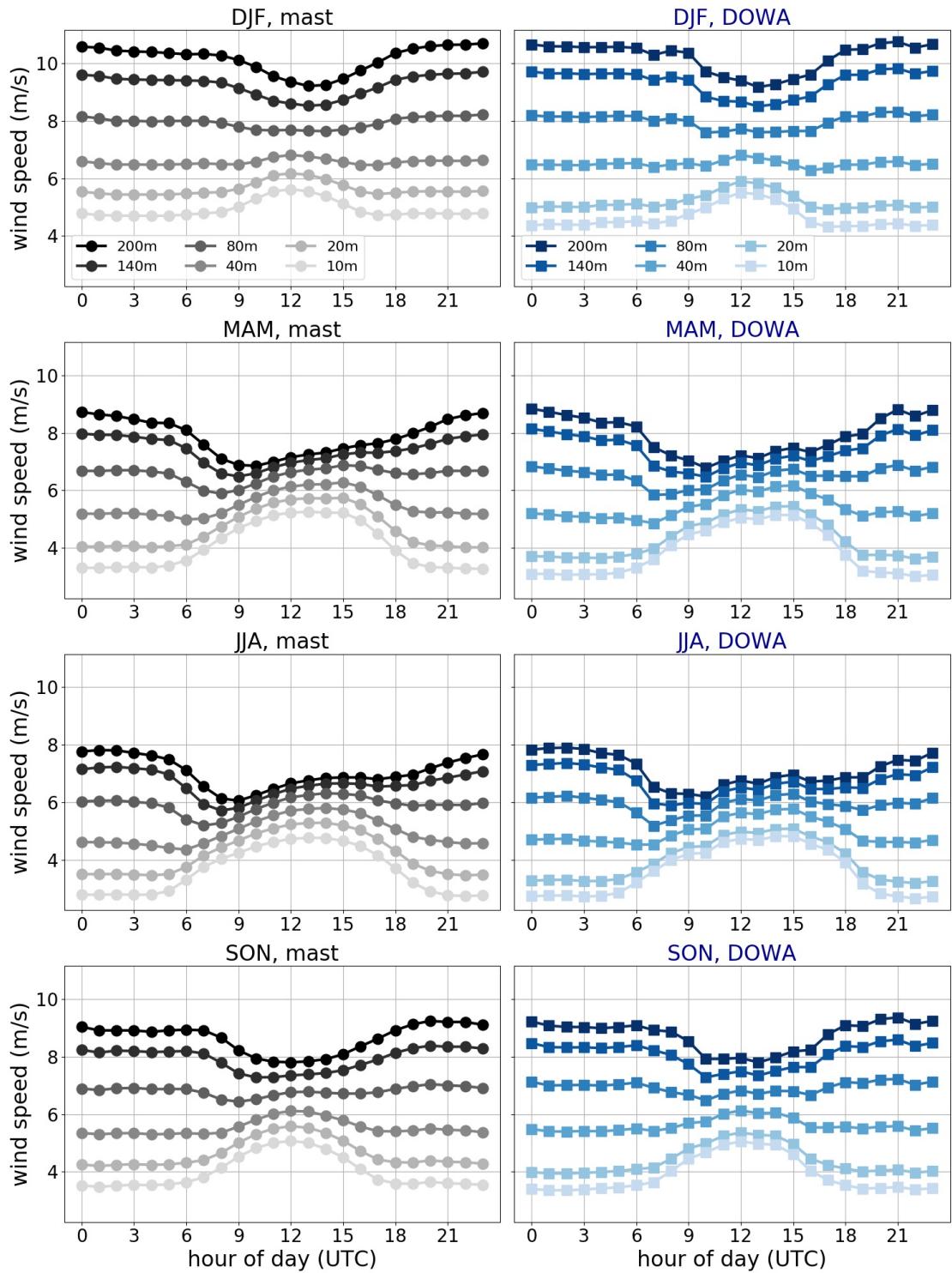
Figure 12: Hourly mean wind speed for the mast measurements (left) and DOWA (right), separated into the four season: winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November).

5.1.6 Mean wind speed and bias profiles

In Fig. 13 the height profiles of the mean wind speed (left panel) and the mean bias (right panel) for the full period of 10 years are shown. The latter is also given in Table 2. Model variance is indicated in the bias plot, but these are almost too small to be visible. The profiles show an increase of the mean wind speed with height. DOWA and KNW are very similar for the higher levels (80, 140 and 200 m), with DOWA having slightly lower negative biases than KNW, but all within an absolute value of 0.1 m/s. At 40 m the absolute bias of DOWA and KNW is smaller than 0.1 m/s. These biases all are within the measurement uncertainty, and therefore no distinction between DOWA and KNW can be made for these heights. DOWA and KNW deviate at lower levels (10 and 20 m), where DOWA shows a positive bias of at most 0.3 m/s, while KNW has a bias with an absolute value smaller than 0.1 m/s. For these lowest levels one can conclude that KNW performs better than DOWA.

ERA5 shows an almost constant positive bias of about 0.5 m/s, whereas ERA-Interim has negative bias at lower levels and a positive bias at higher levels. The mean wind speeds at 200 m for ERA-Interim and ERA5 are almost the same.
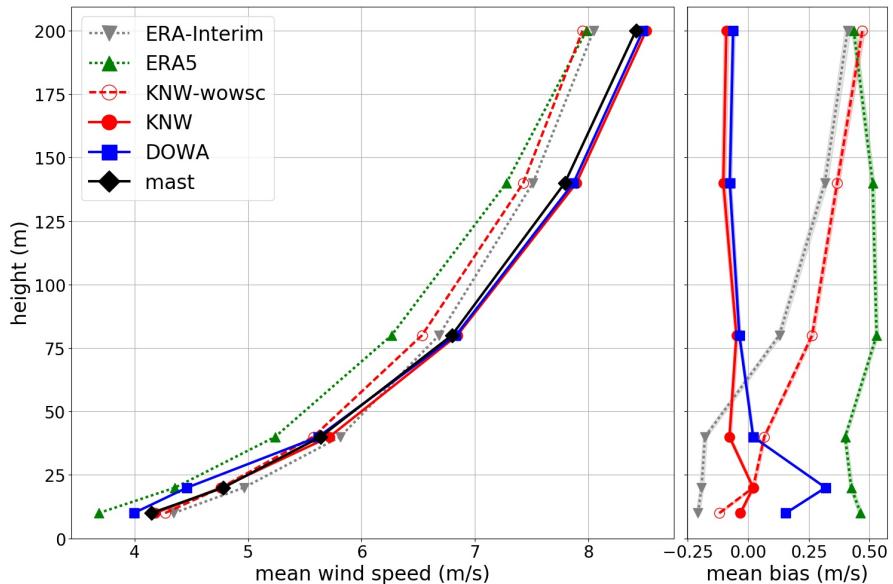
Figure 13: Height profile of the mean wind speed (left) and mean bias (right), showing mast measurements (black), DOWA (blue), KNW atlas (red), KNW atlas without windshear correction (red, dashed), ERA5 (green, dotted) and ERA-Interim (gray, dotted).

height (m)	DOWA	KNW	KNW$_{wowsc}$	ERA5	ERA-Interim
10	0.16	-0.03	-0.12	0.46	-0.21
20	0.32	0.02	0.02	0.43	-0.19
40	0.02	-0.08	0.07	0.40	-0.18
80	-0.04	-0.05	0.26	0.53	0.13
140	-0.08	-0.10	0.37	0.51	0.32
200	-0.06	-0.09	0.47	0.44	0.41

Table 2: Mean wind speed bias (m/s) of the different models, for the full period of 10 years.
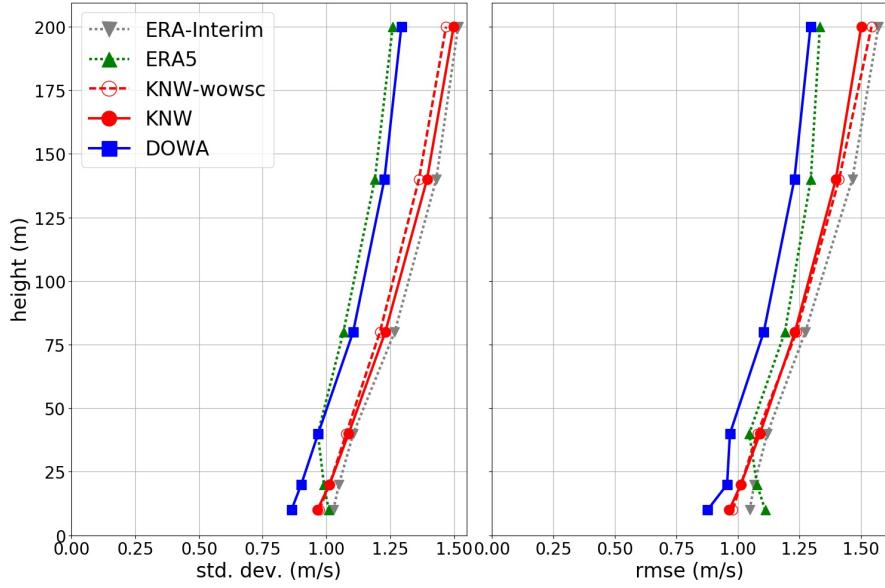
Figure 14: Height profile of the standard deviation of the bias (left) and root mean square error (rmse) (right), showing DOWA (blue), KNW (red), KNW without windshear correction (red, dashed), ERA5 (green, dotted) and ERA-Interim (gray, dotted).

height (m)	DOWA	KNW	KNW$_{wowsc}$	ERA5	ERA-Interim
10	0.86	0.96	0.97	1.01	1.03
20	0.90	1.01	1.01	0.99	1.05
40	0.97	1.09	1.08	0.97	1.11
80	1.10	1.23	1.21	1.07	1.27
140	1.23	1.39	1.36	1.19	1.43
200	1.29	1.50	1.47	1.26	1.52

Table 3: Standard deviation of the wind speed bias (m/s) of the different models, for the full period of 10 years.

height (m)	DOWA	KNW	KNW$_{wowsc}$	ERA5	ERA-Interim
10	0.88	0.96	0.98	1.11	1.05
20	0.96	1.01	1.01	1.08	1.07
40	0.97	1.09	1.08	1.05	1.12
80	1.11	1.23	1.24	1.19	1.27
140	1.23	1.40	1.41	1.30	1.47
200	1.30	1.50	1.54	1.33	1.57

Table 4: Root mean square error (rmse) (m/s) of the wind speed between the measurements and the different models, for the full period of 10 years.

In Fig. 14 and Table 3 and Table 4 the height profiles of the standard deviation of the bias (left panel) and root mean square error (rmse) between the measurements and the models (right panel) are shown. Standard deviation of the bias and rmse are both statistical measures of accuracy. They are defined as follows:

$$\text{std.dev.bias} = \sqrt{(1/N)\sum_{i=1}^{N}\left(\delta_i - \bar{\delta}\right)^2} = \sqrt{(1/N)\sum_{i=1}^{N}\left(x_i - y_i - \bar{\delta}\right)^2}, \tag{3}$$

with bias $\delta_i = x_i - y_i$, where x_i and y_i are the measurements and model output, respectively, N is the number of data points and $\bar{\delta} = (1/N)\sum \delta_i$ is the mean bias, and

$$\text{rmse} = \sqrt{(1/N)\sum_{i=1}^{N}(x_i - y_i)^2}, \tag{4}$$

from which it can be seen that in case the mean bias $\bar{\delta}$ is zero, the standard deviation of the bias and the rmse are the same.

For DOWA the standard deviation of the bias and the rmse range from 0.9 to 1.3 m/s for heights of 10 to 200 m, while for KNW these values range from 1.0 to 1.5 m/s. Thus, DOWA has a smaller standard deviation and rmse than KNW, which already indicates a better correlation between the model output and measurements. This will be further discussed below (Sect. 5.1.5 and 5.3). The wind shear correction applied to KNW changes the bias, but does not have a large effect on the correlation: the standard deviation and rmse of KNW and KNW-wowsc are very similar.

For ERA-Interim the standard deviation and rmse are slightly larger than KNW; For ERA5 the standard deviation is slightly smaller than DOWA for heights above 40 m, while the rmse is larger for all heights (because of the significantly larger bias).

5.2 Weibull parameter profiles

The wind speed distributions are shown in Appendix E. To compare these distributions we fit the two-parameter Weibull distribution to the data:

$$f(U) = (k/A)(U/a)^{k-1} \exp\left[-(U/a)^k\right], \tag{5}$$

where U is the wind speed, and the two fit parameters the shape parameter k and the scale parameter A, the latter being proportional to the mean wind speed of the distribution. The height profiles of the resulting Weibull fit parameters are shown in Fig. 15. The scale parameter A increases with height; this and the comparison between the measurements and the models is essentially the same as the behavior of the mean wind speed as shown in Fig. 13. The shape parameter k increases with height up to 80 m, but then starts to slowly decrease with height, which is consistent with Cabauw wind data analysis of more than 35 years ago (see Ref. [20], pag. 136)[2]. There are small differences between the measurements and the models, but the change with height is almost the same.

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[2]As wind is slowed by friction at the surface, the spread in possible wind speeds will in general be smaller nearer the surface. That is why the value of k will generally decrease with height. There are two other mechanisms that play a role in the change of k with height:

- On land: k increases with height up to about 75 m due to diurnal cycle at the surface which introduces a larger spread in possible wind speeds and a lower value of k at the surface.

- At sea: k decreased even more with height because the sea surface roughness depends on the wind speed: the sea gets rougher at high wind speeds and due to friction, winds are slowed more. The effect of the sea surface roughness on the wind speed becomes increasingly smaller with height, allowing higher winds to persist aloft while being slowed near the surface. This means that the range of possible wind speeds (i.e. the spread of the wind speed distribution), and therefore the value of k, should decrease with height.
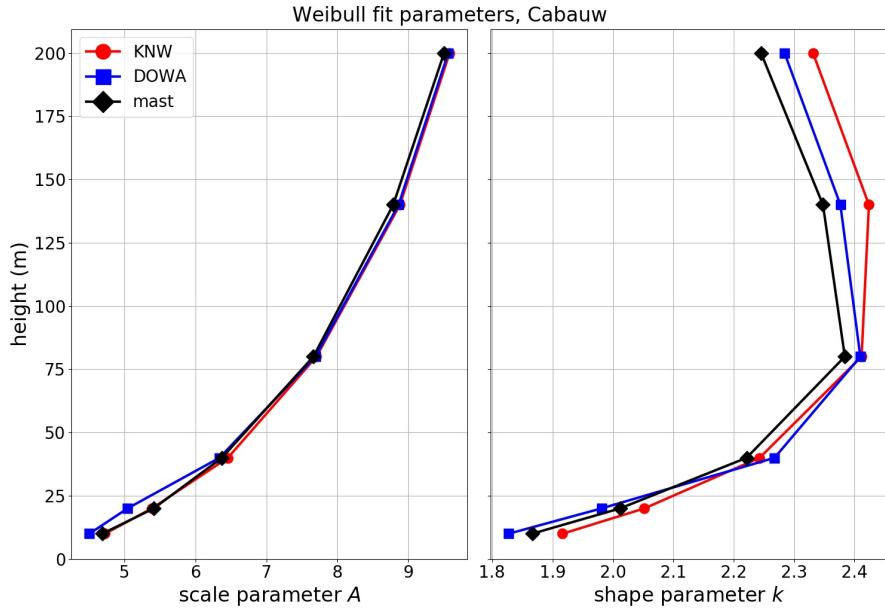
Figure 15: Height profiles of the Weibull scale parameter A (left) and shape parameter k (right), showing mast measurements (black), DOWA (blue) and KNW atlas (red).

5.3   Hourly wind speed correlation

The most direct validation of the models is to consider the hourly correlation between the model output and the mast measurements. In Fig. 16 and 17 the DOWA wind speeds are plotted against the mast wind speeds for the different heights. 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[3]. 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 Table 5 and Fig. 18, for the DOWA and KNW-atlas. For DOWA the slope ranges from 0.88 to 0.94, while for KNW from 0.89 to 0.90. For the higher levels (80, 140 and 200 m) the slope for DOWA is closer to 1 than KNW. For DOWA the offset ranges from 0.2 to 0.6 m/s, and is always smaller than KNW, for which the offset ranges from 0.5 to 1.0 m/s. For DOWA R^2 ranges from 0.87 to 0.90, and is always closer to 1 than KNW, for which R^2 ranges from 0.84 to 0.86. Overall, these results indicate that DOWA provides an improvement in the correlation compared to KNW, in particular when considering heights from 80 m upwards.

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[3]In statistics, the coefficient of determination, denoted R^2 or r^2 and pronounced "R squared", is the proportion of the variance in the dependent variable that is predictable from the independent variable(s) and ranges from 0 to 1.

height (m)	slope		offset (m/s)		R^2	
	DOWA	KNW	DOWA	KNW	DOWA	KNW
10	0.91	0.90	0.20	0.46	0.87	0.84
20	0.88	0.89	0.25	0.48	0.87	0.84
40	0.91	0.92	0.51	0.53	0.87	0.84
80	0.92	0.90	0.55	0.70	0.87	0.84
140	0.93	0.90	0.58	0.90	0.88	0.85
200	0.94	0.90	0.61	0.95	0.90	0.86

Table 5: Results of the linear regression fit in terms of the slope, offset and R^2 parameters, comparing DOWA and KNW.
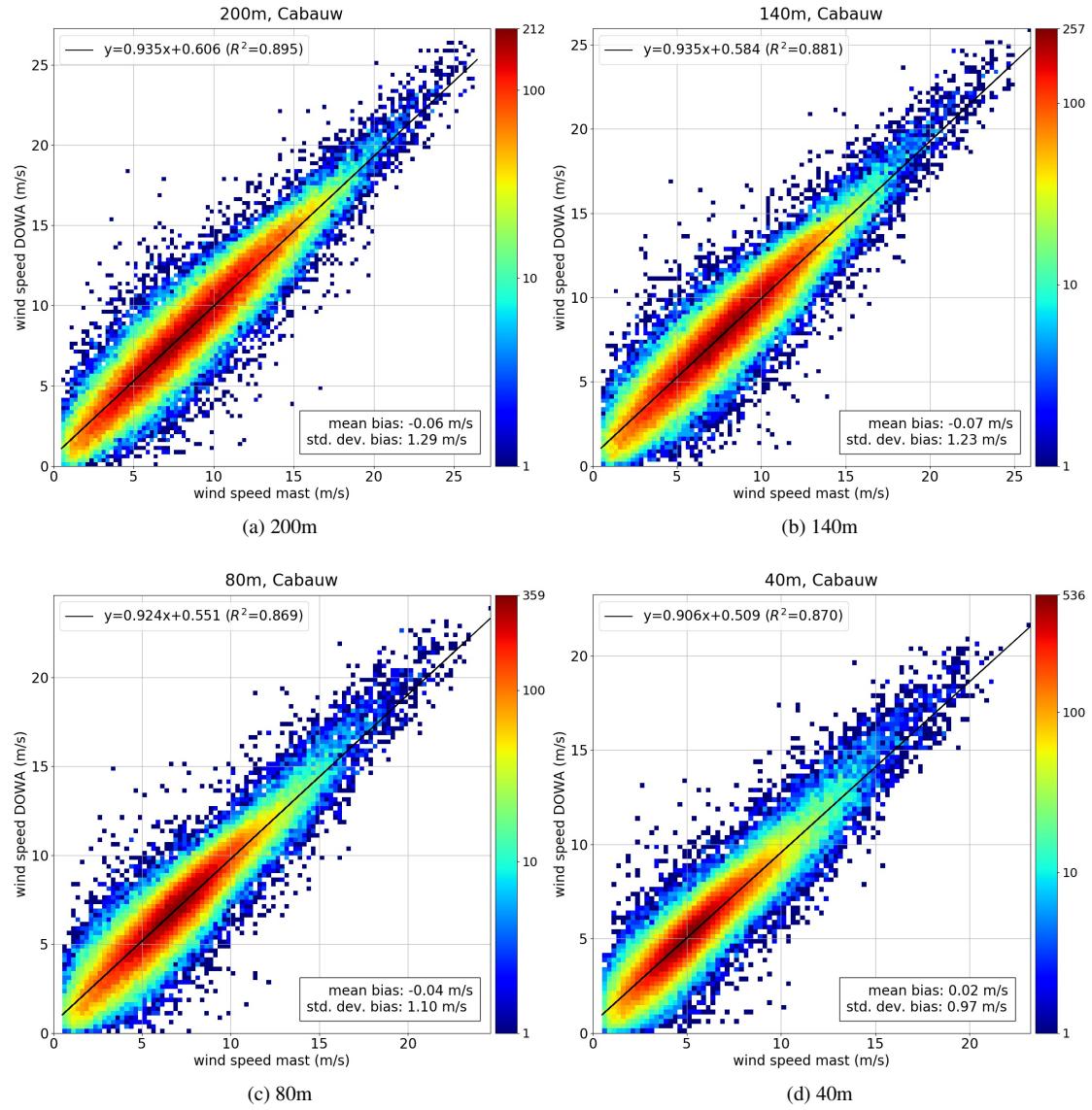
Figure 16: Scatterplot of the DOWA and mast wind speed data (visualized as a density plot with logarithmic color scale), showing the result of a linear regression (slope, intersect and R^2) and the mean bias and standard deviation of the bias.
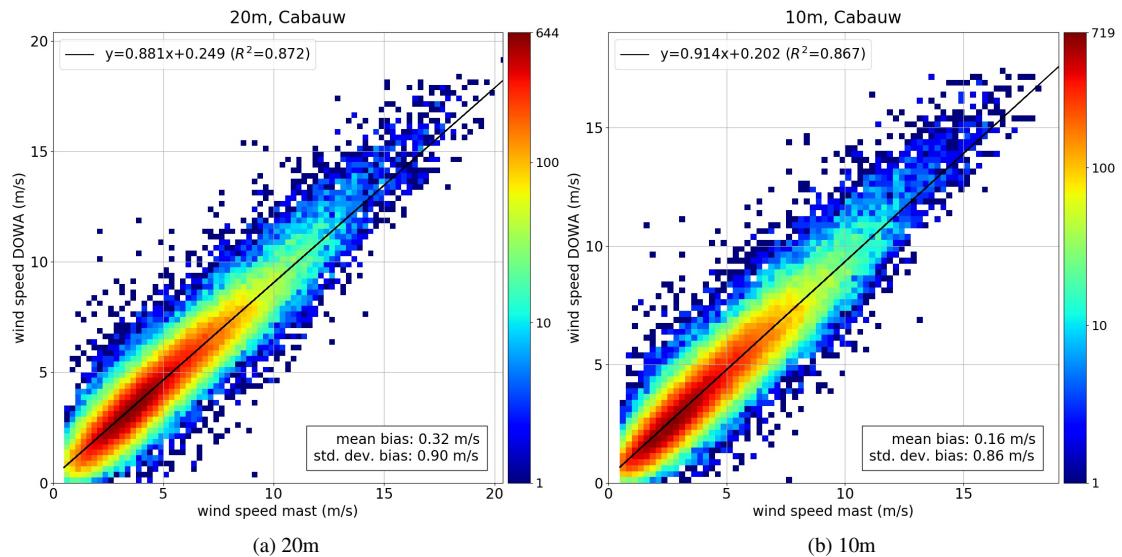
Figure 17: Continuation of Fig. 16.
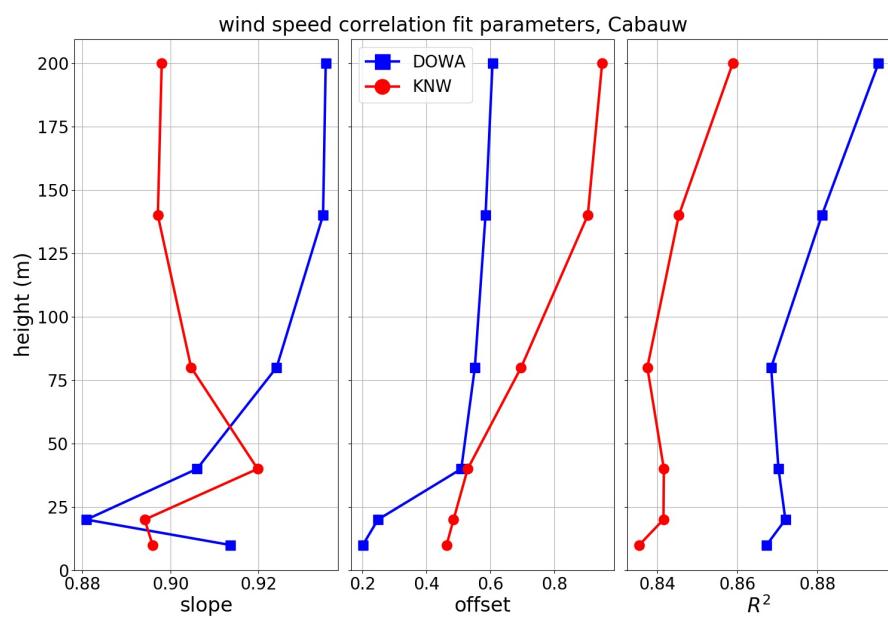
Figure 18: Height profile of the results of the linear regression (slope, offset and R^2) of the wind speed data, comparing the DOWA (blue) and KNW atlas (red).

5.4 Mean wind direction bias profiles

In this section a validation of the wind direction data is performed. Height profiles of the mean bias, standard deviation of the bias and the rmse for the different models[4] are shown in Fig. 19 and Tables 6-8. In general the mean bias decreases with increasing height. For DOWA the mean bias ranges from -6° to -2° with increasing height, and these biases are similar or slightly larger than those of KNW. ERA5 performs similar to DOWA and KNW for the higher levels (80, 140, 200 m), and a bit worse for the lower levels (10, 20 and 40 m). ERA-Interim performs worse for all heights, showing a larger negative bias up to -15° at 10 m. Also the standard deviation and the rmse decreases with increasing height, and their values are nearly identical. For DOWA the standard deviation ranges from 25° to 19°, and is slightly smaller than that of KNW for all heights. ERA5 and ERA-Interim show standard deviations similar to those of DOWA and KNW, respectively.

The standard deviation in the wind direction is very sensitive to the selected wind speed range. In

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[4]With regards to wind direction the KNW atlas without wind shear correction is the same as the KNW atlas and is therefore omitted in this section.
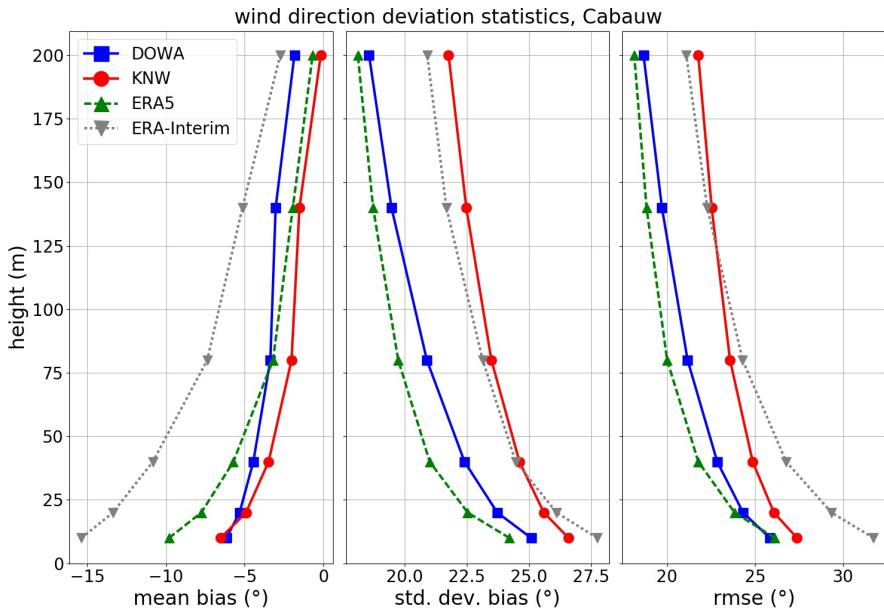
Figure 19: Height profile of the mean bias, standard deviation of the bias and rmse of the wind direction data: DOWA (blue), KNW atlas (red), ERA5 (green, dashed) and ERA-Interim (gray, dotted).

height (m)	DOWA	KNW	ERA5	ERA-Interim
10	-6.2°	-6.5°	-9.8°	-15.4°
20	-5.3°	-4.9°	-7.7°	-13.4°
40	-4.4°	-3.5°	-5.7°	-10.8°
80	-3.4°	-2.0°	-3.2°	-7.4°
140	-3.0°	-1.5°	-1.9°	-5.1°
200	-1.8°	-0.2°	-0.7°	-2.7°

Table 6: Mean wind direction bias of the different models, for the full period of 10 years.

height (m)	DOWA	KNW	ERA5	ERA-Interim
10	25°	27°	24°	29°
20	23°	26°	23°	26°
40	22°	25°	21°	24°
80	21°	23°	20°	23°
140	19°	22°	19°	22°
200	19°	22°	18°	21°

Table 7: Standard deviation of the wind direction bias of the different models, for the full period of 10 years.

height (m)	DOWA	KNW	ERA5	ERA-Interim
10	26°	27°	26°	32°
20	24°	26°	24°	29°
40	23°	25°	22°	27°
80	21°	24°	20°	24°
140	20°	23°	19°	22°
200	19°	22°	18°	21°

Table 8: Root mean square error (rmse) of the wind direction between the measurements and the different models, for the full period of 10 years.

Fig. 20 the same results are shown for DOWA and KNW (solid lines), but now compared with part of the data for which wind speeds below 4 m/s are discarded (dashed lines). Clearly, the mean bias hardly changes but the standard deviation is reduced by a factor of about two.

The mean bias in the wind direction can be further investigated by considering the separate wind sectors. The directional wind direction bias for DOWA and KNW is shown in Fig. 21. For all heights the largest (negative) bias is found between 120° and 240°, which includes the prevailing wind direction (see Appendix D), and this behavior is present in both DOWA and KNW. For the lowest levels DOWA has a bias that exceeds -10° in the 150° to 180° wind sector.

Density plots with the wind direction bias as function of wind direction for DOWA are shown in Appendix F.
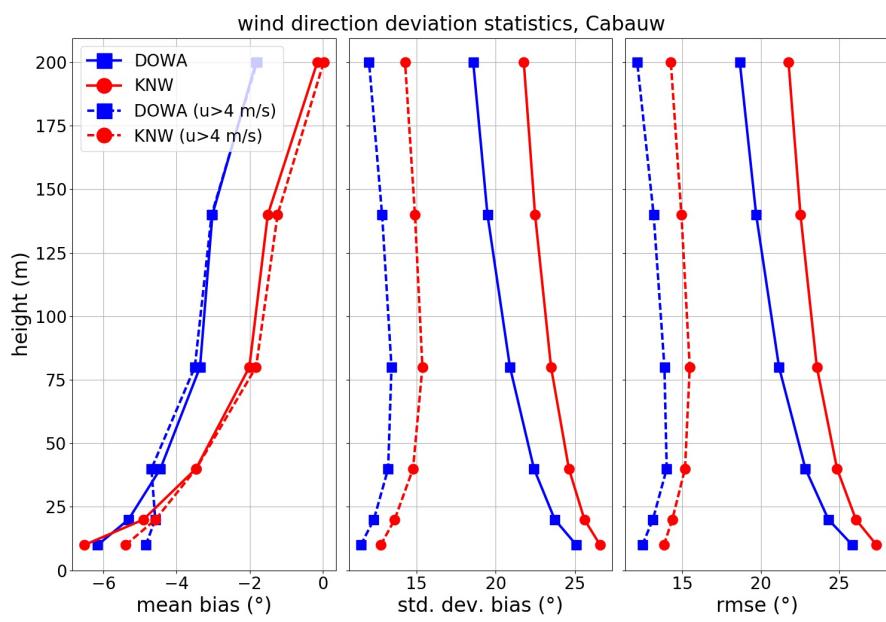
Figure 20: Height profile of the mean bias, standard deviation of the bias and rmse of the wind direction data, comparing the DOWA (blue) and KNW atlas (red). Solid lines are all data, dashed lines only data with wind speed larger than 4 m/s.
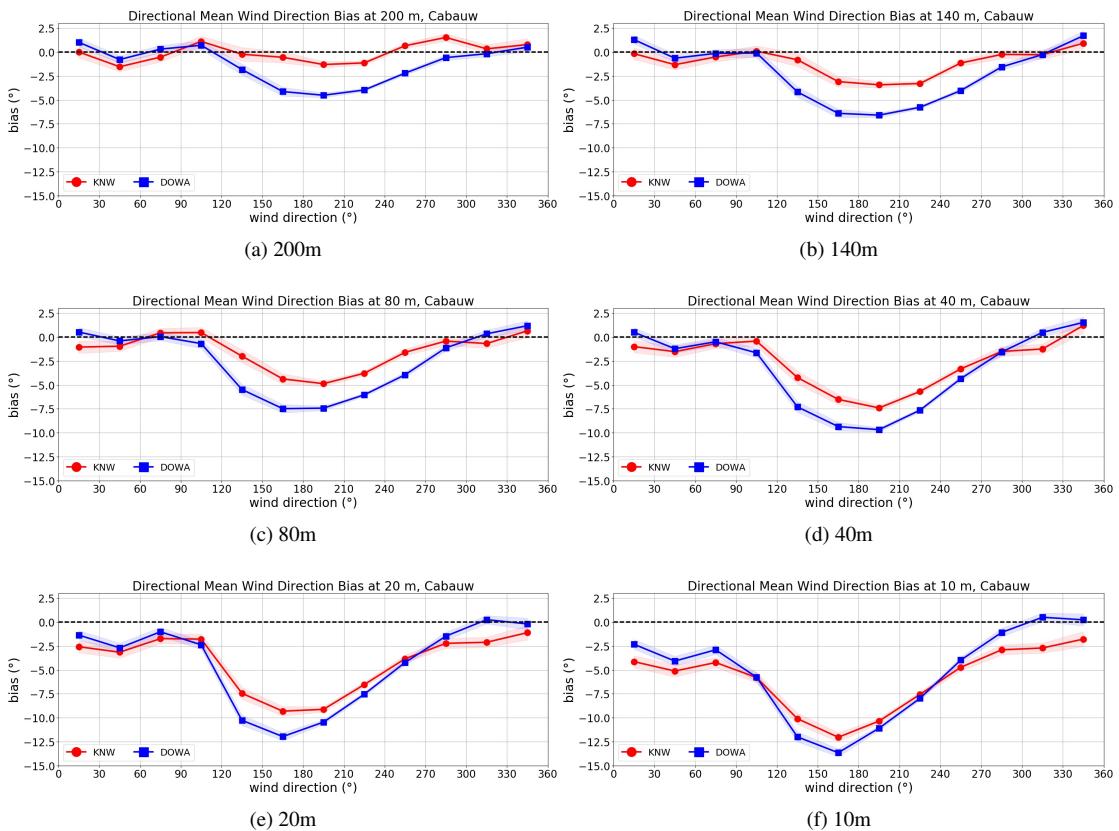
Figure 21: Directional wind direction bias, with sector width of 30°, showing DOWA (blue) and KNW atlas (red). Note the different scales on the *y*-axis.

5.5 Extreme value analysis

In Fig. 22 the wind speed at (a) 80 m and (b) 200 m is shown as function of return period, based on an extreme value analysis. A GPD (General Parato Distribution) fit is applied to these data to estimate the once in 10 year extreme. The GPD-fit of the mast measurements, DOWA and KNW differ little and lie within each other's fit accuracy at a return value of 10 years, as shown by the vertical error bars representing the 90% confidence level. This means that within the uncertainty there is no difference between the mast measurements, DOWA and KNW regarding the once in 10 year extreme wind speeds. For the KNW-atlas this was already concluded in Ref. [3].

(a) 80m   (b) 200m
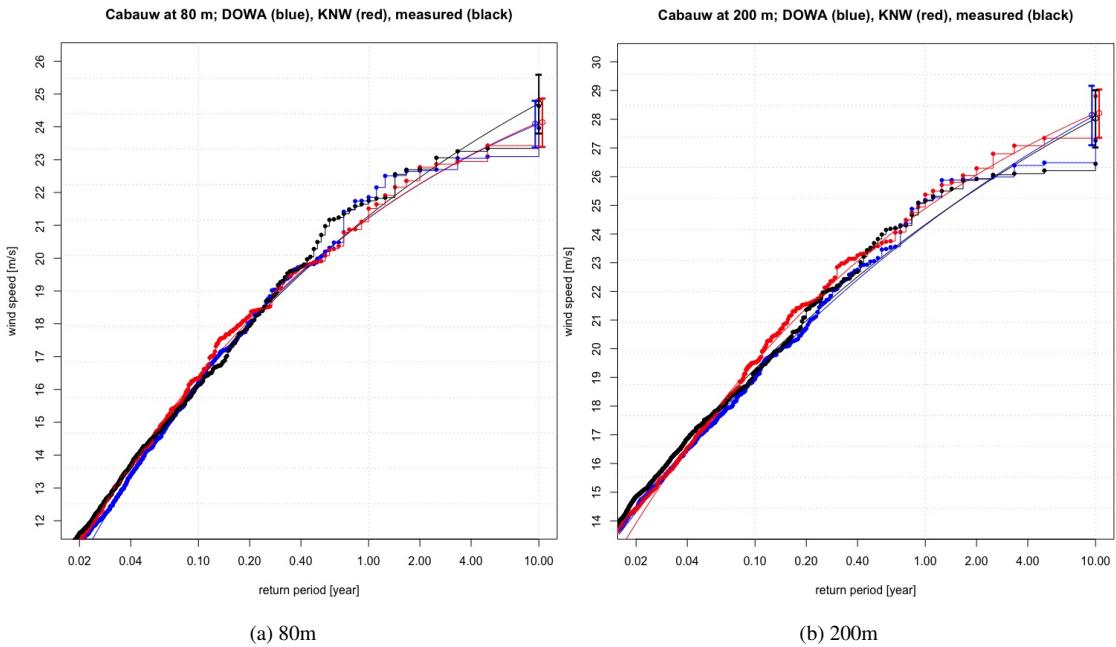
Figure 22: Extreme value analysis, showing the wind speed as function of return period for the mast measurements (black dots), DOWA (blue dots) and KNW atlas (red dots) for (a) 80 m and (b) 200 m. The solid lines (without the dots) are the results of a GPD (General Parato Distribution) fit to the data. For the last data points at 10 year return period the uncertainty (90% confidence level) is indicated by the vertical error bars.

6 Discussion

In this work, the validation of DOWA and a comparison with the KNW-atlas and the ECMWF global reanalyses is performed by direct comparison between the model and the Cabauw meteo mast wind measurements. A general problem for comparisons between model data and measurements is that models represent volume averages at a pint in time and measurements times averages on one location. Are the characterization of the grid box representative for the measurement location? This is much more of an issue for onshore locations than offshore. For instance, the average roughness of the grid box will in general be different (typically higher) from the actual local roughness, which hinders comparisons with models and observed surface winds [21]. This issue mostly impacts the wind comparison at the lower levels, which are much more sensitive to the local environment in the vicinity of the measurement site than the wind at higher altitudes. In addition, heterogeneity of the location site can make this issue wind direction dependent.

The differences in model performance of DOWA and KNW can be due to many aspects, including differences in the global reanalysis dataset, the version of HARMONIE (including difference in roughness map or turbulence scheme), whether or not additional data assimilation in HARMONIE or cold starts are applied. It very difficult and beyond the scope of this validation work to attribute the validation difference between DOWA and KNW to all these different aspects. The most striking observation are the higher mean wind speed biases of DOWA for the 10 and 20 m levels (see e. g. Fig. 13). For these levels DOWA underestimates the mean wind speed by 0.2-0.3 m/s, which can be attributed to the bias during the winter months. The KNW wind speed biases at those levels are below 0.1 m/s. This difference might be a result of the setting of the so-called XRIMAX parameter [22], which a threshold that controls the mixing [23]. For HARMONIE version 40 (DOWA) the XRIMAX parameter is set to zero, limiting mixing. As a result, model wind at lower levels is underestimated. For HARMONIE version 37 (KNW) the XRIMAX parameter is non-zero (0.2), resulting in a difference between DOWA and KNW.

Finally, in preparing the different datasets, several choices have been made which may impact the validation results. This includes the temporal averaging of the measurement data and the model gridpoint selection. Their impact are discussed in Appendix A and Appendix B, respectively.

7 Conclusions

DOWA has been validated with 10 years of Cabauw wind mast measurements between 10 and 200 m heights, and compared to the KNW atlas and the global reanalyses ERA-Interim and ERA5. In terms of long-term climatological comparisons, the DOWA and KNW wind speed biases are within 0.1 m/s for heights of 40 m and above. This means these biases are within the measurement accuracy. For the lowest levels (10 and 20 m) DOWA underestimates the mean wind speed by 0.2-0.3 m/s, which might be attributed to a particular parameter setting in HARMONIE version 40 (see Sect. 6). The KNW wind speed biases at those heights are below 0.1 m/s. The standard deviation of the wind speed bias for DOWA increases with height and ranges from 0.9 to 1.3 m/s (0.1-0.2 m/s smaller than those of KNW).

The diurnal cycle is better captured by DOWA than by KNW (which can be attributed to the absence of cold starts in DOWA) although still some minor non-physical features are present in DOWA due to the three hourly data assimilation. Linear regression on the hourly wind speed data gives for DOWA a slope and a R^2 that ranges from 0.88 to 0.94 and 0.87 to 0.90, respectively, which are slightly better than KNW (slope: 0.89-0.92, R^2: 0.84-0.86).

The DOWA mean wind direction bias decreases with height and ranges from -6° to -2°, which is similar to KNW at lower levels and and larger (more negative) than KNW by 1° to 2° at higher levels. The standard deviation in the wind direction bias for DOWA also decreases with height and ranges from 20° to 25°, which is 2° -3° smaller than those of KNW.

KNW and DOWA outperform ERA-Interim and ERA5 for all analysis and for all heights, demonstrating that downscaling those global reanalysis datasets with HARMONIE adds skill.

References

[1] http://www.dutchoffshorewindatlas.nl.

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Acknowledgment

A Mast measurement time averaging

The wind atlases have an hourly output (except ERA-Interim, which is 6-hourly) that represent the state of the atmosphere at the full hour. The Cabauw meteomast measurements used are 10-minute averaged output. To validate DOWA with Cabauw measurements, one hour of Cabauw measurements are averaged, i. e. six 10-minute averaged data values are taken, namely those belonging to the half hour before and half hour after the full hour. This method is conform the one used to validate the KNW-atlas [3], in which 60 minutes averaging time was motivated by comparing the mast and model once-a-year winds for different averaging times.

Here we compare the validation results for DOWA and KNW for averaging times around the full hour of 20, 40 and 60 minutes of the mast measurements. In Fig. 23 the height profiles of the mean wind speed (left panel) and the mean bias (right panel) are shown. No difference between the three averaging time can be observed. In Fig. 24 the height profiles of the standard deviation of the bias (left panel) and root mean square error (rmse) between the measurements and the models (right panel) are shown. Here the standard deviation and rmse decrease with increasing averaging time, but the comparison between DOWA and KNW remains the same. In Fig. 25 the results of the linear regression fits (slope, offset and R^2) are shown. The results improve (i. e. slope closer to one, offset closer to zero, R^2 closer to one) with increasing averaging time, but again this behavior is the same for DOWA and KNW. Finally, in Fig. 26 the height profiles of the mean bias, standard deviation of the bias and rmse for DOWA and KNW wind direction are shown. For the mean bias no differences can be seen, the standard deviation and rmse decrease with increasing averaging time.

To conclude, within averaging times of one hours no effect is seen on the overall bias in wind speed and wind direction, but regarding the standard deviation and rmse the results depend on the chosen averaging time. However, the comparison between DOWA and KNW does not depend on this choice.
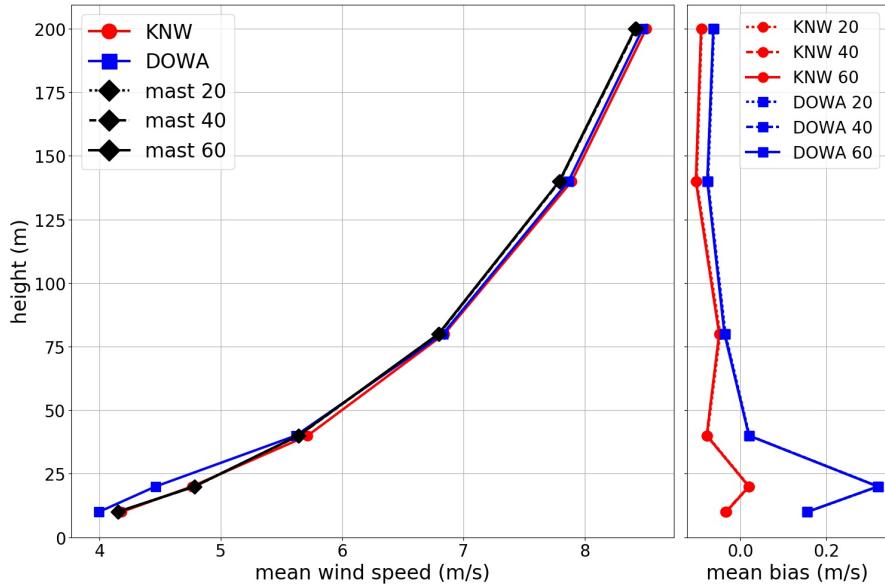
Figure 23: Height profile of the mean wind speed (left) and mean bias (right), showing mast measurements (black), DOWA (blue) and KNW atlas (red), for different averaging times (20, 40 and 60 minutes) of the mast measurements.
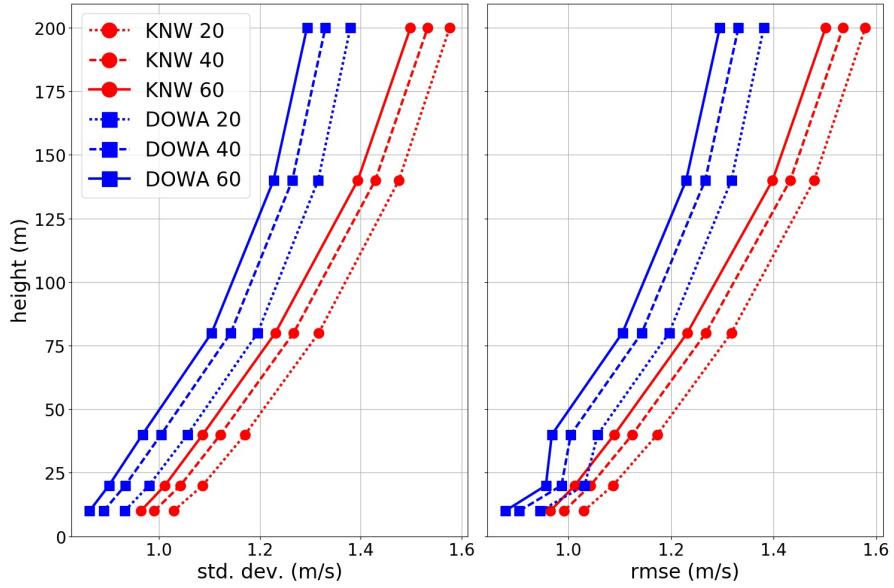
Figure 24: Height profile of the standard deviation of the bias (left) and root mean square error (rmse) (right), showing DOWA (blue) and KNW (red), for different averaging times (20, 40 and 60 minutes) of the mast measurements.
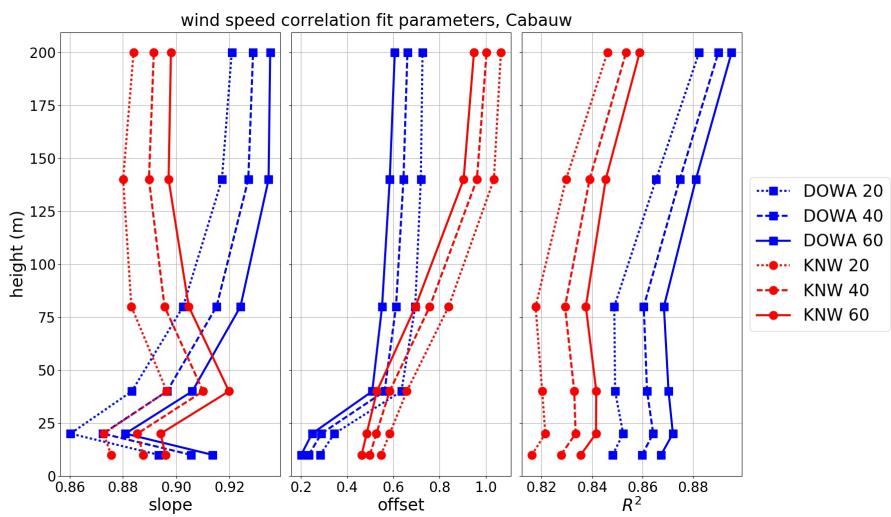
Figure 25: Height profile of the results of the linear regression (slope, offset and R^2) of the wind speed data, comparing the DOWA (blue) and KNW atlas (red), for different averaging times (20, 40 and 60 minutes) of the mast measurements.
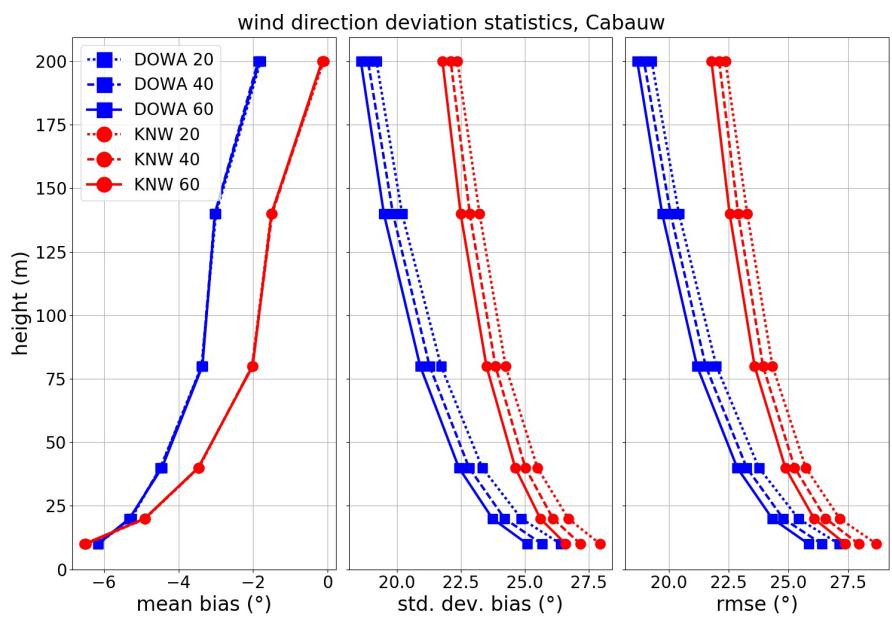
Figure 26: Height profile of the mean bias, standard deviation of the bias and rmse of the wind direction data, comparing the DOWA (blue) and KNW atlas (red), for different averaging times (20, 40 and 60 minutes) of the mast measurements.

B Grid point selection

The coordinates of the Cabauw meteorological mast are 51.9703° N, 4.9263° E. For DOWA and KNW the nearest grid point is taken:

- DOWA:
  - grid point indices x=99, y=74;
  - 51.96548° N, 4.936425° E;

- KNW:
  - grid point indices x=95, y=71;
  - 51.962802° N, 4.918203° E;

For ERA-Interim and ERA5 four coordinates are chosen for which the dataset are downloaded from ECMWF, namely (51.875° N, 4.875° E), (52° N, 4.875° E), (51.875° N, 5° E), (52° N, 5° E), and these datasets are linearly interpolated for the Cabauw mast location.

The grid points of DOWA and KNW, with respects to the Cabauw mast location, are displayed in Fig. 27. The sensitivity of the grid point selection is investigated by comparing the main DOWA validation
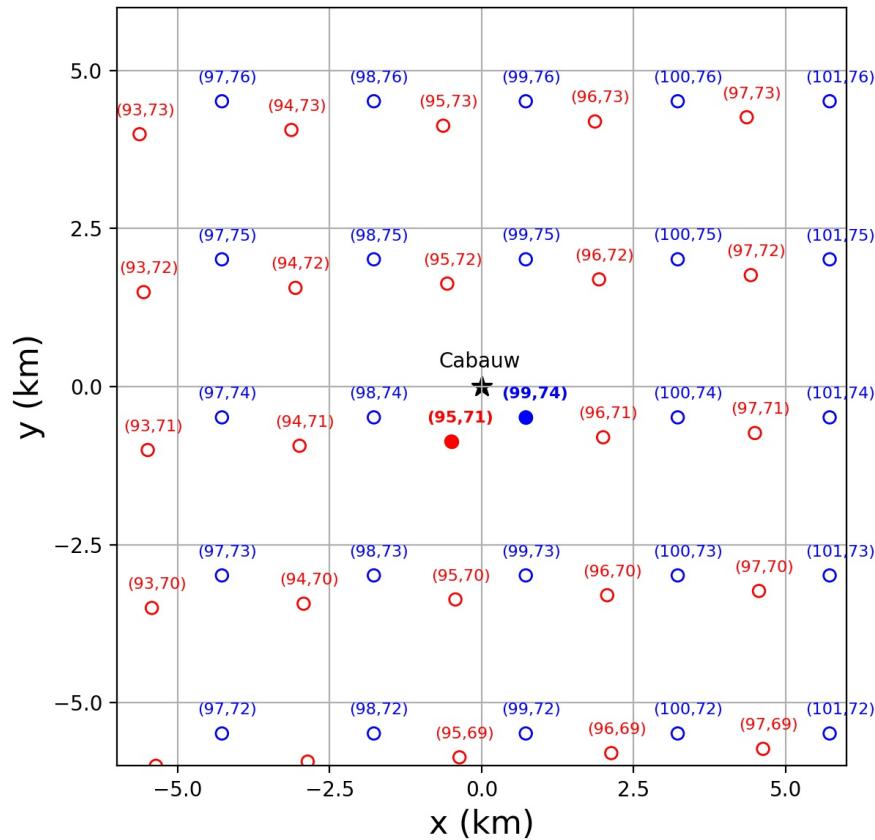
Figure 27: Grid points of DOWA (blue) and KNW (red).
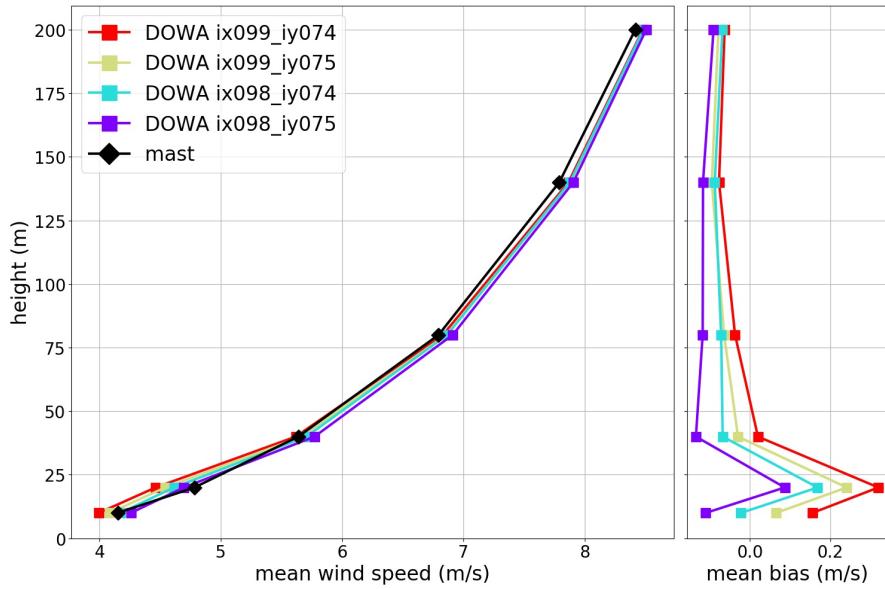
Figure 28: Height profile of the mean wind speed (left) and mean bias (right), showing mast measurements (black) and the four nearest grid points of DOWA.

results for the four closest grid points around the Cabauw mast. Results are shown in Fig. 28 for the mean wind speed and bias, Fig. 29 for the standard deviation and rmse of the mean wind speed, Fig. 30 for the linear regression fit parameters, and Fig. 31 for the mean bias, standard deviation and rmse in the wind direction. The closest grid ([99,74], which has been used throughout this validation study) is given in the red color. The largest impact is seen for the wind speed mean bias and slope, which the largest difference at 10, 20 and 40 m height, while in all other aspect the impact is very small.

These results show the sensitivity of the choice of grid point, which is quite large for the mean bias and slope for the lower levels up to 40 m. This is probably related the difference between the grid box averaged roughness and local, wind direction dependent, roughness, which determine the wind speed at the lower levels. Considering this sensitivity, one should be very cautious in drawing strong conclusions on the validation results at those heights.

For the higher levels, the roughness of multiple surrounding grid boxes start to play a role, instead of that of the single grid point, and the larger scale wind direction dependent roughness can be resolved. This explains why at 200 m the mean bias and slope of the four grid points are nearly the same.
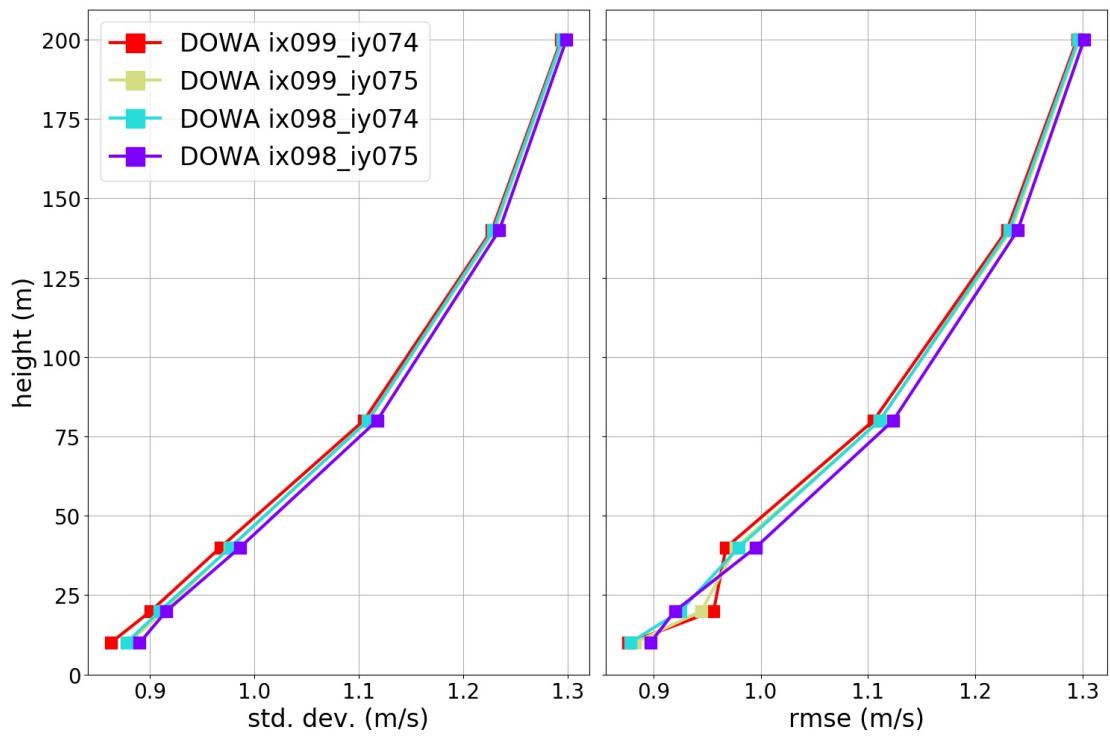
Figure 29: Height profile of the standard deviation of the bias (left) and root mean square error (rmse) (right), showing the four nearest grid points of DOWA.
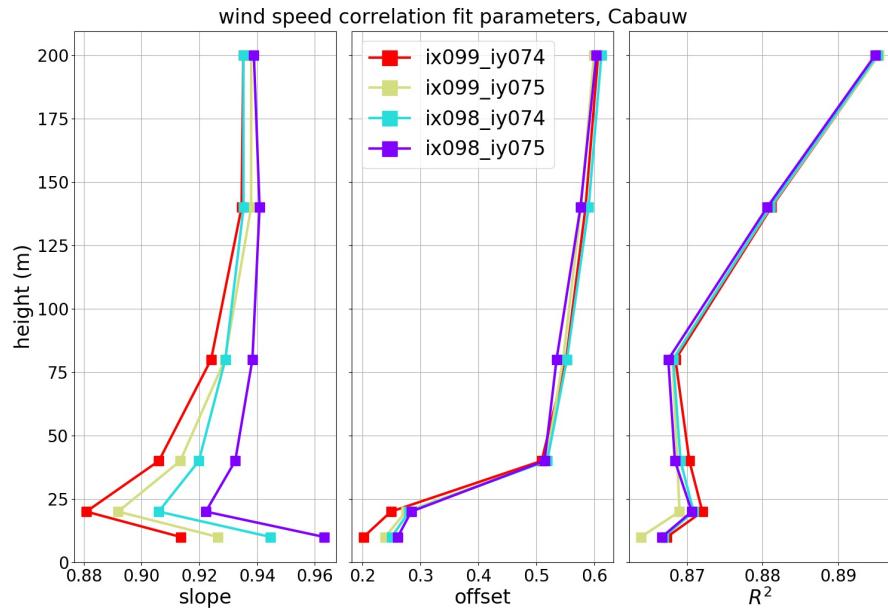
Figure 30: Height profile of the results of the linear regression (slope, offset and R^2) of the wind speed data, comparing the four nearest grid points of DOWA.

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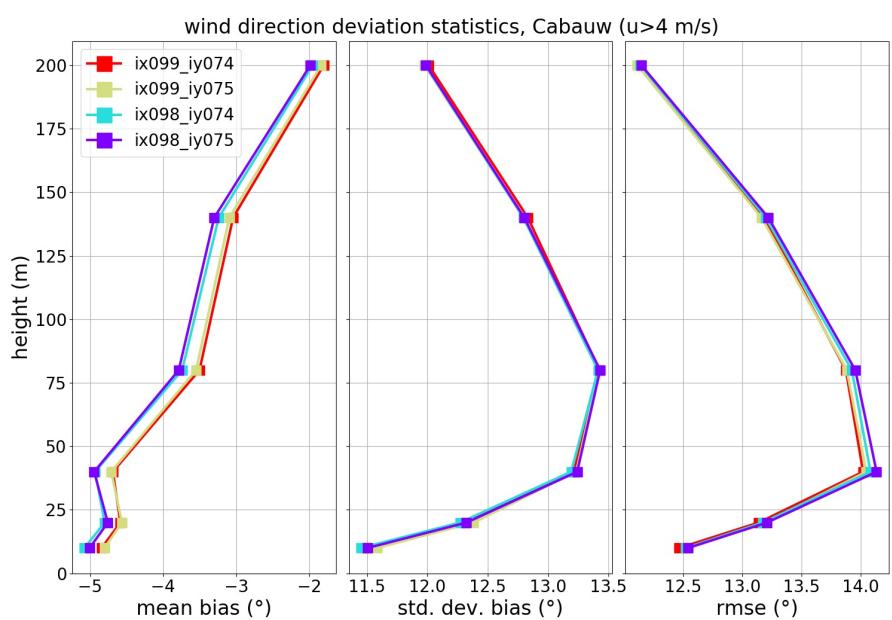
Figure 31: Height profile of the mean bias, standard deviation of the bias and rmse of the wind direction data, comparing the four nearest grid points of DOWA.

C 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 $\sigma_{mean} = \sigma/\sqrt{N}$, 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_{mean}^2. 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 on basis of an autoregression of order 1 model AR(1) [24] (as a more simple alternative to bootstrap methods) on data of the form:

$$x_{k+1} = \alpha x_k + \varepsilon_k \tag{6}$$

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

$$\hat{\tau}_D = \frac{1 + \hat{\alpha}}{1 - \hat{\alpha}} \tag{7}$$

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

$$\hat{\alpha} = \frac{\sum_{k=1}^{n-1} \tilde{x}_k \tilde{x}_{k+1}}{\sum_{k=1}^{n-1} |\tilde{x}_k|^2}. \tag{8}$$

Eq. 8 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. Values of $\hat{\tau}_D$ for the full period are given in Table 9. For directional mean Eq. 8 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.

height (m)	DOWA	KNW	ERA5	ERA-Interim
200	3.2	4.3	4.7	1.0
140	3.0	4.0	4.5	1.0
80	2.7	3.7	4.1	1.0
40	2.5	3.6	4.2	1.0
20	2.8	4.0	5.7	1.0
10	3.0	4.3	7.2	1.0

Table 9: $\hat{\tau}_D$ values for the different models and heights, for the full period of 10 year. Note that $\hat{\tau}_D$ for ERA-Interim is 1.0 (i.e. uncorrelated data) because its output is only 6-hourly. Taking only data every 6-hours from DOWA, KNW or ERA5 would also result in $\hat{\tau}_D = 1.0$.

D Wind direction distributions
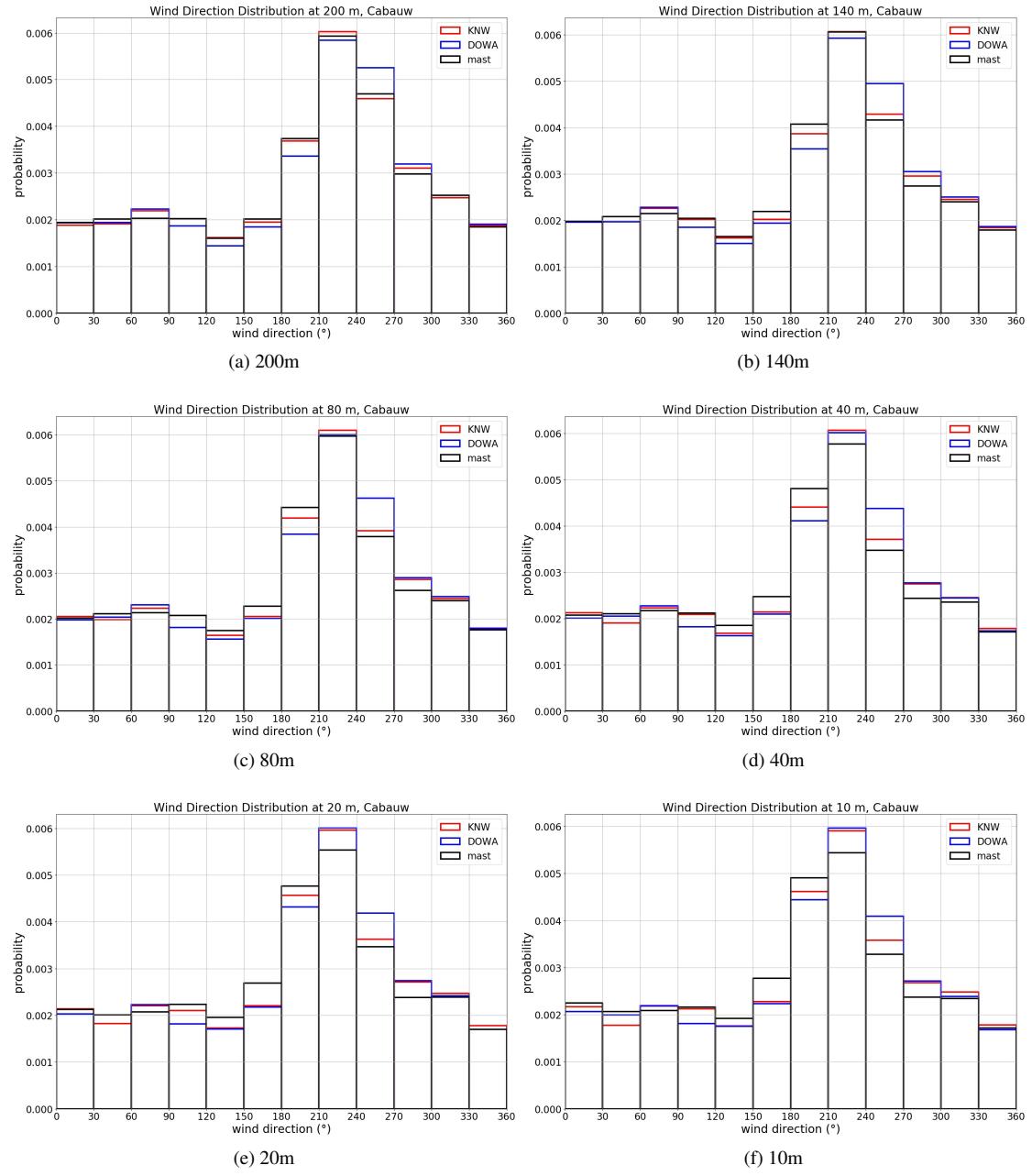
Figure 32: Wind direction distributions, with sector width of 30 °, showing mast measurements (black), DOWA (blue) and KNW (red).

E   Wind speed distributions

(a) 200m

(b) 140m

(c) 80m

(d) 40m

(e) 20m

(f) 10m
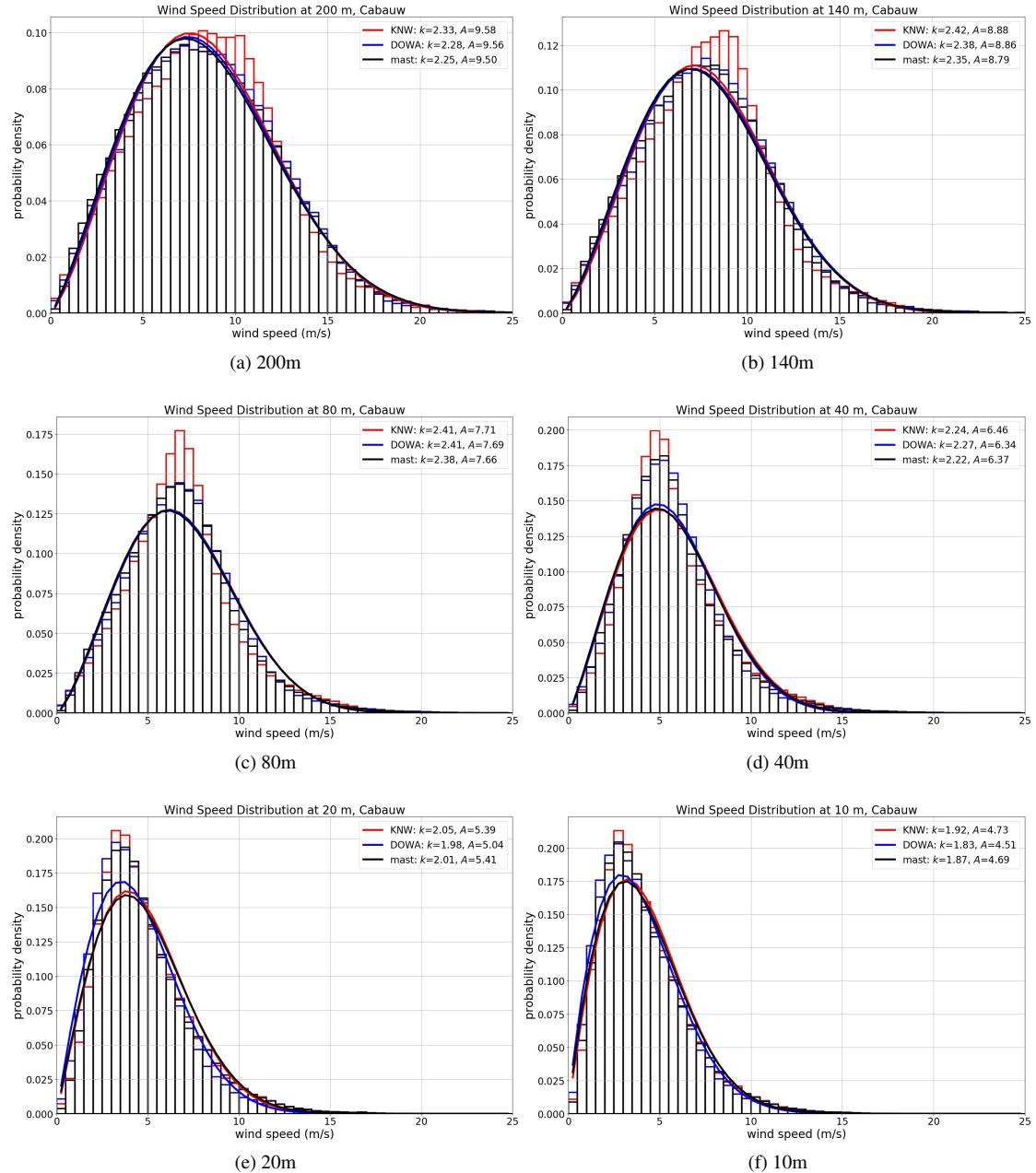
Figure 33: Wind speed distributions, with bin width of 0.5 m/s, showing mast measurements (black), DOWA (blue) and KNW (red) and corresponding Weibull fits (resulting fit parameters indicated in the legends).

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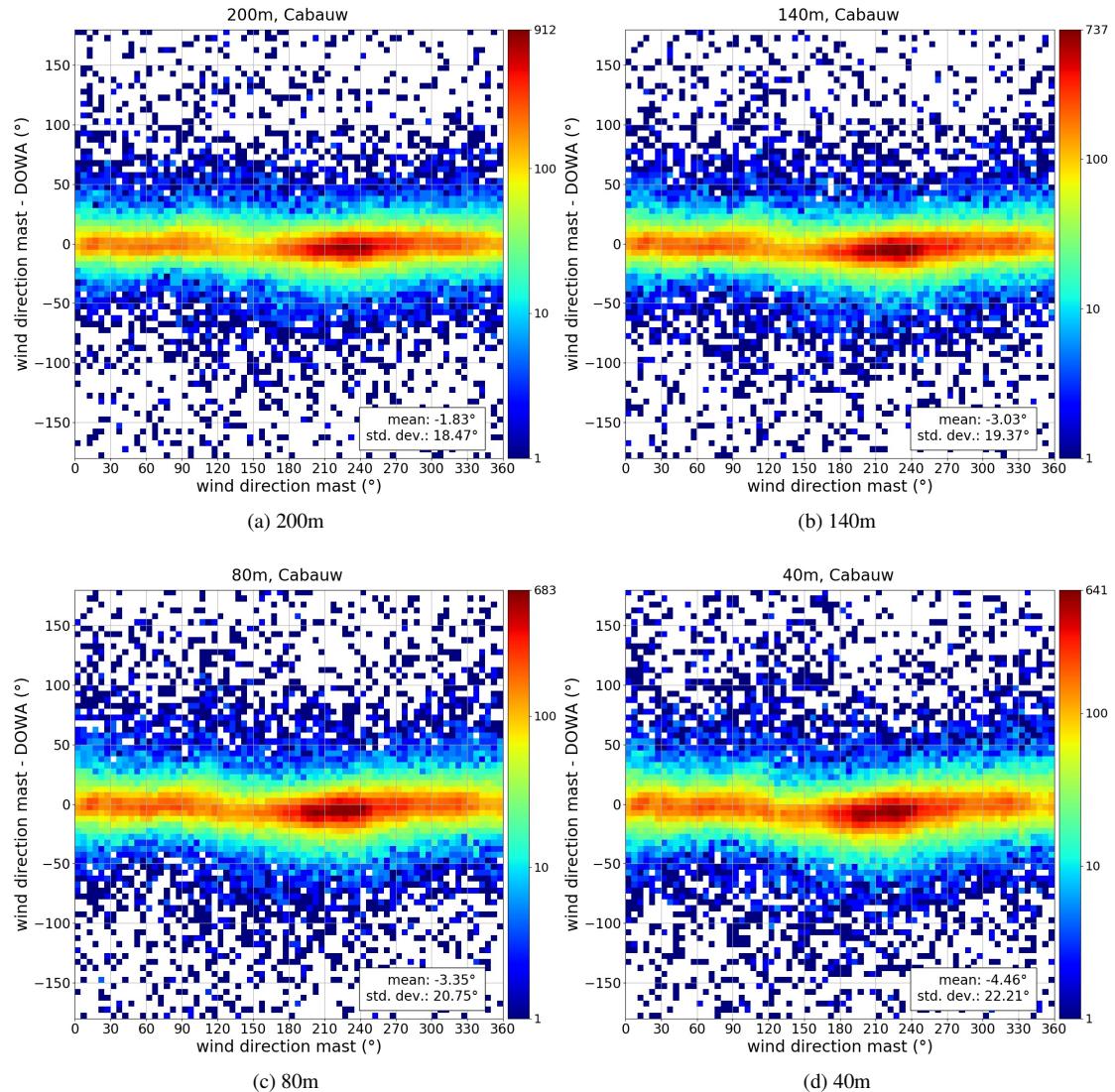
Figure 34: Scatterplot of the DOWA and mast wind direction data (visualized as a density plot with logarithmic color scale), showing the mean and standard deviation of the difference between the mast measurements and DOWA.

(a) 20m
(b) 10m
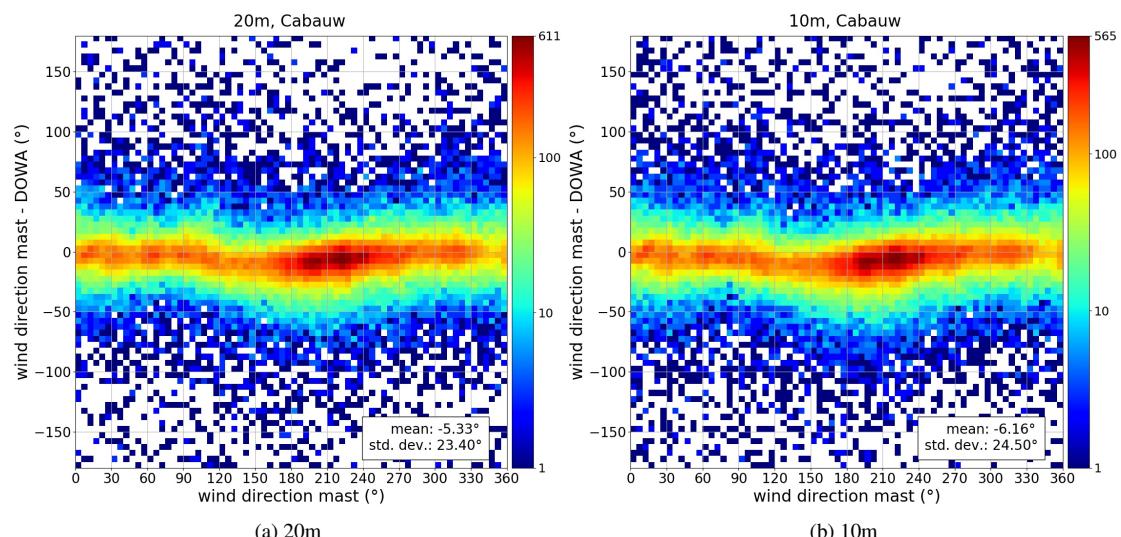
Figure 35: Continuation of Fig. 34.