Royal Netherlands
Meteorological Institute
Ministry of Infrastructure
and Water Management

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De Bilt, 2019 | Technical report; TR-380

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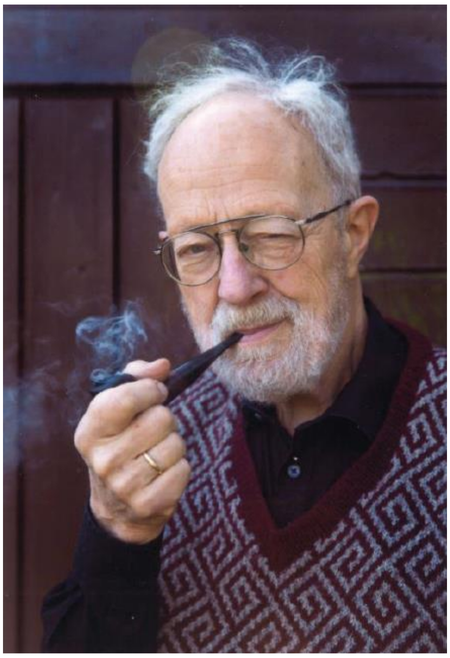

Jon Wieringa (29 March 1938 - 1 November 2019).
Er is niets dat voor altijd sterft. Er blijft altijd iets achter. Een klein deeltje waaruit iets nieuws groeit.

I would like to dedicate this report to Jon Wieringa who sadly passed away on the 1st of November 2019 before I could share this report with him. Jon left KNMI about 30 years ago when we joined. We only got to know him in 2011 when we left our forecaster jobs to work on the wind map in the "Bosatlas van het Klimaat" and have since then kept in touch. Jon was a remarkable man, very dedicated and not only intelligent (known as "the wind professor"), but also wise. It was a great compliment when he said about 5 years ago that he would leave wind in our capable hands so that he could focus more on meteorology for agriculture. His passion for meteorology was never ending … until now.

We will miss you Jon.
Andrew Stepek and Ine Wijnant

Abstract

The Dutch Offshore Wind Atlas (DOWA) is a wind atlas covering a period of 11 years, from 2008 until and including 2018[1]. Regional numerical weather model HARMONIE and additional satellite and aircraft measurements were used to downscale the global re-analysis ERA5 to a dataset of hourly information on a 2.5 by 2.5 km grid spacing and up to 600 m height.

Making the Dutch Offshore Wind Atlas (DOWA) was part of the DOWA-project. The DOWA project is executed by the project partners ECN part of TNO, Whiffle and KNMI and supported with Topsector Energy subsidy from the Ministry of Economic Affairs and Climate Policy (SDE+ Hernieuwbare Energie Call). Information on the project can be found on the DOWA website: (https://www.dutchoffshorewindatlas.nl/about-the-atlas)[2].

In this report you will find all the information you need to work with the dataset.

Acknowledgement

We would like to thank ECN part of TNO and Whiffle, our partners in this project, for their co-operation. Also we would like to thank ECMWF[3], and in particular Dominique Lucas, for helping us to make the HARMONIE reanalysis on their supercomputer in the most efficient way. Finally, we would like to acknowledge that this project was supported with Topsector Energy subsidy from the Ministry of Economic Affairs and Climate Policy.

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[1] And may be extended with more years.
[2] Released on the 17th of January 2019.
[3] European Centre for Medium-range Weather Forecasts

Content

1. Description of the dataset

The DOWA dataset is generated using *Copernicus Climate Change Service* Information [2017/2018] and is based on the global ERA5 global reanalysis which generates 3D wind fields consistent with all available measurements and the laws of physics. ERA5 already captures 40 years (1979-2019), but will be expanded to (1950-present). ERA5 is “downscaled” using Version 40h1.2.tg2 of mesoscale weather model HARMONIE-AROME (abbreviated as HARMONIE in the rest of this report) with a horizontal grid spacing of 2.5 km.

The DOWA is the successor of the KNMI North Sea Wind (KNW) atlas. Both the DOWA and the KNW-atlas are a “downscaled” global re-analysis, but they are made with improved versions of the models and in a fundamentally different way.

ERA-Interim and the KNW-atlas are described in Appendix A, the new model versions ERA5 and HARMONIE Version 40h1.2.tg2 in sections 1.1 and 1.2. The improved method will be described in section 1.3.

In the table below the main differences between KNW and DOWA are summarized:

KNMI North Sea Wind (KNW) atlas	**Dutch Offshore Wind Atlas (DOWA)**
• 1-1-1979 until 31-8-2019 18 UTC[4] (40+ years)	• 1-1-2008 until 31-12-2018 (11 years)[5]
• Captures the variability of the North Sea wind climate (40 years long enough)	• Does not capture the variability of the North Sea wind climate (10 years not long enough)
• Based on re-analysis ERA-Interim and 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 Version 37h1.1 and 37h1.2.bugfix).	• Based on re-analysis ERA5 (follow-up of ERA-Interim with higher spatial and temporal resolution) and mesoscale weather model HARMONIE Version 40h1.2.tg2 (improved wind information because turbulence is better modelled)
• HARMONIE used as downscaling-tool only (data-assimilation of measurements in ERA-Interim only)	• Additional measurements assimilated in HARMONIE (ASCAT-satellite surface wind measurements and MODE-S EHS aircraft wind profile measurements)
• Climatological information up to and including a height of to 200 m	• Climatological information up to and including a height of 600 m
• Lacks the information required for further LES-downscaling	• Information required for further LES-downscaling included
• 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
• Uniform wind shear correction applied	• No wind shear correction required

[4] After this global reanalysis ERA-Interim no longer available, so downscaling with HARMONIE no longer possible.
[5] The year 2018 was created as an extra year (the original DOWA-proposal included only 10 years 2008-2017).

The 11 year ERA5-HARMONIE reanalysis was made on a domain of 800 by 800 grid points (2000 by 2000 km) and saved on a domain of 789 by 789 grid points (1970 by 1970 km)[6]. The domain is centered around Cabauw (yellow area in Figure 1). Specifically for the DOWA-project a dedicated set of output files was created for a smaller subdomain (red area in Figure 1). Both the whole domain and the domain made publicly available are larger in the DOWA than in the KNW-atlas (Figure 1).

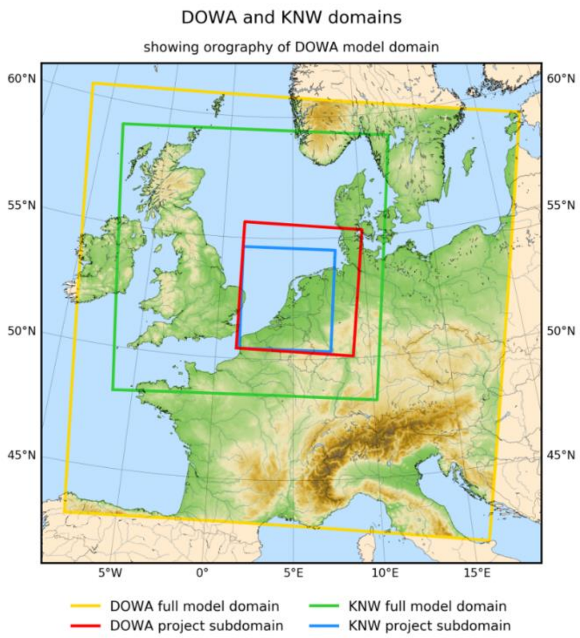

Figure 1: ERA5-HARMONIE domain (yellow) of 789x789 points and DOWA-subdomain of 217x234 points (red). ERA-Interim-HARMONIE domain of 500x500 points (green) and KNW-subdomain of 170x188 points (blue).

1.1 ERA5

ERA5 is the fifth generation atmospheric reanalysis of the global climate made available by ECMWF and will (once completely available) eventually replace ERA-Interim (appendix A). ERA5 contains hourly data; horizontal grid spacing 31 km; vertical grid spacing 137 levels up to about 80 km; 3 hourly uncertainty info (grid spacing 62 km) + extra info including 100m wind. The main differences between ERA-Interim and ERA5 are:

- ERA5 will eventually be available from 1950-now (ERA-Interim from jan 1979-aug 2019)
- ERA5-data available every hour (ERA-Interim 6 hourly)
- ERA5 horizontal grid spacing of 31 km (ERA-Interim 79 km)
- ERA5 vertical grid spacing 137 levels up to about 80 km (ERA-Interim 60 levels)
- ERA5 has 3 hourly uncertainty info (grid 62 km) and extra parameters including 100 m wind
- ERA5 used a newer model version of the ECMWF-model (see https://confluence.ecmwf.int//pages/viewpage.action?pageId=74764925 for complete list)

[6] Spectral grid implies that 11 grid points at the northern edge and 11 grid points at the eastern edge of the domain cannot be used.

1.2 HARMONIE

HARMONIE[7] (HIRLAM ALADIN Research on Mesoscale Operational NWP In Euromed) is the numerical weather prediction model that KNMI uses operationally since 2012. It is extensively tested and continually improved by the HIRLAM-ALADIN consortium (Figure 2). HARMONIE is a non-hydrostatic limited-area model which runs on a very high resolution grid (spacing of 2.5 km). For more details on HARMONIE see [Seity, 2011], [Bengtsson, 2017] and www.hirlam.org. The CY37h1.1 version of HARMONIE (released on 13 June 2012) was used to make the KNW-atlas (Appendix A) and the CY40h1.2.tg2 version to make the Dutch Offshore Wind Atlas DOWA (1.2.5). Compared to the CY37h1.1 version, the CY40h1.2.tg2 version of HARMONIE gives better wind information because of an improved turbulence parametrization [Lenderink, 2004] and [Bengtsson, 2017]: HARATUUP (HARATU-update). In [De Rooy, 2017] was shown (for HARMONIE version CY38) that the HARATUUP turbulence scheme verified better against e.g. ASCAT scatterometer winds, SYNOP 10 m winds, Cabauw winds and radiosonde winds than other turbulence parametrizations (to CBR that was used in version CY37h1.1 and to HARATU). The improved turbulence scheme also resulted in better data assimilation of available measurements (fewer measurements were rejected).

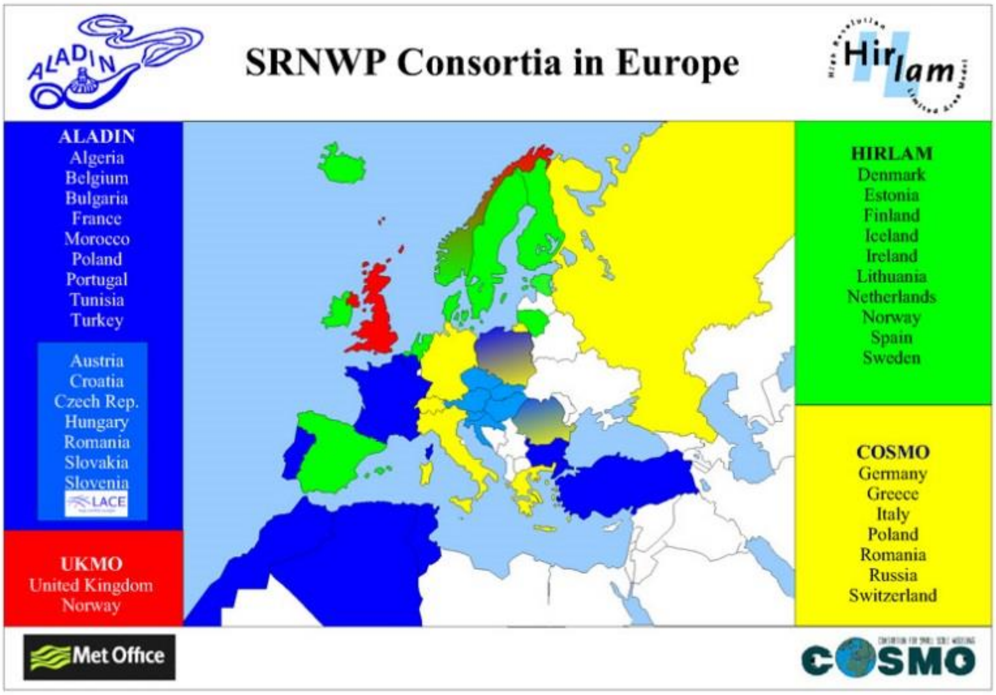

Figure 2: participating countries in HIRLAM (green) and ALADIN (blue) consortium.
(source: http://www.eumetnet.eu)

[7] Also known as HARMONIE-AROME, but abbreviated as HARMONIE in the rest of this report.
https://journals.ametsoc.org/doi/10.1175/MWR-D-16-0417.1

1.3 Method

The DOWA was made in a fundamentally different way from how the KNW-atlas was made:

- **Assimilation of measurements:** for the KNW-atlas, HARMONIE was used only as a downscaling-tool without feeding the model with additional measurements (the only measurements included were the ones that were used to make the ERA-Interim reanalysis). For the DOWA, HARMONIE's full potential as a weather forecast model was leveraged by assimilating additional (not used in ERA5) – both conventional and innovative – measurements. The 3DVAR assimilation technique was used to assimilate measurements every 3 hours at the beginning of each HARMONIE forecast cycle (see explanation below). Innovative measurements included high-resolution satellite surface wind fields (ASCAT) and aircraft wind profile measurements (MODE-S EHS). As a result of using this data-assimilated HARMONIE, the quality of the time series and the representation of the diurnal cycle improved. More info on data-assimilation methods for convective-scale weather prediction can be found in [Gustafsson, 2018].

- **Cold start:** for the KNW-atlas, we started every 6 hours with the ERA-Interim re-analysis and used the +1h up to and including +6h forecast of HARMONIE (no data assimilation) to make the atlas. Every 6 hours we started with a new ERA-Interim reanalysis (cold start). There are no cold starts in the DOWA-runs, except at the very beginning of each parallel stream (see 1.3). DOWA is made with +1h, +2h and +3h forecasts of HARMONIE within a domain of 800 by 800 grid points around KNMI meteomast Cabauw, which is part of the Cesar-observatory[8]. Every hour the boundaries of the domain (North, South, East and West at all model levels) are fed with ERA5-reanalyses data. We initialize every 3 hour forecast cycle with the latest HARMONIE-forecast of the previous cycle (no cold start with ERA5) and data-assimilation of measurements.

The calculations to downscale the ERA5-dataset with HARMONIE Version 40h1.2.tg2 were done on the ECMWF supercomputer from the 21st of November 2017 until September 2018 (2008-2017) and from November 2018 to June 2019 (2018). The aim was to produce 7 DOWA-days every day (1 DOWA-year in 50 days), but we could not do more than 6.6 DOWA-days per calendar day. The DOWA-project also required that we finished the calculations in less than a year. The only way to do that was to run simultaneous "streams" and to "glue" them together: stream A (2010-2012), stream B (2013-2014), stream C (2008-2009), stream D (2015-2017) and 2018 as an extra year. Based on the analyses described in Appendix B, streams were glued one month after cold starts. So stream C and A are glued on the 1st of February 2010, stream A and B on the 1st of February 2013, stream B and D on the 1st of February 2015 and stream D and 2018 on the 1st of February 2018.

[8] https://www.knmi.nl/kennis-en-datacentrum/uitleg/meetmast-cabauw ; http://www.cesar-observatory.nl/index.php?pageID=7001

1.4 Variables

The list of variables saved for the DOWA-subdomain is given under 1 and 2. Where mentioned the 17 height levels refer to: 10, 20, 40, 60, 80, 100, 120, 140, 150, 160, 180, 200, 220, 250, 300, 500 and 600m.

(1) Variables that are made publicly available[9] through the KNMI Data Centre and are validated in the DOWA-project (for the red domain):

- Wind speed at 17 height levels
- Wind direction at 17 height levels

(2) Variables that are made publicly available9 through the KNMI Data Centre, but are not validated in the DOWA-project (for the red domain):

- Air pressure at 17 height levels
- Air temperature at 17 height levels
- Relative humidity at 17 height levels

(3) **Variables that are NOT part of the DOWA-project, but are temporally made publicly available on the KNMI Data Centre (KDC: https://data.knmi.nl/datasets/dowa_netcdf_daily_3d_extra/1) and later possibly on Amazon Web Services (S3 One Zone-IA). The data can be used freely as long as KNMI is cited as the source of the information. The data is not validated. Beware: it is a very large dataset (yellow domain) and downloading the data will take a lot of time! Variables are either given on single levels (fixed heights e.g. at sea or ground level, 2 m, 10 m or in the soil) or on model levels (in [hPA][10]):**

Variables at single level:

- Surface **roughness length** (z0) [m]
- Surface **roughness length** for heat in air (z0h) [m]
- Air **pressure** at specified altitude above mean sea level (psl) [Pa]
- Surface air **pressure** (ps) [Pa]
- Sea surface **temperature** at mean sea level (sst) [K]
- Surface **temperature** (ts) [K]
- Atmosphere boundary layer **thickness** (zmla) [m]
- Accumulated surface downward eastward **stress** (tauu) [kg m^{-1} s^{-1}]
- Accumulated surface downward northward **stress** (tauv) [kg m^{-1} s^{-1}]
- **Cloud area** fraction (clt) [0-1]
- **Cloud area** fraction low-level cloud (below 2500m) in atmosphere layer (cll) [0-1]
- **Cloud area** fraction medium level cloud (2500-5000m) in atmosphere layer (clm) [0-1]
- **Cloud area** fraction high-level cloud (above 5000m) in atmosphere layer (clh) [0-1]
- Accumulated surface net **shortwave flux** in air (rsns) [J m^{-2}]
- Accumulated surface net **longwave flux** in air (rlns) [J m^{-2}]
- Accumulated top-of-atmosphere net **shortwave flux** (rsnt) [J m^{-2}]
- Accumulated top-of-atmosphere net **longwave flux** (rlnt) [J m^{-2}]
- Accumulated surface downwelling **longwave flux** in air (rlds) [J m^{-2}]
- Accumulated surface downwelling **shortwave flux** in air (rsds) [J m^{-2}]
- Accumulated surface upward **sensible heat flux** (hfss) [J m^{-2}]
- Accumulated surface upward **latent heat flux evaporation** (hfls_eva) [J m^{-2}]
- Accumulated surface upward **latent heat flux sublimation** (hfls_sbl) [J m^{-2}]
- Atmosphere **convective inhibition (CIN)** as calculated by Harmonie CAPE type 5 (cin_harm) [J kg^{-1}]

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[9] Until May 2020

[10] There are 65 model levels. Model levels are not in "fixed" hPA-levels, but depend on the surface pressure. The higher the model levels, the less dependent on the surface pressure: the highest model level is at 10 hPa.

- Atmosphere **convective inhibition (CIN)** conform ECMWF definition (cin_ecmwf) [J kg-1]
- Atmosphere **convective available potential energy (CAPE)** as calculated by Harmonie CAPE type 5 (cape_harm) [J kg^{-1}]
- Atmosphere **convective available potential energy (CAPE)** conform ECMWF definition (cape_ecmwf) [J kg^{-1}]
- **Rainfall** amount in one hour (prrain) [kg m^{-2}]
- **Snowfall** amount in one hour (prsn) [kg m^{-2}]
- Surface **snow amount** (snw) [kg m^{-2}]
- **Graupel** amount in one hour (prgrpl) [kg m^{-2}]
- Air **temperature** at 2 m height (tas) [K]
- Max air **temperature** over one hour at 2 m height (tasmax) [K]
- Min air **temperature** over one hour at 2 m height (tasmin) [K]
- **Specific humidity** (huss) at 2 m height [-]
- Eastward **wind** at 10 m height (uas) [m s^{-1}]
- Northward **wind** at 10 m height (vas) [m s^{-1}]
- Max eastward wind **gust** (3 sec averaged wind speed) at 10 m height between current and previous hour (ugs) [m s^{-1}]
- Max northward wind **gust** (3 sec averaged wind speed) at 10 m height between current and previous hour (vgs) [m s^{-1}]

Variables at all HARMONIE model levels:

- **Geopotential** (phi) [m^2 s^{-2}]
- Air **temperature** (ta) [K]
- Eastward **wind** (ua) [m s^{-1}]
- Northward **wind** (va) [m s^{-1}]
- **Vertical velocity** (vv) [m s^{-1}]
- **Specific humidity** (hus) [-]
- **Cloud area** fraction in atmosphere layer (cl) [0-1]
- Mass fraction of **cloud ice** in air (cli) [-]
- Mass fraction of **cloud liquid water** in air (clw) [0-1]

Soil variables:

- Soil **temperature**: top soil layer per patch (tg_LO1.PON)
- Soil **temperature**: deep soil layer per patch (tg_LO2.PON)
- Volume fraction of **liquid water in soil** layer: top soil layer per patch[11] (wsa_L01.P0N) [-][12]
- Volume fraction of **liquid water in soil** layer: root layer per patch (wsa_L02.P0N) [-]
- Volume fraction of **liquid water in soil** layer: deep soil layer per patch (wsa_L03.P0N) [-]
- Volume fraction of **frozen water in soil:** top soil layer per patch (isa_L01.P0N) [-][13]
- Volume fraction of **frozen water in soil:** deep soil per patch (isa_L02.P0N) [-]

More info on HARMONIE-40h1 parameters (accessible for KNMI staff):
https://hirlam.org/trac/wiki/HarmonieSystemDocumentation/Forecast/Outputlist/40h1

[11] HARMONIE distinguishes between 2 patches: “open land” and “forest”. Soil parameters for these patches are stored separately.
[12] [-] = m^3 liquid water/ m^3 soil
[13] [-] = m^3 ice/ m^3 soil

For 2016 and 2017 and 12 locations (Figure 3) there are additional variables (vertical profiles and large-scale dynamic tendencies of the wind components, temperature and specific humidity) made available to enable LES downscaling of HARMONIE using the large scale or dynamic tendency method (see explanation below). The information is stored as a single column and 10x10 km and 30x30km averages. For 2018 the same information is available for the entire DOWA subdomain (red Figure 1) at a one hour frequency.

Nudging method

HARMONIE is nested in the global ECMWF model by nudging HARMONIE at the lateral boundaries towards the atmospheric state of the ECMWF model. This way, weather processes acting on scales larger than the domain size of HARMONIE are introduced into the limited area domain. In a similar way, LES can be nested in HARMONIE by nudging LES at the lateral boundaries towards HARMONIE. The main advantage of this approach is that certain weather events, like for example frontal passages, are transferred in a realistic way from HARMONIE to LES. However, as LES explicitly resolves turbulence and HARMONIE not, the air near the lateral boundaries needs some time to adjust from the non-turbulent state in HARMONIE to the turbulent state in LES. This requires a sufficiently large LES domain (of the order of 50 km), which makes this approach computationally demanding.

Large scale or dynamic tendency method

As an alternative to the nudging method, information about the weather on scales larger than the LES domain can also be provided to the LES model in the form of large-scale dynamic tendencies. These large-scale dynamic tendencies are the mean tendencies of (for example) the advection of momentum (wind), temperature and moisture acting on the LES domain, and are added to the LES model as a horizontally homogeneous forcing (i.e., only varying with height). This method was pioneered at KNMI and the TU Delft and is currently used by Whiffle, with the large-scale tendencies estimated from 3-hourly routine output of the ECMWF model. Given the short-term variability of the weather, the use of 3-hourly (instantaneous) forcings might mean that details on shorter time scales are lost. The innovative aspect of the DOWA project is to output the dynamic tendencies directly from HARMONIE, at a high temporal frequency, and with the tendencies accumulated in time. This should assure that the full dynamic tendencies are transferred from HARMONIE to LES.

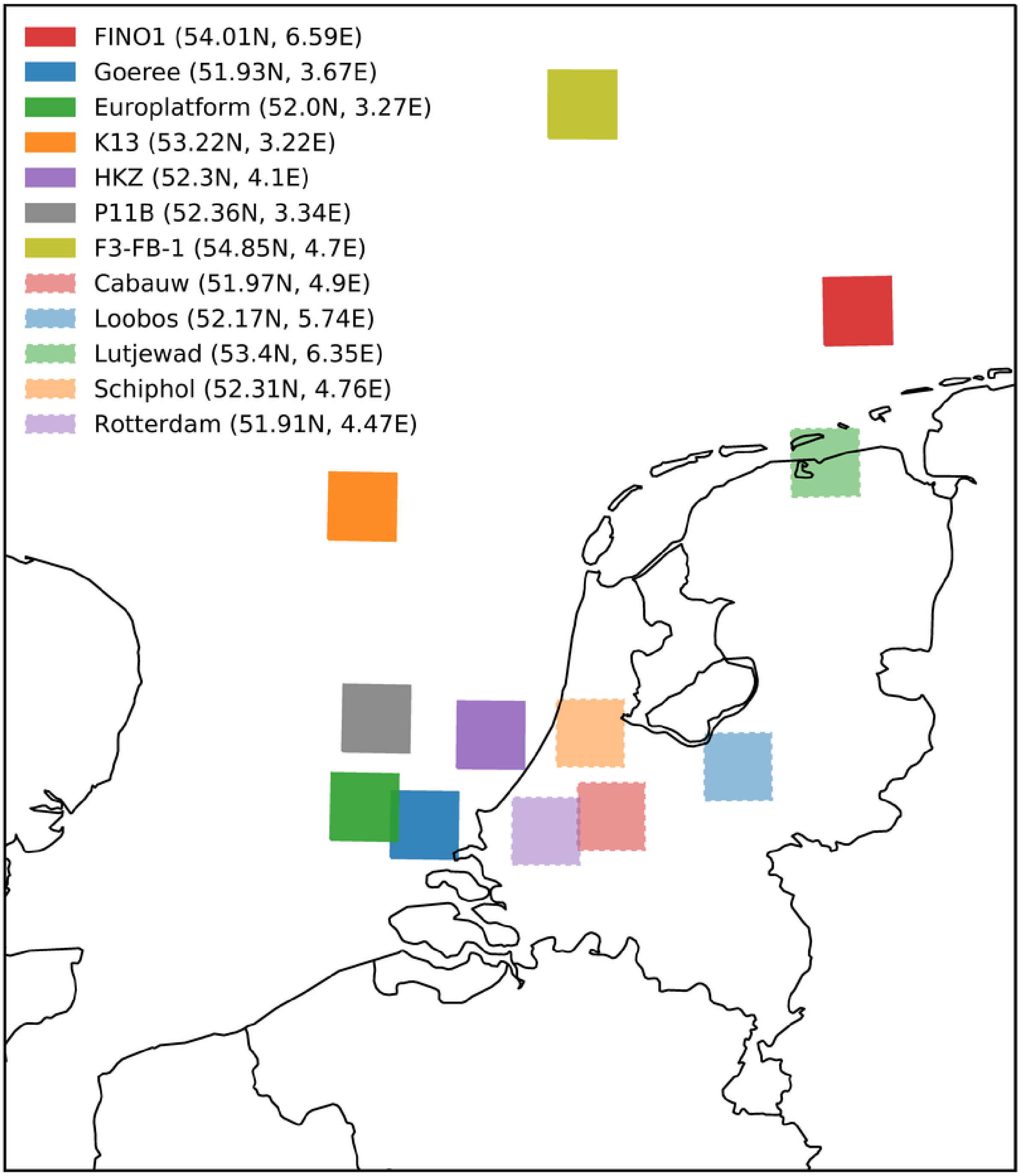

Figure 3: For 2016 and 2017 additional variables (stored as a single column and 10x10 km and 30x30km averages, output at a 10 minute frequency) are made available to enable LES-simulations with the nudging method. Can be made available via KNMI for an admission fee.

2. Validation

The DOWA-winds are extensively validated, mainly as part of the DOWA-project. In this chapter we will summarize the results of these validations, but we refer to the specific validation reports for further reading:

- [Duncan1, 2019] Duncan, J.B., G.J. Marseille and I.L Wijnant, 2019. DOWA validation against ASCAT satellite winds. TNO report 2018 R11649.
- [Duncan2, 2019] Duncan, J.B., I.L. Wijnant and S. Knoop, 2019: DOWA validation against offshore mast and LiDAR measurements. TNO report 2019 R10062
- [Knoop1, 2019] Knoop, S. , P. Ramakrishnan and I.L Wijnant, 2019, DOWA validation against Cabauw meteomast wind measurements. KNMI Technical Report TR-375
- [Knoop2, 2019] Knoop, S., 2019: DOWA validation against coastal lidar wind measurements. KNMI Technical Report TR-376
- [Valk, 2019] Valk, C. de, and I.L. Wijnant, 2019. Uncertainty analysis of climatological parameters of the DOWA (DOWA-project WP 6.1. KNMI Technical Report TR-379

Temporal and spatial differences between model data and measurements

Fundamental differences exist (temporal and spatial) between model data (re-analysis or wind atlas) and measurements. The wind atlas data (the KNW-atlas and the DOWA) are provided at one-hour intervals (i.e. 00:00 UTC, 01:00 UTC, etc.) and represent a best estimate of the wind conditions at that hour for a 2.5 km by 2.5 km grid box of tens of meters deep. Wind atlas data are therefore instantaneous volume averages. Compared to anemometer and lidar measurements which average over much smaller volumes, the model values fluctuate less rapidly. Averaging the anemometer measurements over longer time periods provides wind speeds that fluctuate less rapidly too. In the mast/LiDAR validation report of the KNW-atlas [Stepek, 2015] it was argued (based on an analysis with FINO1 winds at 100 m height) that the instantaneous volume-averaged KNW-atlas values should each be compared to an hourly averaged measurement value. This is what we also did for the DOWA-validation[14]. In order to get hourly averaged measurements, measurements from a half-hour before and a half-hour after the wind atlas hour (i.e. six total 10-min mean measurements) were averaged (scaler averages as opposed to vector averages) to produce an hourly measurement value that could be used for validation. Because the measurement time stamp refers to the beginning of the 10-min averaging period, measurements at 00:30 UTC (i.e. referring to the time period between 00:30 UTC and 00:40 UTC), 00:40 UTC, 00:50 UTC, 01:00 UTC, 01:10 UTC, and 01:20 UTC were averaged to validate the wind atlas wind speed and direction values at 01:00 UTC.

Scatterometer measurements are footprint averages (2D). It is important to realise that grid-spacing is not the same as spatial resolution. The ASCAT coastal product provides wind measurements on a 12.5 x 12.5 km grid, but the effective resolution is 25 km. This is comparable to the effective resolution of the HARMONIE model: the grid-spacing is 2.5 x 2.5 km, but the effective resolutions equals 7-10 times the model grid size (so 15-25 km).

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[14] However, a spectral analyses performed in [Valk, 2019] described in section 3 showed that DOWA-data are “real” for averaging times of 10 hours and more.

Collocated datasets

Before being able to perform any kind of validation, model data (reanalysis/atlas) and measurements have to be collocated. This means that only those model data are used when measurements are available (in other words: periods without measurements are excluded from the validation). For the DOWA-validation an analogous ‘one-hour’ measurement value was derived as long as there was at least one valid measurement within the one-hour period.

Height adjustments

Adjustments were made to account for height differences between model (reanalysis/atlas) and measurements. A cubic-spline interpolation scheme was used to interpolate the model data to the site-specific measurement heights.

No wind farm wake effects

DOWA produces an undisturbed wind climatology without wake effects from neighbouring wind farms (in ERA5 and HARMONIE Version 40h1.2.tg2 the North Sea is without wind farms). So only wind measurements that are not disturbed by wind farm wakes can be used to validate the DOWA winds.

The maximum wake effect (minimum wind speed and maximum turbulence intensity) will be “felt” just behind the last turbine (array) and at hub height. The length of the wake will depend on how fast the kinetic energy harvested by the wind farm can be replenished by turbulent diffusion, mainly from the atmosphere above (and less so from the area beside the wake). The stronger the turbulent diffusion, the shorter the wake. Turbulent diffusion depends on the stability of the atmosphere (more unstable, more turbulent diffusion), the wind speed (higher wind speeds, more turbulent diffusion) and the number of “active” wind turbines (more rotating turbines, more turbulent diffusion). The wake at lower levels will always be longer than at hub height.

[Christiansen, 2005] and [Hasager, 2015] have shown with synthetic-aperture radar (SAR) measurements that in unstable and near-neutral atmospheric conditions wind farm wakes at 10 m heights can still be detected 20 km downstream from a wind farm [Boon, 2018]. In theory the wind farm wake could be even longer in stable atmospheric conditions, but on the North Sea the atmosphere is predominantly unstable or near-neutral [Sathé, 2011] and [Holtslag, 2016]. Therefore a 20 km length was used to denote the maximum wake impact distance of a neighbouring wind farm: if a wind farm was detected within 20 km from the measurement location, data from these wind directions were excluded from the DOWA validation.

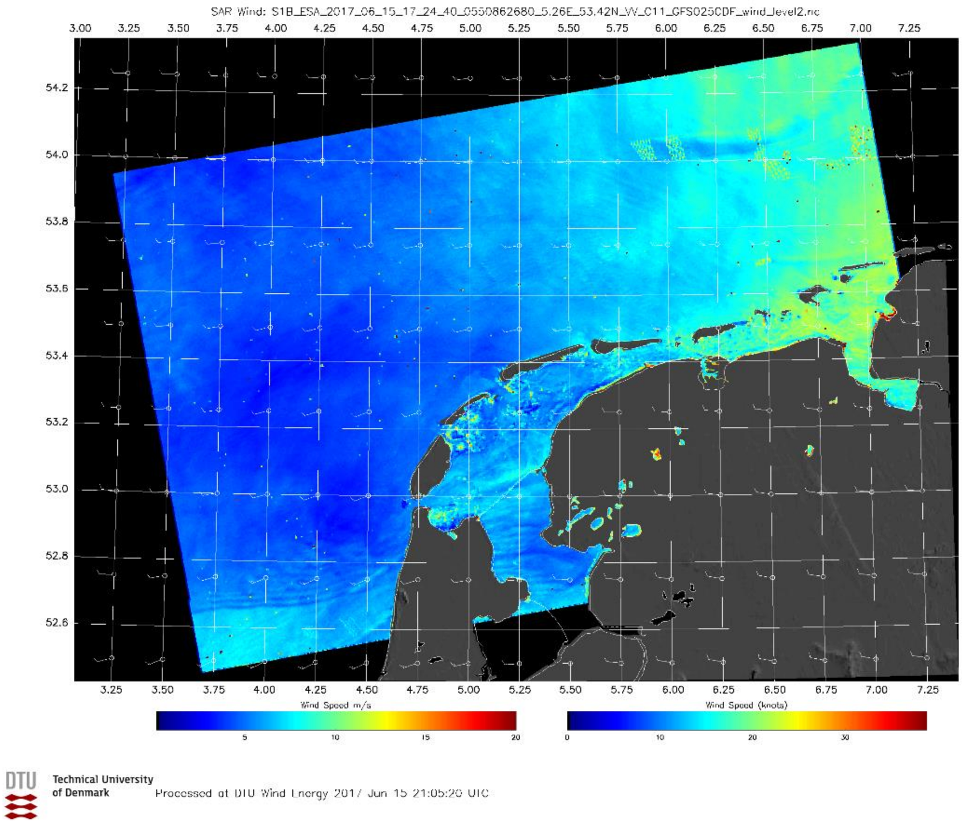


Figure 4: Example of a wake captured by SAR behind wind farm Gemini (siurce: web portal for Satellite Winds from the DTU wind energy group https://satwinds.windenergy.dtu.dk/).

Bias and precision

One of the main reasons for making the DOWA was to improve upon the ability of the KNW-atlas to accurately depict hourly wind field variability (i.e. correlation) and the diurnal cycle. So the validation efforts include not only assessment of climatological bias, but also of hourly correlation and precision.

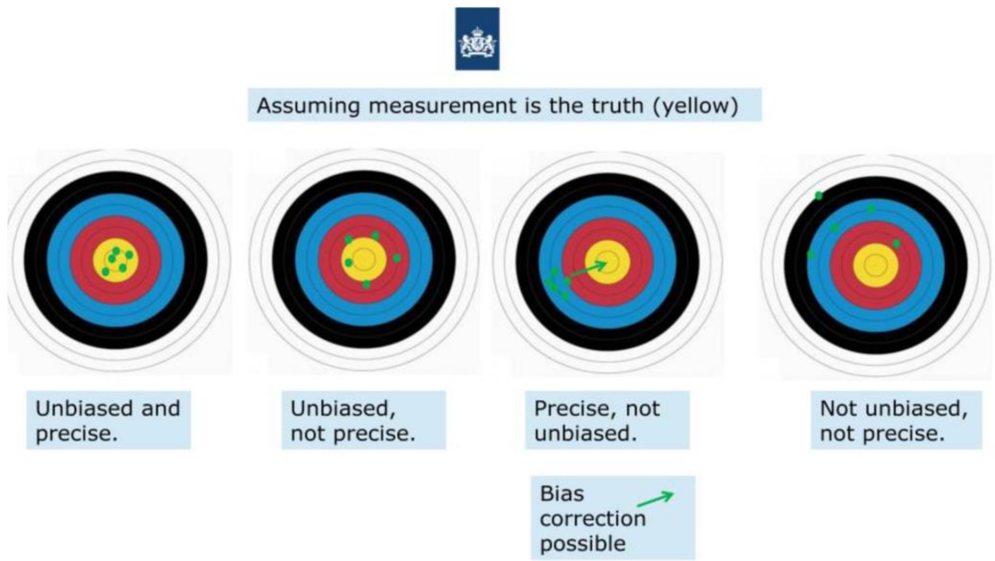


Figure 5: Illustration of bias (in the mean) and precision.

Figure 5 gives an illustration of the difference between bias (in the mean) and precision. Precision of a data source refers to the "random" (non-systematic, non-predictable) error. A bias (average offset) can be corrected for, a lack of precision introduces an uncertainty that cannot be avoided.

There are different ways of describing precision:

- Standard deviation (SD) of the difference between measurement and model (in section 2.1 "ASCAT 10m wind validation", section 2.2 "Offshore mast and lidar wind profile validation"[15], section 2.3 "Cabauw wind profile validation" and section 2.4 "Coastal lidar wind profile validation"
- Standard deviation of the mean bias (SDMB). The method to calculate this depends on whether the underlying data are independent (then SDMB = SDB/√N with N the number of measurements) or dependent (in that case the N-value needs to be adapted: see appendix C [Knoop1, 2019]). The model variance is the $SDMB^2$. (in section 2.3 fig 20/21/24 "Cabauw wind profile validation" and section 2.4 fig 28 "Coastal lidar wind profile validation").
- Root Mean Square Error (RMSE), which equals the SDB if the mean bias is zero[16] (in section 2.2 "Offshore mast and lidar wind profile validation", section 2.3 "Cabauw wind profile validation" and section 2.4 "Coastal lidar wind profile validation").
- Precision of data about the fitted linear regression line R^2 (in section 2.2 "Offshore mast and lidar wind profile validation", section 2.3 "Cabauw wind profile validation" and section 2.4 "Coastal lidar wind profile validation")
- SD of the unbiased noise term or the non-biased RMSE (in section 3 "Uncertainty assessment") based on triple or quadruple collocation analyses

For the uncertainty assessment of the DOWA-winds (section 3) a new method has been introduced to assess the relative bias: Quantile-quantile (QQ) plots that give the relationship between the sorted values from one data source and the sorted values from another data source.

2.1 ASCAT 10m wind validation

The ASCAT coastal product[17] 10-m equivalent winds (Figure 6 top) were used to examine the performance of 10m winds over the North Sea from (1) the DOWA and (2) its predecessor the KNW-atlas and their hosting re-analysis , respectively (3) ERA5 and (4) ERA-Interim.

KNMI has produced the ASCAT coastal product operationally since November 2006 as part of the EUMETSAT OSI-SAF (Ocean and Sea-Ice Satellite Application Facility). This satellite product provides measurements of the 10-m equivalent neutral[18] wind speed and direction at a 12.5-km grid on a 525-km swath on both sides of the satellite track with a 725 km gap in between. The effective horizontal resolution of these measurements is 30 km. The ASCAT coastal product can accurately measure wind speed as close as 15 km from the coast. Measurements are available from 2007, but this validation study only covers 2013 similar as was done in the previous KNW-atlas validation report. The Metop-A satellite carrying ASCAT passes the North Sea twice a day: south bound at 09:30 UTC and north bound at 21:30 UTC: periods when scatterometer measurements were not available were not used in the validation.

On the quality of ASCAT:

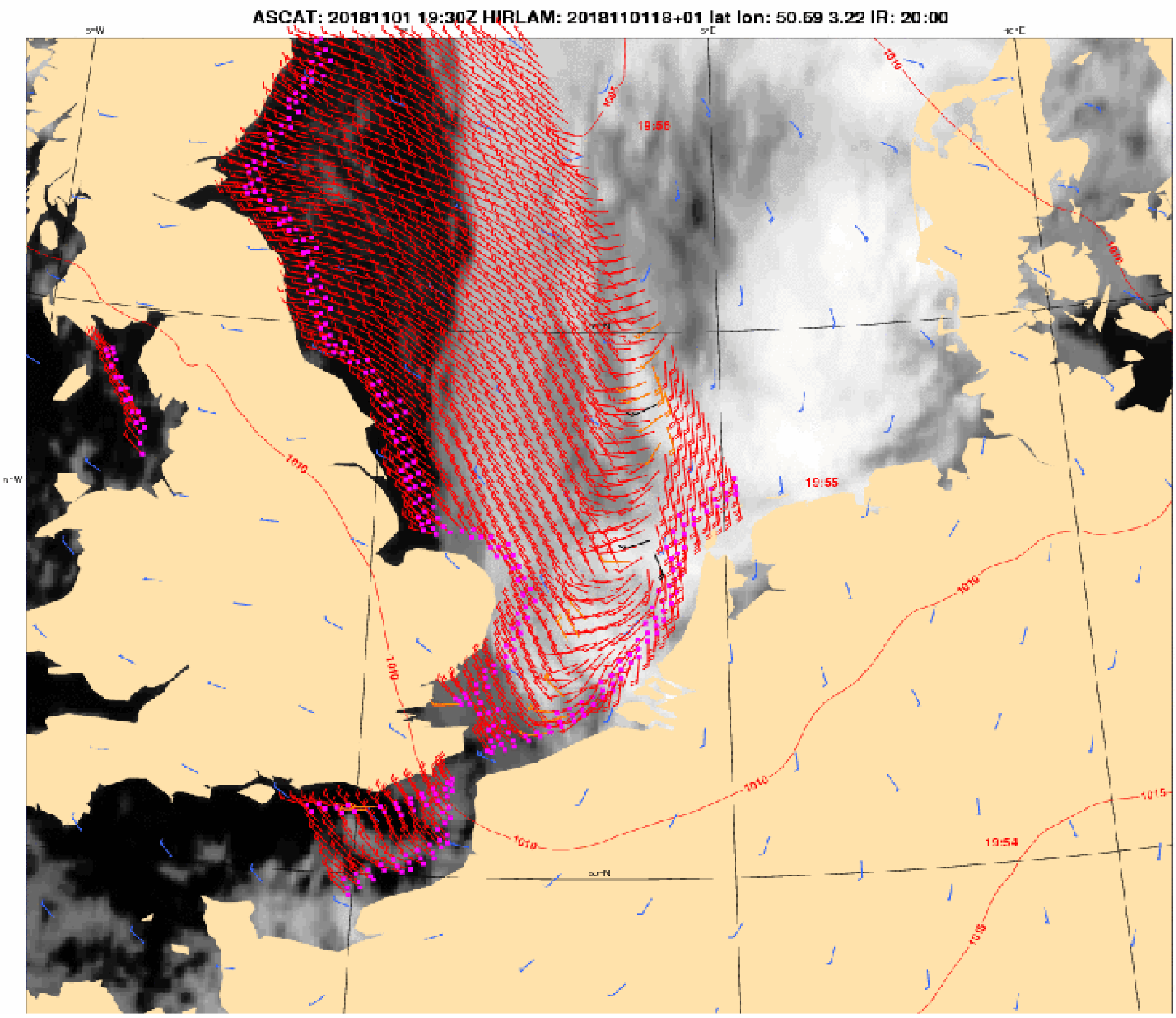
- All ASCAT winds are calibrated against 10-m equivalent neutral wind speeds from moored buoy measurements all over the world.
- ASCAT slightly underestimates the wind speed. The wind speed bias is less than -0.23 m s^{-1} in coastal areas (i.e. ≤ 50 km from the coast) and -0.29 m s^{-1} elsewhere.

[15] Duncan calls this "standard deviation of the bias", but in fact it is the standard deviation of the hourly wind speed deviation.
[16] Section 5.5 [Knoop1, 2019]
[17] http://www.knmi.nl/scatterometer/ascat_osi_co_prod/ascat_app.cgi
[18] A 10 m equivalent neutral wind speed is the wind speed at 10m height derived from the scatterometer roughness measurements at the sea surface assuming neutral stability and a logarithmic wind profile.

- The standard deviation of the error between ASCAT and buoy measurements is less than 1.6 m s^{-1} for both the u and the v wind components (Verhoef and Stoffelen 2013).
- ASCAT coastal products are also compared to ECMWF model winds in real-time for quality assurance purposes.
- The ASCAT coastal product is virtually free of rain contamination.
- Data from port areas were not considered in this validation study because of the anchor area problem[19], but these anomalous results are still displayed in the spatial plots.

Because North Sea ASCAT measurements are only available twice a day (09:30 UTC and 21:30 UTC), the temporal resolution is too coarse to resolve the diurnal cycle. Including additional scatterometers, e.g. the Indian [00 and 12 UTC passes] and the Chinese [6 and 18 UTC passes], would make validation of the diurnal cycle possible. However, this was beyond the scope of this study, as was using the whole of the collocated dataset (2008-2018) instead of just one year (2013).

The ASCAT-validation work focused on examining how well the DOWA represents the 10-m wind speed, wind direction, and the corresponding zonal and meridional wind components compared to the ASCAT scatterometer winds (1) for the whole North Sea (Figure 6 middle) and (2) for a coastal zone from 15-30 km away from the Dutch coast (Figure 6 bottom).



[19] In the ASCAT coastal product are significant outliers near the main harbors such as Rotterdam. This is because often lots of ships (sometimes about 100) wait at the anchor areas near the harbors and contaminate the back scattered ocean signal measured by the scatterometer. QC screens some of the ship-reflection contaminated measurements at low winds, but less so at high wind speeds (when there is little contrast between contaminated and good signals). As a result the scatterometer measures unrealistically high winds at anchor areas along the Dutch and Belgian coast. Improving QC is work in progress at KNMI.

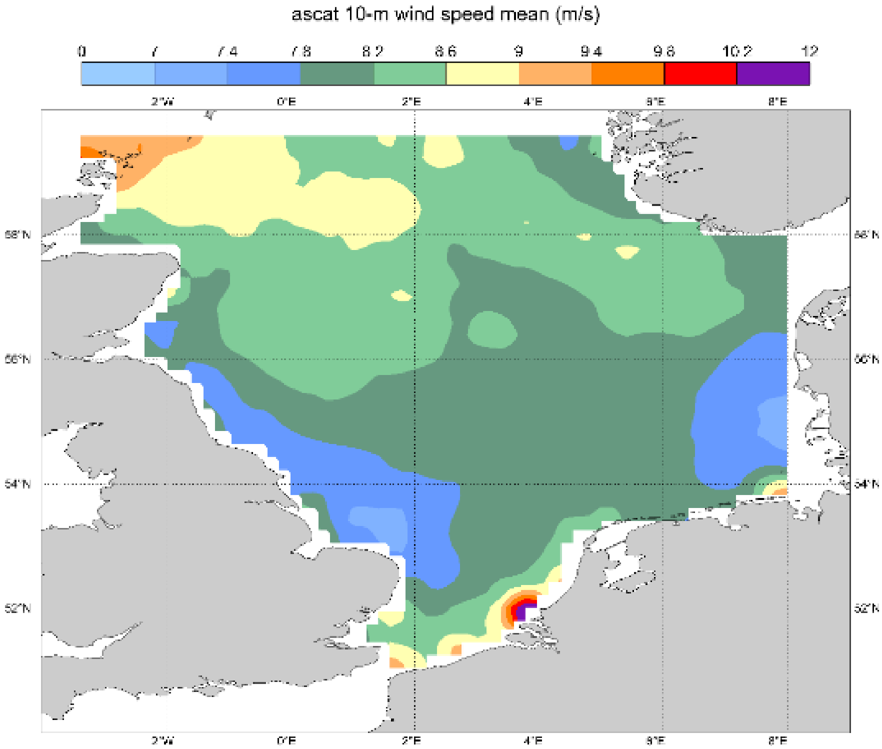


Figure 6 (top, on previous page): ASCAT 10-m wind measurements from a single Metop-A overpass on 1-11-2018 at 19:56 UTC. Picture shows the scatterometer winds (in arrows or flags) with an infrared satellite image (from METEOSAT, GOES or GMS) and numerical weather prediction model winds (currently only HIRLAM forecast in the Northern Atlantic region, in blue arrows or flags). Scatterometer winds are plotted on a cell spacing of 25 km (so only quarter of wind vectors is plotted), (middle): annual mean 10-m equivalent wind speed over the North Sea as measured by ASCAT during 2013; anomalously high wind speeds near Rotterdam are indicative of the 'anchor issue' (see text for details) and (bottom): example of ASCAT measurements within the coastal validation domain. Source: [Duncan1, 2019].

The main results of the ASCAT 10m wind validation are:

Figure 7:

For most of the North Sea DOWA overestimates the ASCAT wind speed at 10 m height (O-B bias is negative)[20]. The overestimation is on average less than 0.2 m/s which is comparable to the bias of the KNW-atlas and ERA5: DOWA does not reduce the wind speed bias. The major improvements of the DOWA compared to the KNW-atlas and the global reanalysis ERA5 and ERA-Interim can be found when analyzing the O-B standard deviation (figure 8 and 9).

The O-B bias for wind direction is less for DOWA than for ERA5 (not shown).

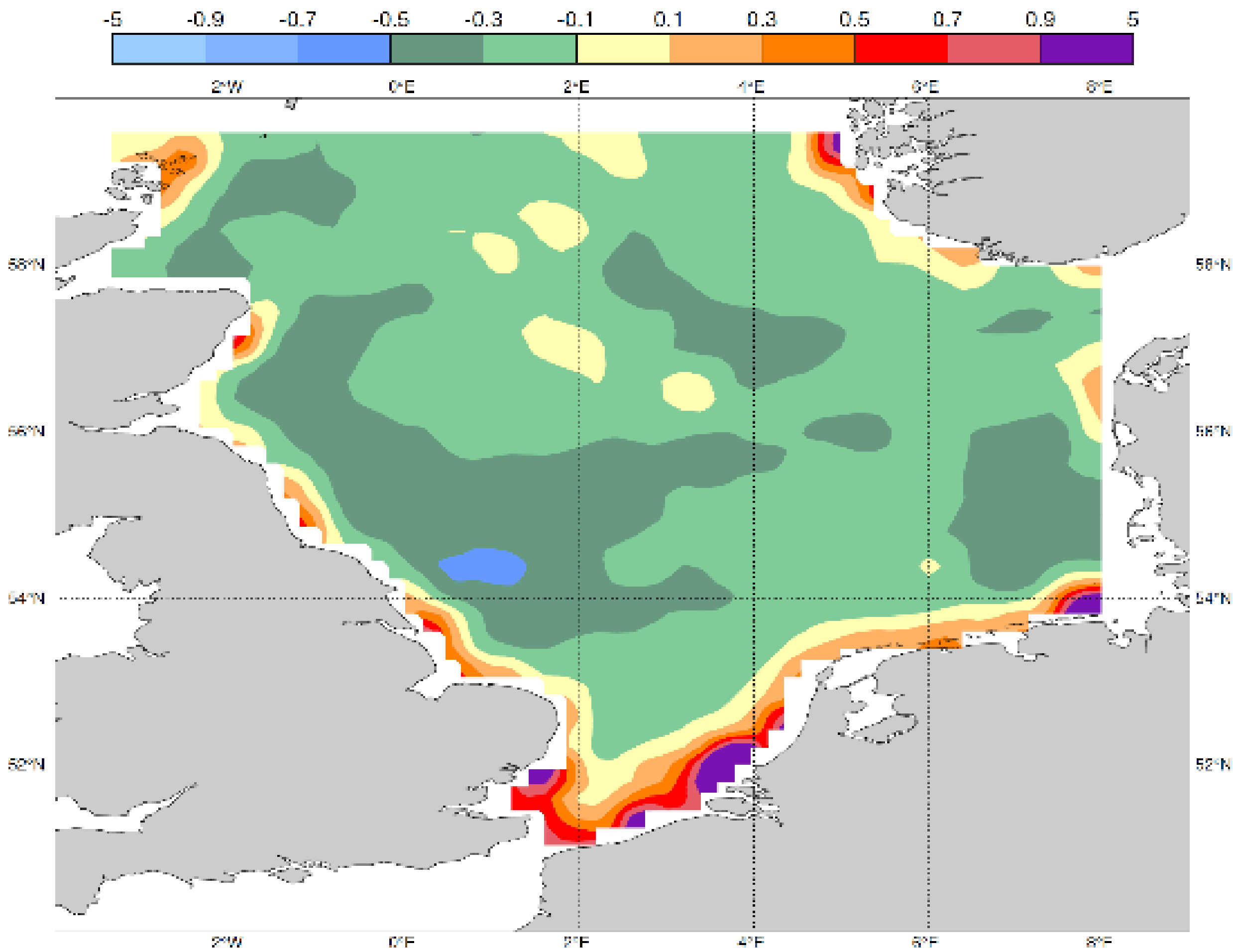
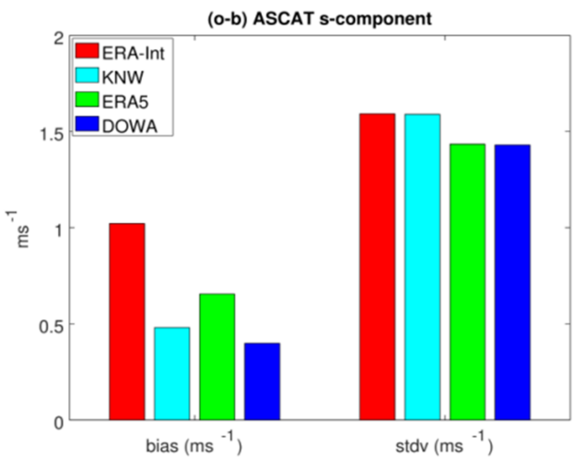


Figure 7: Spatial plot of the O-B bias for the North Sea. Source: [Duncan1, 2019].

[20] Purple zone is result of the Rotterdam anchor area problem explained at the beginning of this section.

Figure 8:

- Figure 8 (left): For the coastal zone (between 15 and 30 km offshore) ERA-Interim, KNW-atlas, ERA5 and the DOWA all underestimate the 10 m wind speed compared to the ASCAT measurements (for the whole North Sea DOWA overestimates the ASCAT wind speed at 10 m height (see Figure 7).
- Figure 8 (left): Both the KNW-atlas and the DOWA reduce the bias compared to their hosting reanalyses (ERA-Interim & ERA5): bias KNW 0.4 m/s and DOWA 0.3 m/s.
- Figure 8 (left): The standard deviation of the o-b statistic lends insight into the level of **realistic** and **real** detail produced by the reanalyses or the wind atlases. The smaller the (o-b) standard deviation value, the more agreement there is between the added wind field variance created by the reanalysis or atlas and the ASCAT measurements (i.e. the atmospheric structures generated by the model are consistent with those observed both spatially and temporally). The (o-b) standard deviation generally increases as a result of downscaling to finer resolutions (i.e. the finer details look realistic, but are not real; partly due to "double penalty effect" where the model is penalized twice if its forecast for a specific location and time is incorrect), but we do not see this here: both KNW and DOWA add realistic and real detail to their hosting reanalyses ERA-Interim and ERA5 (with lower resolution). Also ERA5 improves on ERA-Interim and the DOWA produces the most realistic and real wind speed fields.
- Figure 8 (right): All reanalyses/atlases give a wind direction at 10 m height that is more veered compared to ASCAT (negative o-b statistic bias): difference small < 5°
- Figure 8 (right): KNW & DOWA both reduce bias compared to their hosting reanalyses (ERA-Interim & ERA5)
- Figure 8 (right): DOWA resolved wind direction structure is slightly better (o-b standard deviation smaller) than that produced in ERA5 despite the higher resolution



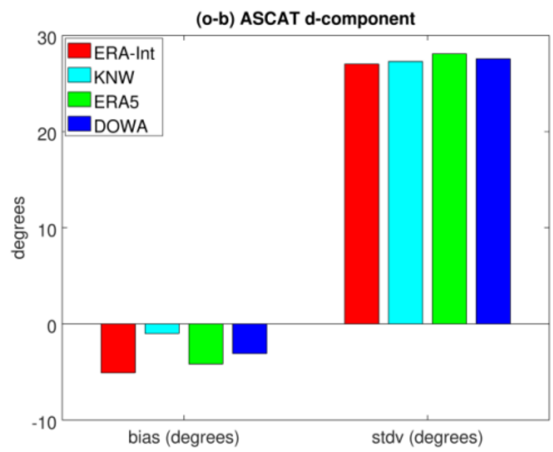


*Figure 8 (left): O-B (measurement – reanalyses/atlas) 10 m **wind speed** statistics in coastal zone. (Right): O-B 10 m **wind direction** statistic for coastal zone. Source: [Duncan1, 2019].*

Figure 9:

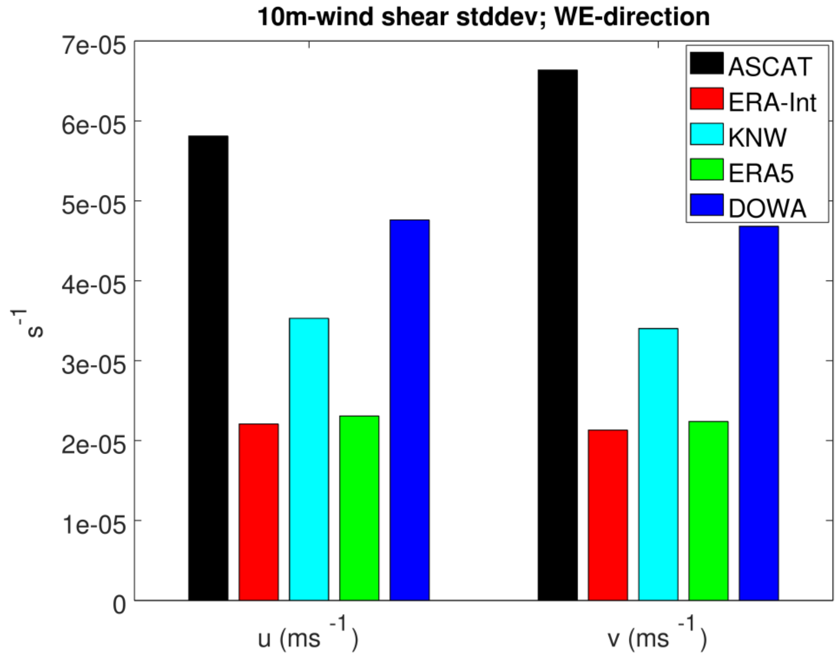


Figure 9: standard deviation of the west-east (horizontal) wind speed shear at 10 m. The horizontal wind speed shear (defined as the difference in horizontal wind speed between two successive model grid points divided by the distance between those grid points, here averaged over the North Sea domain) provides an indication of the spatial detail and structures resolved within the reanalysis or wind atlas. Source: [Duncan1, 2019].

Comparing the horizontal wind speed shear evident within the reanalysis/wind atlas to that based on ASCAT measurements (Figure 9) lends insight into whether the model-resolved structure is realistic or not. The lower the standard deviation value, the smoother (i.e. less structure) the resolved wind field. Note that this comparison does not reveal if the details are real (actually occur at the same point in time or at the exact same location).

Figure 9 shows that:

- The ASCAT-measurements are the most realistic (largest stand deviation). The measured wind field structure is best represented by the DOWA, followed by the KNW-atlas.
- HARMONIE manages to add substantially more realistic detail to the wind field of DOWA from ERA5 than to the KNW-atlas from ERA-Interim (difference between ERA5 and ERA-Interim fairly small). This may be due to (1) the quality of HARMCy40 as opposed to HARMCy38 (HARATU, see section 1.2) or (2) the new method used to make the DOWA including additional data-assimilation.

2.2 Offshore mast and lidar wind profile validation

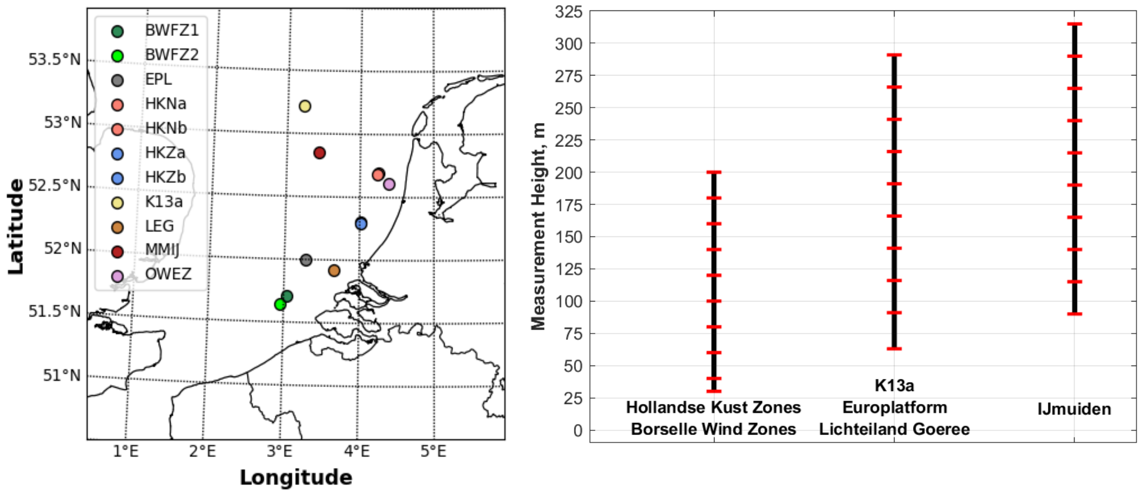


Figure 10 (left): 9 measurement sites used for the offshore mast and wind lidar validation of the DOWA: Borssele Wind Farm Zone (BWFZ), Europlat (EPL), Hollandse Kust Noord (HKN), Hollandse Kust Zuid (HKZ), K13a, Lichteiland Goeree (LEG), Meetmast Ijmuiden (MMIJ) and Offshore Wind Farm Egmond aan Zee (OWEZ). There are two floating wind lidars at HKN and HKZ (not individually plotted on the map). (Right): wind lidar sampling heights (red lines) for the 7 lidar measurement sites. Source: [Duncan2, 2019].

Figure 10 (left) gives an overview over the validation sites with wind profile measurements. At MMIJ[21] and OWEZ the wind profile was measured with cup anemometers (wind speed) and wind vanes (wind direction) mounted on a mast. For every measurement height there are 3 sets of instruments on different sides of the mast and the measurements least disturbed by the mast are selected for the validation (or measurements are combined in such a way that mast effects are minimalized). Measurement heights at MMIJ are 27m, 58m and 85/87m (85m cup anemometer and 87m wind vane). At OWEZ: 21m, 70m and 116m. At MMIJ, EPL, K13a wind profiles were measured with a platform mounted ZephIR 300s lidar, at LEG with a platform mounted WINDCUBEv2 lidar. At HKN, HKZ and BWFZ wind profiles were measured with two ZephIR 300s lidars per site (floating lidars mounted on a buoy). The measurement heights for the wind lidar measurements are summarized in figure 10 (right). None of the measurements are available for the full 11-year DOWA-period. The availability of “undisturbed” (no wind farm wake effects) measurements ranges from 1,5 years (EPL) to about 4.5 years (MMIJ[22]). The measurement campaign at BWFZII was only 5 months long and disturbed by wind farm wake effects for wind directions between 135 and 315°.

Before validation the uncertainty in the offshore measurements was assessed by TNO part of ECN at 1.2-1.8% (MMIJ mast 92m), 1.9-4.8% (MMIJ mast 85m) and 1.7-2.1% (MMIJ mast 58m/27m), 3.4% (OWEZ mast), 2.5-3.5% (platform mounted lidar) and 3.1-4.2% (floating lidar)[23]. Only differences between model and measurement that are larger than the measurement uncertainty can be attributed to model error.

The uncertainty of the MMIJ mast and fixed (platform mounted) wind lidar measurements was also assessed by [Valk, 2019] with a quadruple collocation analyses between the DOWA (90m), the KNW-atlas (90m), the platform mounted lidar measurements (90m) and the cup anemometer mast measurements (85m). Considering the full wind speed range, the uncertainty (defined as the non-biased RMSE, normalised by the average wind speed at MMIJ at 90m of about 10m/s) is about 2% for the mast measurements (better than found by ECN part of TNO) and 3.5% for the platform mounted wind lidar (comparable to found by ECN part of TNO[24]). The uncertainty in the wind direction measurements is however much larger. Similar analyses have been done for other wind speed ranges.

[21] The wind speed that is derived from the raw measurements is often referred to as the “true wind speed” (or “derived wind speed”). ECN part of TNO supplied the true wind speed and directions at MMIJ for validation.
[22] MMIJ measurements used from 2-11-2011 to 11-3-2016 although 2011 measurements are faulty [Valk, 2019].
[23] For further details on the (quality of the) offshore mast and wind lidar measurements we refer to [Duncan2, 2019].
[24] And 12% for the DOWA and 15% for KNW (section 3).

The main results of the offshore mast and lidar wind profile validation (focus on MMIJ) are:

Figure 11:

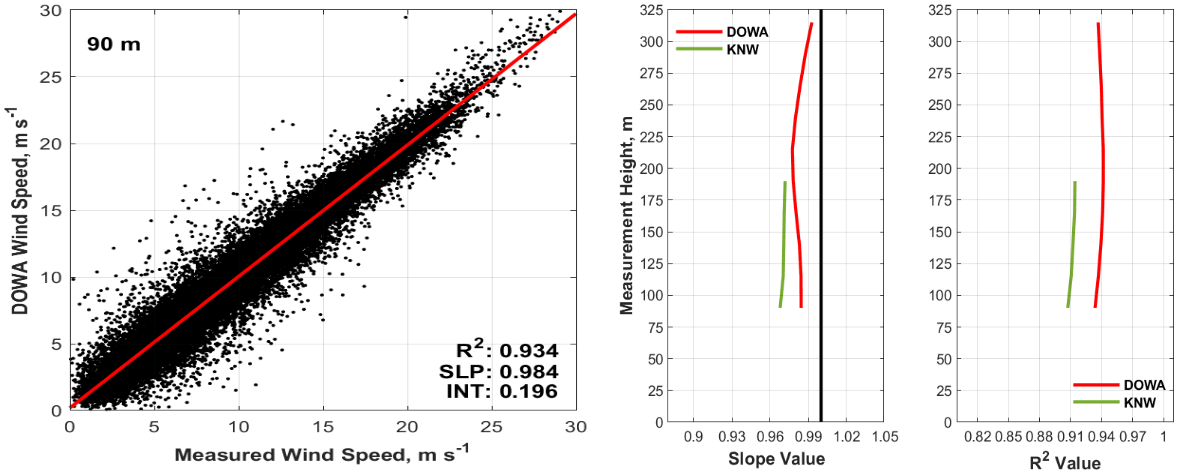


Figure 11 (left): Scatterplot of the DOWA and lidar wind speeds at MMIJ. (Right): vertical differences in the value of the linear least-squares regression slope and R^2 (indicates the precision of the data about the fitted linear regression line). Source: [Duncan2, 2019].

Figure 11 (left) shows the scatterplot of the DOWA and lidar wind speeds at 90m height at MMIJ. The red line represents the line: ($wind_{DOWA} = SLP * wind_{MEASURED} + INT$) where SLP is the slope (the closer to 1 the better) and INT the intercept (the closer to 0, the better). R^2 indicates the precision of data about the fitted linear regression line (the closer to 1, the better). The plots in figure 11 (right) indicate improved hourly correlation in DOWA (compared to KNW) for all validated heights at MMIJ (DOWA slope and R^2 closer to 1). This is the same for all other lidar and mast validation measurements (not shown).

Figure 12:

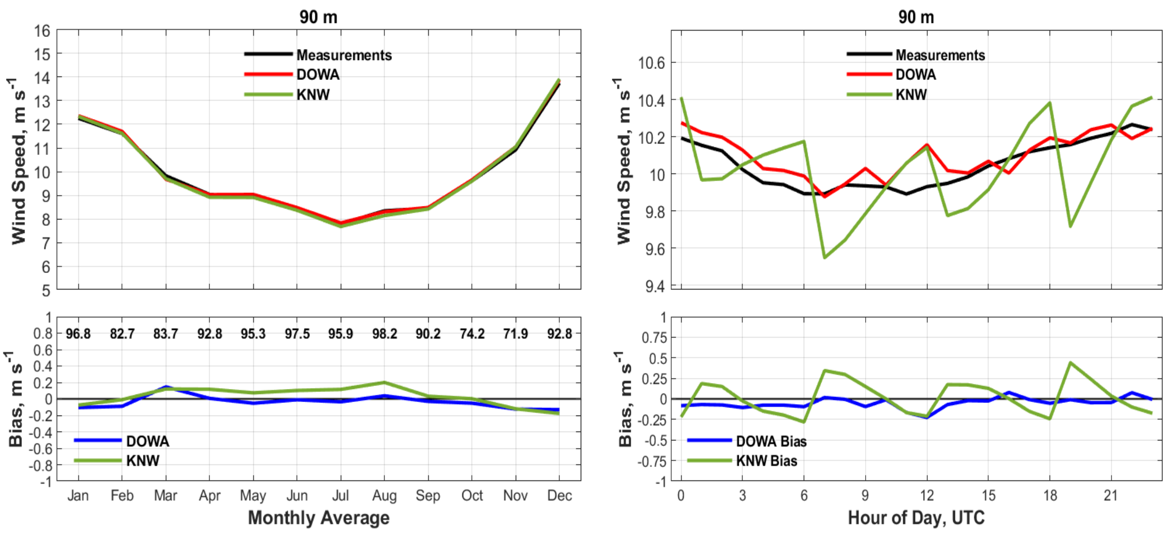


Figure 10 (left): monthly and (right) hourly averaged wind speeds from DOWA, KNW and platform mounted lidar measurements MMIJ (90m). Source: [Duncan2, 2019].

Figure 12 (left) makes clear that DOWA does not improve the monthly climatology of the KNW-atlas. DOWA does however improve the diurnal cycle (Figure 12 right) due to removal of "cold starts" (section 1.3).

Figure 13:

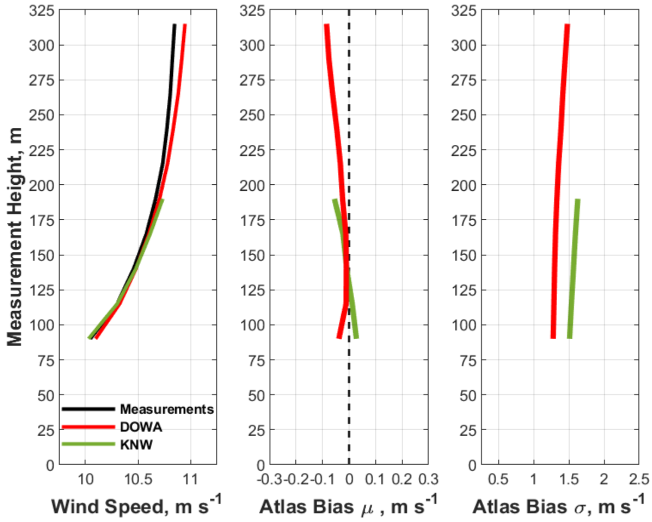


Figure 13 (left): vertical profile of the wind speed measured with platform mounted lidar (black) compared to that from DOWA (red) and the KNW-atlas (green). (Middle): mean wind speed bias μ (measured wind speed - atlas wind speed) and (right) the standard deviation σ of the hourly wind speed deviation. Source: [Duncan2, 2019].

Figure 13 (middle) shows that the mean bias of the wind speed (difference between the wind speed measured with the platform mounted lidar and the DOWA wind speed) at MMIJ is less than 0.1 m/s for all heights. For all sites and heights (except for OWEZ[25]) the mean wind speed bias is within measurement accuracy of 0.4 m/s (not shown). The standard deviation of the hourly wind speed deviation[26] for MMIJ is smaller (better) in DOWA than in KNW for all heights (Figure 13 right). This is also the case for all other validation sites (not shown).

Figure 14:

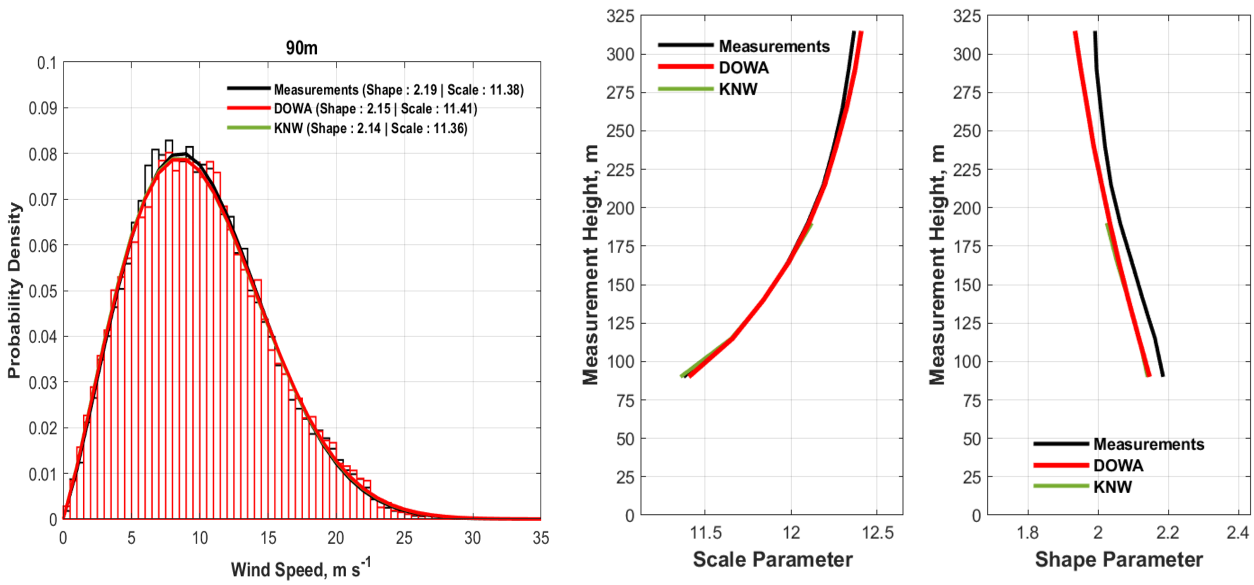


Figure 14 (left): Wind speed distribution and (right) Weibul-parameters at MMIJ (90 m) based on wind speeds measured with platform mounted lidar (black), DOWA (red) and the KNW-atlas (green). Source: [Duncan2, 2019].

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[25] At OWEZ disturbed winds may have been used. The wind direction filter used by Duncan is different from the one used for the KNW-validation: only wind measurements between 135° ad 315° are undisturbed after June 2006 (Kouwenhoven, 2007).
[26] Referred to as “the standard deviation of the hourly wind speed bias” by Duncan.

Figure 14 shows that there is hardly any difference between the wind speed distribution and Weibull parameters based on the platform mounted lidar measurements at MMIJ and those from the DOWA and the KNW-atlas. Just like in the KNW-mast validation report [Stepek, 2015] the Weibull shape and scale parameter were calculated with formula 5.18 from [Wieringa, 1983]:

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

where $F(U)$ is the cumulative Weibull distribution function (i.e. the chance of exceeding wind speed U), k is the Weibull shape parameter, and A is the Weibull scale parameter. Wind speed bins of 0.5 m/s from 4 m/s up to and including the bin containing the 99th percentile of the distribution were fitted. The parameter A is proportional to the mean wind speed of the distribution and the parameter k depicts the shape of the distribution. The value of k is inversely proportional to the spread of the wind speed distribution. Therefore, large k values indicate less variation in the wind.

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 75m 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 15/16:

The validation of the wind direction in the DOWA has been less extensive. Figure 15 and 16 show that the representation of the wind direction in DOWA is comparable to the representation of the wind direction in the KNW-atlas. The most significant discrepancies between the atlases and the measurements (platform mounted wind lidar at 90 m and vane at 85 m) occur for wind directions between South and West and between west and North, so for wind direction bins associated with the climatologically dominant wind directions. In [Duncan1, 2019] it is argued that the differences are caused by the fact that for prevailing wind directions the method is sensitive to the choice of bins: if a wind direction bin is aligned with the predominant wind direction, then just a few degree difference could significantly impact the probability density within the neighboring wind direction bins.

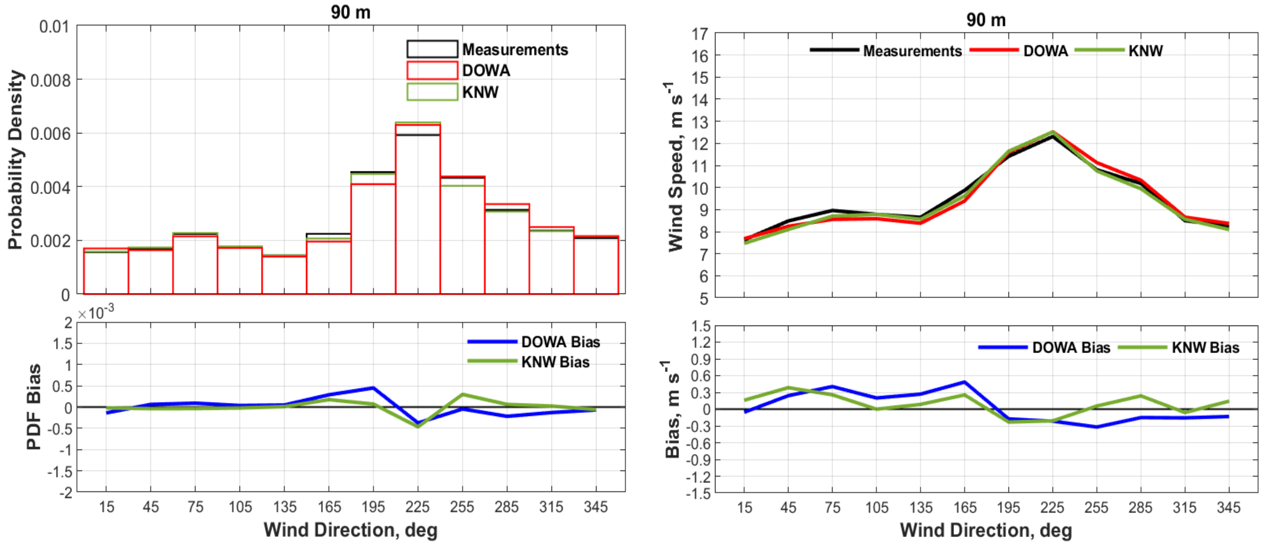

Figure 15 (left): Wind direction distribution (probability density function PDF) and the PDF wind direction bias (platform mounted lidar measured wind direction - atlas wind direction) and (right) the mean wind speed per wind direction bin and corresponding bias at MMIJ (90m).

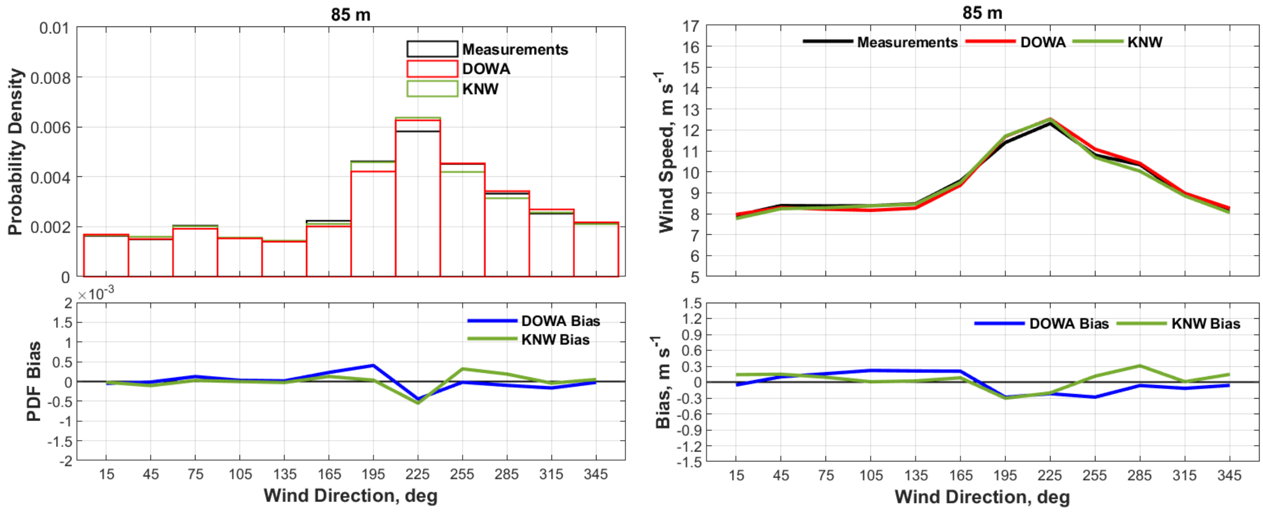

Figure 16: same as Figure 15, but then for wind vane measured wind direction at MMIJ (85m). Source: [Duncan2, 2019].

2.3 Cabauw wind profile validation

Figure 17: Cabauw meteorological mast, referred to as the A-mast in text below (photo by Ine Wijnant, KNMI)

The DOWA has been validated with cup anemometer wind speed and vane wind direction measurements from the 213 m high Cabauw mast near Lopik in Utrecht (51.971N, 4.927E)[27] for the period 2008-2017:

- At the levels 40, 80, 140, and 200 m of the 213m high A-mast the wind direction is measured at three booms and wind speed is measured at two booms: measurements least disturbed by the mast are selected for the validation (Figure 17).
- 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.

The accuracy of the cup anemometers at Cabauw is 1% (or 0.1 m/s for low wind speeds), and the accuracy of the wind vane 0.5° [Knoop1, 2019].

The main results of the Cabauw wind profile validation are:

[27] The Cabauw mast part of the CESAR (Cabauw Experimental Site for Atmospheric Research) Observatory http://www.cesar-observatory.nl/

Figure 18/19:

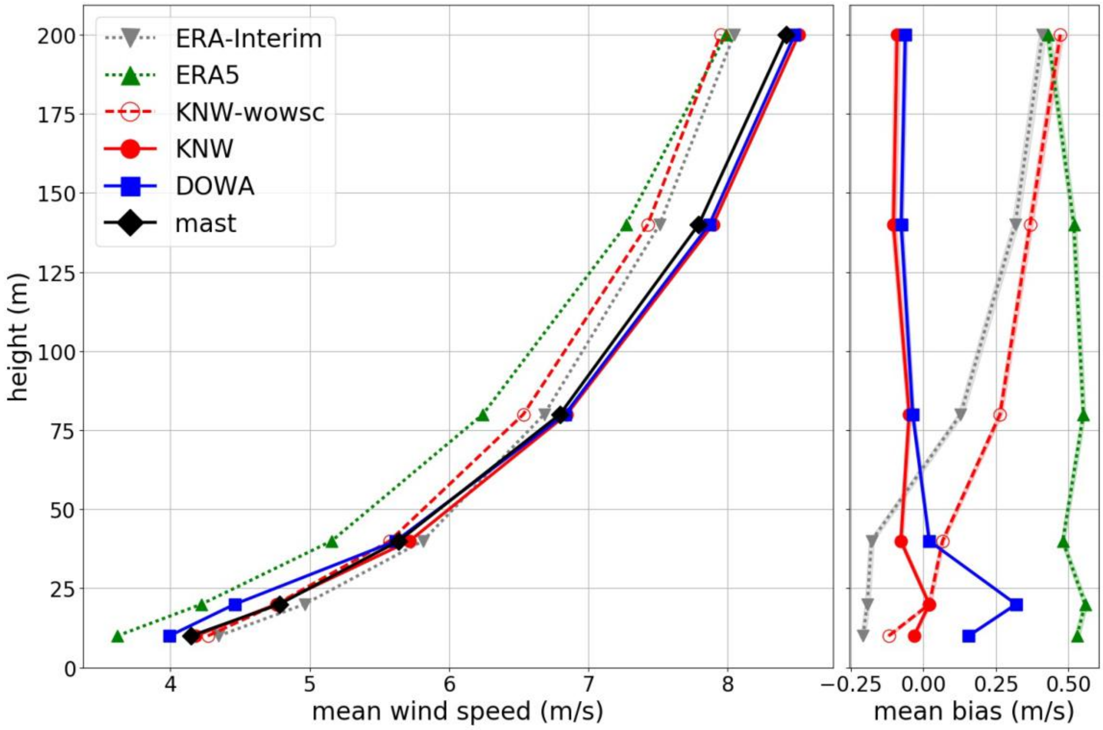

Figure 18: height profile of the mean wind speed (left) and mean bias (right), showing mast measurements (black), DOWA (blue), KNW-atlas (red), KNW-atlas without wind shear correction (red, dashed), ERA5 (green, dotted) and ERA-Interim (gray, dotted). Source: [Knoop1, 2019].

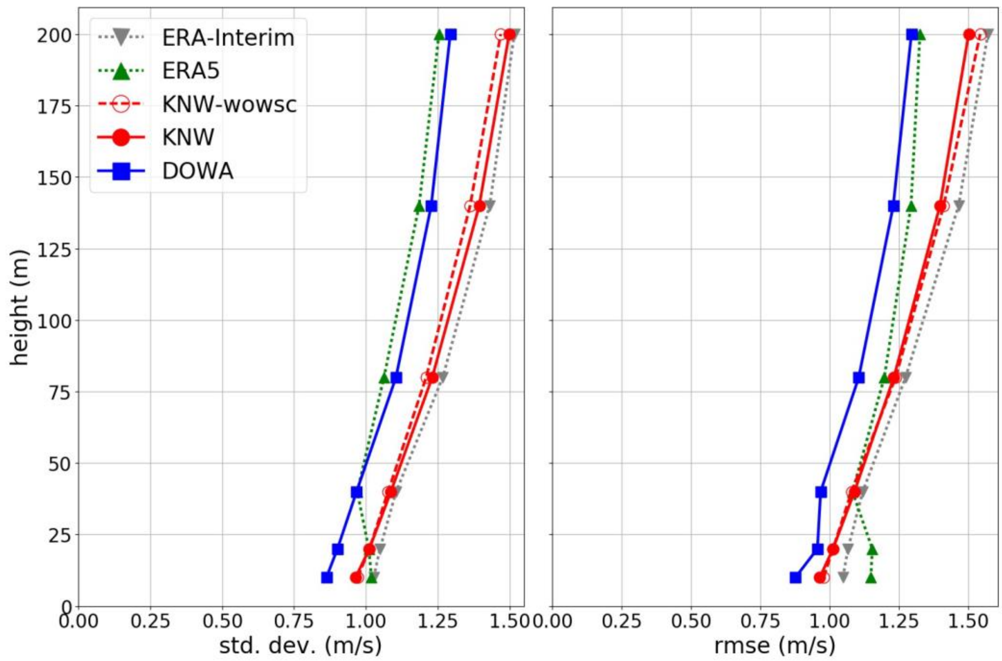

Figure 19: height profile of the standard deviation of the hourly wind speed deviation[28] (left) and root mean square error rmse (right), showing DOWA (blue), KNW (red), KNW without shear correction (red, dashed), ERA5 (green, dotted) and ERA-Interim (grey, dotted). Source: [Knoop1, 2019].

[28] Referred to as the standard deviation of the bias by Knoop.

Figure 18 shows that the DOWA captures the mean wind speed profile at Cabauw really well for heights above 20m (bias less than 0.2 m/s). Where for the KNW-atlas, the HARMONIE Version 37h1.1 winds needed to be post-processed (uniform wind shear correction), the HARMONIE Version 40h1.2.tg2 winds did not: as a result of the improved turbulence scheme HARATU in HARMONIE Version 40h1.2.tg2, the average wind profile is almost unbiased compared to the measurements. The higher mean biases for 10 and 20 m height (higher than in the KNW-atlas) are a result of the setting of the XRIMAX parameter, which a threshold that controls the mixing. For HARMONIE Version 40 (DOWA) this is set to 0, limiting mixing. As a result, model wind at lower heights is underestimated. For HARMONIE Version 37 (KNW) the XRIMAX parameter is 0.2 (not zero), hence the difference. The impact of the XRIMAX-setting is less clear/significant offshore.

It becomes clear from figure 18 that the DOWA has a much smaller bias compared to the measurements than its hosting reanalysis model ERA5. This was to be expected. It is however strange to see that for wind speeds below 200m the bias for ERA5 (grid size 31 km) is significantly higher than for ERA-Interim (grid size 80 km). A large bias in ERA5 (and MERRA and NEWA) was also found by [Kalverla, 2019] who compared mean wind profiles to MMIJ measurements.

Figure 19 shows that the DOWA has a smaller standard deviation and rmse than KNW for all heights, which implies that DOWA correlates better with the measurements than KNW (figures 21 and 23 also show this).

Figure 20/21:

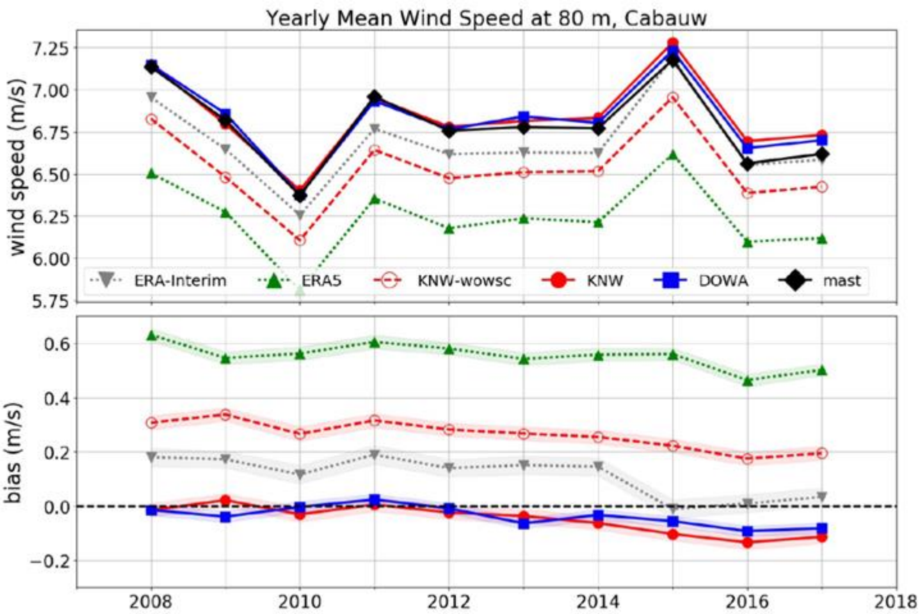

Figure 20: yearly mean wind speed at 80 m height, showing mast measurements (black), DOWA (blue), KNW-atlas (red), KNW-atlas without wind shear correction (red, dashed), ERA5 (green, dotted) and ERA-Interim (gray, dotted). The upper panel shows the wind speed of both mast measurements and models, the lower panel the bias between the mast measurements and the models. Model variance is indicated by the shaded areas in the bias plots. Unclear what happened to ERA-Interim in 2015. Source: [Knoop1, 2019].

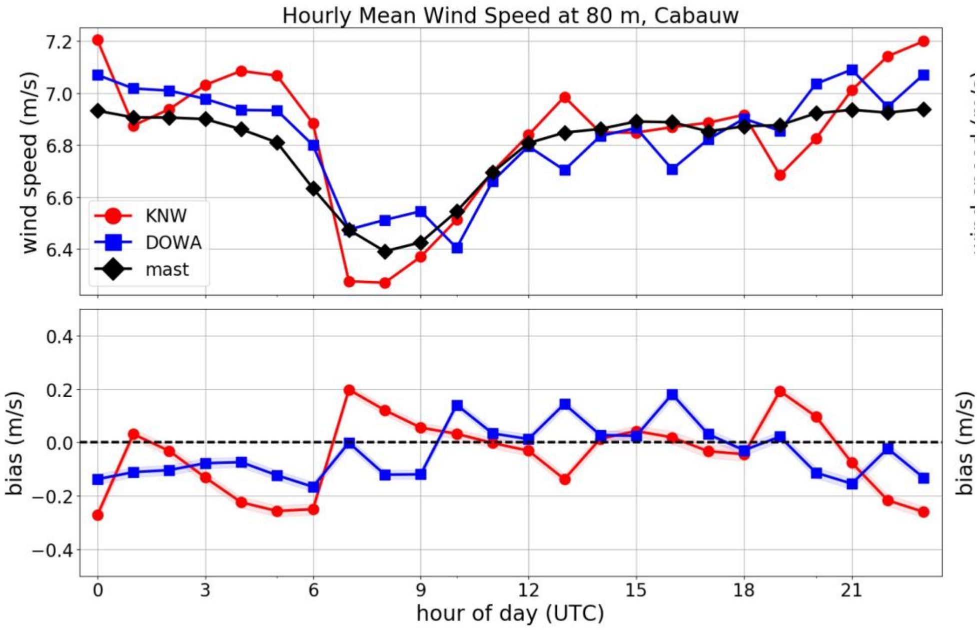

Figure 21: hourly mean wind speed at 80 m height, showing measurements (black), DOWA (blue) and KNW-atlas (red). The upper panel shows the hourly mean wind speed measured and modelled at 80 m height at Cabauw , the lower panel the bias between the measurements and the models at 80 m height. Model variance is indicated by the shaded areas in the bias plots. Source: [Knoop1, 2019]

From figure 20 it becomes clear that the mean wind speed is captured very well in the DOWA and the KNW-atlas (bias in yearly average wind speed less than 0.2 m/s). The improvement compared to the hosting reanalysis is most striking between ERA5 (positive bias/underestimation of about 0.5 m/s) and the DOWA (at most a negative bias of the measurements of less than 0.1 m/s).

Figure 21 shows that the diurnal cycle is captured by both the KNW-atlas and the DOWA, but the non-physical “jumps” in the biases are less strong and more frequent in the DOWA. The KNW “jumps” correspond with the cold starts every 6 hours and the DOWA “jumps” with the 3 hourly data-assimilation. Differences between night and day can be explained by the fact that the Mode-S EHS measurements are only assimilated during the day when there is air traffic.

Figure 22/23:

Linear regression is performed to quantify the correlation between the DOWA and the measured wind speeds at Cabauw. As in 2.2, the line: ($wind_{DOWA} = SLP * wind_{MEASURED} + INT$) is fitted to the measurements. Figure 22 shows that at 80 m height the slope of the regression line is 0.924 (the closer to 1 the better), the intercept 0.551 m/s (the closer to 0 the better) and the value of R^2 0.869 (the closer to 1 the better). Compared to MMIJ at 90m (Figure 11 left) the fit is (as to be expected) worse:

	Cabauw 80 m	**MMIJ 90 m**
Slope regression line	0.924	0.984
Intercept regression line	0.551	0.196
R^2	0.869	0.934

Figure 23 shows that DOWA performs better than KNW for all heights (except for the slope below 80 m): R^2 for the DOWA is significantly better (closer to one) than for the KNW-atlas, indicating an improvement in the correlation.

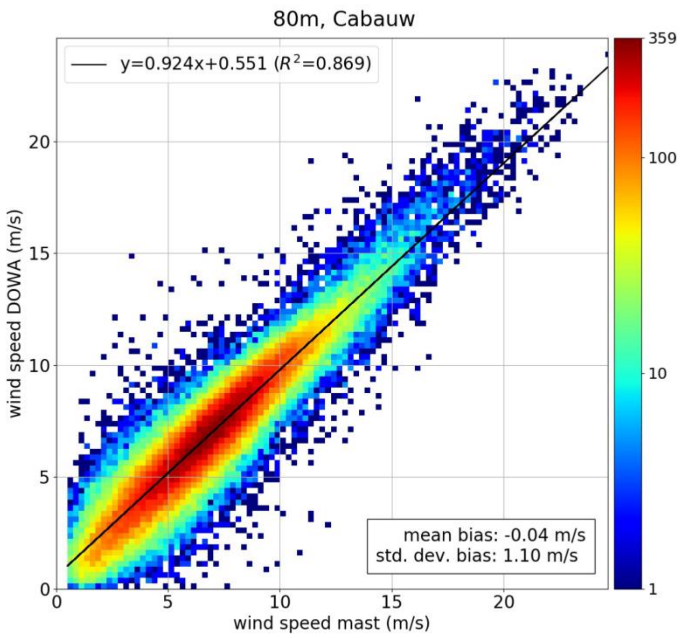

Figure 22: scatterplot of the DOWA and the mast wind speed measurements at Cabauw at 80 m height (visualized as a density plot with logarithmic color scale), showing the result of a linear regression (slope, intercept and R^2) and the mean bias and standard deviation of the bias. Source: [Knoop1, 2019].

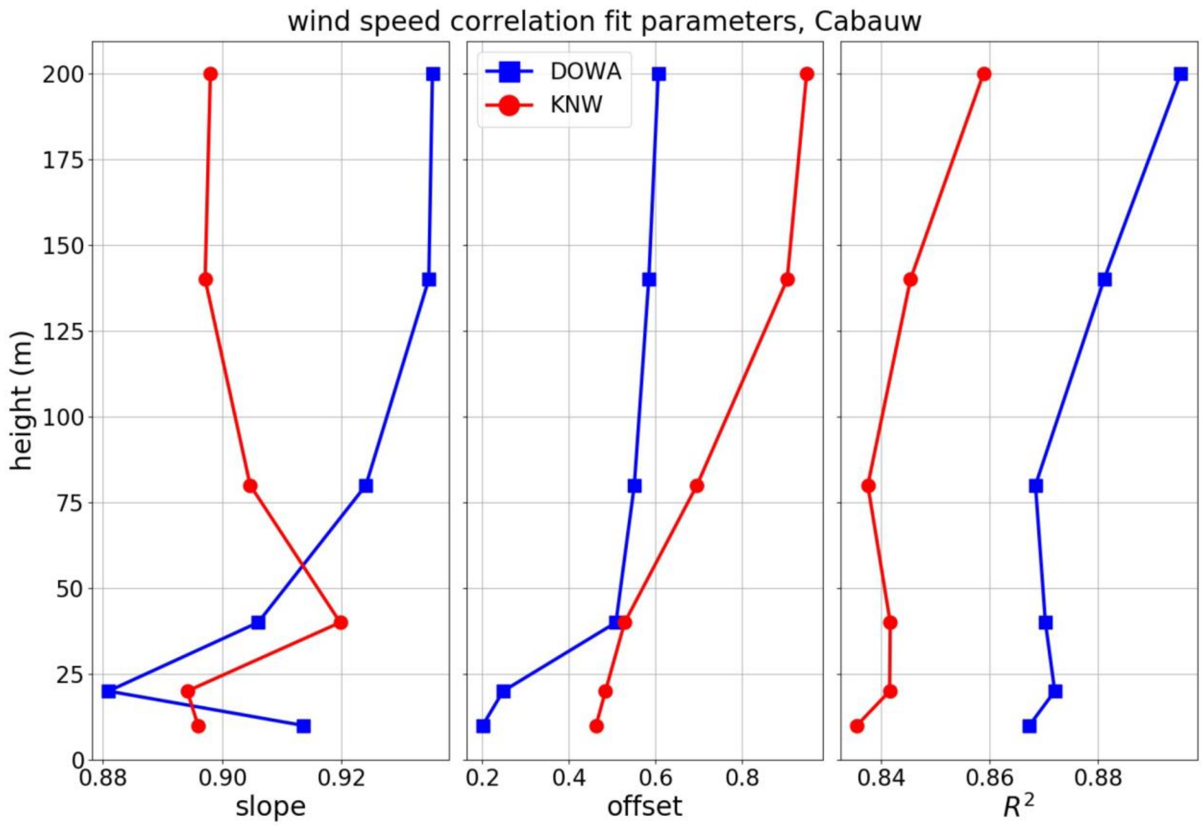

Figure 23: Height profile of the results of the linear regression (slope, offset or intercept and R^2) of wind speed data, comparing DOWA (blue) and KNW-atlas (red) for Cabauw. Source: [Knoop1, 2019].

Figure 24/25:

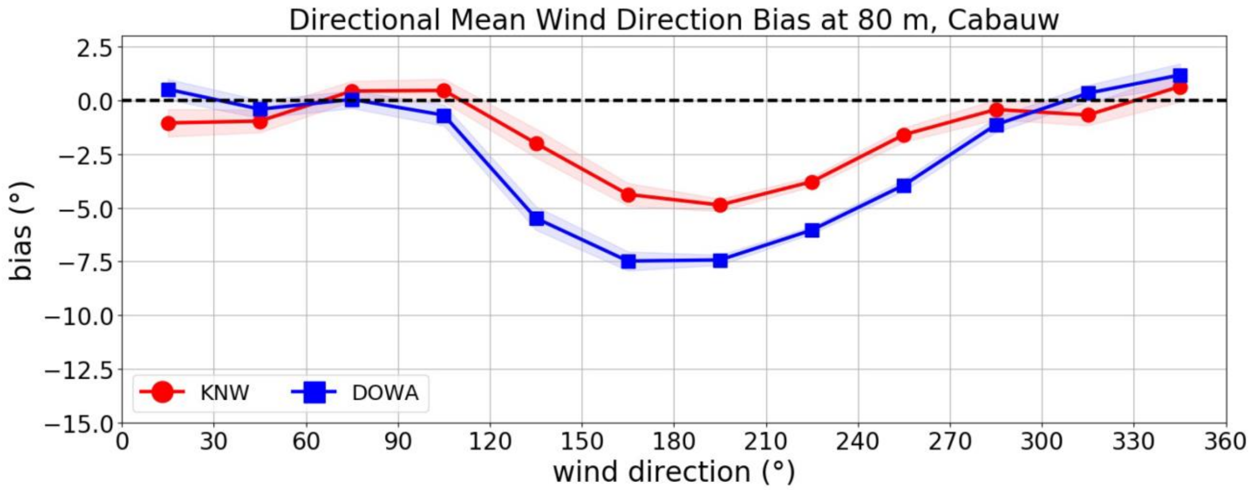

Figure 24: Directional wind direction bias with sector width of 30°, showing DOWA (blue) and KNW-atlas (red). Model variance is indicated by the shaded areas in the bias plots. Source: [Knoop1, 2019}.

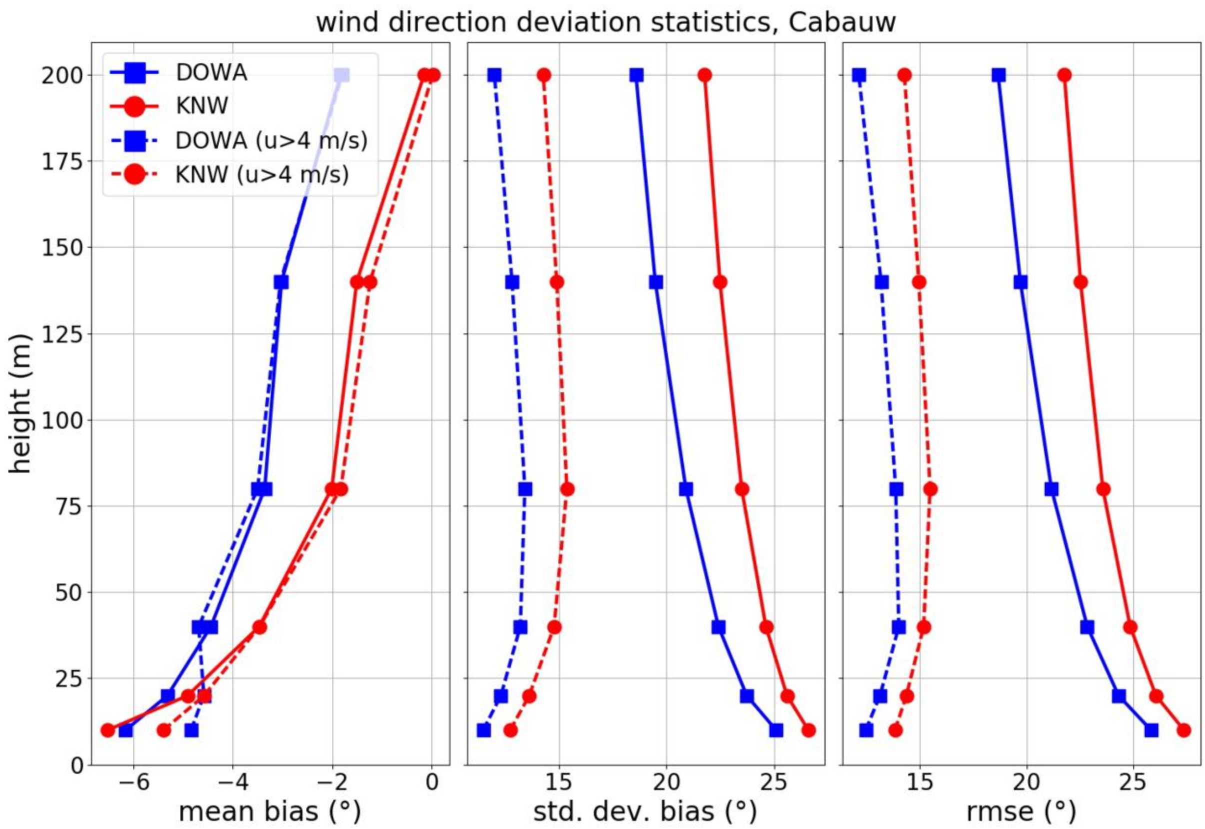

Figure 25: Height profile of the mean bias (left), the standard deviation of the hourly wind speed deviation (middle) and the RMSE (right) of the wind direction measurements, comparing the DOWA (blue) and the KNW-atlas (red). Solid lines are all measurements, dashed lines only measurements larger than 4 m/s. Source: [Knoop1, 2019].

Figure 24 shows that for both the DOWA and the KNW-atlas the bias in wind direction is almost zero for half of the wind directions, but negative (model wind direction veered compared to measured wind direction) for wind directions between 120-270° (SE-WEST). Figure 25 (left) makes clear that for all heights the wind direction bias is smaller for the KNW-atlas than for the DOWA and that for this bias it does not matter whether the low wind speeds (below 4 m/s) are included or not. The standard deviation and RMSE however, are smaller (better) for the DOWA than for the KNW-atlas and become even smaller if low wind speeds are not included.

Figure 26:

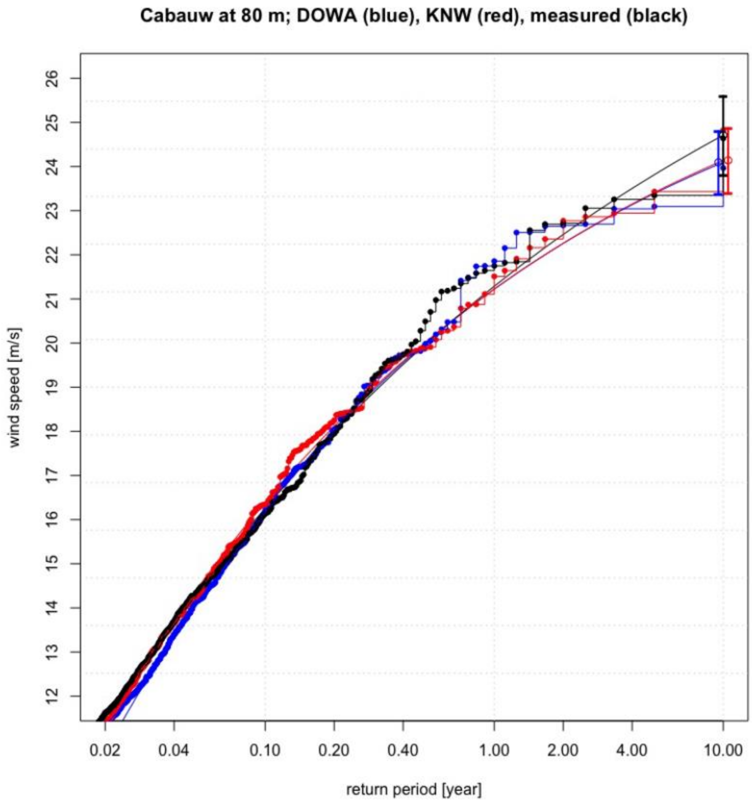

Figure 26: Wind speed as function of the return period for mast measurements (black dots), the DOWA (blue dots) and the KNW-atlas (red dots) for 80 m height. The solid lines (without dots) are the results of a GPD (General Parato Distribution) fit to the data. For the data points with a 10 year return period the uncertainty (90% confidence level) is indicated by the vertical error bars. Source: [Knoop1, 2019].

As can be seen from figure 26 the GPD[29]-fit of DOWA (blue line) and KNW (red line) at 80 m height are identical and differ little from the GPD-fit of the measurements (black line). The vertical error bars (representing ± 1 standard deviation) for wind speeds with a return period of 10 years (once in 10 year wind speeds) show that the GPD-fits of the atlases and measurements lie within each other's fit accuracy This means that the once in 10 year DOWA or KNW extreme wind speeds are as reliable as those based on measurements. The same is true at 200m height (not shown).

[29] General Parato Distribution

2.3 Coastal lidar wind profile validation

Areas with large changes in surface roughness (land-sea or town-countryside e.g.) are often the most difficult to describe by weather models: gridboxes that are e.g. on the coast are a mix of land and sea and the gridbox average roughness that is used in the model is mostly too low for the land part of the grid box and too high for the sea part of the gridbox. That is why it is interesting to look at the quality of the DOWA (compared to the KNW-atlas) on a site on the coast. In [Knoop2, 2019] this is done with wind lidar measurements on the Tweede Maasvlakte (red dot in figure 27) that were available from the 6th of April 2017 until the 15th of May 2018. The wind lidar on a 12 m high dike provides wind measurements on 11 levels up to 203 m height (above sea level). There are some disturbances in the measurement from the dike, but not at the higher levels. The manufacturer claims an instrumental accuracy of the lidar measurements of less than 0.1 m/s for wind speed and less than 0.5˚ for wind direction [Knoop2, 2019].

Figure 27: Location Tweede Maasvlakte (left) and land-sea mask in KNW-atlas (middle) and the DOWA (right) where green is land in HARMONIE and blue is sea. Source: [Knoop2, 2019].

The main results of the Tweede Maasvlakte wind profile validation are:

Figure 28:

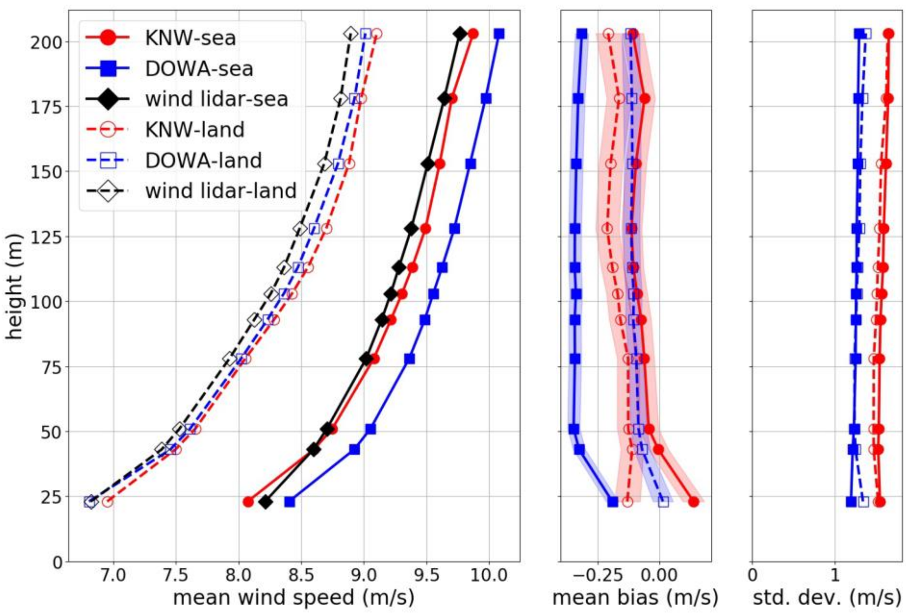

Figure 28: Height profiles of the mean wind speed (left), mean bias (middle) and standard deviation of the hourly wind speed deviation (right), showing wind lidar measurements (black), DOWA (blue) and KNW-atlas (red). Land wind (dashed lines/open symbols) and sea wind (solid lines/closed symbols). Model variance is indicated by the shaded areas in the bias plots. Source: [Knoop2, 2019].

Figure 28 shows that for DOWA the mean bias for land wind (blue dashed line) is smaller than for wind from the sea (wind directions between 215˚ and 30˚). For KNW the opposite is true. The KNW bias is significantly better (smaller) than DOWA-bias for sea wind. For land wind DOWA bias is only slightly better (smaller). So the DOWA does not improve the bias, but the standard deviation of the bias is slightly better (smaller) in the DOWA (for all heights and both land- and sea winds).

Figure 29:

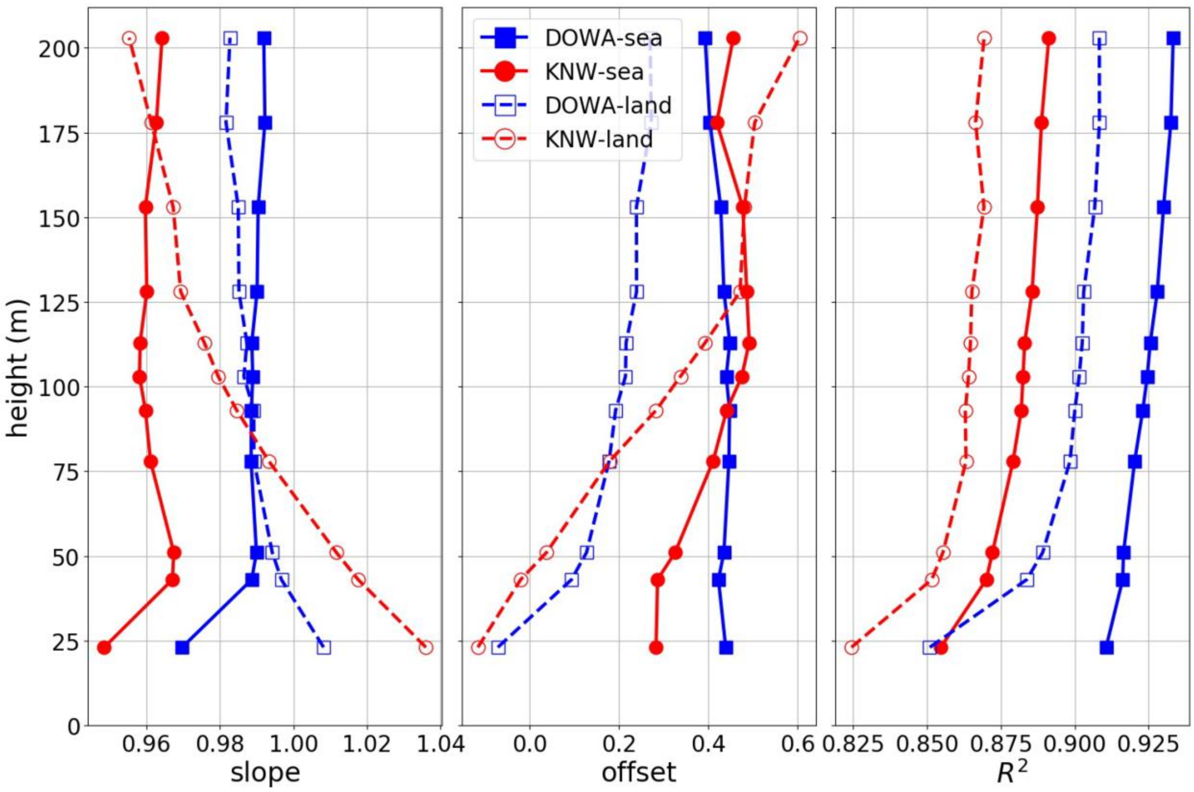

Figure 29: Height profile of the results of the linear regression (slope, offset or intercept and R2) of wind speed data, comparing DOWA (blue) and KNW-atlas (red) for Tweede Maasvlakte. Source: [Knoop2, 2019].

Figure 29 shows the slope, offset and value of R^2 as a function of height for de Tweede Maasvlakte (for explanation of figure 29, see figure 23: the atlas is better when offset (= intercept) is closer to zero and slope and R^2 closer to one). The values of the slope and R^2 are clearly better for the DOWA than the KNW-atlas, both for land- and sea winds. This implies an improved hourly correlation in the DOWA compared to the KNW-atlas. The difference in the KNW and DOWA offset (equal to the bias if the slope would be equal to one) is small, but the offset is significantly larger for sea-winds than for land-winds for levels below 100m.

3. Uncertainty assessment

The uncertainty of the DOWA winds has been assessed and compared to the uncertainty of the KNW-atlas [Valk, 2019]:

- (3.1) **Precision** of the DOWA and KNW wind data. Precision of a data source refers to the random (non-systematic, non-predictable) error. Bias can be corrected for, but a lack of precision introduces an uncertainty that cannot be avoided. Tripe collocation and quadruple collocation analysis have been used to assess the precision.
- (3.2) **Relative bias** of the DOWA and KNW atlas data compared to anemometer and lidar measurements at Meetmast IJmuiden (MMIJ). The bias in wind speed is assessed by means of quantile-quantile (QQ) plots that provide the relationship between the sorted values from one data source and the sorted values from another data source. Also, the bias in wind shear is assessed using QQ-plots.
- (3.3) **Uncertainty in wind resource assessments (WRA) based on 10 years of wind data**. To assess this uncertainty, a bootstrap method is used, both with and without accounting for multi-year dependence.

An analyses of the frequency and coherence spectra of the collocated wind speeds (3.4) was also part of the uncertainty assessment.

3.1 Precision (triple and quadruple collocation)

Precision is a measure of the non-systematic (non-predictable, random) error. The size of this error is usually given by a standard deviation (or its square, the variance). The smaller the estimated standard deviation of the random error, the more precise the data source. A bias can be corrected for, but a lack of precision introduces an uncertainty that cannot be avoided. A simple picture of the distinction between precision and bias (in the mean value, in this case) is given in figure 5.

In [Valk, 2019] triple and quadruple collocation analyses have been performed to assess the precision of the DOWA and KNW-atlas. The main results of the quadruple collocation are (results triple collocation not shown):

Figure 30:

Wind speed range	mast	lidar	DOWA	KNW
All	0.21	0.36	1.23	1.48
0.0-7.5	0.04	0.46	1.26	1.51
7.5-11.8	0.10	0.32	1.27	1.53
11.8-	0.24	0.34	1.13	1.39

Wind speed range	mast	lidar	DOWA	KNW
All	0.19	0.89	1.95	2.16
0.0-7.5	0.23	0.73	1.91	2.16
7.5-11.8	0.07	0.66	2.03	2.23
11.8-	0.20	1.19	1.89	2.06

Figure 30: Estimated precision (non-bias RMSE) in wind speed (table above) and wind vector (table below) for mast, lidar, DOWA and KNW data at 90 m height at Meetmast Ijmuiden from a quadruple collocation analysis. Rows: for all data, and for data in three classes of wind speed (mean from all four sources).

Figure 30 shows that at 90 m height:

- DOWA wind speeds are more precise than KNW wind speeds
- The random errors in the measurements are almost negligible in comparison to the random errors in the DOWA and KNW data. This implies that the KNW-validation [Stepek, 2015] and the DOWA-validation [Duncan2, 2019] against mast and lidar measurements at MMIJ provides a reliable picture of the error statistics of the KNW and DOWA data.
- Mast measurements are more precise than lidar measurements.

With a climatological average of the wind speed at 90 m height at MMIJ of about 10 m/s (Duncan2, 2019] the values in Figure 30 can be normalized to a coefficient of variation (CV). This results in a CV of 2% for mast wind speed and wind vector, 4% for lidar wind speed and 9% for lidar wind vector.

3.2 Relative bias (QQ-plot)

The relative bias (bias compared to measurements from another data source) of the DOWA and the KNW-atlas were assessed by means of quantile-quantile (QQ) plots, which give the relationship between the sorted values from one data source and the sorted values from another data source. The main advantage of using a QQ-plot to assess the relative bias is that it is easy to assess in which wind speed regime the atlas performs well. The results are:

Figure 31:

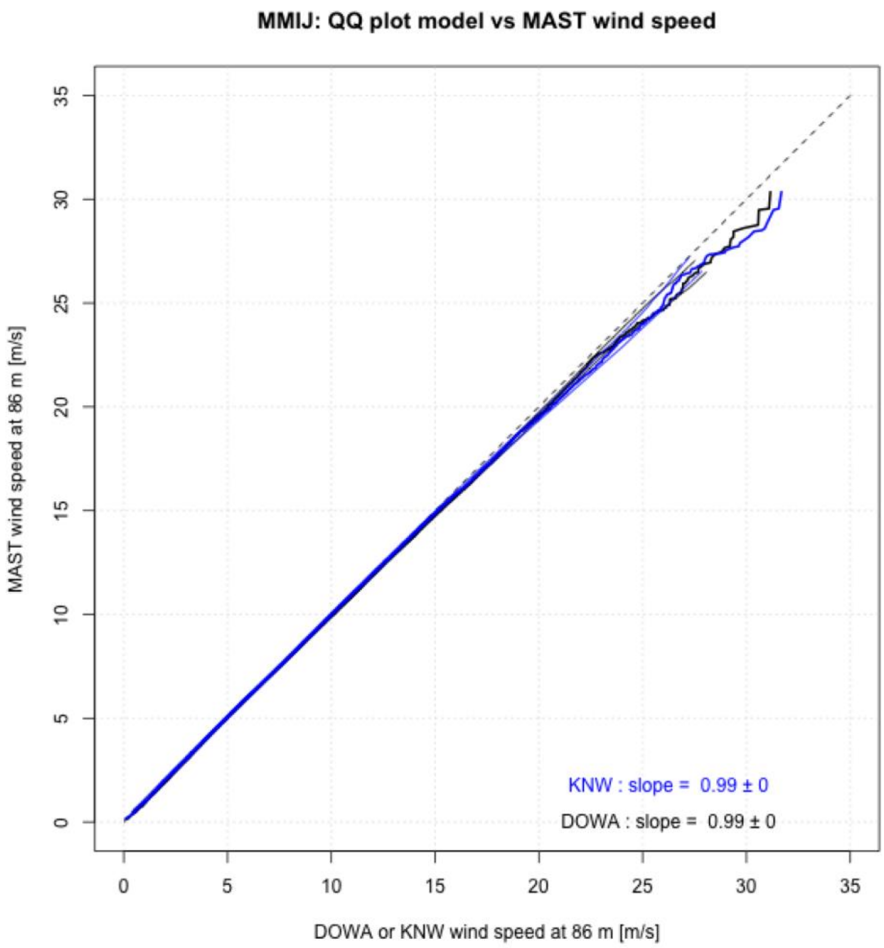

Figure 31: Quantile-quantile plots of MMIJ wind speed data at 86 m height from two sources: mast vs. DOWA (black), and mast versus KNW (blue). Thin lines (barely visible) indicate the 90% compatibility interval. Source: [Valk, 2019].

Figure 31 shows that the relative bias of the DOWA and the KNW is very small for wind speeds up to 25 m/s. For higher wind speeds both the DOWA and the KNW-atlas slightly overestimate wind speeds compared to the anemometer wind measurements on the mast. The QQ plots are very precise, as can be seen in the narrow 90% compatibility intervals shown by the thin lines in the plots: these are barely visible as they often coincide with the QQ plot. The intervals were estimated by generating 1000 synthetic data sets having similar characteristics as the original data set (using the “moving block bootstrap” method; Figure 32), and computing the QQ plot for each of them. Because QQ-plots have little bias and are precise compared to other methods, they are very suitable as an alternative to regression-based measure-correlate-predict (MCP) methods for WRA, which are prone to large uncertainty if the data are imprecise and/or correlation is low [Valk, 2019].

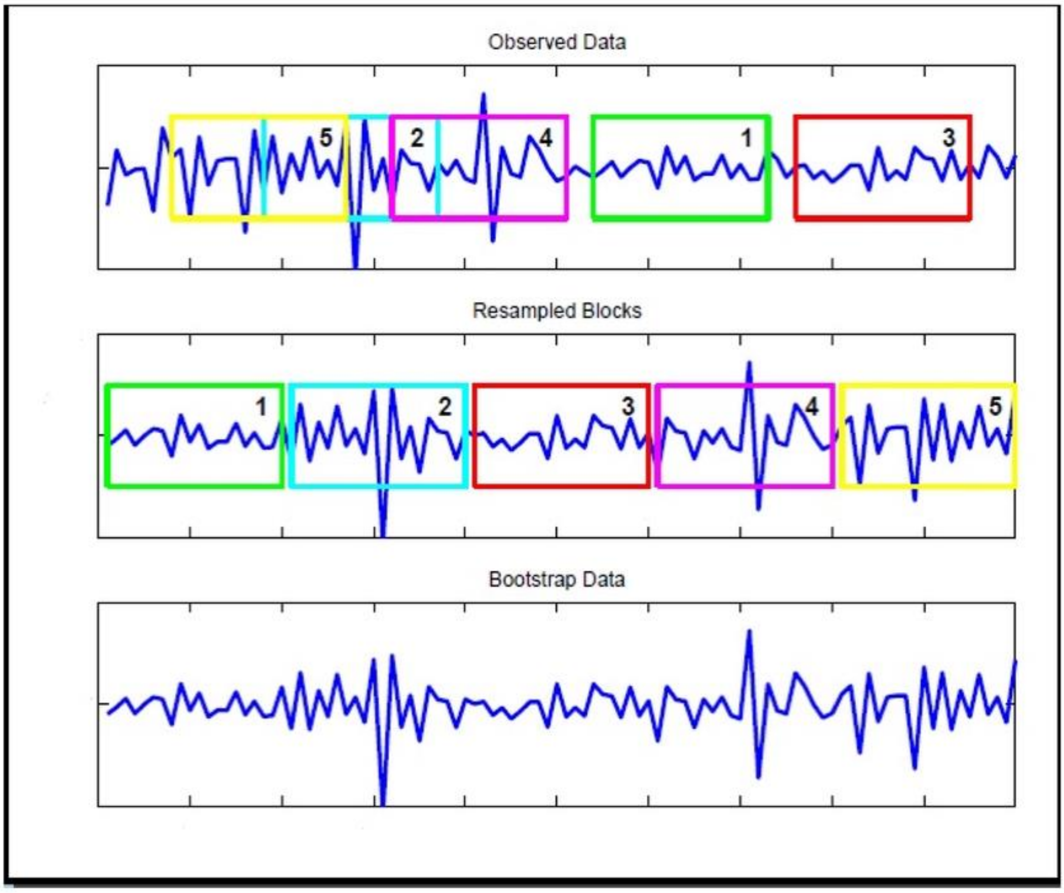

Figure 32: illustration of the block bootstrap method applied in this study. Time-intervals of 62.5 days are drawn randomly with replacement, and new time-series are created by stringing the data within these blocks together. This way a 1000 synthetic datasets were created from which a 1000 QQ-plots were calculated. Source: [Valk, 2019].

3.3 Uncertainty in WRA based on 10 years of wind data (bootstrap method)

The block bootstrap method (figure 32) is also used to assess which uncertainty is introduced by only using 10 years of wind data for wind resource assessments (WRA): what is the uncertainty in an estimate of wind climatology from 10 years of data and how representative is the wind climate over the last 10 years for the wind climate over the next 10 years?

Two different bootstrap schemes were applied to create 500 synthetic wind data sets covering 10 years:

- Scheme A: draw 10 random blocks of 1 year with replacement from 10 years of the DOWA
- Scheme B: draw a random block of 10 years from 40 years of KNW data, and within this block, apply method A. This method accounts for multi-year dependence of the wind climate as is described e.g. in [DNV GL, 2016] and [Ronda, 2017].

In order to assess the effect of including multi-year dependence (scheme B) or not (scheme A) the value of W90/W50 was compared from both schemes where W90 is the 10-year wind exceeded with a probability of 90% and W50 the 10-year mean wind exceeded with probability of 50%. With both schemes a value of W90/W50 of 0.99 is obtained, indicating that wind variability on multi-year time scales does not contribute a great deal to the uncertainty in reference yield over a 10 year period. However, for scheme B, the outcome is highly uncertain as the block size of 10 years is rather large in comparison to the 40 year length of the data record [Valk, 2019].

3.4 Spectral analyses of collocated wind speeds

Spectral analyses were performed with collocated[30] wind speeds measured with anemometer (on wind mast) and lidar and from the DOWA and KNW-atlas (MMIJ at 90 m height). The results are:

Figure 33/34/35

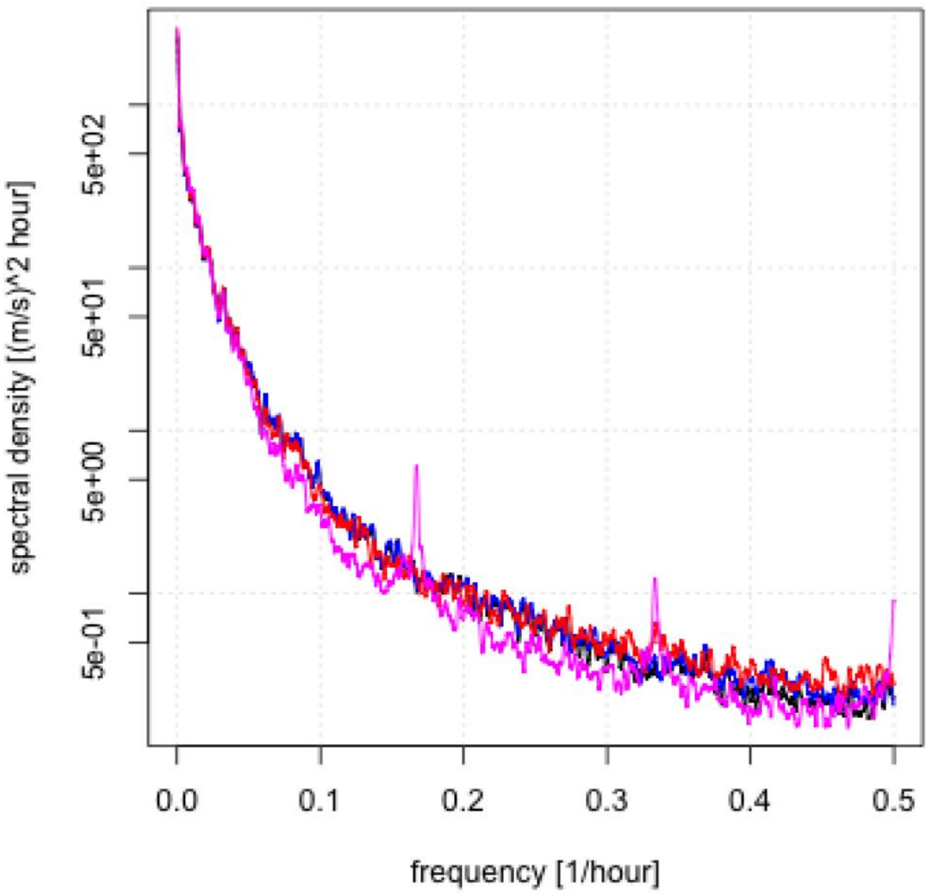

Figure 33: F*requency spectra of collocated wind speed data from mast (black), lidar (blue), DOWA (red) and KNW (magenta) at 90 m height at MMIJ. Source: [Valk, 2019].*

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[30] Collocated means that only data are used that were simultaneously available from all data sources: in this case anemometer measurements on the mast, lidar measurements and DOWA and KNW-atlas wind speeds.

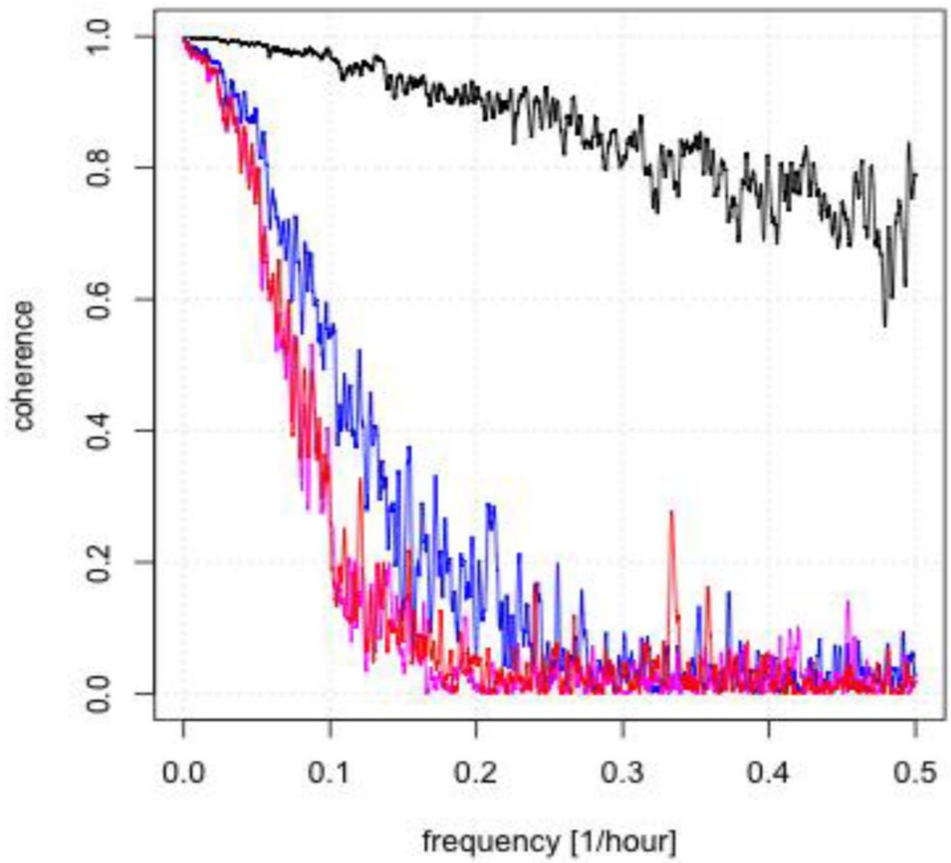

Figure 34: Coherence spectra of collocated wind speed data: mast/lidar (black), mast/DOWA (blue), lidar/DOWA (red) and DOWA/KNW (magenta). Source: [Valk, 2019].

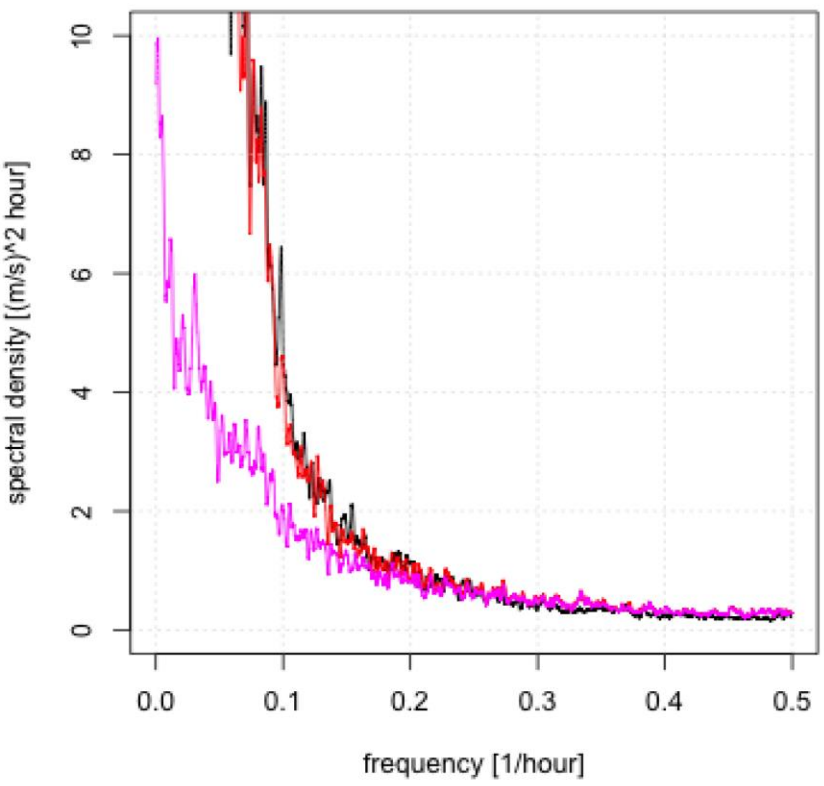

Figure 35: Spectra of mast (black) and DOWA (red) wind speed, and estimated noise spectrum of DOWA (magenta). Source: [Valk, 2019]

For the uncertainty assessment of the DOWA (and the KNW-atlas) the frequency spectra of the collocated wind speed data (mast, lidar, DOWA and KNW-atlas) were compared. The frequency spectra (Figure 33) show that DOWA can reproduce the sizes of wind fluctuations at all periods from 3 years (frequency almost 0.0) to 2 hours (frequency 0.5/hour). The KNW spectrum is only slightly lower than the DOWA spectrum[31]. This means that the wind fluctuations in DOWA and KNW on these time-scales are **realistic**. However, they are not necessarily **real** (that is, matching the measured fluctuations).

How real the wind fluctuations of DOWA and KNW are, can be assessed with coherence spectra (Figure 34). The coherence function[32] between mast and lidar measurements is high over the entire frequency range (black lines). The lowest coherence between mast and lidar measurements is 0.6 for frequency 0.45 (period of 2.2 hours). The coherence between DOWA and the mast measurements (blue) is much lower. If we assume that a coherence of 0.6 or higher is good (which is approximately the minimal value of the mast/lidar coherence), then we conclude that the coherence between DOWA and mast measurements is good for frequencies below 0.1/hour. So based on this, the DOWA values are real for averaging times above 10 hours. The coherence between the DOWA and the lidar measurements is good for frequencies below 0.07/hour (periods above 14 hours).

To conclude: the DOWA and KNW reanalyses generate realistic wind speed fluctuations on all time scales, but these agree with the observed wind speed fluctuations only when averaged over ten hours or more. So the average diurnal cycle may be represented fine, but fluctuations on time scales smaller than ten hours differ from reality.

The noise spectrum of the DOWA (the spectrum of wind speed fluctuations in DOWA unrelated to the observed wind, so **not real**) is obtained by combining the spectra and coherence functions in figure 33 and 34. Based on the triple and quadruple collocation analyses described in section 3.1, the noise in the mast measurements is low. The noise spectrum of DOWA may therefore be estimated as S(1-C), with S the DOWA wind speed spectrum and C the coherence between DOWA and mast measurements. Figure 35 shows that the wind speed spectrum of DOWA (red) almost coincides with its noise spectrum (cyan) for periods below roughly 7 hours (frequencies above 0.15/hour): the DOWA wind speeds at these time scales are almost entirely noise and although they are realistic, they are not real.

4. DOWA compared to measurements in other studies

At the time of writing this report [Kalverla, 2019] has just published his PhD-thesis where he compared the wind profile at MMIJ to ERA5, the DOWA and the New Wind Atlas NEWA. His conclusion is that the DOWA significantly outperforms NEWA and represents anomalous events such as low level jets quite well. The DOWA is also used in the POV-Waddenzeedijken studie[33] where DOWA winds were found to validate well against the high wind speeds measured during the Sinterklaasstorm in 2013 at location Uithuizerwad (Groningen).

[31] The narrow peaks at about 2, 3 and 6 hours (frequencies of 0.5, 0.33 and 0.17/hour) in the KNW spectrum are most likely related to the 6-hourly restarts.

[32] Also known as “coherency squared”; it can be regarded as the square of a correlation coefficient between the components of the two signals lying within a narrow frequency band. Phase shifts do not reduce the coherence.

[33] No publication available at the time of writing this report.

5. Examples of DOWA-climatology

In the image library of the DOWA website[34] examples are given of information that can be derived from the DOWA wind climatology. Figure 36 shows locations with specific information in the image library of the DOWA-website. There are also maps in the image library for the red DOWA-domain described in Figure 1 (the locations in Figure 36 are referred to as + symbols in these maps).

Figure 36:

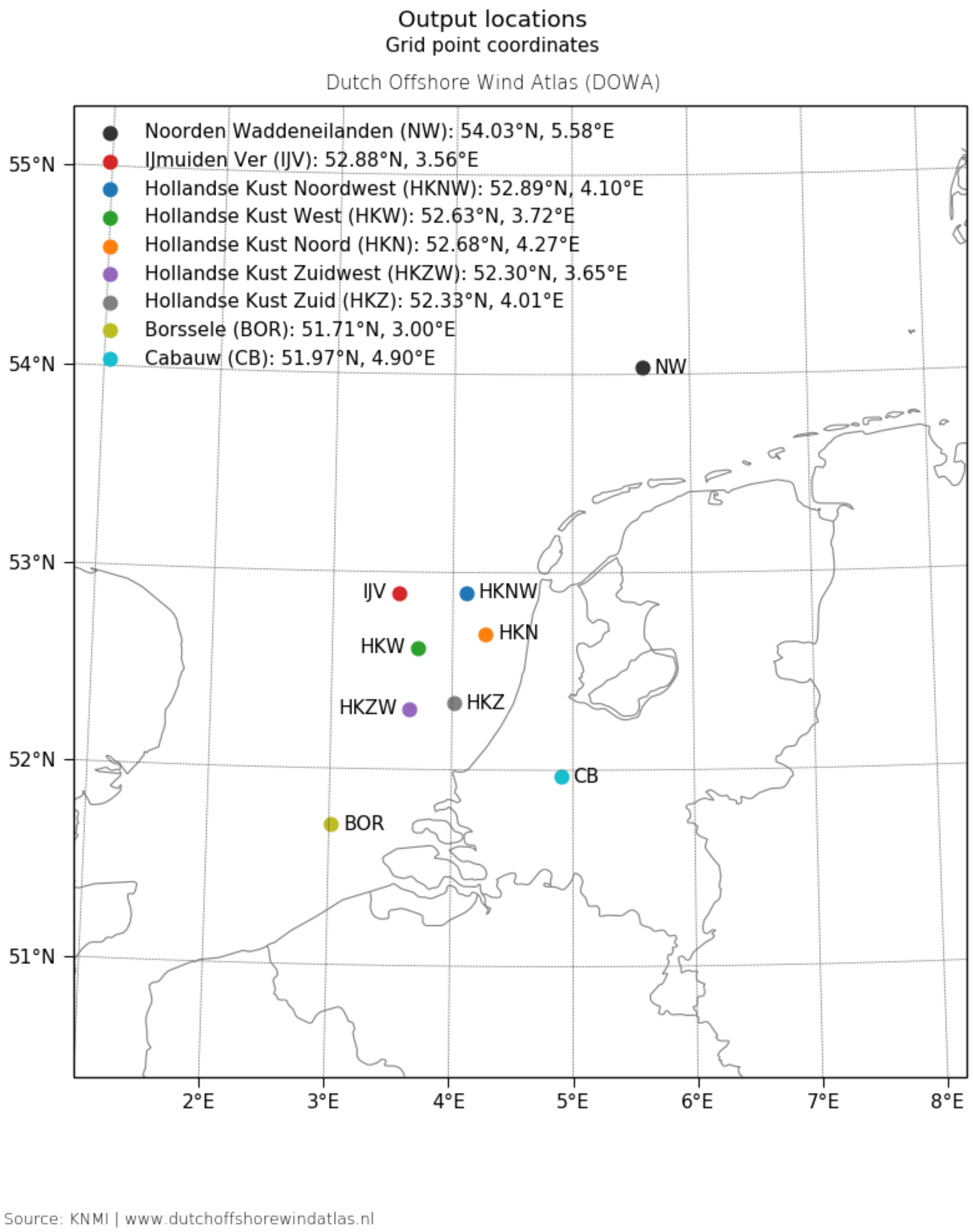

Figure 36: Locations with specific information in the image library of the DOWA-website. There are also maps in the image library for the red DOWA-domain described in Figure 1. There these locations are referred to as + symbols Source: [www.dutchoffshorewindatlas.nl].

[34] https://www.dutchoffshorewindatlas.nl/atlas/image-library

Figure 37:

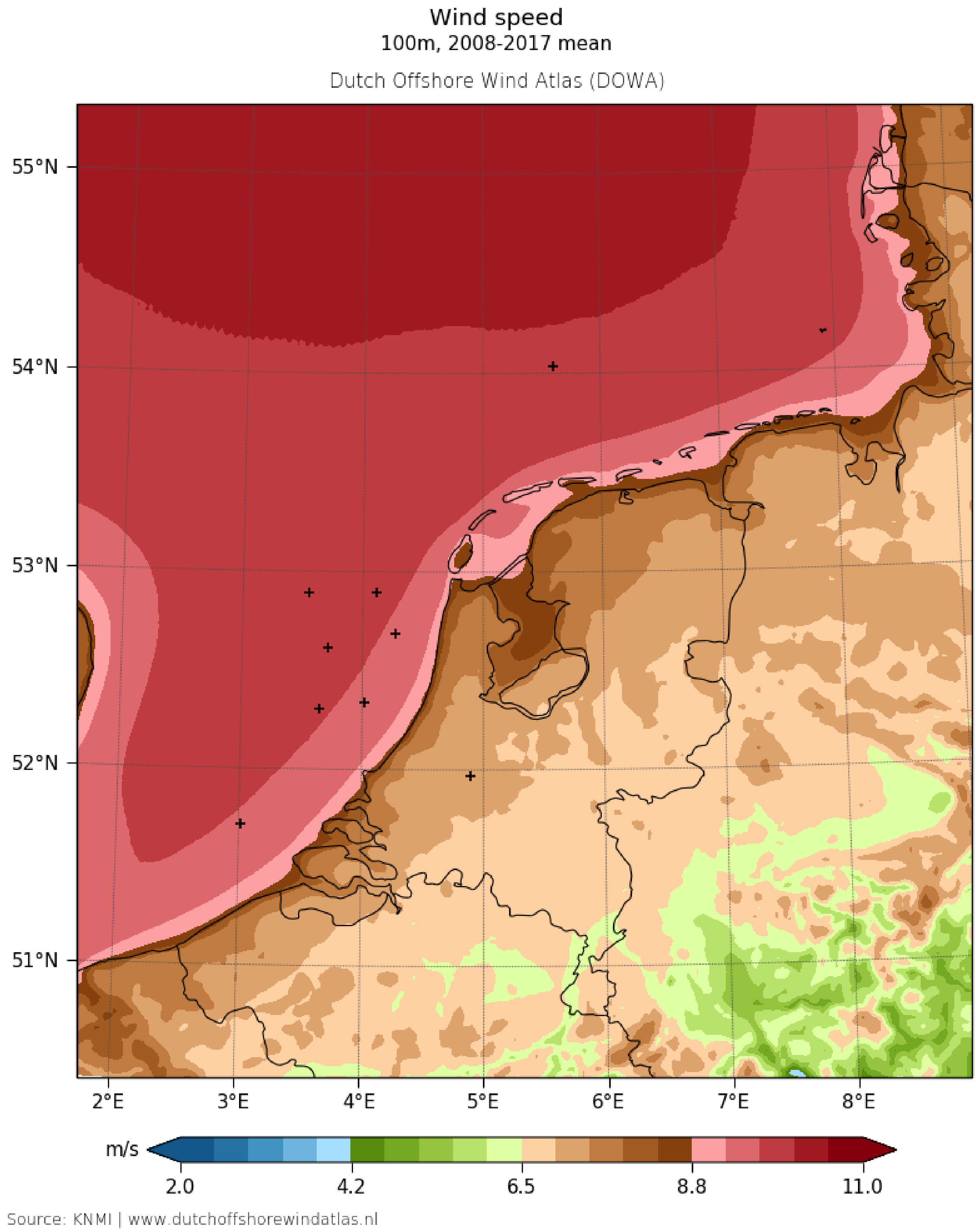

Figure 37: 10 year (2008-2017) average wind speed at 100 m height. The + symbols refer to the locations in Figure 36. Source: [www.dutchoffshorewindatlas.nl]

Figure 37 shows the 10 year (2008-2017) average wind speed for the DOWA-domain at 100 m height. These kind of images are also available for other heights: 17 levels between 10 and 600m.

Figure 38 shows Weibull scale (left) and Weibull shape parameter (right) for offshore location Borssele as a function of height. The Weibull scale parameter is a “measure” for the average wind speed. As to be expected, the average wind speed is higher at higher levels and higher in winter and autumn than in summer and spring. The Weibull shape parameter k is a “measure” for the shape of the wind speed distribution: the higher k, the smaller the spread in wind speeds. At sea the spread of possible wind speeds near the surface is smaller (so k higher) than further aloft: surface friction limits higher wind speeds at the surface, while lower wind speeds are possible for all heights. The climatological profile of the shape parameter is different for land (see figure 39): there the diurnal cycle causes a wider range of possible wind speeds near the surface (and figure 40 shows that k at lower levels at Cabauw is smaller than at lower levels at OWEZ offshore). This effect becomes smaller further aloft (k increases). Above about 100 m the effect of the diurnal cycle is no longer present and k starts to decreases with height again, just like offshore.

Figure 38/39/40:

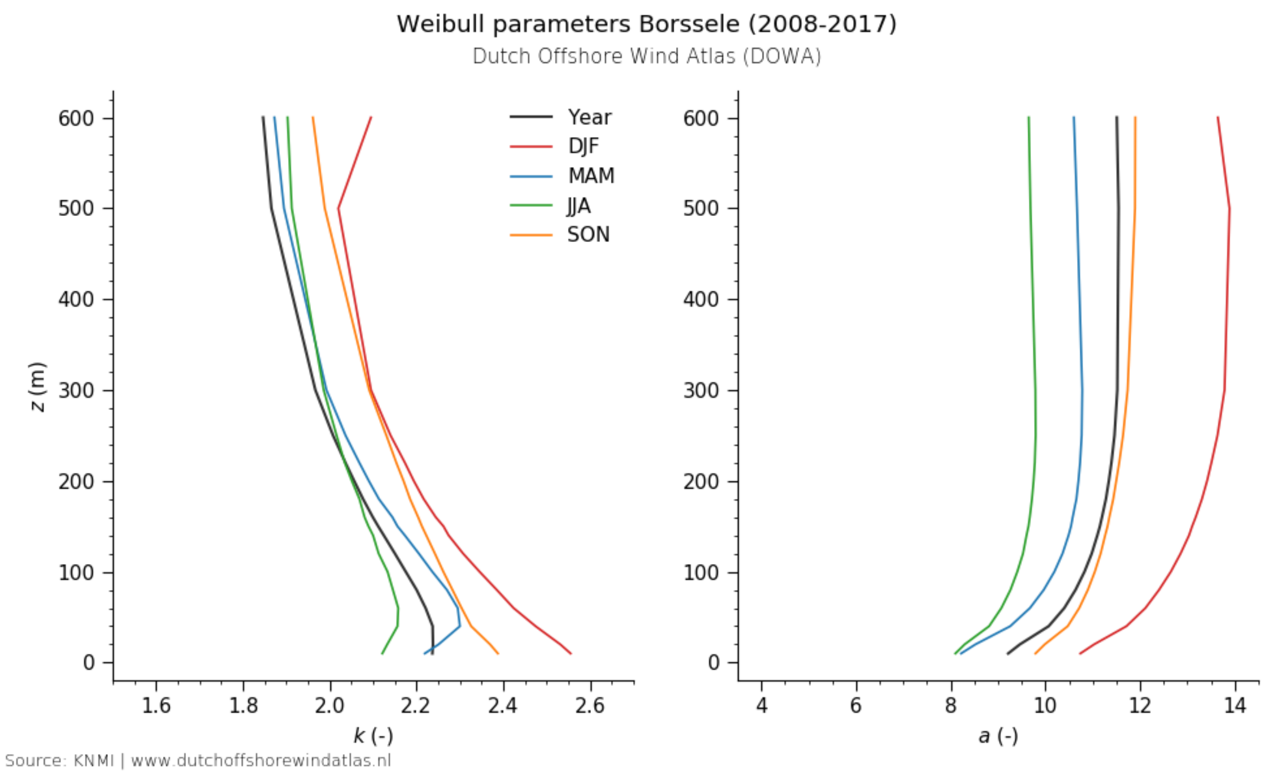

Figure 38: Weibull shape parameter k (left) and scale parameter a (right) as a function of height for Borssele. In black 10 year average for the whole year, in red 10 year average for the winter months December, January and February, in blue 10 year average for the spring months March, April and May, in green 10 year average for the summer months June, July and August and in yellow 10 year average for the autumn months September, October and November. Source: [www.dutchoffshorewindatlas.nl]

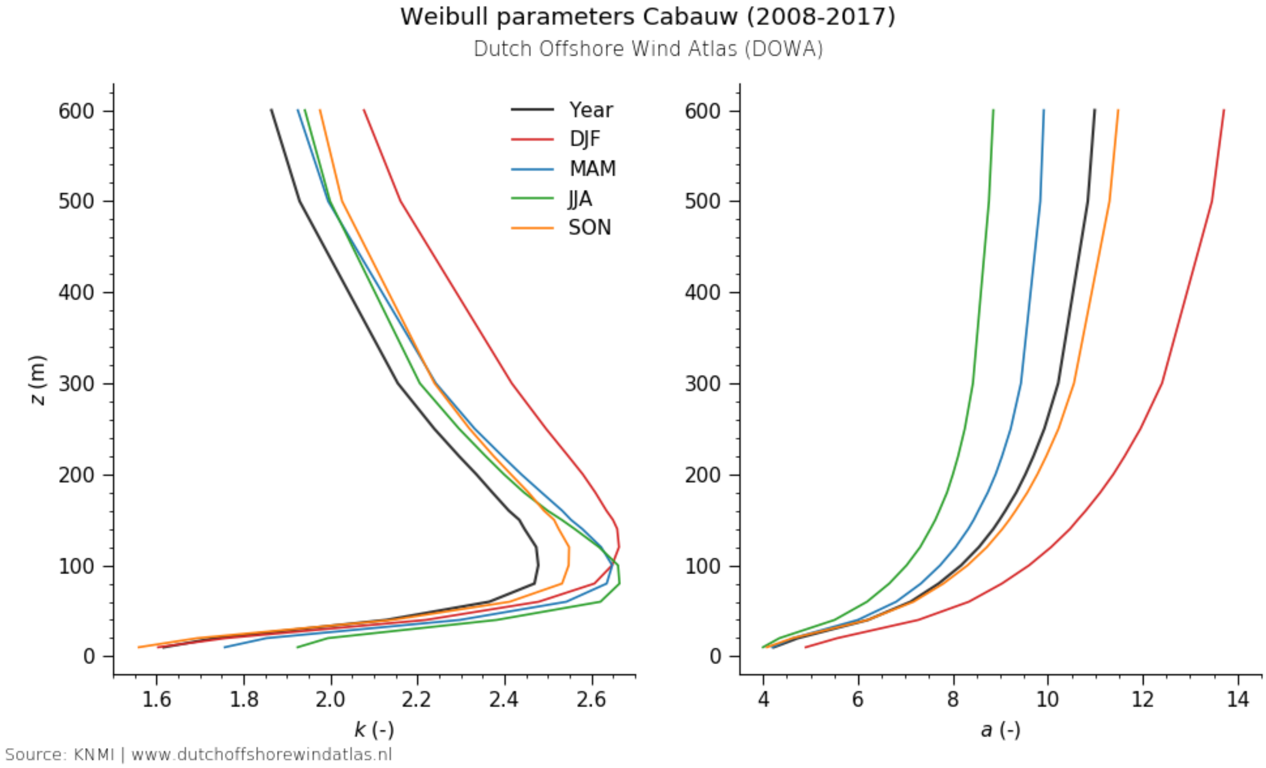

Figure 39: as figure 38, but then for Cabauw. Source: [www.dutchoffshorewindatlas.nl]

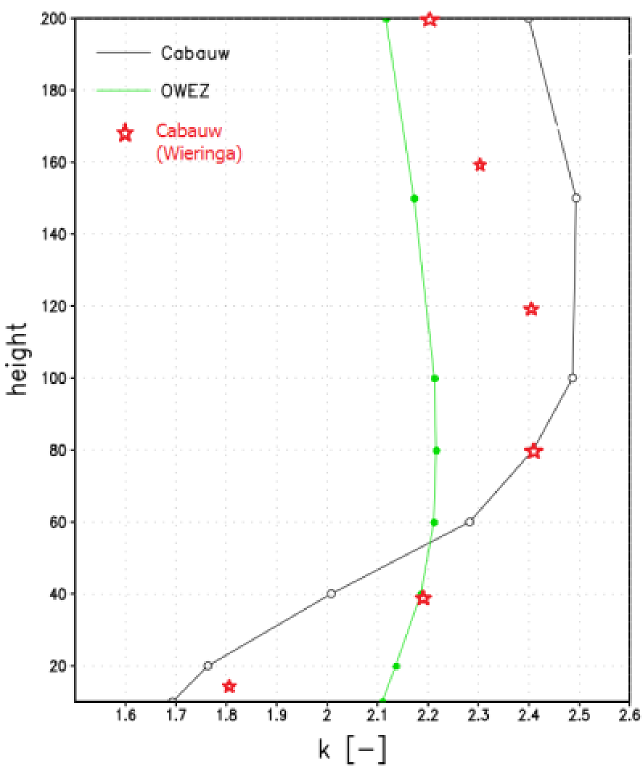

Figure 40: Weibull shape factor k based on 1979-2013 KNW wind speeds as a function of height for Cabauw (black) and Offshore Wind Farm Egmond aan Zee OWEZ (green). The stars (red) in the plot are k-values measured at Cabauw from [Wieringa, 1983, p 136]. At 10m height the value for k at Cabauw is smaller than offshore, at 100m height it is the opposite. Source: [Stepek, 2015]

Figure 41 shows the 100 m wind speed for Borssele averaged over 2008-2017, per year (left), month (middle) and hour in the day (right). From the yearly averages it becomes clear that 2010 was a particularly bad year for wind energy. The figure also shows that for Borssele at 100 m height the KNW-atlas gives slightly lower average wind speeds than the DOWA for the whole period 2008-2017, mainly because of differences in the summer months (Figure 41 middle). For Borssele at 100m height, the KNW 39 year (1979-2017) mean (9.50 m/s) is slightly lower than the DOWA 10 year (2008-2017) mean (9.59 m/s): for other sites the differences at 100 m are equal or smaller (Figure 42). Figure 41 (right) shows the average diurnal cycle: where in the KNW-atlas the 6 hourly cold starts are clearly visible, the average diurnal cycle in the DOWA looks much more realistic.

Figure 41/42:

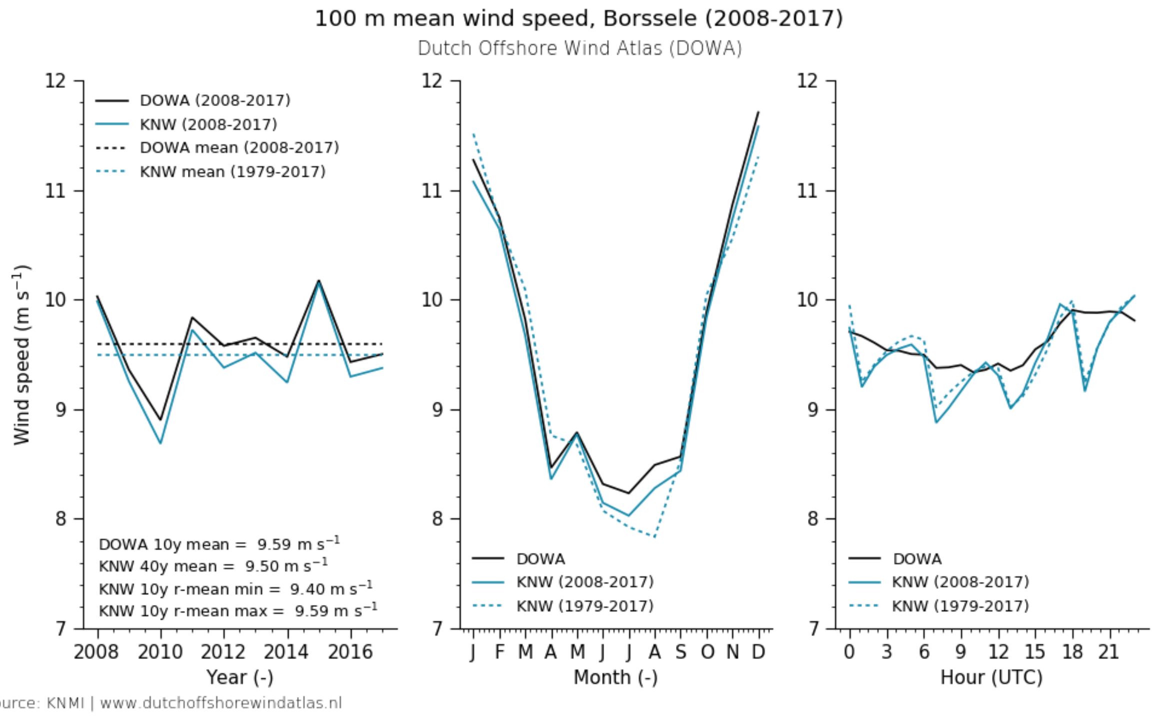

Figure 41: mean wind speed at Borssele wind farm zone at 100 m height, averaged per year (left), month (middle) and hour of the day (right) based on the DOWA (2008-2017) and the KNW for (1997-2017) and for (2008-2017). Source: [www.dutchoffshorewindatlas.nl].

Location (100 m height)	39 year (1979-2017) mean KNW minus 10 year (2008-2017) mean DOWA
Borssele	-0.09 m/s
Hollandse Kust Noord	-0.03 m/s
Ten Noorden van de Wadden	+0.03 m/s
Ijmuiden Ver	-0.02 m/s
Hollandse Kust Zuidwest	-0.08 m/s
Hollandse Kust Zuid	-0.09 m/s
Hollandse Kust West	-0.04 m/s
Hollandse Kust Noordwest	-0.01 m/s
Cabauw	+0.09 m/s

Figure 42: difference between the 39 year (1979-2017) mean wind speed at 100 m height based on the KNW-atlas and the 10 year (2008-2017) mean wind speed at 100 m height based on the DOWA.

The last example given here from the image library is the wind rose (more on the website). The wind rose shows per 30 degree wind direction bin the frequency of occurrence of those wind directions and the average wind speed per bin. Occasions where the wind speed was 1 m/s or less are not considered because at such speeds wind vanes often do not operate correctly. This is done for all central points of the offshore wind farm zones. Figure 43 shows that the prevailing wind direction at 100 m height at Borssele central point is southwest (20% of the time). 100 m wind speeds from that direction range up to 25 m/s.

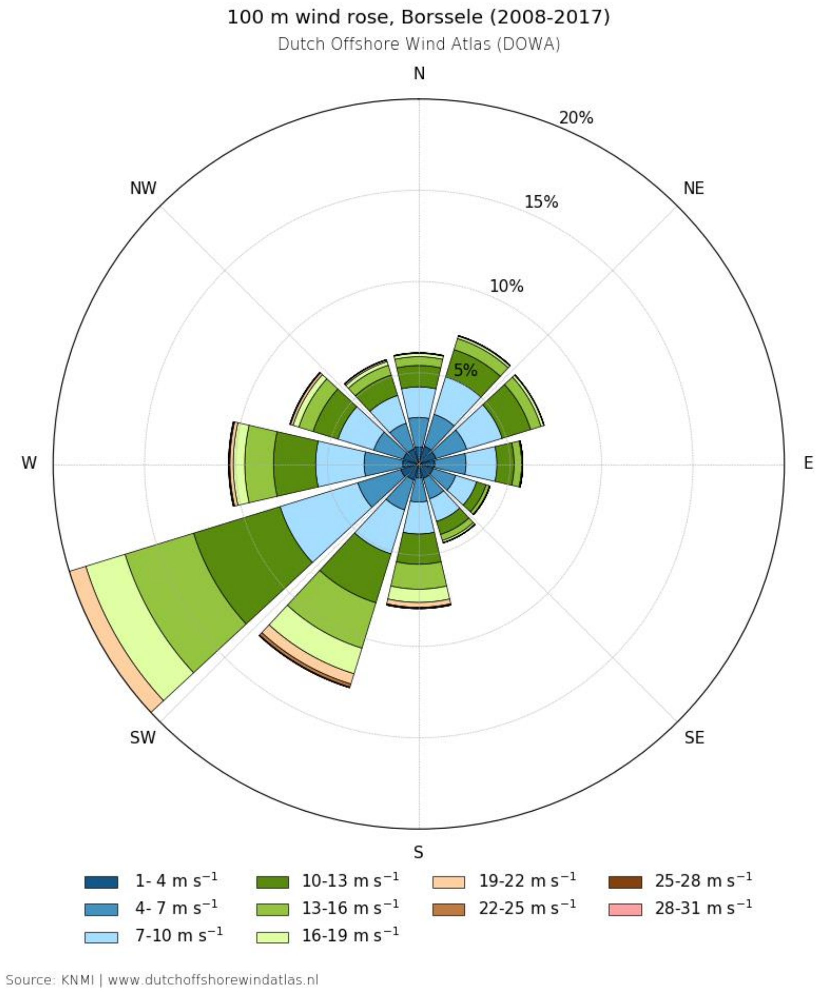

Figure 43: wind rose at central point Borssele at 100 m height. Source: [www.dutchoffshorewindatlas.nl].

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Appendix A: KNW-atlas

ERA-Interim

The ERA-Interim reanalysis dataset from ECMWF (European Centre for Medium Range Weather Forecasts, www.ecmwf.int) combines one of the leading numerical weather prediction models (ECMWF model) with an advanced data-assimilation system [Dee, 2011]/[Baas, 2014]. The resulting analysis has long been considered a best-estimate, in statistical sense, of the state of the atmosphere since it is based on the very short-term model forecast adjusted to match the observations of that moment in time. ERA-Interim is available from January 1979 until August 2019, gives full 3D analyses of the global atmosphere at a T255 spectral truncation (which corresponds to a grid size of about 80 km) and provides a 6-hourly temporal output. ERA-Interim was used to make the KNMI North Sea Wind (KNW) atlas.

KNW-atlas

In 2013 KNMI released the KNMI North Sea wind atlas[35]. It was the first atlas based on a period long enough to capture the variability of the Dutch wind climate and includes information on levels above 100m, which are relevant for e.g. wind energy.

The KNW-atlas is based on the ERA-Interim reanalysis dataset. The KNW-atlas produced in 2013 captured 35 years (1979-2013) of measurements. During the DOWA-project the KNW-atlas has been extended to more recent years using the same model-setup to guarantee a homogeneous dataset. At the end of the DOWA-project the KNW-atlas will capture more than 40 years: jan 1979-aug 2019. The ERA-Interim dataset is downscaled using the CY37h1.1 version of HARMONIE with a horizontal grid of 2.5 km and a temporal resolution of 1 hour. The wind speeds are tuned to match the measurements made at KNMIs 200 m tall meteorological mast at Cabauw and the same wind shear correction factor is applied uniformly throughout the whole KNW-atlas area. More information on the HARMONIE model set-up that was used to make the KNW-atlas can be found in [Geertsema, 2014].

The wind speed information in the KNW-atlas has a climatological (long-term averages and extremes) accuracy of less than 0.5 m/s at 10 m height and one of less than 0.2 m/s at higher levels (e.g. hub height), the latter being comparable to the accuracy of wind measurements.

All information on the KNW-atlas can be found on http://projects.knmi.nl/knw/index.html.

[35] The KNW-atlas is financed by the Directorate-General for Spatial Development and Water Affairs (DGRW) of the Dutch Ministry of Infrastructure and the Environment (IenM), now called the Ministry of Infrastructure and Water Management (IenW): https://www.government.nl/ministries/ministry-of-infrastructure-and-water-management

Appendix B: gluing of parallel streams

As mentioned in 2.1 of this report there are no cold starts in the DOWA-runs, except at the very beginning of each parallel stream. In this appendix we describe how we tested the effect of a cold start by comparing (1) DOWA-data for January 2015 calculated in stream D (2015-2017), so with a cold start on the 1st of January 2015 to (2) DOWA-data for January 2015 calculated in stream B (2013-2014), so with January 2015 as an extra month and without a cold start. Based on this we decided to glue the streams together one month after the cold start of stream D (1st of February 2015).

We expect the largest difference between stream B and stream D to be in the soil parameters: it takes HARMONIE longer to change the ERA5-soil parameters (especially the deeper layers) than the atmospheric parameters. Figure B1 shows the difference between the soil moisture for January 2015 at a grid point near Cabauw based on the D stream and the B-stream (D-B) for three soil layers. L01 is the top layer and L03 the lowest layer. For the two lower layers (L02 and L03) there is hardly any difference between B and D, for the top layer (L01) the difference is almost gone after one week. The difference around the 20th of January is because this was a very convective period: HARMONIE can resolve convection, but not exactly where it occurs, so different runs will predict convection at different locations.

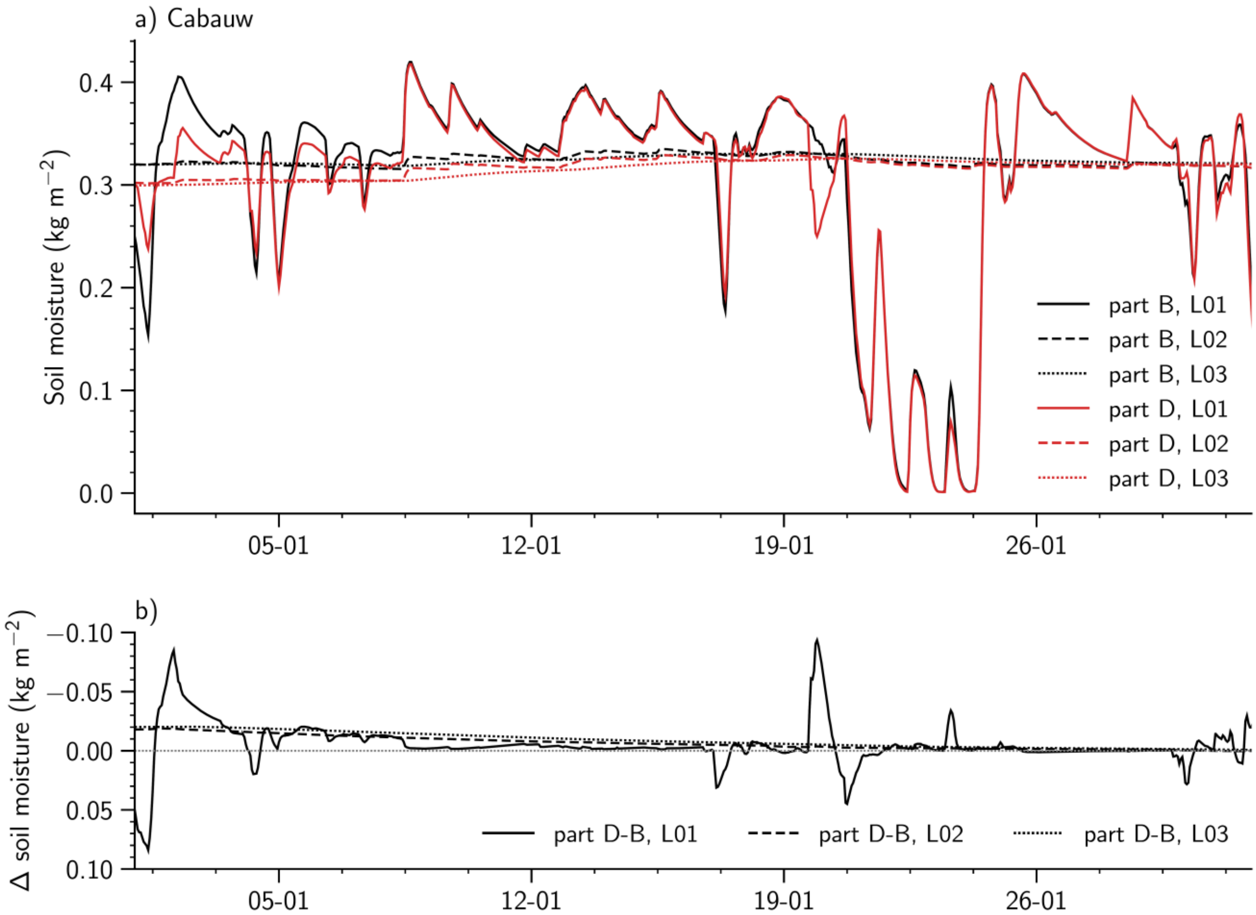

Figure B1: a) Evolution of soil moisture near Cabauw in Januari 2015, in both the B and D streams, for the top (L01), middle (L02) and deepest (L03) soil layers. b) Difference in soil moisture between the B and D streams for all soil layers [courtesy Bart van Stratum].

Figure B2 and B3 (wind speed and wind direction for grid points near Cabauw, Meetmast Ijmuiden and FINO1) show that the time series from stream B and D are very similar. The largest differences are in the "convective period" around the 20th of January.

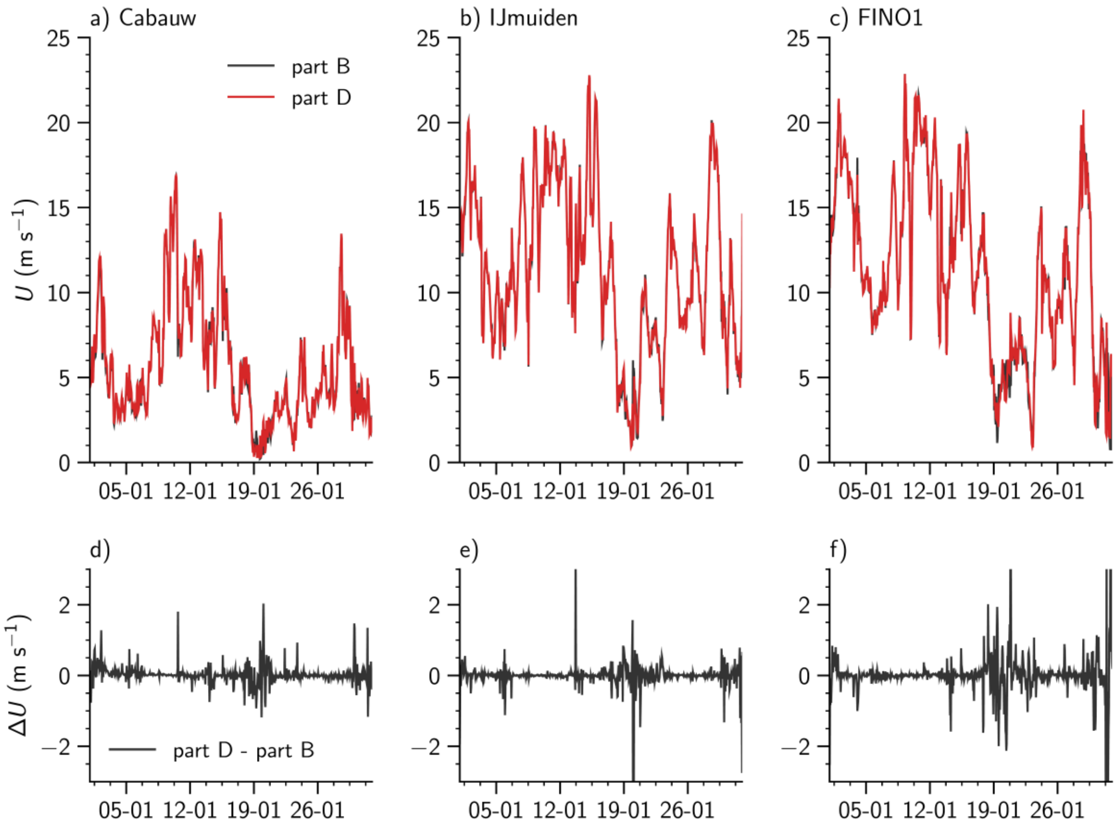

Figure B2: top row: January 2015 wind speed at 10 m height, for grid points near Cabauw, Ijmuiden and FINO1, in both the B and D streams. Bottom row: difference in wind speed between the B and D streams.

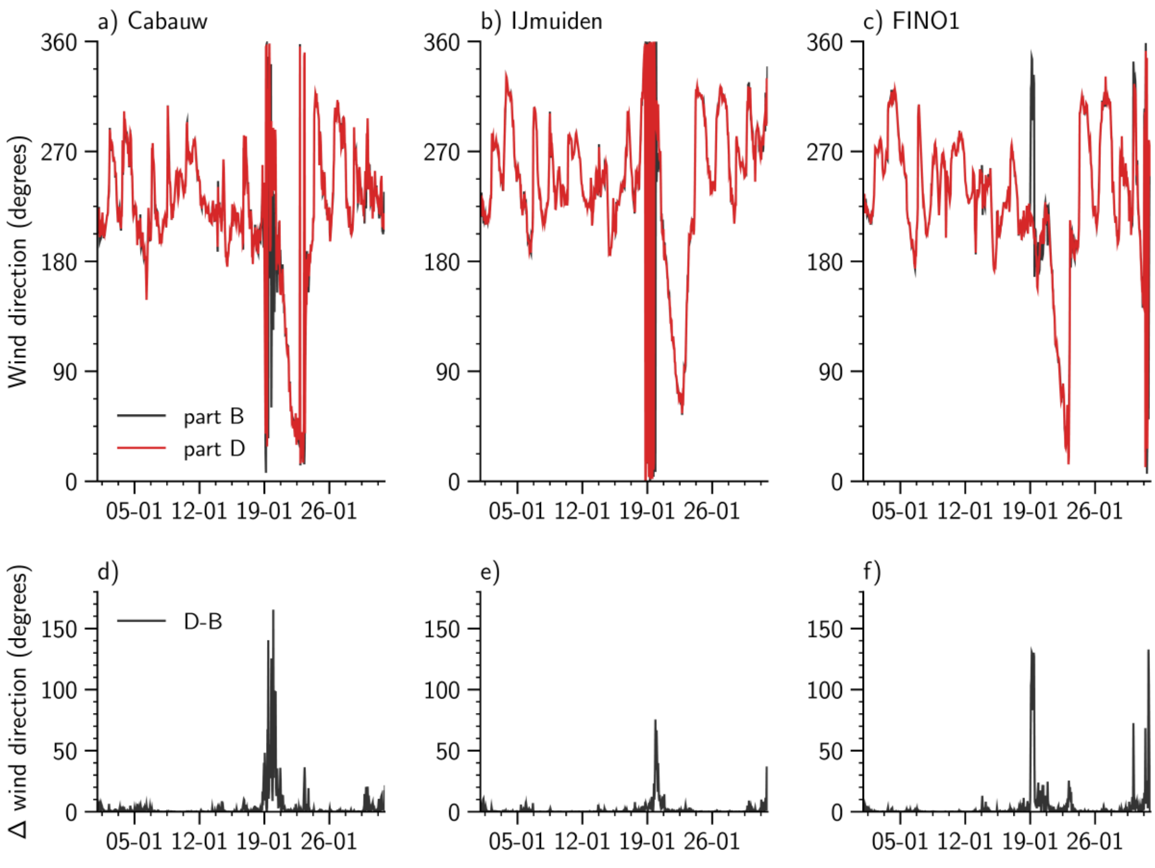

Figure B3: Like figure B2, for the wind direction.

Figure B4 shows the hypothetical effect of gluing stream B and D on the 20th of January (where the difference is at its largest). The jump from stream B to D is not unrealistic, and comparable to the typical hourly variability in wind speed and direction.

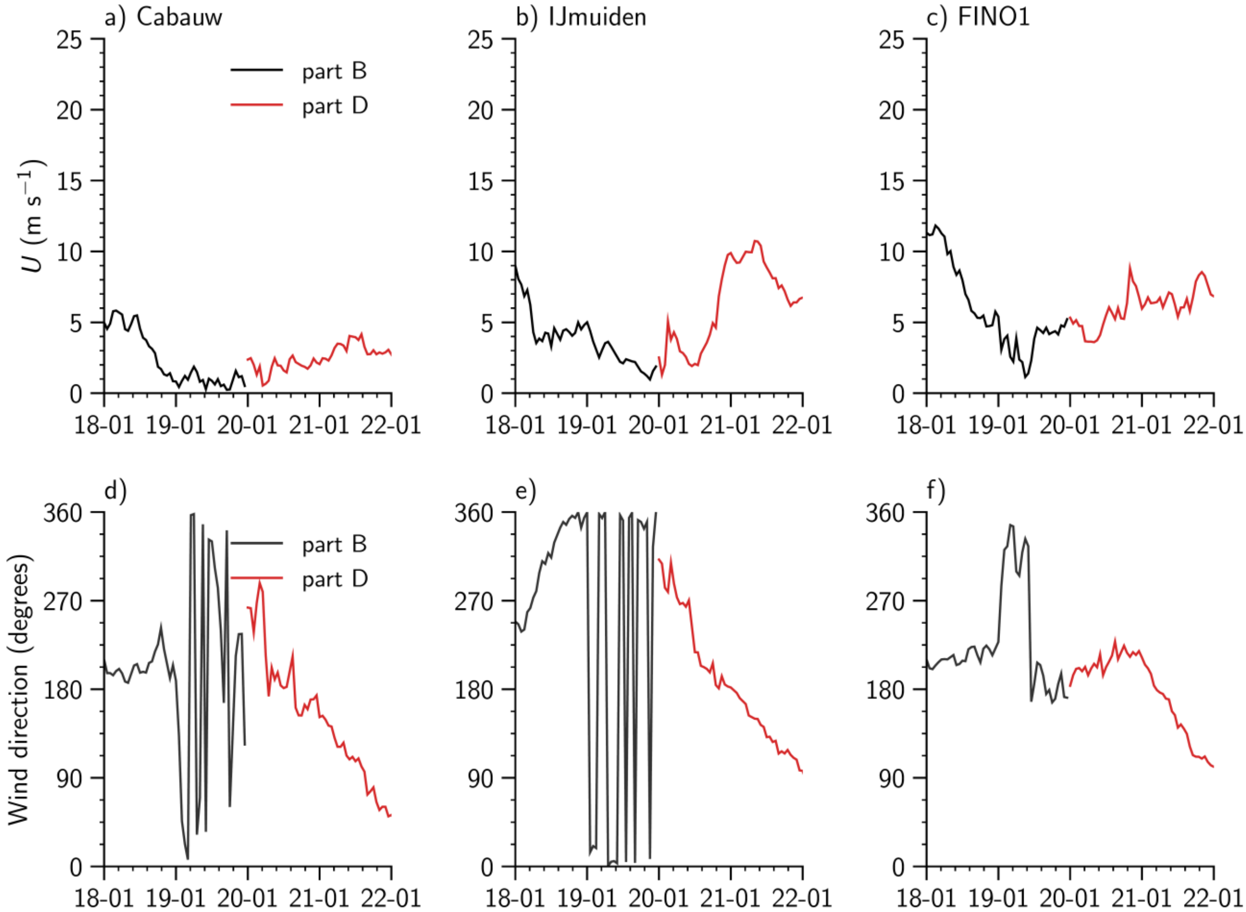

Figure B4: The (hypothetical) effect of combining the B and D stream during the convective period around 20-01-2015. Top row: wind speed near Cabauw, Ijmuiden en FINO1, bottom row: wind direction [courtesy Bart van Stratum].

So even when we glue the streams at the worst moment (during a convective period) the "jumps" are realistic. In figures B5-B7 streams B and D are glued on the 1st of February 2015. It shows the "jumps" for the wind profiles (B5) and the wind direction at 10 (B6) and 100m (B7) for 6x6 locations in the Dutch NL-subdomain (red area Figure 1). Generally the "jumps" are small and the largest ones are around 3.5E between 51.6 and 53.2N where convection was strong on the 1st of February 2015.

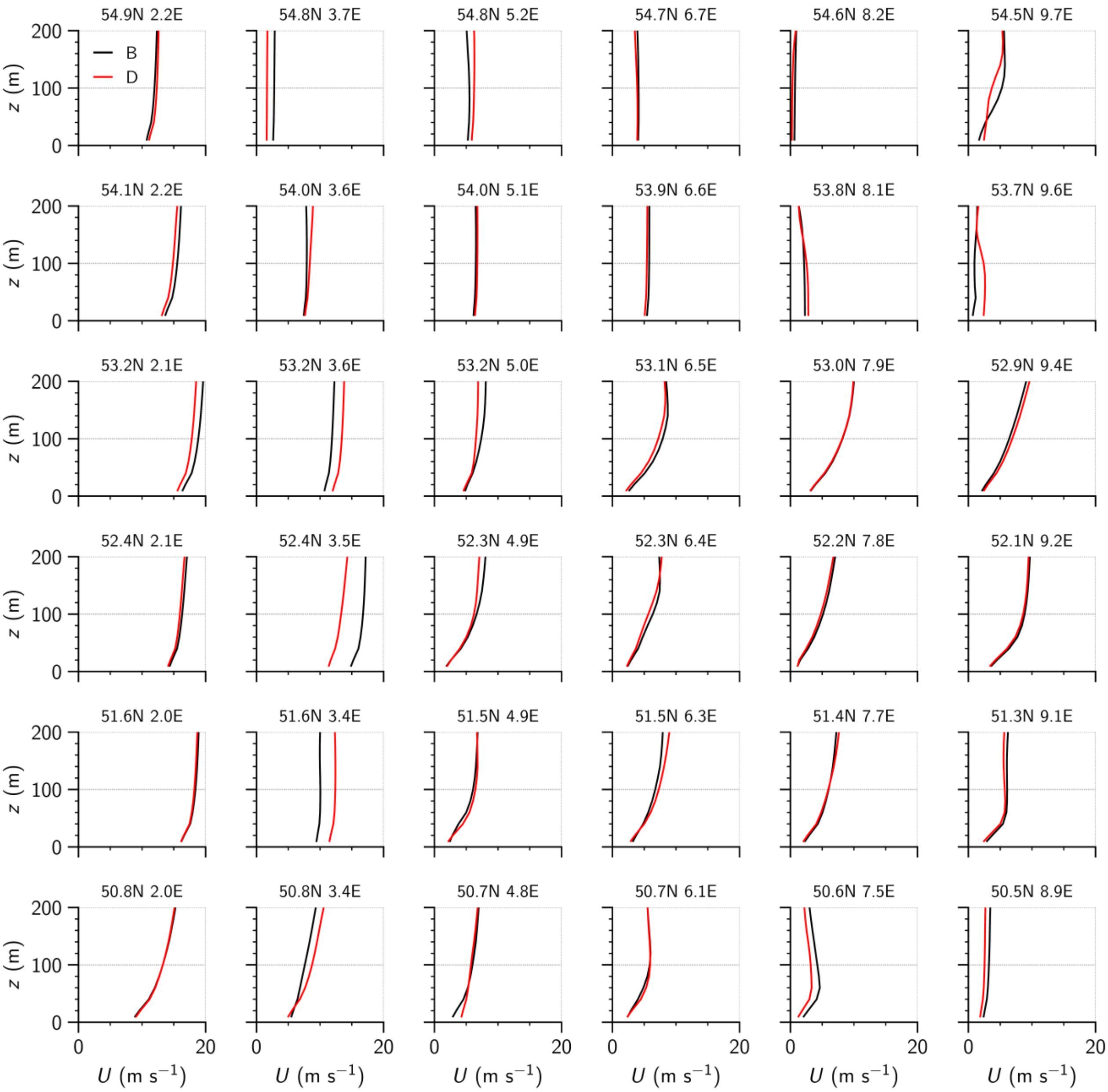

Figure B5: Impact on the wind speed profile of merging the B and D stream at 01-02-2015 00 UTC. In black the last profile from the B stream and in red the first value from the D stream.

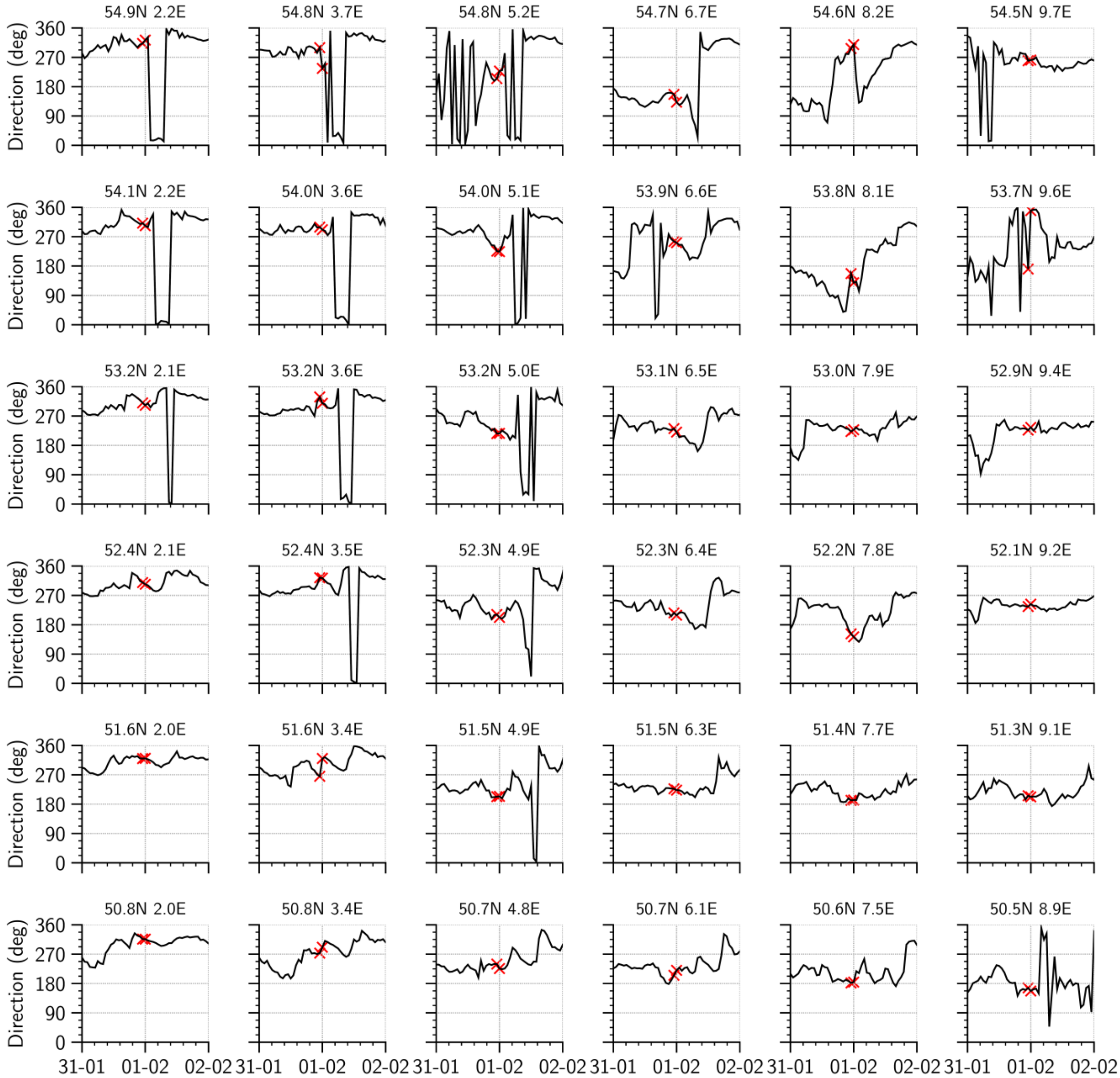

Figure B6: Impact on the 10m wind direction of merging the B and D stream at 01-02-2015 00 UTC. The two red markers indicate the last value used from the B stream, and the first value from the D stream.

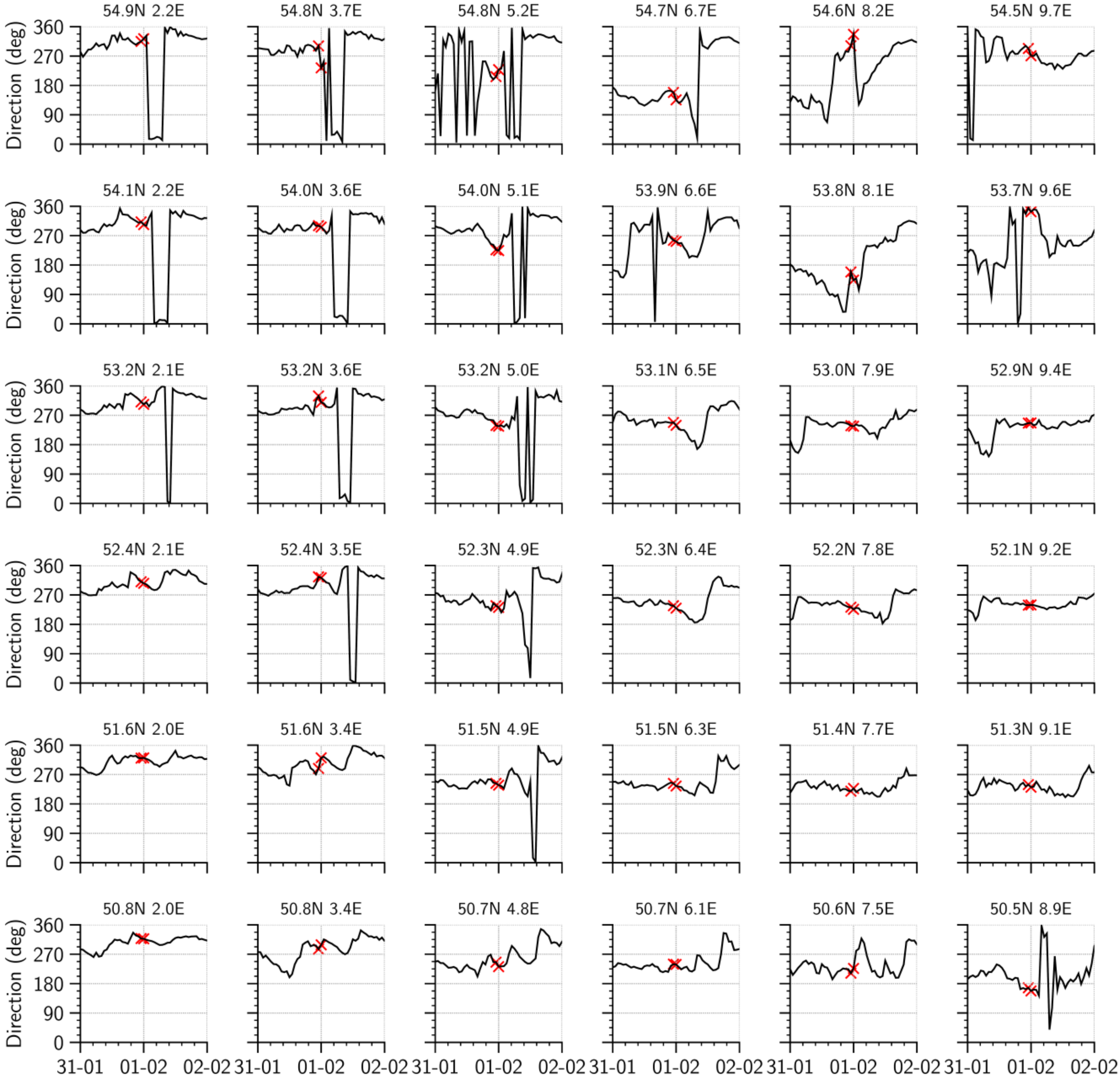

Figure B7: idem B6, but at 100 m height.

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