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**TNO report**

**TNO 2020 R10295 | Final report**

# Dutch Offshore Wind Atlas
# Public final report

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# Samenvatting

TNO, Whiffle en KNMI hebben gezamenlijk het 'Dutch Offshore Wind Atlas' (DOWA) project uitgevoerd in het kader van TKI Wind op Zee en met subsidie van het Ministerie van Economische Zaken en Klimaat, Nationale regelingen EZ-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland. Het project liep van 1 juli 2017 tot 31 december 2019. In dit rapport beschrijven wij de doelen, activiteiten en resultaten van het project en onderstaand vatten wij de belangrijkste conclusies samen.

Allereerst, hebben we een nieuwe en verbeterde windatlas voor de Noordzee, i.e. de 'Dutch Offshore Wind Atlas', gevalideerd en vrijgegeven. Deze wordt publiekelijk beschikbaar gesteld via het 'KNMI Data Centre' KDC. DOWA bevat nu de volledige periode van januari 2008 tot december 2018 en de validatie laat zien dat de correlatie van DOWA met offshore metingen heel goed is. Specifiek laat DOWA een 17 % betere weergave van het dagelijkse ritme zien dan de 'KNMI North sea Wind' KNW atlas. Daarnaast, hebben we KNW bijgewerkt voor de afgelopen jaren, i.e. tot augustus 2019, zodat het in totaal een termijn van meer dan 40 jaar bevat.

Ook hebben we de windcondities op de Noordzee gekarakteriseerd tot op 300 m hoogte, gebruik makende van offshore meetstations en KNW, en zelfs tot op 600 m hoogte, gebruik makende van DOWA. Als we ons richten op specifieke 'low level jets' en we beschouwen de 4 jaar metingen bij offshore meteorologische mast IJmuiden, dan zien we dat deze typisch 4 % van de tijd voorkomen.

In de duinen van Petten is een korte scanning LiDAR meetcampagne succesvol uitgevoerd, welke voor de eerste keer profielen laat zien tot op 1500 m hoogte.

Methodieken zijn ontwikkeld en getest die demonstreren dat 'Large Eddy Simulation' LES genesteld kan worden in het weermodel HARMONIE om nog nauwkeurigere windveldinformatie te geven. Dit maakt de weg vrij om gedetailleerde windveldmodellering met hoge resolutie te koppelen aan grote schaal weermodellering.

Een windparkparametrizatie is succesvol geïmplementeerd in HARMONIE. Deze is vergeleken met het weermodel WRF met dezelfde windparkparametrizatie en gevalideerd met satelliet metingen, (drijvende) LiDAR metingen, mast-gemonteerde cup anemometer metingen, LES simulaties en vermogensdata. Alle analyses geven aan dat de implementatie op een fysisch betekenisvolle manier werkt.

Een windturbineparametrizatie is succesvol geïmplementeerd in het LES model GRASP en gevalideerd met veldmetingen. Vervolgens, zijn drie Noordzee windparkzones gemodelleerd, i.e. Borssele windparkzone, Hollandse Kust Noord windparkzone en Hollandse Kust Zuid windparkzone. Validatieresultaten laten zien dat GRASP gemiddelde windsnelheden goed vergelijken met drijvende LiDAR metingen ter plaatse. In bijna alle gevallen was de gemiddelde afwijking minder dan of iets hoger dan 0.1 m/s.

GRASP inkomende windvelden zijn gekoppeld aan de aero-elastische code AeroModule. Deze koppeling is gebruikt om de impact van extreme gebeurtenissen, onder welke 'low level jets', op een 10MW referentie windturbine te simuleren. De resulterende belastingen voor de geselecteerde gevallen zijn 30-70 % hoger dan die van het referentie ontwerpbelastingsspectrum. We merken op dat de referentie windturbine conservatief ontworpen kan zijn.

DOWA windvelden gekoppeld aan de windpark ontwerptool FarmFlow laten zien dat vermogensopbrengstschattingen erg dicht bij de geobserveerde opbrengsten van het OWEZ windpark zijn. We hebben een verbetering van 3 % gezien ten opzichte van het gebruik van KNW windvelden.

Als laatste zijn nieuwe methodes ontwikkeld om de onzekerheid van DOWA in te schatten: collocatie van meerdere datasets voor precisie, kwantiel-kwantiel plaatjes voor relatieve afwijking en een ‘bootstrap’ methode voor de onzekerheid van 10 jaar data.

# Summary

TNO, Whiffle and KNMI have jointly executed the Dutch Offshore Wind Atlas (DOWA) project within the framework of TKI Wind op Zee and with subsidy from the Ministry of Economic Affairs and Climate, through RVO. The project ran from the 1st of July 2017 until the 31st of December 2019. In this report we describe the main activities and results from the project and below we summarize the main conclusions.

First and foremost, we have validated and released a new and improved wind atlas for the North Sea, i.e. the Dutch Offshore Wind Atlas. It is publicly being made available through ‘KNMI Data Centre’ KDC. DOWA currently includes the full period from January 2008 until December 2018 and the validation shows that the correlation of DOWA with offshore measurements is very good. Particularly, DOWA shows a 17 % better representation of the diurnal cycle than the ‘KNMI North sea Wind’ KNW atlas. In the same line, we have updated KNW for the recent years up to August 2019 now covering a total of more than 40 years.

Also, we have characterized the North Sea wind conditions ranging up to heights of 300 m, using offshore measurement stations and KNW, and even up to 600 m, using DOWA. If we focus on low level jets and we consider the 4 years of measurements at offshore meteorological mast IJmuiden, we see that they typically occur about 4 % of the time.

A short scanning LiDAR measurement campaign was successfully executed in the dunes of Petten, showing for the first time profiles up to 1500 m height.

Tools have been developed and tested that demonstrate that ‘Large Eddy Simulation’ LES can be nested inside the weather model HARMONIE to give even more accurate wind field information. This paves the way for coupling high resolution, detailed wind field modelling to large scale weather modelling.

A wind farm parameterization was successfully implemented in HARMONIE, compared to the weather model WRF with the same wind farm parametrization and validated against satellite measurements, (floating) LiDAR measurements, mast mounted cup anemometer measurements, LES simulations and power data. All analyses indicate that the implementation is working in a physically meaningful way.

A wind turbine parameterization was successfully implemented in the LES model GRASP and validated with field measurements. Consequently, three North Sea wind farm zones are modelled, i.e. Borssele wind farm zone, the Hollandse Kust Noord wind farm zone and the Hollandse Kust Zuid wind farm zone. Validation results show that GRASP mean wind speeds compare well to the on-site floating LiDAR measurements. In almost all cases the wind speed bias was less than or slightly higher than 0.1 m/s.

GRASP inflow wind fields have been coupled to the aero-elastic solver AeroModule. This coupling has been used to simulate the impact of extreme events, among which low level jets, on a 10MW reference wind turbine. The resulting loads for the selected events are about 30-70 % lower than those from the reference design load spectrum. We do note that the reference wind turbine may be designed conservatively.

DOWA wind fields coupled to the wind farm design tool FarmFlow show that power production estimates are very close to the observed yields of the OWEZ wind farm, we have seen an increase of 3 % with respect to using KNW wind fields.

Last, but not least, new methods have been developed to assess the uncertainty of DOWA: collocation of multiple datasets to assess precision, quantile-quantile (QQ) plots to assess relative bias and a bootstrap method to assess the uncertainty in 10 years of data.

# Contents

# 1 Introduction

The North Sea is expected to see an exponential growth in offshore wind energy in the next decade which implies that the demand for high quality wind climatology (and weather forecasts) will only increase. The Netherlands has a target of 4.5 GW offshore wind power in Dutch continental waters in 2023 and is expected to be no less ambitious after 2023. Wind energy is harvested at increasingly higher levels, not only because wind turbines keep getting larger, but also because new methods of producing wind energy are being introduced (e.g. kite power). High quality wind climatology (including information on wake effects) at levels around hub height, but also at tip height and in levels above the wind farms will help to give a more accurate estimate of the wind potential on the North Sea, and of the energy yield that can be expected of future wind farms. The availability of an accurate and validated wind atlas assists multiple parties (e.g. government, project developers, resource assessment parties and funding bodies). This reduces costs for developers whilst increasing transparency in the wind energy industry, leading to higher investor confidence and further reductions in the LCOE.

With this in mind, TNO, Whiffle and KNMI jointly executed the Dutch Offshore Wind Atlas (DOWA) project within the framework of TKI Wind op Zee and with subsidy from the Ministry of Economic Affairs and Climate, through RVO. The project ran from the 1st of July 2017 until the 31st of December 2019. In this report we describe the goals of the project, the starting points before this project, the main activities and results from the project. As such, we report on the method, results, discussion in chapter 2, the conclusions, recommendations and follow-up in chapter 3 and on the deliverables in chapter 4.

## 1.1 Goals

The consortium has the goal to make DOWA available, i.e. a significantly more accurate version of KNMI's current offshore wind atlas (KNMI North sea Wind atlas, KNW) including long term climatology and wind field information aiming specifically at the wind energy industry. The atlas includes the North Sea region up to heights of 600 m. This atlas, in combination with measurement data and simulation methods, aims to significantly improve the estimates of wind farm annual energy production and turbine loads. Eventually, this leads to a reduction in offshore wind energy costs through better designs of the wind farms, higher value of produced energy through better forecasts and reduced Cost of Capital. Specifically, we formulate the goals of the project as follows:

1. Detailed wind information tailored to the needs of the wind energy sector will be publicly disseminated through the generation of a validated wind atlas (DOWA). DOWA will be made available in a similar manner as the current KNW atlas.
2. Tools will be developed so that the information in DOWA can be downscaled with Large Eddy Simulations (LES) to give accurate and detailed wind field information at specific wind farm sites.
3. Developments are tested to account for windfarm clusters in weather forecasting model HARMONIE.
4. Data and tools are developed to improve annual energy production (AEP) estimations and turbine load calculations.

# 2 Method, Results and Discussion

## 2.1 Work package 1: Update of existing KNW atlas

In this work package, we tackled among others the extension of KNMI North Sea Wind Atlas (KNW) atlas until the recent year and the execution of state-of-the-art scanning LiDAR measurements. This is described below.

### KNW atlas updated until August 2019

ECN (now TNO) published its first Offshore Wind Atlas (OWA1) in 2004, which is a numerical wind atlas based on data from KNMI's HiRLAM (High Resolution Limited-area Atmospheric Model). OWA1 is based on the numerical data of the years 2000-2003, and was validated using data of offshore and coastal wind stations measured in the same period. A second version OWA2, an update of OWA1, was issued by ECN in 2011. Again it was based on atmospheric data from the HiRLAM, but now a longer period was considered. In addition sea depths originating from the Hydrographic Service of the Royal Netherlands Navy were used in order to estimate the wave height (sea surface roughness).

In 2013 KNMI delivered the KNW atlas. State-of-the-art knowledge of meteorology, wind climate, measurements and weather models were combined and tailored to the needs of the wind energy sector, covering a total period of 35 years (1979-2013). It is based on the global reanalysis ERA-Interim (and all measurements assimilated in this reanalysis) from the European Centre for Medium-Range Weather Forecasts (ECMWF) and it was downscaled using the atmospheric model HARMONIE. A uniform (i.e. the same for all locations and all heights) wind shear correction was applied based on comparison with measurements at Cabauw. This shear-corrected KNW-atlas was validated against mast and scatterometer wind measurements. Results demonstrated the ability of the KNW-atlas to accurately depict the long-term averaged wind speeds. Because of the method that was used to make the KNW-atlas (i.e. six-hourly 'cold starts' with the much coarser global reanalysis model ERA-Interim), the KNW-atlas did not exhibit a strong correlation with the hourly wind measurements. Also, a limitation of the KNW wind atlas is that it lacked data from after 2013.

Therefore, during the first stage of the project (second half of 2017), the existing KNW atlas was updated for the period 2013 to August 2017 so that it could be used for wind resource assessments of the Borssele and Hollandse Kust Zuid (HKZ) wind farms. After that KNW was updated every 3 months in time to include a new month of wind data, so that by the end of May 2019 KNW was updated including wind data until February 2019. After that and beyond the scope as described in the project proposal, KNW was updated until August 2019. This is also the end of KNW, because the mesoscale model behind KNW, ERA Interim, is no longer available anymore from ECMWF for beyond August 2019. Its successor, and the driving force of DOWA, ERA5 definitively takes over from that moment onwards. So, the KNW-atlas captures more than 40 years (Jan 1979-Aug 2019), which is very important to understand interannual variability. Hence, long term wind variation is at our disposal.

### High altitude scanning LiDAR measurements

ECN (now TNO) has invested in a state-of-the-art long range scanning LiDAR system, i.e. a WindCube 200S from Leosphere. This system is able to measure radial wind speeds, i.e. wind speeds in the projection of the LiDAR beam, in any given direction up to 7km. This system was used for the first time in the DOWA project.

For a short period of 2 months (November and December 2017), the scanning LiDAR was installed in the dunes of the TNO Petten premises. It was configured in the so-called DBS mode that it is able to acquire wind speed and direction directly above the system up to an height of 1500 m, taking into account a still reasonable data count. Above this altitude, there are not enough backscattered signals to get reliable measurements.

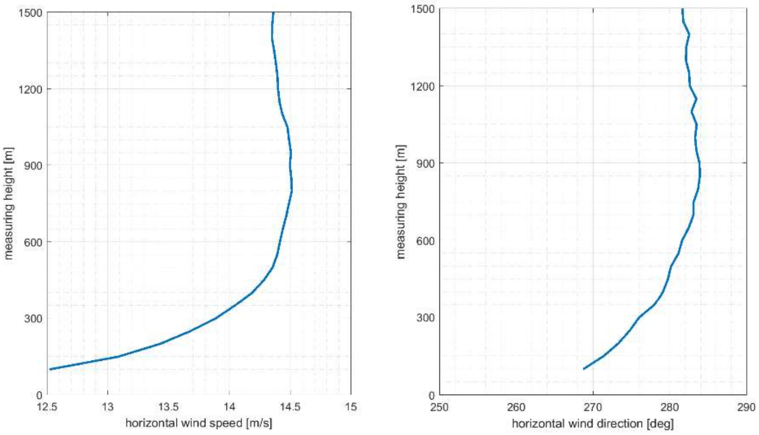

Figure 1: Left: Scanning LiDAR horizontal wind speed against measuring height. Right: Scanning LiDAR horizontal wind direction against measuring height

For this period and for this area KNMI also delivered the KNW results and the LiDAR and KNW results were compared. Although, at first sight the scanning LiDAR and the KNW winds compared reasonably well, in fact a decent comparison could not be made, because the period was too short, the terrain too complex considering the resolution of KNW and the overlap of simultaneous data too scarce. Nevertheless, the project partners are very pleased with these first scanning LiDAR measurements at such a high altitude. This scanning LiDAR technology is promising for the future.

## 2.2 Work package 2: Understanding of the offshore wind resource up to high altitudes

Using various offshore measurement platforms, which comprise measurements up to high altitudes, we have examined the offshore wind conditions in terms of wind profiles and low level jets  (LLJ).

### Offshore measurement platforms

Supporting the huge development of offshore wind energy at the North Sea, the Ministry of Economic Affairs and Climate has contracted TNO directly to operate and maintain a wind measurement infrastructure at the North Sea. An overview of this infrastructure, including a link to all measured data, is provided at www.windopzee.net. Aim is to improve the understanding of the offshore wind environment and seven of these measurement sites were used in this respect. They comprise: meteorological mast IJmuiden (MMIJ), static LiDARs on the K13a platform, Lichteiland Goeree platform (LEG), Europlatform (EPL) and floating LiDARs in the Hollandse Kust Noord and Hollandse Kust Zuid wind farm zones (HKN WFZ and HKZ WFZ) and Borssele zone (BWFZ). Here, meteorological mast Ijmuiden is instrumented at various levels with cup anemometry to measure horizontal wind speed (27m, 58m and 85m) and with wind vanes to measure wind direction (27m, 58m and 87m). The platforms and the buoys host LiDARs to measure wind speed and direction at various heights. The type of LiDARs and the height settings are provided in Table 1.

Figure 2: Overview of the measurement stations in the North Sea

Table 1: Overview of measurement stations in the North Sea, including LiDAR type, measurement heights and data collection period, etc.

| Measurement Location Identifier | LiDAR Type (x 2—2 onsite LiDARs) | Mounting Procedure | Measurement Heights (m) (From:Interval:End) | Data Collection Period (S = start, E = end) |
|---|---|---|---|---|
| MMIJ | ZephIR 300s | Platform Mounted | 90:25:315 | S: 01-Nov-2011<br>E: 09-Mar-2016 |
| EPL | ZephIR 300s | Platform Mounted | 91:25:291 and 63 | S: 30-May-2016<br>E: 31-Dec-2017 |
| LEG | WINDCUBEv2 | Platform Mounted | 91:25:291 and 63 | S: 17-Nov-2014<br>E: 31-Dec-2017 |
| K13a | ZephIR 300s | Platform Mounted | 91:25:291 and 63 | S: 01-Nov-2016<br>E: 31-Mar-2018 |
| HKN | ZephIR 300s x 2<br>(Sites A and B) | Floating | 60:20:200 and 30 and 40 | S: 10-Apr-2017<br>E: 31-Oct-2017<br>**Period A = Period B** |
| HKZ | ZephIR 300s x 2<br>(Sites A and B) | Floating | 60:20:200 and 30 and 40 | S: 05-Jun-2016<br>E: 28-Feb 2018<br>**Period A = Period B** |
| BWFZ | ZephIR 300s x 2<br>(Sites I and II) | Floating | 60:20:200 and 30 and 40 | **Site I:**<br>S: 11-Jun-2015<br>E: 27-Feb-2017<br>**Site II:**<br>S: 12-Feb-2016<br>E: 07-Jul-2016 |

## Offshore profiles

In order to better understand North Sea wind conditions, analyses were performed on wind speed and direction measurements by LiDAR at the eight offshore measurement locations distributed throughout the North Sea. LiDAR enabled measurement of the North Sea wind conditions at relatively high altitudes (i.e. ≤ 315 m) and therefore was used to examine vertical profiles of wind shear and veer. The largest wind shear was observed with south-westerly wind directions and high wind speeds, and in general wind direction veered (i.e. clockwise turn) with height. The wind speed distribution as defined by the Weibull probability distribution with scale parameter A and shape parameter k was also determined at each measurement location and height. Measurement-site wind speed distributions exhibited inter-annual variability and varied as a function of height and proximity to the coast. The Weibull scale parameter on average increased with height, while the Weibull shape parameter decreased with height. Vertical tendencies in the Weibull scale parameter were expected (i.e. wind speed on average increases with height); however, vertical tendencies in the Weibull shape parameter were nontrivial. This reduction in the Weibull shape parameter with height indicates that although the winds become less turbulent with height, the range of possible wind speeds is larger at higher altitudes (i.e. wider distribution, where it should be known that the width of the distribution determines the scale factor). Further, correlation in wind speed and direction between LiDAR measurement locations was determined in order to examine the potential applicability of measurement-correlate predict methods within the North Sea.

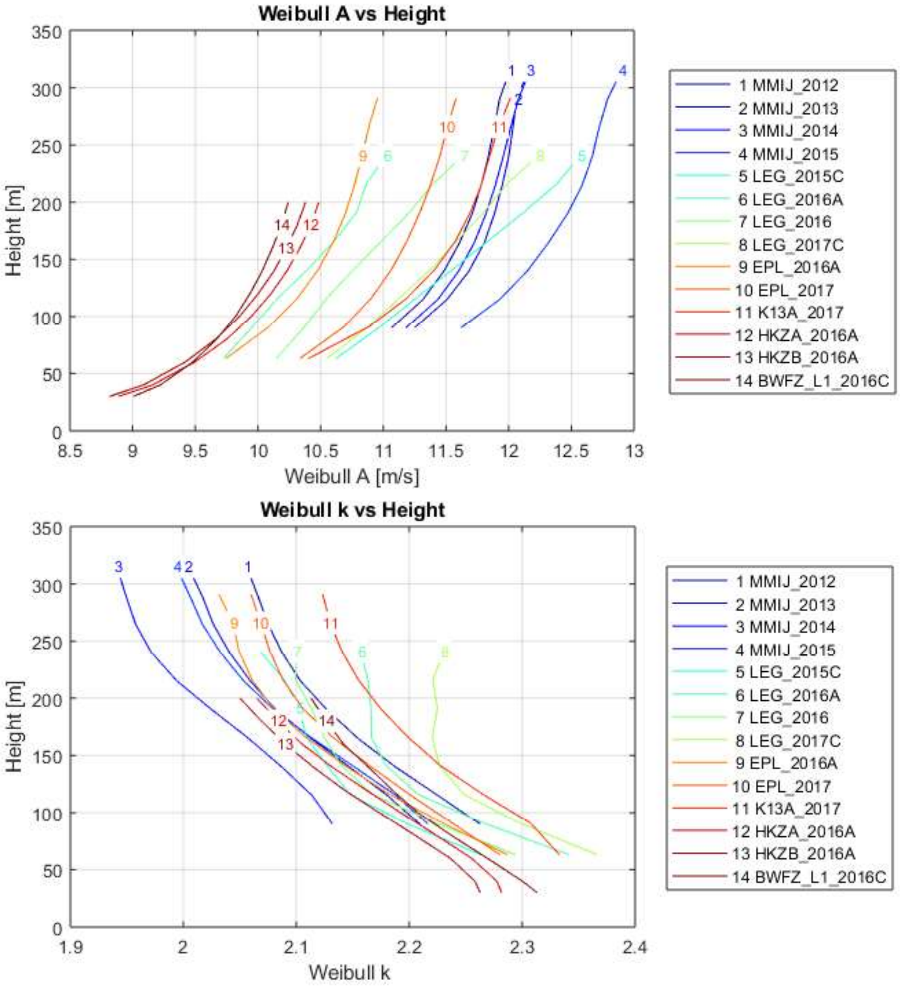

Figure 3: Variation of the Weibull parameters A (top) and k (bottom) with height for various measurement stations and years

KNW atlas wind speed comparisons were made to LiDAR measurements at LEG, HKZA, and HKZB and overall, the KNW atlas compares well with these measurements. The analyses are not meant as validation of KNW – this is already done elsewhere – but to deepen the understanding of high altitude offshore wind resource.

The creation of the DOWA is explicitly part of work package 3. However, within the framework of work package 2 DOWA data have been used to assess the wind conditions at the North Sea extending beyond traditional hub heights (100 m or so), beyond the maximum heights that LiDAR measurements can cover and KNW maximum heights (around 300m). DOWA provides the unique opportunity to assess the wind conditions at altitudes up to 600 m and they certainly differ from those at 100 m. Firstly, the average wind speed at 600 m is 10.7 m/s, compared to 9.9 m/s at 100 m. Wind directions over the North Sea at 600 m are predominantly southwesterly and exhibit a mean clockwise turn of 8 degrees from 100 m over the entire DOWA timespan. The general observation is that the wind field at 600 m is independent from wind speed reductions due to land-sea interaction, which are still present at 100 m. Hourly wind speed and wind direction variations indicate highest hourly wind speed averages of 11 m/s over the Dogger Bank region of the North Sea, and lowest hourly averages at locations within 60 km from the Dutch coast. The hourly wind direction distributions indicate a consistent clockwise turn of 10-15 degrees from 100 m. The wind speed and wind direction profiles are similar for both nearshore and far shore locations oriented in the same direction from the Dutch coast.

**Low level Jets**

Analyses were performed on offshore wind measurements to provide enhanced characterization of the North Sea wind climate. Of particular interest was the spatiotemporal behavior of the offshore low level jet (LLJ) – an anomalous wind event that can significantly impact both wind turbine power performance and loading (for details on this impact we refer to section 2.3.5). LLJs are characterized by a maximum in the vertical wind speed profile relatively close to the surface. LLJ frequency, vertical wind profile characteristics, and onset mechanisms have been extensively studied onshore. However, accurate measurement of the offshore wind environment at high altitudes (i.e. above typical mast heights [~100 m]) has historically been limited. Therefore, less is known regarding the behavior of the offshore LLJ. The above indicated offshore measurement platforms enable accurate measurement of atmospheric boundary layer (ABL) winds at high altitudes, thereby increasing the ability to study anomalous wind behavior offshore. Within this study, wind data from seven different North Sea measurement platforms – including several located within wind farm zones – were analyzed to investigate North Sea LLJ behavior. Here, the measurement periods vary from site to site and range between 1 year and 4 years.

LLJ frequency was examined in this study using identification criteria established in previous research. At MMIJ, considering a period of over 4 years, a LLJ wind profile was detected 3.87 % of the time with the LLJ maxima occurring on average at 101.51 m with a mean wind speed of 9.28 m/s. LLJ frequency and LLJ maxima height and strength varies between measurement locations, but also depends heavily upon both seasonal cycle and the site-relative measurement height and vertical sampling range. At MMIJ, LLJ frequency increases to 7.56 % during the summer and 6.61 % during the spring. Whereas during the fall and winter, MMIJ LLJ frequency is significantly reduced. Measurement sites that sampled the ABL wind field across a greater vertical range and at higher heights typically detected a larger number of LLJs, as well as higher mean values of LLJ maxima height and wind speed. A novel method was also established in this study to systematically define LLJ events so that LLJ temporal behavior (i.e. onset time and duration) could be quantitatively examined. LLJ events typically initiated during the night at MMIJ and persisted for an average duration of 96.6 minutes. However, the LLJ event duration distribution was heavy-tailed (positive skew), with several LLJ events lasting in excess of 10 hrs. Despite exhibiting seasonal dependencies, LLJ duration did not significantly differ between sites – unlike LLJ frequency and LLJ maxima height and strength.

Despite impediments to direct inter-site comparison (i.e. variations in site-measurement height and seasonal data availability), techniques were established to explore on a first-order basis North Sea LLJ spatial coherence. Research demonstrated that if a LLJ were detected at a given measurement site, there was a high likelihood (> 70 %) that a LLJ wind profile would also be detected at a neighboring measurement site within a 24-hr period. This supports prior research that LLJs are not spatially isolated events, but rather can occupy significant spatial areas.

In addition to the above also ten years of ERA5 reanalysis data were combined with meteorological mast and LiDAR observations from the 10 offshore platforms (From the above mentioned 7 campaigns, in fact 3 of them comprise 2 floating LiDAR systems. For more details we refer to the deliverables.) to investigate low-level jet characteristics over the Dutch North Sea. The objective of this was to combine the best of two worlds: (1) ERA5 data with a large spatiotemporal extent but inherent accuracy limitations due to a relatively coarse grid and an incomplete representation of physical processes and (2) observations that provide more reliable estimates of the measured quantity but are limited in both space and time. We have demonstrated the effect of time and range limitations on the reconstructed wind climate, with special attention paid to the impact on LLJ.

We have observed that the representation of LLJs in ERA5 is poor in terms of a one-to-one correspondence, and the jets appear vertically displaced (“smeared out”). However, climatological characteristics such as the shape of the seasonal cycle and the affinity with certain circulation patterns are represented quite well, albeit with different magnitudes. We have therefore experimented with various methods to adjust the modelled LLJ rate to the observations or, vice versa, to correct for the erratic nature of the short observation periods using long-term ERA5 information. While quantitative uncertainty is still quite large, the presented results provide valuable insight into North Sea LLJ characteristics. These jets occur predominantly for circulation types with an easterly component, with a clear peak in spring, and are concentrated along the coasts at heights between 50 and 200 m. Further, it is demonstrated that these characteristics can be used as predictors to infer the observed LLJ rate from ERA5 data with reasonable accuracy.

## 2.3 Work package 3: Creation of a new, validated North Sea wind atlas

### Background and rationale

The DOWA was developed to improve hourly correlation and to better resolve the vertical profile of wind speed without incorporating a uniform shear-correction factor. DOWA uses an updated version of the global ECMWF reanalysis (ERA5), as well as an updated version of the HARMONIE numerical weather model (Cycle 40h1.2.tg2) that was used to transform the global reanalysis into a regional wind atlas. The method that was used to make the atlas was changed. In DOWA, the ‘cold starts’ within the global reanalysis, as used in KNW, were removed and at three-hour intervals aircraft and satellite measurements were assimilated. In the table below the main differences between KNW and DOWA are summarized:

Table 2: Overview of main differences between KNW and DOWA

| KNMI North Sea Wind (KNW) Atlas | Dutch Offshore Wind Atlas (DOWA) |
|---|---|
| 40+ years: 1-1-1979 until 31-8-2019 | 11 years: 1-1-2008 until 31-12-2018 |
| Captures the variability of the North Sea wind climate (40 years long enough) | Does not capture the variability of the North Sea wind climate (11 years not long enough) |
| Based on re-analysis ERA-Interim and mesoscale weather model HARMONIE | Based on re-analysis ERA5 (follow-up of ERA-Interim with higher spatial and |

| | |
|---|---|
| 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). | 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 |

**Coverage and content**
The project subdomain of the DOWA consists of 217x234 grid points centered around KNMI meteorological mast Cabauw with a grid spacing of 2.5km (red domain in figure 4). This means that the domain is about 542,5km x 585km large. The DOWA provides hourly information for an 11 year period (1-1-2008 until and including 31-12-2018), where the year 2018 was an extra to the 10 year climatology that was promised in the project proposal.

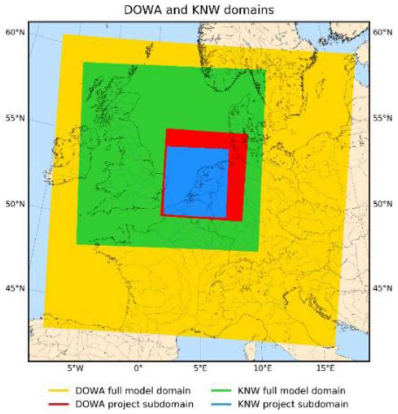

Figure 4: *ERA5-HARMONIE domain (yellow) of 789x789 points and DOWA-subdomain of 217x234 points (red). ERA-Interim-HARMONIE domain of 500x500 points (green) and KNW-subdomain of 170x188 points (blue).*

The (sub)list of variables saved for the DOWA-subdomain is listed below. 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:

- Wind speed
- Wind direction
- Air pressure
- Air temperature
- Relative humidity
- Etc.

## Validation

Wind data measured by LiDAR (both platform-mounted and floating) and instrumented meteorological masts (cup anemometers and wind vanes) were used in this study to examine the performance of the two wind atlases (KNW-atlas and DOWA). Measurements at ten different sites were used for validation (Table 1 and Figure 2).

The comparisons demonstrate that the hourly correlation in the DOWA is better than in the KNW-atlas. In concrete numbers, considering all LiDAR measurement locations and heights, the mean linear regression slope increased from 0.94 (KNW) to 0.97 (DOWA) and the mean $R^2$ value increased from 0.87 (KNW) to 0.91 (DOWA).

Related to the above, the diurnal cycle is better represented. This, without losing significant ability to denote monthly mean and annual average wind speeds. Also, the DOWA performs similar to the KNW-atlas in its depiction of vertical changes in wind speed with height (i.e. vertical wind shear). A better representation of the diurnal cycle is demonstrated from the fact that considering all LiDAR measurement locations, the DOWA shows a reduction of hourly wind speed bias from a mean value of 1.53 m/s within the KNW-atlas to a mean value of 1.27 m/s within the DOWA. Also, the scatter around the mean wind speed bias is reduced; on average, the $\sigma$ value of the hourly wind speed bias was reduced by 0.26 m/s (16.99 %).

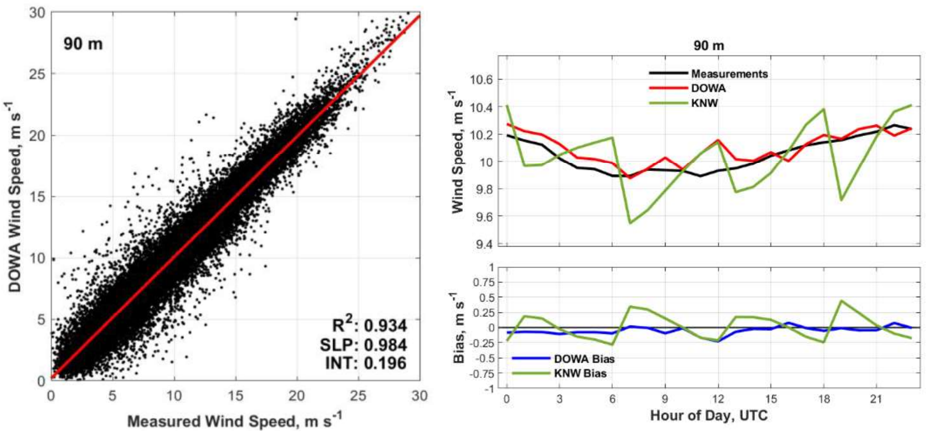

Figure 5: Left: Scatter plot of DOWA wind speeds against MMIJ wind speeds at 90m. Right: Hourly mean wind speeds (top) and bias (bottom). Bias = measured – atlas.

DOWA was further validated using Advanced Scatterometer (ASCAT) measurements, with meteorological mast Cabauw measurements and with measurements from a LiDAR close to shore. Basically, these validations confirm what was previously found and described above. We present a summary of the results below:

- ASCAT measurements come from the Metop-A satellite that passes the North Sea twice a day: south bound at 09:30 UTC and north bound at 21:30 UTC, and provides wind speeds at 10m height across the entire North Sea. With this horizontal spread this validation nicely complements the validation at the various, individual measurement stations. The standard deviation of the difference in wind speed (ASCAT measurements minus model) as well as wind direction was smallest for the DOWA as compared to KNW and ERA5.
- 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 for the period 2008-2017 and at the levels 40, 80, 140, and 200 m of the 213m high. It is found that the average difference (bias) between

DOWA wind speeds and those measured at Cabauw varies between -0.1 m/s to 0.3 m/s for the different heights. Significant differences between DOWA and KNW are only found at 10 and 20 m heights, where KNW performs better. For heights above 20 m there is no significant difference between DOWA and KNW regarding 10-year averaged wind speed bias. The diurnal cycles is better captured by DOWA compared to KNW, and the correlation is slightly improved in DOWA.

- The quality of the DOWA (compared to the KNW-atlas) was also assessed for a site on the coast (Tweede Maasvlakte) with ZephIR 300 wind lidar measurements by Ventolines (commissioned by RWS) that were available for 13 months from 6-4-2017 until 15-5-2018. The LiDAR, positioned on a 12 m high dike, provided wind measurements for 11 levels up to 203 m height (above sea level). DOWA a mean bias in the wind speed of -0.2 m/s (i. e.DOWA overestimates the wind speed), with a standard deviation of 1.2 m/s, which for KNW are -0.1 m/s and 1.5 m/s, respectively. DOWA captures the diurnal cycle much better than KNW and seasonal patterns in the diurnal cycle are also nicely reproduced.

**Comparison to EMD-ConWx**
The above mentioned atlases are not the only source for this type of wind information. ConWx in collaboration with EMD (EMD-ConWX) produces a European mesoscale dataset (available via a subscription) using the in-house mesoscale model of ConWX and ERA-Interim as the global boundary dataset. The EMD-ConWX European dataset is updated monthly with a three-month delay to real time. Ecofys previously performed a wind resource assessment of the Borssele Wind Farm Zone and found that the KNW-atlas demonstrated better correlation with measurements. These results have motivated the current study that aims to document the improvement of the DOWA (a publicly available resource) to the subscription-based EMD-ConWX European mesoscale dataset at three locations across the North Sea. In this respect, ten-minute average wind data provided by platform-mounted LiDAR at MMIJ, LEG and EPL were used to compare the representation of North Sea wind conditions in the DOWA and the EMD-ConWx European mesoscale dataset. The most significant conclusion from this is that the DOWA provides improved hourly wind speed correlation compared to the EMD-ConWx European mesoscale dataset.

## 2.4 Work package 4: Detailed wind field modelling for wind resource assessment and wind turbine load assessment

After the study of free stream wind conditions from measurements and from DOWA, we now consider finer scale modelling and the impact of wind turbines and wind farms in the wind modelling. As such, we consider wind turbine parametrization in LES and wind farm simulation in LES as well as in HARMONIE. Last, but not least we consider the nesting of LES in HARMONIE.

**LES WT parametrization**
GPU-Resident Atmospheric Simulation Platform (GRASP) is an LES model developed by Whiffle that performs its core routines on Graphics Processing Units (GPUs). The origin of GRASP lies in an LES code that is commonly referred to as DALES: Dutch Atmospheric Large Eddy Simulation. DALES has been and is still widely used in the boundary layer meteorology community. To overcome the barrier of the large computational costs that have long prohibited the use of LES in operational weather forecasting, the DALES model was translated to a code that runs most of its computational routines on GPUs.

Mesoscale models are usually nested in large scale models by prescribing the values of the hosting model to the edges of the mesoscale model domain. In principle, such a method could be used for nested LES simulations as well, but it requires very large simulation domains to allow for sufficient development of turbulence in the LES. To overcome this, LES models are usually run with periodic boundary conditions and prescribe the large-scale boundary conditions only as tendencies, i.e. the state variables contain an extra forcing term to account for the large-scale processes. This setting to run an LES coupled to a large-scale numerical weather prediction (NWP) model has been extensively described in literature. We use ERA5 fields for the large-scale boundary conditions.

GRASP uses an actuator disk parametrization to model the turbine wake and this parametrization only needs information about the power curve, thrust curve, rotor diameter and hub height. This information is publicly available or can be estimated with good accuracy. The parametrization calculates the drag forces (using the thrust curve) and rotational forces (using the power curve) based on the local wind speed, taking the actual induction into account. Individual yaw control based on the local wind direction is applied to the turbines.

The GRASP-model including turbine wake effect was validated with a scanning LiDAR wake measurement campaign jointly executed by ECN (now TNO) and the University of Bergen. Here, a scanning LiDAR from the University of Bergen was deployed at the ECN Wind turbine Test Site (EWTW) to scan the wake of a 2.5MW R&D turbine. As mentioned before, the rotor is represented by a so-called actuator disc which is modelled through an axial force (often called thrust) coefficient $C_{Dax}$ and a power coefficient $C_P$. The axial force coefficient has a direct impact on the wake characteristics by which it is a pre-requisite to include in every wake model. The power coefficient has little direct impact on the wake characteristics, but it is still an important quantity to derive the turbine power from the incoming wind (wake) conditions. These characteristics are usually supplied on rotor level. This goes together with an assumption of constant loading over the rotor disc without radial variation. Ignoring the radial load variation is a major simplification because this variation determines the wake characteristics behind a turbine to a large extent (at least in the near wake. In order to include the load variation along the blade in a wake analysis one could think of implementing the aerodynamic model (chord, twist, airfoil data) of the R&D machine blades in GRASP. Unfortunately this was not possible since the aerodynamic blade properties are restricted. Therefore, TNO calculated the power and axial force coefficients on sectional level with their AeroModule code. This serves as an intermediate solution: The detailed aerodynamic blade properties remain restricted but the sectional characteristics still provide information on the radial load distribution.

### LES Wind farm simulation

Three areas at or around planned wind farm zones were simulated using GRASP. The sites are the BWFZ, the HKN WFZ and the HKZ WFZ. Wind farms at these three sites have recently been tendered (BWFZ and HKZ WFZ) or will be tendered soon (HKN WFZ). As a part of the tendering procedure, RVO has organized floating LiDAR measurement campaigns that provide useful data to compare the model results with (see also section 2.3.3 validation). Different time periods were selected for each site that seemed most relevant regarding present measurement campaigns and operation of present turbines. Unfortunately, for the Borssele and HKN sites, a number of days are missing as a result of missing or incorrect large-scale weather input data.

High resolution information (time: 10mins; space: 64x64m) are made available for 18 heights: 10, 30, 51, 72, 93, 115, 137, 159, 182, 205, 229, 277, 328, 380, 434, 490, 548 and 608m. So roughly for every 20 m for heights up to 225m and for every 40 m for heights above 225m and up to 600m. Through the DOWA website two datasets are made available

- Daily files with hourly-averaged wind speed (and standard deviation) for areas around BWFZ (exp006), HKN WFZ (exp101) and HKZ WFZ (exp205) made with Whiffle's Large Eddie Simulation model GRASP. Wind farms have been included in GRASP for the periods they have been operational.
- Time series with 10-minute averaged wind speed, wind direction, air pressure, relative humidity and temperature from GRASP using tendencies constructed from the ECMWF reanalysis ERA5. Wind parks have been included in GRASP for the periods they have been operational. The files with *_fs_* in the file name contain free-stream fields, i.e. without wind parks. The time series contain values at heights from 10 to ca. 600m. The attribute experiment in the NetCDF files indicates the wind park: Borssele (006), Hollandse Kust Noord (101) or Hollandse Kust Zuid (205).

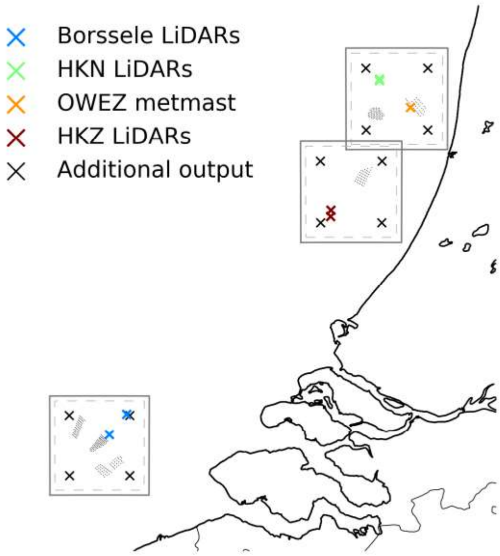

Figure 6: Three domains containing the Borssele, HKN and HKZ wind farm zones that have been modelled in GRASP. The coloured crosses indicate available measurements and the grey crosses indicate what additional output exists.

Validation results show that GRASP mean wind speeds compare well to the LiDAR measurements at all sites. In almost all cases the wind speed bias was less than or slightly higher than 0.1 m/s, which can be considered accurate compared to typical biases of other wind atlases. The only notable exception was the OWEZ met mast, where GRASP showed an overprediction of the wind speed of nearly 0.6 m/s. More analysis is needed to establish whether this overprediction is due to modelling errors or observational errors.

### HARMONIE wind farm cluster parametrization

We implemented a wind turbine parameterization in HARMONIE. In the presence of wind turbines, this parameterization adds an elevated drag term to the atmosphere, which locally decelerates the flow. The kinetic energy that is extracted from the atmosphere, but not converted into electric power, is used as a source term of turbulence kinetic energy (TKE).

As a first validation of the new wind turbine parameterization in HARMONIE, four 48-hour experiments were compared to both experiments with the original code in the Advanced Research Weather Research and Forecast WRF-ARW model, and available offshore measurements near the Dutch/Belgium coast. Next, we repeated 6 months of the DOWA reanalysis with the wind farm parameterization and all current offshore wind farms in the North-Sea region included. The motivation for this experiment was twofold: first, to more thoroughly validate the wind farm parameterization. During the chosen period from January to (including) June 2016, two floating LiDARs were available in the Borssele wind farm zone, one in the Westermost Rough wind farm, with additionally FINO1 tower measurements near the Alpha Ventus wind farm. Since all these measurements are in or near existing wind farms, they are ideal for validating the new wind farm parameterization. Secondly, the six month experiment allowed us to quantify the impact of the offshore wind farms on the Dutch offshore and coastal meteorological conditions.

We summarize the results of this effort as follows:

- A wind turbine parameterization was successfully implemented in HARMONIE-AROME;
- Both the comparison with WRF, and the validation of the 6 month reanalysis with offshore measurements, indicate that the implementation is working in a physically meaningful way;
- The inclusion of the wind farm parameterization improves the wind forecast near wind farms, where not accounting for the drag from wind turbines results in an overestimation of wind speed in HARMONIE-AROME.

The wind farm parameterization is available to the HARMONIE-AROME community, with potentially interesting applications in both weather forecasting and research.

**Nesting LES in HARMONIE**

NWP models like HARMONIE typically operate on a (horizontal) resolution in the order of 1-10 km. In contrast, LES typically operates on a resolution in the order of 10-100 m. Due to increases in computational resources, and the increased complexity of LES models, it has now become feasible to explore the use of LES within the framework of NWP models. Here, we directly downscale a mesoscale model with LES and we explore two new methods to nest LES in the HARMONIE model, i.e. for relatively small LES domains and for relatively large LES domains. In the former the mean atmospheric state varies little across the LES domain and in the latter the mean atmospheric state can vary significantly. The LES experiments were performed with DALES.

Regarding the small domain LES downscaling work, the main outcomes are (1) the availability of a modified version of HARMONIE which can calculate and output the dynamic model tendencies, and (2) the production of three years of dynamic tendencies from the DOWA/HARMONIE reanalysis. As a first validation of the new downscaling method using the dynamic tendencies from HARMONIE, we used DALES to simulate a two week period of realistic weather over Cabauw. Overall, the results are in good agreement with the Cabauw observations, and LES reproduced both the intra and inter-day variability of the realistic weather well.

Regarding nesting large domain LES in models like HARMONIE, and as most LES models use cyclic boundaries, a variation on nesting with lateral boundary nudging was developed, which allows the use of lateral boundary nudging without interfering with the cyclic boundaries. This method allowed us to nest DALES in HARMONIE, without the need for extensive and complex changes in the DALES code.

The nesting of a turbulence resolving model like LES in a non-turbulence resolving model like HARMONIE, always results in some spinup of turbulence near the inflow boundaries (a result of a switch of soil/land-surface scheme). With an idealised test case, we explored several methods to reduce this spinup. The method with synthetic turbulence, which perturbs the inflow fields, provides a small improvement and reduction in the spinup, and is easy to incorporate in more complex and/or realistic cases. The method with turbulence recycling greatly reduces the spinup, but is more difficult to unite with complex in and outflow patterns. As a proof of concept, we demonstrated the nesting of DALES in the HARMONIE reanalysis. Despite the simple setup, this allowed us to introduce and contain a realistic case, with a (for LES standards) complex flow pattern, in LES.

## 2.5 Work package 5: Validation of detailed wind field modelling

In this work package, we assess the loads as calculated on a 10 MW wind turbine in response to 5 extreme wind events (extreme LLJ, extreme Turbulence intensity (TI) extreme TKE, extreme shear and extreme veer) on the North Sea. The turbine on which the loads are calculated is the 10 MW Reference Wind Turbine (RWT) as designed in the EU project AVATAR. The extreme wind events have been selected from a year-long simulation with the operational LES code GRASP. The resulting extreme wind events are then fed as wind input to the aero-elastic solver PHATAS. PHATAS is coupled to the AeroModule which is a code with two aerodynamic models, a Blade Element Momentum (BEM) method and a Free Vortex Wake method AWSM. The calculated loads as response to these extreme wind events are compared with the loads from a reference design load spectrum which is available from the AVATAR project. This reference design load spectrum is calculated with a conventional procedure along the IEC standards. By comparing the loads in response to the extreme events with those from the conventional design load spectrum, the importance of extreme wind events is assessed for practical (load) purposes.

**Validation of LES wind fields**
A validation of the selected LES wind fields has taken place by comparing the calculations with measurements from meteorological mast IJmuiden (table 1) for a period of a year (01-12-2014 to 01-12-2015). We conclude that the extreme wind cases that were selected based on the GRASP model output, represent 'real weather'. That is to say, there is a strong qualitative and often quantitative agreement between the modelled and observed extreme events of LLJ, wind shear, wind veer, TI and TKE. Although the quantitative agreement for the selected LLJ is moderate, it is encouraging to see that for many other LLJ events in the simulated year, the size of the modelled wind shear is comparable to the size of the measured wind shear. Moreover most modelled and measured LLJ's occur in situations with low turbulence and large vertical wind direction veer (indicating stable stratification). However, more validation is needed, in particular on turbulence characteristics at high altitudes (particularly higher than 100 meter).

**Loads impact on wind turbines**
Regarding the load modeling, a successful coupling has been established between the LES wind field model GRASP from Whiffle and the aero-elastic code PHATAS (with AeroModule) from TNO. Thereto extreme events, including a LLJ, are selected from a 1 year simulation of GRASP wind fields. These events are fed as wind input files to the PHATAS code and used to simulate the AVATAR 10 MW RWT at an off-shore location.

The resulting equivalent loads (EQL) and extreme loads for the selected events are, roughly speaking, 30-70% lower than those from the reference design load spectrum of the AVATAR RWT. As such, the often heard expectation that low level jets have significant impact on loads is not confirmed for the present off-shore situation. This is partly explained by the very low turbulence intensities which go together with the LLJ. However the deterministic EQL from the LLJ shear is also lower than the deterministic EQL from design load case 1.2 from the IEC design standard. This is due to the fact that the shear from the LLJ is not very extreme in comparison to the shear from the IEC standards. The LLJ shear profile then leads to a 2P (2 times the rotor frequency) variation instead of a 1P (rotor frequency) variation from 'normal shear' but the amplitude is smaller resulting in a lower fatigue damage. From the results one could hypothesize that the combination of the shear and turbulence levels from the IEC standards may often lead to conservative loads. However much more research is needed to warrant a conclusion, especially in the validation of the on-site turbulent wind fields.

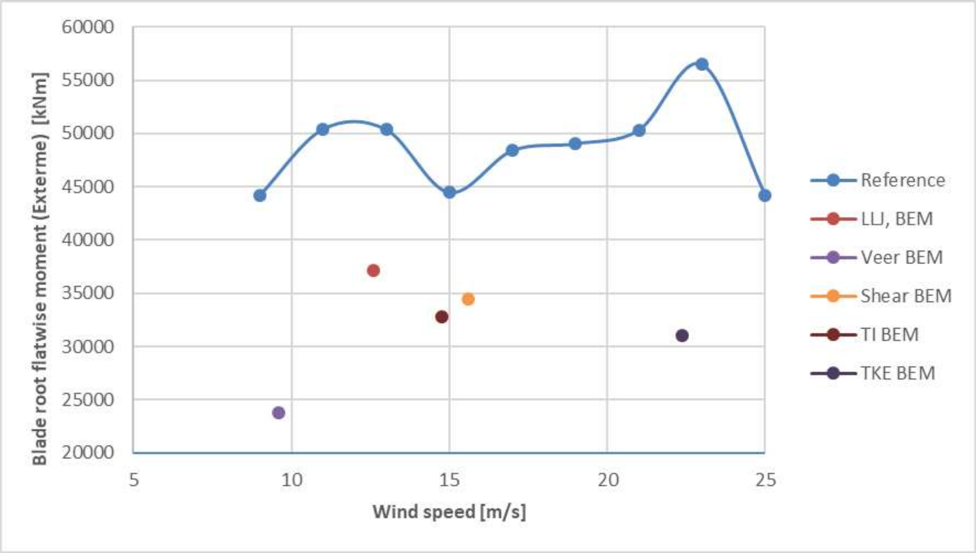

Figure 7: Blade root flatwise bending moment as function of wind speed for the reference case as well as a number of extreme cases

It is noted that the present LLJ has, more or less by coincidence, a maximum velocity close to hub height. A study on different hub heights didn't show a very different outcome but the limited domain size of the LES wind field made that the hub height could not increase with more than 20 meter. A study with a much taller tower (and so an extended domain size) is recommended.

For the selected extreme events the EQL from the more physical AWSM model are considerably lower than the EQL of BEM model which indicates that BEM overpredicts fatigue loads. The difference is largest for the shear driven cases and for a rigid construction. Efforts should be undertaken to improve the BEM fatigue calculations for such shear events.

The present research can be considered as a 'pilot' study to investigate the potential of a coupling between turbine response models and high fidelity wind models. The success of it leads to the recommendation to explore such coupling even further for the calculation of a full design load spectrum. This makes it possible to assess the validity of a conventional method for the calculation of a design load spectrum based on stochastic wind simulators. The higher fidelity of the present method makes that eventually design calculations could be based on physical wind models.

Although the coupling between PHATAS and GRASP was very successful the interfacing through GRASP output and PHATAS wind input files can be improved. Ideally an integrated approach should be developed without the need of interface files.

## 2.6 Work package 6: Uncertainty quantification and power production estimation recommendations

In this last part, we have quantified the uncertainties in DOWA. Also, we have performed yield assessments using Offshore Wind farm Egmond aan Zee (OWEZ) as test case. We do this using FarmFlow in combination with DOWA.

### DOWA uncertainty

Following the validation of DOWA in work package 3, we have assessed the uncertainty of the DOWA climatological parameters, and compared it to the uncertainty in the KNW atlas. Here, we use statistical methods to do so and in particular, the following aspects are studied: precision, bias and multi-year variability.

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. We use triple collocation and quadruple collocation analysis to assess the precision. The standard deviation (more precisely: the root-mean square non-bias error) of DOWA wind speed is estimated to be 1.23 m/s, as compared to 0.36 m/s for the platform mounted LiDAR wind speed and 0.21 m/s for mast-mounted anemometer wind speed. For KNW, the value is 1.48 m/s, so DOWA is more precise.

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. The relative bias of DOWA wind speed is very low (of the order of 1%) in comparison to mast measurements and platform-mounted LiDAR measurements at meteorological mast IJmuiden. For some 30 degrees wind directional bins, this is somewhat larger. For KNW, the bias is similar, although slightly lower for some directional bins. Bias in the relation between wind speeds at different altitudes in the DOWA data appears to be very low as well, possibly with the exception of high wind speeds at high altitude (90 - 290 m). The spread in wind shear is lower in DOWA than in the measurements.

With the above, we believe that QQ plots have proven to be an accurate method to assess bias, resilient against low precision of the data and low correlation. Therefore, it is recommended as an alternative to regression-based MCP (measure, correlate, predict) methods for correction of bias in reference wind records in wind resource assessment.

To assess the uncertainty in wind resource assessments based on 10 years of wind data, we use a bootstrap method, both with and without accounting for multi-year dependence. The uncertainty due to variability of the 10-year average wind climate appears to be small: the ratio P90/P50 for the reference yield over 10 years is estimated to be 0.98, both from 10 years of DOWA data by assuming that annual averages of wind statistics are mutually independent, and from 40 years of KNW data by a method accounting for multi-annual dependence. However, being based on at most 40 years of data, these assessments are highly uncertain.

### Yield assessment using DOWA

We have made wind farm power predictions with DOWA input and compared them with measurements. Here, we used OWEZ as “pilot site”, where operator NoordzeeWind was kind enough to provide us with OWEZ production data for the period 2008-2010. We have simulated the production of OWEZ wind farm design tool FarmFlow using time series of wind data from both DOWA and KNW for comparison with the power production data.

The OWEZ wind farm is located 10 to 18 km off the coasts of Egmond aan Zee, with a size of 27 km$^2$. It consists of 36 Vestas V90 3MW wind turbines with a total capacity of 108 MW. These wind turbines have a rotor diameter of 90 m, a hub height of 70 m above means sea level and a capacity of 3 MW. The standard power curve of the Vestas V90 3MW is used together with the thrust curve.

DOWA contains time series on a 2.5 by 2.5 km grid spacing with 20 m height spacing around hub height. Around the OWEZ wind farm a quadrangle has been defined with its vortices coinciding with grid locations of DOWA, where virtual met masts are placed in FarmFlow. At these virtual met masts, time series from DOWA for the year 2010 at 60, 80 and 100 m have been imported including wind direction, wind speed, pressure, temperature and relative humidity. From the last three variables, the air densities have been determined. The normalized wind speed time series at the four locations and three heights are transformed to 12 wind roses, containing the frequency distribution of the wind direction over twelve sectors, and per sector the Weibull parameters of the wind speed distribution. Finally, the 12 wind roses have been interpolated per sector towards the locations and hub height of the 36 wind turbines. For comparison between results with DOWA and KNW wind data input, the same approach has been repeated with KNW wind data.

The simulated yield from FarmFlow with DOWA wind are very close to the observed yields. Although the simulations with KNW wind show almost the same trend between individual turbines, the yields are approximately 3% below the observed values. This difference between DOWA and KNW wind as input in the simulations is according to expectations, since the KNW time series show a 2% lower average wind speed in comparison with DOWA, which is in agreement with results from the validation study on DOWA (see section 2.3.3).

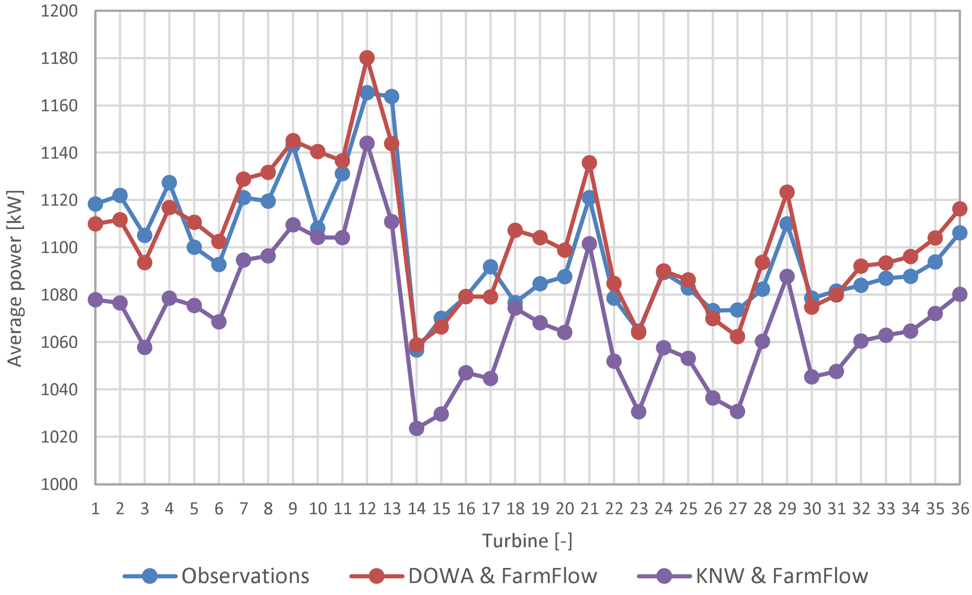

Figure 8: Observed (blue) average power per turbine and modelled average power per turbine for FarmFlow in combination with both DOWA (red) and KNW (purple).

## 2.7 Work package 7: Dissemination of work packages

Dissemination is an important aspect of the project and hence explicitly part of it. How and which project results would be disseminated, was agreed upon and planned in the project proposal through work package 7. In that respect the deliverable list in appendix A is quite specific. Nevertheless, we provide a short overview of all disseminating activities, below.

*Knowledge dissemination*

- Reports and data: The results of the project, like the atlas data themselves, download manuals, validation and other reports, are publicly available through the website www.dutchoffshorewind.nl.
- Articles: From the project, there are a few scientific publications:
  - P.C. Kalverla, et al. ‘Low-level jets over the North Sea based on ERA5 and observations: together they do better’, Wind Energy Science 4, 193-209, 2019

    - J.G. Schepers, P. van Dorp, R.A. Verzijlbergh, H.J.J. Jonker and P. Baas, 'Aero-elastic loads on a 10 MW turbine exposed to extreme events selected from a year-long Large-Eddy Simulation over the North Sea', submitted to Wind Energy Science and currently under review
- Oral presentations
    - J.W. Wagenaar, I.L. Wijnant, R. Verzijlbergh, 'Dutch Offshore Wind Atlas', R&D North Sea Offshore Wind Energy, De Bilt, February 2018.
    - J.W. Wagenaar and P.A. van Dorp, 'Dutch Offshore Wind Atlas', WindDays 2018, Rotterdam, June 2018.
    - J.W. Wagenaar, 'Dutch Offshore Wind Atlas', EERA JP Wind Annual Event, Amsterdam, September 2018.
    - J.G. Schepers, et al., 'Aero-elastic loads on a 10 MW turbine exposed to extreme events selected from a year-long Large-Eddy Simulation over the North Sea', Wind Energy Science Conference, Cork, June 2019.
    - B. Bulder, et al. 'Validation of the Dutch Offshore Wind Atlas (DOWA) with offshore mast and LiDARs', WindEurope WRA technology workshop, Brussels, June 2019.
    - B. Bulder, et al. 'Reducing the uncertainty in the AEP estimate using DOWA', WindEurope Offshore, Copenhagen, November 2019.
    - I.L. Wijnant, 'Wind Energy: big, different and fast data', ICT-circle Growing Green, November 2019

*Public Relations*

- Pers releases:
    - At the start of the project we made a press release with title: 'More accurate North Sea wind information cuts cost of offshore wind energy', 6th of November 2017.
    - At the release of the DOWA atlas we made a press release entitled: 'New Dutch Offshore Wind Atlas delivers the most accurate North Sea wind information for offshore wind energy´, 17th of January 2019.
- Project support: When we released DOWA in January 2019, we pro-actively approached and informed the project support letter writers (see project proposal) as well as other stakeholders like RVO and Economic Affairs and Climate.
- Webinar: At the end of the project we held a webinar to present the results of the project and how these can be used in wind yield analyses.
- LinkedIn: We have posted several items on LinkedIn with respect to this project.
- TKI Wind op Zee 'Project in Beeld'. TKI Wind op Zee has contracted 'Rekelproducties' to make a movie to promote the DOWA project.

# 3 Conclusions, Recommendations and Follow-up

## 3.1 Conclusions

The Dutch Offshore Wind Atlas has been validated and is publicly being made available through KDC (same as KNW). DOWA currently includes the full period from January 2008 until December 2018 and in the same line KNW has been updated up to August 2019. The validation shows that the correlation of DOWA with offshore measurements is very good. Particularly, DOWA shows a 17 % better representation of the diurnal cycle than KNW.

We have characterized the North Sea wind conditions ranging up to heights of 300 m, using offshore measurement stations and KNW, and even up to 600 m, using DOWA. Focusing particularly on low level jets and considering 4 years of measurements at MMIJ, we have seen that they typically occur about 4 % of the time.

A short scanning LiDAR measurement campaign was successfully executed in the dunes of Petten, showing for the first time profiles up to 1500 m height.

Tools have been developed and tested that demonstrate that LES can be nested inside HARMONIE to give even more accurate wind field information. This paves the way for coupling high resolution, detailed wind field modelling to large scale weather modelling.

A wind farm parameterization was successfully implemented in HARMONIE. Both the comparison with WRF with the same wind farm parametrization, and a more extensive validation comparing the 6 month of HARMONIE with wind farm parametrization to offshore measurements, indicate that the implementation is working in a physically meaningful way.

A wind turbine parametrization was successfully implemented in LES (GRASP) and validated with field measurements. Consequently, three North Sea wind farm zones are modelled, i.e. Borssele wind farm zone, the Hollandse Kust Noord wind farm zone and the Hollandse Kust Zuid wind farm zone. Validation results show that GRASP mean wind speeds compare well to the on-site floating LiDAR measurements. In almost all cases the wind speed bias was less than or slightly higher than 0.1 m/s.

LES inflow wind fields coupled to an aero-elastic solver (AeroModule) were used to simulate the impact of extreme events, among which low level jets, on a 10MW reference wind turbine. The resulting loads for the selected events are about 30-70 % lower than those from the reference design load spectrum. We do note that the reference wind turbine may be designed conservatively.

DOWA wind fields coupled to a wind farm design tool (FarmFlow) show that power production estimates are very close to the observed yields of the OWEZ wind farm, we have seen an increase of 3 % with respect to using KNW wind fields.

Last, but not least, new methods have been developed to assess the uncertainty of DOWA: collocation of multiple datasets to assess precision, quantile-quantile (QQ) plots to assess relative bias and a bootstrap method to assess the uncertainty in 10 years of data.

## 3.2 Recommendations

### Extending DOWA

DOWA is the natural successor of KNW on the one hand because the ECMWF has decided to stop with ERA-interim and continue with ERA5. Here, ERA-interim is the driving force of KNW and ERA5 that of DOWA. On the other hand DOWA has shown to have a higher accuracy and better representation of the diurnal cycle than KNW. Therefore, we recommend to keep updating DOWA to present and make it publicly available. Also, we recommend to update DOWA retrospectively, i.e. for years before 2008, in order to create multiannual wind information for grasping interannual variability of the wind speed.

As our yield assessments showed a reduced uncertainty when using DOWA (as compared to KNW or EMD-ConWx) we have recommended this atlas to standardization fora as IEC TC88 and MEASNET on site assessment.

### Wind farm cluster model validation

Currently, the effect of wind farm(s) (clusters) is not part of DOWA and tests executed in the project show that technically progress is made to do so. In the same line wind farm parametrization efforts in LES showed that entire wind farms can be simulated real time. What these models lack are accurate validation data. Therefore, we recommend to set-up a measurement campaign where scanning LiDARs measure the wind farm wakes for various atmospheric conditions. This will lead to more precise wind farm modelling, both on the mesoscale as well as the LES scale, leading to even lower wind farm yield uncertainties.

### Detailed wind turbine loading

The project has shown the value of detailed LES wind fields fed in to aero-elastic codes to simulate the loading of modern offshore wind turbines under extreme wind conditions. Without the detailed (LES) wind fields this would not have been possible. As this project was a first step, we recommend to further improve the coupling of detailed wind fields to aero-elastic codes for instance by developing an integrated approach, hence surpassing the need of interface files.

## 3.3 Follow-up

### Wind at Sea

TNO is directly contracted by the ministry of Economic affairs and Climate to operate and maintain a measurement infrastructure for wind energy on the North Sea. All measurement data are being made available through www.windopzee.net. As coordinator of the DOWA project TNO has taken the initiative to discuss the possibilities with the ministry to make the continuation of DOWA part of this same programme. Although discussion are still ongoing, this proposal is considered a positive approach.

### WINS50

TUDelft, Whiffle and KNMI have formulated the WINS50 project in the framework of the TKI Wind op Zee R&D 2019. Here, the HARMONIE weather model will be run for 2019-2021 to produce winds undisturbed by wake effects (extension of the DOWA) and disturbed winds (wake-DOWA). Wake-DOWA will be run for the situation in 2050 and for other possible, future scenarios of offshore wind farms in the North Sea. Computational capabilities of the high-resolution GRASP weather model will be extended to allow for simulations for the entire Dutch North Sea. Wake parametrizations will be further improved. Data produced with HARMONIE and GRASP will be made available to the wind energy sector and used to perform in-depth studies of (uncertainties in) wake modelling and the interactions of large-scale offshore wind energy and the atmosphere.

### Detailed wind turbine loading

Offshore wind turbines are getting bigger and bigger and this trend will continue for a while. With this development they will encounter larger areas of wind fields. The traditional approach of a single inflow wind field at hub height, representative for the whole rotor is clearly insufficient and one should definitely take into account vertical, horizontal and timewise variations. This is even more pronounced when we consider that the larger wind turbines will be developed in a very slender and flexible way, hence the excitations and loadings become increasingly important. These are obviously driven by the incoming wind fields.

As argued above, the project partners have seen the value of coupling detailed wind fields to aero-elastic codes in order to improve the loading on modern and future offshore wind turbines. This will support the design of very large wind turbine, making them structurally and economically feasible. TNO and Whiffle have submitted the AeroLes project proposal to TKI WoZ HER framework to tackle this.

### Spin off outside sector

Obviously, the tools and knowledge developed in this project are applicable for the wind energy sector. The partners wish to stress that the results from the project have directly been used in wind resource studies for the ongoing Dutch offshore tenders. The results have also led to related services on yield study, day-ahead forecast and wind turbine development.

The advances in the project and the improvements in the underlying models, i.e. detailed atmospheric simulation technology and the more general numerical weather prediction models, have led to improvements in meteorology as well; particularly, in weather prediction and simulation.

Other areas where the activities of this project might be relevant are for instance wind loading on structures such as ships, traffic, etc. and support decisions in air quality modelling, construction planning and port areas, to name a few others.

The dataset of DOWA is very rich and contains much more information than wind speed and direction, only. This raises the question what DOWA else could be used for. For instance, one could think of rain/precipitation for wind turbine blade leading edge erosion in operational offshore wind farms. The erosion of blades leads to production loses and eventually blade brake down. Also, solar radiation output of DOWA might be used to estimate the yield of solar panels. This, however, needs to be further investigated.

# 4 Deliverables

Much of the text above is almost literally taken from the following deliverables in which the analyses are presented in more detail. Indirectly, we refer to references therein. All public results can be found on www.dutchoffshorewindatlas.nl and on the websites of the individual institutes:

- D1.1 Extension of KNW
    - All KNW data from 2013 up to August 2019 are available at KDC
- D1.2 Create common dataset
    - For characterizing the offshore wind conditions from offshore platform measurements, we created a common dataset, available at the TNO facilities. The data were extracted from www.windopzee.net.
- D1.4 Scanning LiDAR dataset
    - Scanning LiDAR measurements have been performed. The data are available at the TNO facilities
- D2.1 Characterization of the offshore wind conditions
    - J.B. Duncan, et al., ‘Understanding of the Offshore Wind Resource up to High Altitudes (≤315 m)’, TNO 2018 R11592, 2019
    - J.B. Duncan, ‘Observational Analysis of the North Sea Low-Level Jet’, TNO 2018 R11428, 2018
    - Kalverla, et al. ‘Low-level jets over the North Sea based on ERA5 and observations: together they do better’, Wind Energy Science 4, 193-209, 2019
    - G. Gopalan Achary Venkitachalam, ‘High Altitude Wind Resource Assessment; A study of the North Sea wind conditions using the Dutch Offshore Wind Atlas’, Internship report TUDelft
- D2.2 Industry priorities
    - B. Bulder, ‘Wind resources requirements by wind farm developers’, TNO 2018 M 11166, 2018.
- D3.3 Make DOWA available via KDC:
    - I.L. Wijnant, et. al., ‘The Dutch Offshore Wind Atlas (DOWA) description of dataset’, KNMI Technical report TR-380 2019
    - DOWA Download menu, www.dutchoffshorewindatlas.nl
- D3.4 Validation of DOWA
    - J.B. Duncan, et al. DOWA validation against ASCA’, TNO 2018 R11649
    - J.B. Duncan, et al., ‘DOWA validation against mast/LiDAR’, TNO 2019 R10062
    - S. Knoop, et. al., ‘DOWA validation against Cabauw meteo mast wind measurements’, KNMI Technical report TR-375 2019
    - S. Knoop and I.L. Wijnant, ‘DOWA validation against coastal wind measurements’, KNMI Technical report TR-376 2019
- D3.5 Comparison of DOWA against EMD-ConWx
    - J.B. Duncan, ‘Representation of North Sea Wind Conditions in the DOWA and the EMD-ConWx European Mesoscale Dataset’, TNO 2019 R10427
- D4.1 Methodology for GRASP wake effects
    - J.W. Wagenaar & P. van Dorp, ‘Dutch Offshore Wind Atlas’, Winddays presentation 2018
    - E. Wiegant and R. Verzijlbergh, “GRASP model description and validation report”, 2019-12-05
- D4.2 GRASP timeseries with and without wind turbine parametrization
    - DOWA download menu, ‘Wind Farm Zone LES-simulations’, Whiffle, 2019
- D4.3 Wind farm cluster wake effects

    - B.J.H. van Stratum, et al., “Wind turbine parametrization in HARMONIE-AROME”, KNMI Technical report TR 377, 2019
    - P. Ramakrishan, ‘Evaluation of a wind farm parametrization in an operational mesoscale model’, Master thesis report TUDelft, 2019
- D4.4 Nudging methodologies to nest LES in HARMONIE
    - B.J.H. van Stratum, et al., “Downscaling HARMONIE-AROME with Large-Eddy simulation”, KNMI Technical report TR 378, 2019
- D4.6/D5.1/D5.4 Validation of generated wind fields & Fluid structure interaction
    - J.G. Schepers, et al. ‘Aero-elastic loads on a 10 MW turbine exposed to extreme events selected from a year-long Large-Eddy Simulation over the North Sea’, to be published in Wind Energy Science, http://doi.org/10.5281/zenodo.3403711, September 2019
- D6.1 DOWA uncertainty
    - C. de Valk and I.L. Wijnant, ‘Uncertainty analysis of climatological parameters of the Dutch Offshore Wind Atlas (DOWA)’, KNMI Technical report TR 379, 2019
- D6.2b AEP assessment
    - E.T.G. Bot, ‘Wind farm yield estimation with DOWA’, TNO R10344 2020

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