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DOWA validation against ASCAT satellite winds

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Summary

The creation of the Dutch Offshore Wind Atlas (DOWA) was part of a joint project with ECN part of TNO, Whiffle, and KNMI. The DOWA is a wind atlas based on a 10-year reanalysis, which is an hourly description of the state of the atmosphere using measurements and atmospheric (weather) models. The DOWA attempts to improve upon the ability of the KNW-atlas to accurately depict hourly wind field variability (i.e. correlation). In order to improve upon the KNW-atlas, the DOWA uses an updated version of the global ECMWF reanalysis (ERA5), as well as an updated version of the HARMONIE numerical weather model (Cycle 40h1.2.tg2) that was used to transform the global reanalysis into a regional reanalysis (i.e. a wind atlas). Furthermore, the method that was used to make the atlas was changed—there were no ‘cold starts’ within the global reanalysis and at three-hour intervals additional aircraft and satellite measurements were assimilated. Within this validation report, the DOWA, the KNW-atlas, and global ECMWF reanalyses (ERA-Interim and ERA5) were validated against ASCAT 10-m equivalent wind speed and direction and the corresponding zonal and meridional wind components.

The ASCAT 10-m equivalent wind speed distribution was first examined in order to establish the ability of the atlases/reanalyses to discern general wind conditions. Although some discrepancies existed between ASCAT winds and the atlases/reanalyses (especially between 5 and 9 ms^{-1}), the global ECMWF reanalyses, the DOWA, and the KNW-atlas all demonstrated the ability to reliably replicate the observed wind speed distribution. Direct comparison for the whole North Sea, defined by o-b (observation-minus-model) statistics, show that the DOWA did not reduce the wind speed bias compared to either the KNW-atlas or ERA5. Across the entire North Sea, the DOWA exhibited a mean negative bias of less than 0.2 ms^{-1} (i.e. the DOWA slightly overestimates the wind resource compared to ASCAT). However, while the o-b statistic bias for wind speed was not reduced within the DOWA, the o-b statistic bias for wind direction was less for DOWA than it was for ERA5.

The major improvements of the DOWA compared to the KNW-atlas and the global reanalyses can be found when analyzing the o-b statistic standard deviation, which lends insight into the amount of real and realistic detail produced by the atlases/reanalyses. The o-b statistic standard deviation for wind speed was smallest for the DOWA, and also the DOWA outperformed ERA5 in terms of the o-b statistic standard deviation for wind direction. This improved ability to resolve both real and realistic detail was further demonstrated when analyses were limited to the coastal zone. Within the coastal zone, the DOWA outperformed ERA5 and the KNW-atlas outperformed ERA-Interim in terms of both the o-b statistic bias and standard deviation for wind speed. Similar patterns hold for the o-b statistic bias for wind direction, but not for the o-b statistic standard deviation for wind direction. Analyses of horizontal wind shear between neighboring grid points and 2D spatial plots of North Sea wind also demonstrated the pronounced ability of the DOWA to resolve spatial wind field structures.

Contents

1 Introduction

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

Within the past decade, the Koninklijk Nederlands Meteorologisch Instituut (KNMI) has produced two wind atlases—the KNMI North Sea Wind (KNW) atlas and the Dutch Offshore Wind Atlas (DOWA)—to depict offshore wind conditions across the North Sea. The KNW-atlas is based on the global reanalysis ERA-Interim (and all measurements assimilated in this reanalysis) and 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 (Stepek et al. 2015) and scatterometer (Wijnant et al. 2015) wind measurements. Results demonstrated the ability of the KNW-atlas to accurately depict the wind speed climatology (long-term averages and extremes) with the same accuracy of standard cup and sonic anemometry (Pedersen et al. 2006). 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. New models and methods were therefore used to make the DOWA in order to improve the hourly correlation (diurnal cycle) compared to the KNW-atlas. This report will focus on examining how well the DOWA represents the 10-m wind speed and direction and the corresponding zonal and meridional wind components over sea relative to the ASCAT winds. The performance of the DOWA relative to the KNW-atlas, ERA-Interim, and ERA5 will also be investigated.

This report is structured as follows: section two provides details of the measurements and models used, section three will examine the performance of the atlas and reanalyses data against measurements, and section four will provide a discussion of the results.

2 Atmospheric models and scatterometer winds

2.1 Reanalysis and wind atlas information

Both the KNW-atlas and the DOWA are based on a global ECMWF reanalysis and are downscaled using the atmospheric weather model HARMONIE. The two atlases employ different methods (e.g. cold start versus no cold start) and use different versions of ECMWF reanalysis and the HARMONIE weather model. Information on the models and atlases are provided below.

2.1.1 Reanalysis

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

2.1.1.1 ERA-Interim

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

2.1.1.2 ERA5

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

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

2.1.2 *Numerical weather prediction model: HARMONIE*

HARMONIE (HIRLAM ALADIN Research on Mesoscale Operational NWP In Euromed), also known by the name AROME, is the numerical weather prediction model used operationally by KNMI since 2012. It is continually being improved and tested by the HIRLAM-ALADIN consortium (Figure 1). HARMONIE is a non-hydrostatic limited-area model that runs on a high-resolution grid spacing of 2.5 km. More details regarding HARMONIE /AROME can be found in Seity et al. (2011) and online (www.hirlam.org). HARMONIE model set-up can be found in Toros et al. (2014). HARMONIE version CY37h1.1 was used to produce the KNW-atlas and HARMONIE version CY40h1.2.tg2 was used to make the DOWA. Compared to CY37h1.1, CY40h1.2.tg2 incorporates an improved turbulence parameterization (HARATU) that enables enhanced estimates of wind speed (De Rooy 2017).

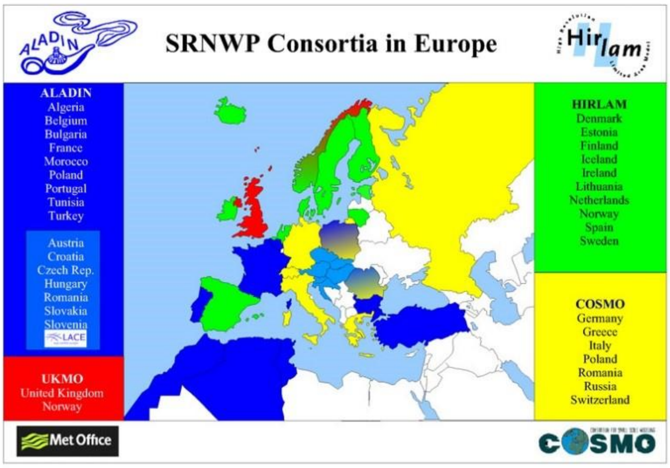

Figure 1 Participating countries in the HIRLAM (green) and ALADIN (blue) consortiums (source: http://www.eumetnet.eu).

2.1.3 *Wind atlases*

2.1.3.1 *KNW-atlas*

The KNMI[1] KNW-atlas was the first atlas based on a period long enough to capture variability in the Dutch wind climate and it was the first Dutch-based atlas to provide wind information above 100 m. The KNW-atlas released in 2013 captured 35 years of atmospheric variability from 1979 to 2013. As part of the DOWA project, the KNW-atlas was extended using the same model-setup to guarantee a homogeneous dataset. The KNW-atlas will eventually encompass more than 40 years (i.e. 1979 – at least March 2019). The downscaling of ERA-Interim using HARMONIE CY37h1.1 resulted in hourly outputted data at a horizontal grid spacing of 2.5 km. Wind speeds were subject to a shear-correction term that was tuned to match wind measurements made at the 200-m Cabauw tower; the shear-correction term was uniformly applied (i.e. the same for all heights and locations) throughout the KNW domain. Prior validation of the KNW-atlas demonstrates a climatological (long-term average and extremes) accuracy that (for wind turbine hub heights typical of the period [~80 m])

[1] 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

is comparable to that of measurements. The accuracy of the long-term average wind speeds was less than 0.5 ms^{-1} at a height of 10 m and less than 0.2 ms^{-1} at higher heights. Additional information on the KNW-atlas can be found online (http://projects.knmi.nl/knw/index.html).

2.1.3.2 *DOWA*

Creating the DOWA[2] was part of a joint project with ECN part of TNO, Whiffle, and KNMI. The DOWA is a wind atlas based on a 10-year (2008-2017) reanalysis. Due to the limited time span of the DOWA, it cannot adequately capture North Sea wind climate variability like the KNW-atlas. Therefore, the DOWA is not expected to provide any significant improvements to the climatological accuracy of the KNW-atlas. However, the DOWA is expected to improve hourly wind correlation. Furthermore, the DOWA atlas provides wind information up to 600 m heights and includes information that can enable Large Eddy Simulation (LES) downscaling from hourly data to less than 60 s and from a 2.5-km horizontal resolution to less than 100 m horizontally. The DOWA domain is also larger than that of the KNW-atlas, even including areas where German wind farms are being planned and built (Figure 2). The DOWA domain is defined by a 789 gridpoint by 789 gridpoint grid that is centered on the KNMI meteomast Cabauw that is a part of the Cesar observatory[3].

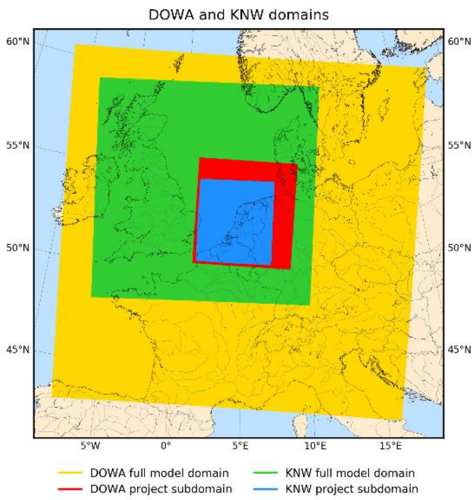

Figure 2 The DOWA was made and saved on a domain of 789 by 789 points centered around Cabauw (yellow area). The shaded portions depict the DOWA and the KNW-atlas domains.

In addition to using new models (i.e. ERA5 instead of ERA-Interim and HARMONIE CY40h1.2.tg2 instead of CY37h1.1), new methodologies were implemented within the DOWA, which are detailed in the bullets below.

- **Assimilation of measurements:**
  - For the KNW-atlas, no additional measurements were assimilated into HARMONIE during the process of downscaling (i.e. the only

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

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

measurements used were the ones assimilated in the ERA-Interim reanalysis).

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

- **Cold start:**
  - For the KNW-atlas, each six-hour forecast period started with the ERA-Interim reanalysis (cold start). Subsequently, HARMONIE (using no additional data assimilation) was used to produce the +1 hr up to the +6 hr forecast.
  - Except at the beginning of each parallel stream[4], no cold starts were used in the DOWA. The DOWA is comprised +1 hr, +2 hr, and +3 hr HARMONIE forecasts. At each hour, the boundaries of the DOWA domain (North, South, East, and West at all model levels) are fed with ERA5 reanalysis data, and each three-hour forecast cycle is initialized using the latest HARMONIE forecast of the previous cycle (i.e. no cold starts with ERA5 data) and data-assimilated measurements.

Relevant differences between the KNW-atlas and the DOWA are summarized in Table 1. Additional DOWA details can be found online (http://www.dutchoffshorewindatlas.nl/).

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

KNMI North Sea Wind (KNW) Atlas	Dutch Offshore Wind Atlas (DOWA)
1979 – 2019 (40 years)	2008-2017 (10 years)
Captures the variability of the North Sea wind climate	Does not capture the variability of the North Sea wind climate
Based on ERA-Interim reanalysis and the mesoscale weather model HARMONIE Cycle 37h1.1	Based on ERA5 reanalysis (follow-up of ERA-Interim with higher spatial and temporal resolution) and the mesoscale weather model HARMONIE Cycle 40h1.2.tg2 (improved wind information because turbulence is modelled better)
HARMONIE only used as downscaling tool (data assimilation of measurements in ERA-Interim only)	Additional HARMONIE data assimilation (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	Includes the information required for further LES-downscaling

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

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

2.2 ASCAT measurements

The ASCAT coastal product[5] 10-m equivalent winds (Figure 3) were used in this study to examine the performance of global ECMWF reanalysis (ERA-Interim and ERA5) and the two wind atlases (KNW-atlas and DOWA) over sea. 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[6] 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 (i.e. the same year that was previously used to validate the KNW-atlas). 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. Therefore, wind atlas validation was only performed at approximately these time intervals (i.e. when ASCAT measurements were available).

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 ms^{-1} in coastal areas (i.e. $\leq$ 50 km from the coast) and -0.29 ms^{-1} elsewhere.
- The standard deviation of the error between ASCAT and buoy measurements is less than 1.6 ms^{-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.
- ASCAT wind measurements near port areas (e.g. port of Rotterdam) are biased because ships enhance the backscatter of radiation. Spurious backscatter can be detected and rejected by quality control algorithms during periods with low winds, but can fail to do so during periods of high winds. Referred to as the anchor issue, this spurious backscatter can cause wind measurements near these areas to be high. Therefore, data from port regions were not considered in this validation study. However, these anomalous velocities are still evident in the spatial plots.

[5] http://www.knmi.nl/scatterometer/ascat_osi_co_prod/ascat_app.cgi

[6] 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.

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. Indian [00 and 12 UTC passes] and Chinese [6 and 18 UTC passes]) would make validation of the diurnal cycle possible. However, this is beyond the scope of this study, as is using the whole of the collocated dataset (2008-2018). Further, it should be noted that although ASCAT observations were assimilated into HARMONIE, and therefore were used to produce the DOWA, it is still a suitable measurement source for validation. This is because DOWA forecasts, and not DOWA analyses, are what is being validated. Only ASCAT measurements within $\pm$90 minutes (i.e. the assimilation window) of the DOWA analyses time (i.e. three-hour cycles were used in the DOWA) were assimilated. Therefore, the DOWA forecasts outside of the assimilation window are independent of the assimilated ASCAT measurements.

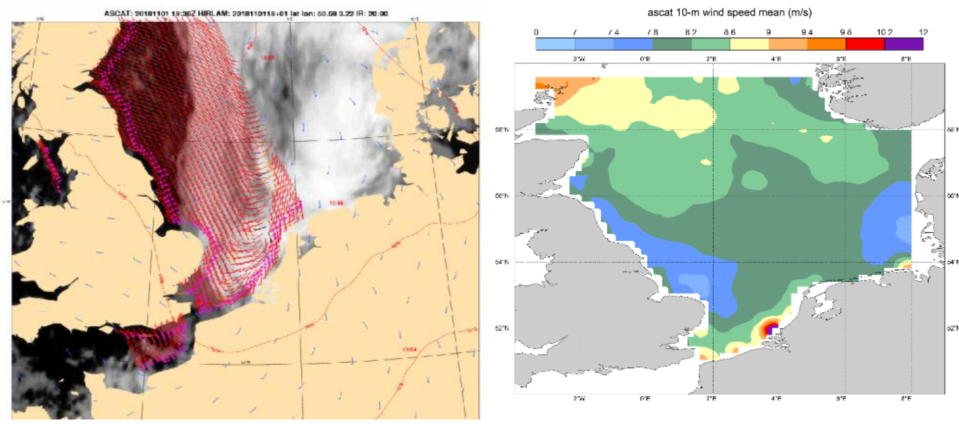

Figure 3 (Left) ASCAT 10-m wind measurements (coastal product on a 12.5-km grid) from a single Metop-A overpass on 1 November 2018 at 19:56 UTC. This picture shows the scatterometer winds (in arrows or flags), with an infrared satellite image (from METEOSAT, GOES or GMS), and numerical weather prediction model winds (currently only HIRLAM forecast in the Northern Atlantic region, in blue arrows or flags). The scatterometer winds are plotted on a cell spacing of 25 km (i.e. only a quarter of the wind vectors is plotted). (Right) The 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).

3 Results

Comparison of ASCAT winds with ERA-Interim, ERA5, the KNW-atlas, and the DOWA was performed for the North Sea domain (Figure 4[left]). This domain is smaller than the full DOWA domain (Figure 2 yellow area), but larger than the DOWA domain that is publicly available (Figure 2 red area). For each ASCAT wind measurement in the North Sea domain, the nearest (both spatially and temporally) reanalysis/atlas wind speed and direction were identified and were used to assess the performance of the respective model in depicting the 10-m equivalent wind speed and direction. The performance of global ECMWF reanalyses and the wind atlases was also examined across a coastal subdomain (or zone), defined as the area between 15 km and 30 km from the Dutch Coast[7]. ASCAT measurement points within this coastal zone from a single overpass of the satellite are provided in Figure 4 (right) to demonstrate the area considered. However, grid point locations within this subdomain will be different for every satellite overpass. Therefore, the plotted grid points are not those used for validation at each date and time stamp.

Figure 4 Example ASCAT measurement locations within the coastal zone.

3.1 Wind speed distribution

The 2013 wind speed distribution at 10 m for both ASCAT and the collocated datasets (ERA-Interim, ERA5, the KNW-atlas, and the DOWA) are provided in Figure 5. The wind speed distributions were compared and the results are summarized below:

- For **2-5 ms^{-1}**: ERA-Interim, ERA5, the KNW-atlas, and the DOWA compare well, but overestimate how often these wind speeds occur compared to ASCAT. This overestimation does not necessarily mean that the reanalysis/atlas wind speed frequencies are wrong because ASCAT winds are known to be less accurate at low wind speeds.

- For **5-9 ms^{-1}**: ERA-Interim and the DOWA slightly overestimate the wind speed probability density compared to that based on ASCAT measurements. The KNW-atlas and ERA-5 slightly underestimate the wind speed probability density (the KNW-atlas more than ERA5) compared that based on ASCAT measurements.

[7] Note that ASCAT can only measure the wind up to 15 km from the coast.

- For **9-13 ms^{-1}**: ECMWF reanalyses and the wind atlases compare well, but slightly overestimate the wind speed probability density compared to that based on ASCAT measurements.
- For **13-25 ms^{-1}**: ERA5 and the KNW-atlas provide the most accuracy compared to ASCAT. ERA-Interim and the DOWA slightly underestimate the probability density within this wind speed range compared to that based on ASCAT measurements.

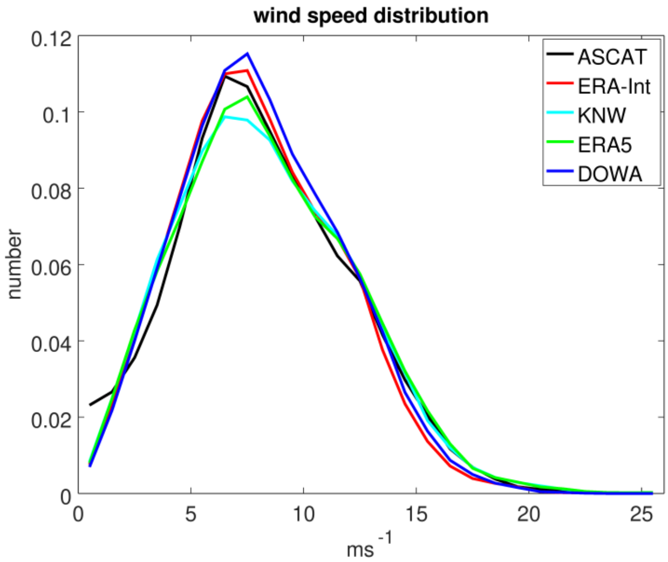

Figure 5 Wind speed distribution at 10 m for 2013 based on the collocated datasets for the North Sea domain. Compare to Fig. 3.8 in http://bibliotheek.knmi.nl/knmipubTR/TR353.pdf where ERA-Interim is called ECMWF-OPER.

It must be noted that the wind speed distribution at 10 m cannot be readily translated to that at hub height (Wijnant et al. 2015). Furthermore, for wind energy purposes, the wind energy distribution below the 'cut-in' wind speed (typically ~ 3-5 ms^{-1}) is not relevant.

3.2 Observation minus model (o-b) statistics

This section examines the mean and standard deviation of the error between the ASCAT measurements and the wind atlas (KNW-atlas and the DOWA) data and between the ASCAT measurements and the reanalyses (ERA-Interim and ERA5) data. This error is referred to as the o-b statistic, where o represents the observation (or measurement) and b represents the reanalyses or wind atlas value. The mean (also referred to as the bias) and standard deviation of the o-b statistic will be provided for wind speed (Figure 6c), wind direction (Figure 6d), and the u (i.e. east-west [Figure 6a]) and v (i.e. north-south [Figure 6b]) wind components. While o-b statistics are provided for the u and v wind field components, they are not explicitly discussed. As previously noted, the Rotterdam anchor issue has been removed from the data that these statistics are based on.

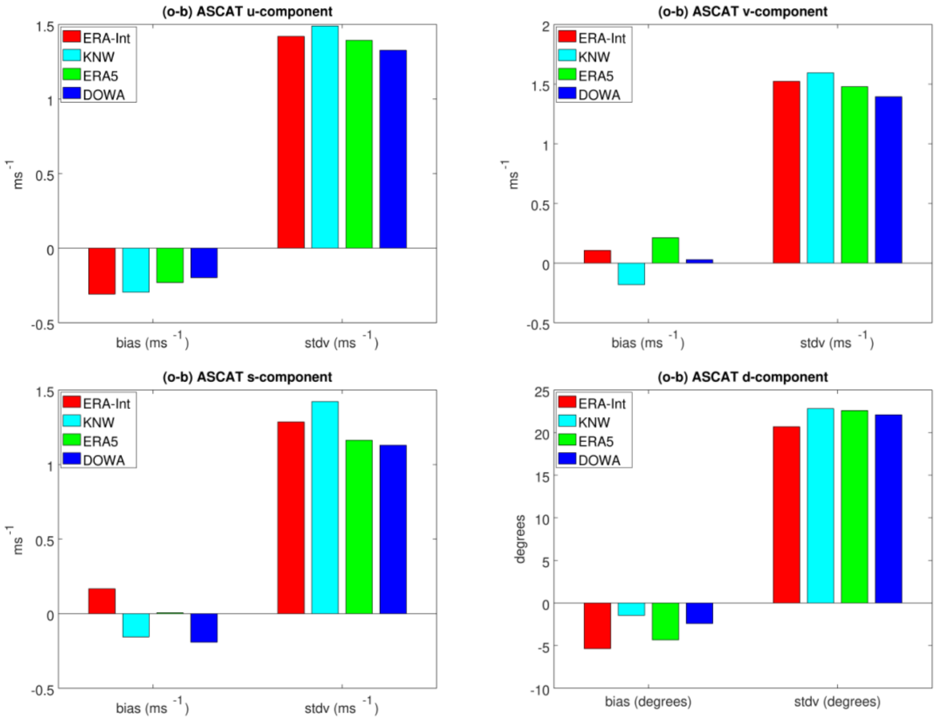

Figure 6 North Sea domain o-b statistic histograms for 2013 of the mean bias and standard deviation of ASCAT versus ERA-Interim (red), KNW-atlas (cyan), ERA5 (green), and the DOWA (blue) for the zonal wind component u (top left), the meridional wind component v (top right), wind speed (bottom left), and wind direction (bottom right).

3.2.1 North Sea Domain

3.2.1.1 O-B mean bias (North Sea domain)

On average the wind speed at the 10-m height differs less than 0.2 ms^{-1} from ASCAT for both the reanalyses and the wind atlases (Figure 6 [bottom left panel]). The KNW-atlas and the DOWA both slightly overestimate the ASCAT measured wind speeds, while ERA-Interim slightly underestimates the wind speed. The o-b statistic bias of ERA5 is almost zero. Previous analyses indicated that ASCAT underestimates buoy wind speeds by about 0.25 ms^{-1}, which means that both the KNW-atlas and the DOWA correspond well with buoy measurements.

The o-b analysis of wind direction indicates that both the reanalyses and the wind atlases (Figure 6 [bottom right panel]) produce a negative wind direction bias (i.e. the wind directions are veered compared to ASCAT); however, the magnitude of this difference was rather small ($\leq 5^0$). Both the KNW-atlas and the DOWA exhibit reduced mean wind direction biases compared to the ECMWF reanalyses; the KNW-atlas improves the average wind direction compared to ERA-Interim and the DOWA improves the average wind direction compared to ERA5.

3.2.1.2 *O-B standard deviation (North Sea domain)*

The standard deviation of the o-b statistic lends insight into the level of realistic and real[8] detail produced by the reanalyses or the wind atlases. The smaller the o-b statistic 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).

- An important result is that ERA5 produces wind fields with more realistic and real detail than ERA-Interim (i.e. the o-b statistic standard deviation of ASCAT-ERA5 is smaller than the o-b statistic standard deviation of ASCAT-ERA-Interim). This means that the additional variance of ERA5 verifies better with the with the ASCAT measurements that does the additional variance of ERA-Interim (see also Marseille et al. (2019) and Belmonte and Stoffelen (2019).

- HARMONIE Cycle 40h1.2.tg2 adds even more realistic and real detail to ERA5 in the DOWA. For both wind speed and direction, the DOWA exhibits a smaller o-b statistic standard deviation value than ERA5. These results are encouraging because they are in contrast to typical model behavior, wherein the o-b statistic standard deviation generally increases as a result of downscaling to finer resolutions (i.e. the finer details look realistic, but are not real). This is partially due to the ‘double penalty effect’, where the model is penalized twice if its forecast for a specific location and time is incorrect (i.e. event predicted where it did not occur and no event predict where it did occur). For low-resolution models (i.e. ERA-Interim), small-scale features are smeared (smoothed), which can improve the statistics (e.g. o-b statistics). This partly[9] explains why the o-b statistic standard deviation of ASCAT-KNW is larger than that of ASCAT-ERA-Interim.

- The standard deviation of the o-b statistic is smaller for the DOWA than for the KNW-atlas, especially for wind speed. This implies that despite these two wind atlases having the same spatial resolution, the detail in the DOWA is more real and realistic than that in the KNW-atlas,.

- The DOWA produces the most realistic and real wind speed fields (i.e. the o-b statistic standard deviation value of ASCAT-DOWA is smaller than that of ASCAT-KNW, ASCAT-ERA-Interim, and ASCAT-ERA5.

- For wind direction, the standard deviation of the o-b statistic is smaller for ERA-Interim than for the DOWA. However, this might be due to the smoothing effect evident within low-resolution models such as ERA-Interim.

3.2.1.3 *Conclusion analysis O-B statistics (North Sea domain)*

Analysis demonstrates that during 2013, the KNW-atlas exhibited a slightly better ability than the DOWA to depict the mean wind state (wind speed and direction) within the North Sea domain. However, the main objective of the DOWA was not to significantly improve the mean wind conditions, but rather its objective was to produce more realistic and real data within the wind fields. This objective was accomplished

[8] “Real” is more than just “realistic”: it means that the phenomena is at exactly the right location and moment in time. Numerical weather model Harmonie can for example very realistically simulate squall lines (whereas ECMWF cannot), but generally they are at the wrong location (not real).
[9] The other part may be that downscaling did not converge within 6 hours, so spurious atmospheric features possibly still present due to (partly) downscaling.

within the DOWA as demonstrated by reduced o-b statistic standard deviation values for both wind speed and direction. This implies that the ASCAT 10-m equivalent winds correlate better with the DOWA than they do with the KNW-atlas. It can be additionally said that the wind fields in ERA5 are more realistic and real than in ERA-Interim and that the DOWA adds more real and realistic detail to the wind fields in ERA5.

3.2.2 *Coastal zone*

Downscaling to finer resolutions is expected to have a larger effect in coastal areas (heterogeneous land-sea interface) than further offshore where the surface is more homogeneous. Therefore, the o-b statistics were also analysed within a coastal zone (Figure 7). These results are even more interesting because future wind farm development is planned for these regions.

In general, model errors were larger within the coastal zones than they were for the entire North Sea domain (note the different y-axis range used in Figure 7 compared to Figure 6). Within the North Sea domain, both the KNW-atlas and the DOWA overestimate the ASCAT mean wind speed (negative o-b statistic bias), while within the coastal zone the atlases underestimate the ASCAT mean wind speed (positive o-b statistic bias). The ECMWF reanalyses underestimate the ASCAT mean wind speeds in both validation domains (i.e. the North Sea and the coastal zone). Compared to the respective ECMWF reanalysis models that the wind atlases are based on, both the KNW-atlas and the DOWA significantly reduce the o-b statistic bias for both wind speed and direction. Within the coastal zone, the mean wind speed bias is approximately -0.4 ms^{-1} for the KNW-atlas and -0.3 ms^{-1} for the DOWA. While the DOWA exhibits a reduced wind speed bias within the coastal zone compared to the KNW-atlas, the KNW-atlas exhibits a smaller wind direction bias than the DOWA.

For the whole North Sea domain, only the DOWA adds realistic and real detail to the coarser reanalysis model, but within the coastal zone both the KNW-atlas and the DOWA do (at least for wind speed). The atlases do not significantly improve the o-b statistic standard deviation of the reanalyses for wind direction (regardless of the validation domain). However, the DOWA resolved wind direction structure is slightly better than that produced in ERA5.

3.3 Horizontal (10m) wind speed shear

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, provides an indication of the spatial detail and structures resolved within the reanalysis or wind atlas[10]. Comparing the horizontal wind speed shear evident within the reanalysis/wind atlas to that based on ASCAT measurements lends insight into whether the model-resolved structure is realistic or not. Here, the standard deviation of the 10-m horizontal wind speed shear averaged over the North Sea domain was used to assess how realistically ERA-Interim, ERA5, the KNW-atlas, and the DOWA represent the atmospheric structures measured by ASCAT. Comparison in the west-east direction is provided in Figure 8. The comparison in the south-north direction is similar, but is not shown. The lower the standard deviation value, the smoother (i.e. less structure) the resolved wind field. Note that this comparison does

[10] An analysis of the horizontal wind speed shear was also performed for the KNW-atlas (http://bibliotheek.knmi.nl/knmipubTR/TR353.pdf 3.2.1): it showed that the KNW-atlas has a similar level of detail as ERA-Interim for the +1h lead time and as ASCAT from +4h lead times

not reveal if the details are real (actually occur at the same point in time or at the exact same location).

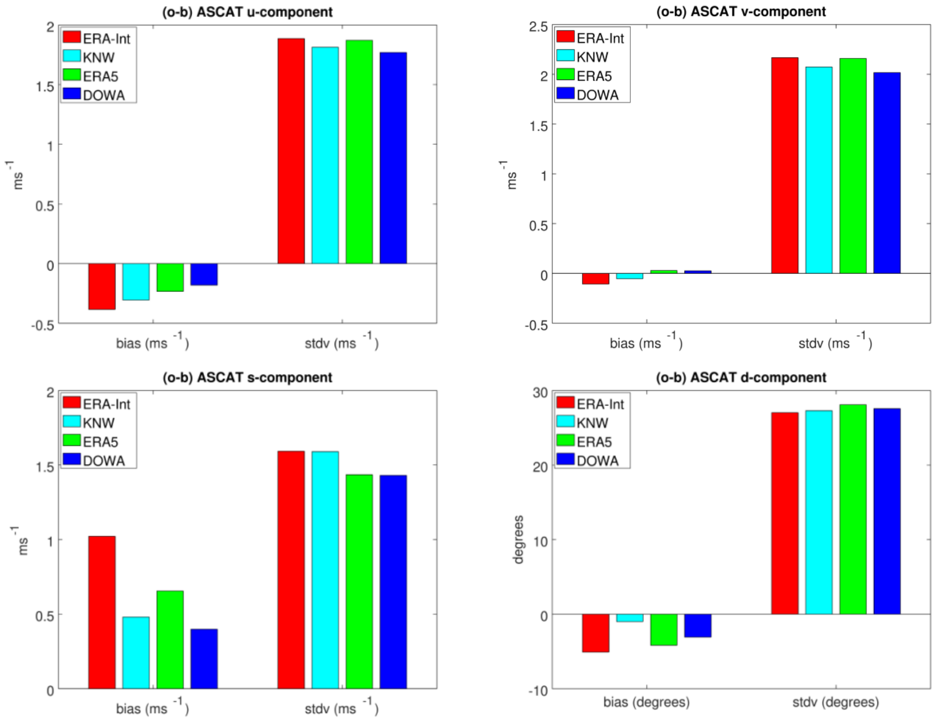

Figure 7 Same as Figure 6, but for the coastal zone (defined in text).

Unlike the analysis in Section 3.2, performance is defined relative to the u and v wind components. As expected, the ASCAT-measured u and v wind components exhibit the largest standard deviation (i.e. are the most realistic). The measured wind field structure is best represented by the DOWA, followed by the KNW-atlas. Despite using the same HARMONIE grid spacing, the KNW-atlas exhibits less detail than the DOWA, mainly because it was generated from ERA-Interim cold starts at 6-hr intervals without any additional data assimilation. A more advanced downscaling-method was used to make the DOWA—i.e. no colds starts and data assimilation was performed every three hours into an improved version of HARMONIE to keep the model on track with the real atmosphere. Both the KNW-atlas and the DOWA were able to considerably outperform the ECMWF reanalysis in terms of producing detail in the u and v wind components. Furthermore, HARMONIE manages to add substantially more realistic detail to the wind field of DOWA from ERA5 than to the KNW-atlas from ERA-Interim. This again demonstrates the advantage of the new data assimilation technique and the improved performance of the new HARMONIE model version.

Although ASCAT measurements were assimilated into the HARMONIE model when making the DOWA, ASCAT measurements were first thinned to avoid oversampling (i.e. adding more detail to the model state than the model can actually resolve). This is why the DOWA-resolved detail is still less than that of the ASCAT measurements.

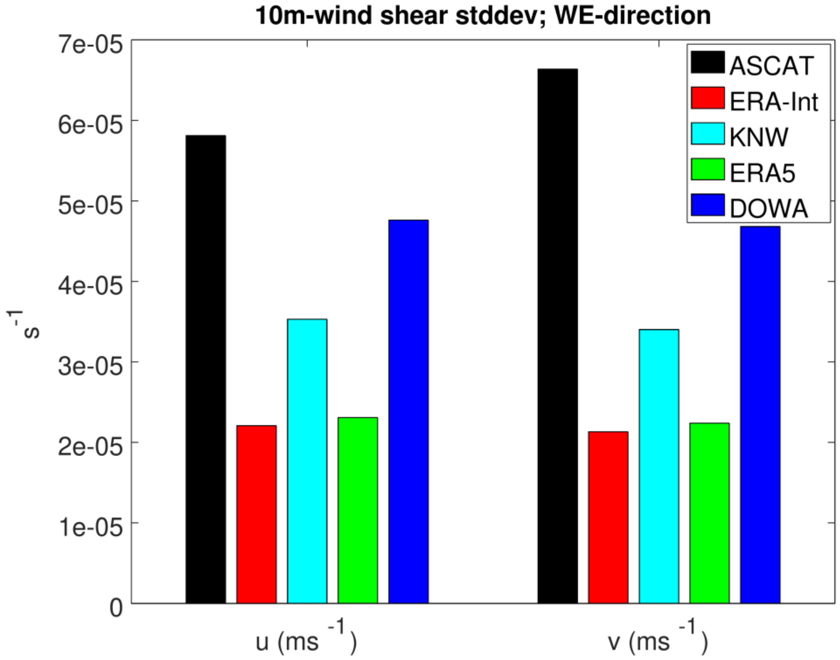

Figure 8 Standard deviation of the 10-m wind component difference between adjacent grid values divided by the grid size (i.e. horizontal shear) in the west-east direction for the zonal (i.e. u) and meridional (i.e. v) wind components.

3.4 Spatial plots

Annual average winds speeds for 2013 were determined for each model grid point within the North Sea domain in order to extract a spatial characterisation of the 10-m wind field. The difference between ASCAT and ERA5 annual average wind speeds are shown in Figure 9 (left), and the difference between ASCAT and the DOWA annual average wind speeds are shown in Figure 9 (right). For most of the North Sea domain, the DOWA overestimates the 10-m wind speed by less than 0.5 ms^{-1}, while the ERA5 exhibits a bias between -0.3 ms^{-1} and +0.3 ms^{-1}. For a large part of the North Sea domain, ERA5 actually exhibits a very small bias between -0.1 ms^{-1} and +0.1 ms^{-1}. However, ERA5 underestimates the 10-m wind speeds significantly in the Dutch coastal region. Figure 9 shows the benefit of downscaling ERA5 with HARMONIE in the coastal zone (i.e. the bias in the 10-m wind speeds is reduced). Differences between ASCAT and the KNW-atlas (Figure 10[left]) and ASCAT and the DOWA (Figure 10[right]) were also examined (note that the quantity model-observation is plotted, which explains the reversed colormap from Figure 9). Near-coastal performance is slightly better for the DOWA than it was for the KNW-atlas (see also Figure 7).

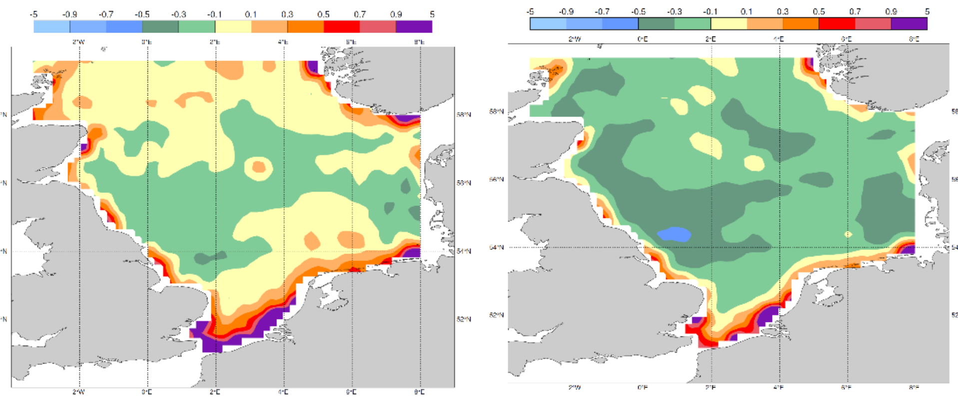

Figure 9 (Left) ASCAT-ERA5 10-m wind speed bias and (Right) ASCAT-DOWA 10-m wind speed bias. Statistics near the Rotterdam port are biased by the anchor issue.

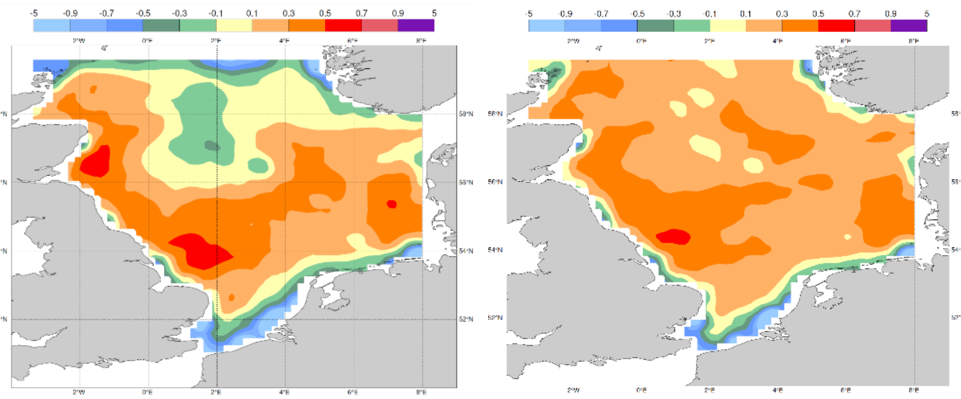

Figure 10 (Left) KNW-ASCAT 10-m wind speed bias and (Right) DOWA-ASCAT 10-m wind speed bias. Statistics near the Rotterdam port are biased by the anchor issue.

4 Conclusions

The creation of the DOWA was part of a joint project with ECN part of TNO, Whiffle, and KNMI. The DOWA is a wind atlas based on a global reanalysis dataset (ERA5) that captures 10 years (2008-2017) of meteorological measurements and generates 3D wind fields consistent with these measurements and the laws of physics. This dataset is downscaled using the weather forecasting model HARMONIE with a horizontal grid of 2.5 km. The aim of making the DOWA was to create an atlas that, relative to the KNW-atlas, could provide: (1) improved hourly correlation and a better representation of the diurnal cycle, (2) wind information up to higher heights (i.e. 600 m), and (3) wind information across a larger horizontal domain. In order to accomplish this, an improved version of ECMWFs global reanalysis was used (ERA5) as the boundary condition as well as a new version of HARMONIE with improved turbulence parameterizations. Also, the method that was used to make the atlas was improved (i.e. no cold starts and additional assimilation of innovative measurements [i.e. ASCAT and MODE-S EHS]). In this report, the performance of the DOWA was validated against ASCAT wind measurements and was compared to the performance of the KNW-atlas and the hosting ECMWF weather reanalyses (ERA-Interim and ERA5). The main conclusions are: (1) the DOWA adds realistic and real detail to ERA5 wind speeds and directions and in that respect is also better than the KNW-atlas, and (2) the DOWA significantly reduces the bias in wind speed for the coastal zone.

The validation of the DOWA based on one year of data (2013) was performed for both the whole North Sea domain and for a coastal zone where Dutch offshore wind farms are planned. For the whole North Sea, the biggest discrepancy between the global reanalyses and the wind atlases occurred for wind speeds between 5 ms^{-1} and 9 ms^{-1}. Within this wind speed range, the DOWA and ERA-Interim both slightly overestimate the wind speed probability density compared to ASCAT, while ERA5 and the KNW-atlas underestimate the wind speed probability density. For other wind speeds, differences with the ASCAT wind speed distribution are small. Considering all ASCAT measurements made across the North Sea domain, both the KNW-atlas and the DOWA on average overestimate the 10-m wind speed, while ERA-Interim slightly underestimate the wind speed, and ERA5 shows a bias of almost zero. Although the DOWA did not significantly improve the o-b statistic wind speed bias compared to the KNW-atlas or ERA5 (the DOWA exhibited a mean bias of less than 0.2 ms^{-1}), the DOWA did demonstrate an enhanced ability relative to ERA5 to depict the annual average wind direction.

The improvements of the DOWA are better demonstrated through analysis of the o-b statistic standard deviation. The standard deviation of the o-b statistic lends insight into the level of real and realistic detail produced by the respective model. The o-b statistic standard deviation for wind speed was smallest for the DOWA, both for the whole North Sea domain and for the coastal zone. Further, the DOWA o-b statistic standard deviation for wind direction was slightly less than that of ERA5. These results demonstrate that an added benefit of the DOWA is improved wind correlation. Within the coastal zone, the o-b statistic wind speed bias is significantly larger than for the whole North Sea, and within this region, the wind speed is underestimated by both the reanalyses and the atlases. However, the KNW-atlas and the DOWA are significantly better than their hosting reanalysis models (ERA-Interim and ERA5) within the coastal zone as defined by the o-b statistic standard deviation for wind speed, and to a lesser extent the o-b statistic standard deviation for wind direction. These results demonstrate the strength of HARMONIE in its ability to produce realistic small-scale structures in the wind field.

Horizontal wind component shear between neighboring model grid points was examined in both the west-east and north-south direction in order to determine the model that best depicts the spatial wind field structure. The DOWA best resolved the spatial wind field structure in the east-west direction, taking ASCAT as reference, and in general both wind atlases outperformed their respective ECMWF reanalysis. Analyses concluded with spatial comparison plots to further emphasize the performance of the ECMWF reanalyses and the two wind atlases. Through this analysis, the strength of the two wind atlases was highlighted in the coastal regions, where the impact of Harmonie downscaling and advanced data-assimilation was demonstrated. For most of the North Sea domain, the DOWA overestimated the 10-m wind speeds by less than 0.5 ms^{-1}.

4.1 Recommendations for future work

Below is a list of recommendations for future work.

- Expand the analysis period from 2013 to encompass 2008 to 2017. Both the DOWA, KNW-atlas, and ASCAT wind measurements are available for this period.
- Incorporate additional wind observing satellites (e.g. scatterometers from India and China) in order to enable diurnal cycle assessment.
- Improve ASCAT wind data quality control procedures in order to resolve the 'anchor issue' that was evident around port harbours such as Rotterdam.
- Perform a more quantitative analysis of the wind speed distribution, rather than just qualitatively speaking about the differences.
  - What are the impacts of these differences on the annual energy production (AEP) predictions?

4.2 Acknowledgements

The authors would like to thank Anton Verhoef for preparing both collocated ASCAT and ERA-Interim datasets and collocated ASCAT and ERA5 datasets. Furthermore, the authors would like to acknowledge that this projected was supported with Topsector Energy subsidy from the Ministry of Economic Affairs and Climate Policy.

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6 Signature

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