Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

Validation of KNW atlas with scatterometer winds
(Phase 3 of KNW project)

I.L. Wijnant, G.J. Marseille, A. Stoffelen, H.W. van den Brink and A. Stepek

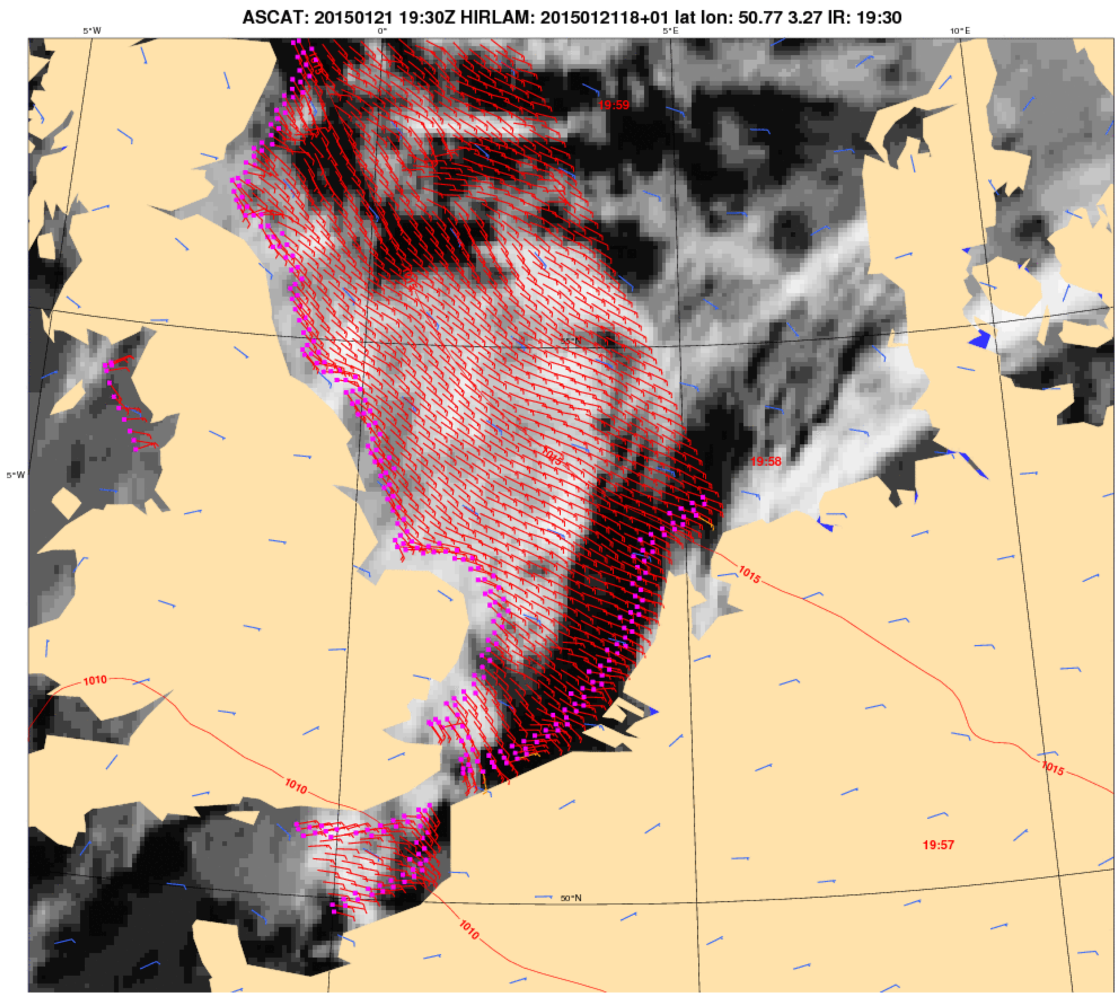
De Bilt, 2015 | Technical report; TR-353

Validation of KNW atlas with scatterometer winds

(Phase 3 of KNW project)

I.L. Wijnant, G.J. Marseille, A. Stoffelen, H.W. van den Brink and A. Stepek

April 2015



Abstract

The KNW (KNMI North Sea Wind) atlas is based on the ERA-Interim reanalyses dataset which captures 35 years (1997-2013) of meteorological measurements and generates 3D wind fields consistent with these measurements and the laws of physics. This dataset is "downscaled" using the state-of-the-art weather forecasting model, HARMONIE with a horizontal grid of 2.5 km. The result is a high resolution dataset of 35 years: the KNW dataset. In this report the KNW winds at 10 m above mean sea level are validated against two datasets of scatterometer measurents: the 10 m wind product derived from the ocean surface winds measured by the Seawinds scatterometer instrument on board the polar orbiting QuikSCAT satellite and the ASCAT (Advanced Scatterometer) coastal product of the EUMETSAT OSI-SAF (Ocean and Sea-Ice Satellite Application Facility).

This report deals with the validation of the KNW wind atlas in the horizontal dimension with measurements valid at 10 m above the sea surface. In another report we validate the atlas in the vertical dimension against measurements made on 3 tall masts in the North Sea (Stepek et al, 2015). The reports are identical from the introduction up to and including section 1.1.3. The KNW dataset that is validated horizontally has not been corrected for the model's underestimation of the vertical shear of the horizontal wind speed (since this has little effect on the wind speed at 10 m) whereas the vertically validated dataset has been corrected. The vertically validated dataset falls just within the area bounded by 50.25-54.75 NB and 1.50-8.25 EL (publicly available from the middle of 2015) whereas the horizontally validated dataset covers the whole of the North Sea. To avoid confusion: the KNW dataset is different from the North Sea wind climatology described in KNMI TR343 (Wijnant et al, 2014). Both the KNW dataset and the climatology of TR343 are based on re-analyses model ERA-Interim, but the "downscaling" procedures used are different. The KNW dataset followed up the wind climatology of TR343 so quickly that the TR343 dataset was never made available to a wider public.

- The probability of 10 m wind speeds of > 10 m/s occurring along the Dutch west coast is correctly modelled by the KNW atlas and more than half the wind energy produced by wind turbines on the North Sea is generated at these wind speeds. The atlas overestimates the probability by less than 5% in English coastal waters and 3% or less further offshore. These conclusions are based on comparison with both QuikSCAT and ASCAT scatterometer measurements. Comparison with the vertical validation results indicates that the conclusions for the 10 m wind speed may also be valid in general terms at wind turbine hub height.
- The KNW atlas 10 m wind speeds are on average 0.3-0.4 m/s too high for most of the North Sea. For the southern part (including the wind energy areas Borssele and Hollandse Kust) the KNW atlas underestimates the 10 m wind speed by 0.1-0.3 m/s and probably slightly more. The comparison with both scatterometers supports the first conclusion. The second is based on the comparison with the QuikSCAT measurements (as there is only one year of ASCAT measurements and in that area the ASCAT measurements may be contaminated by the influence of the anchor areas). Comparison with the results of the vertical validation against tall measurement masts indicates that it cannot be assumed that the overestimation found at 10 m height means that KNW also overestimates the wind speed at wind turbine hub height.
- The KNW atlas does not make use of HARMONIE at its full potential since the development of small-scale spatial structures, starting from smooth ERA-Interim fields, is still ongoing 6 hours into the forecast and KNW is based on the first 6 hours of the HARMONIE forecasts.

Acknowledgement

We want to thank the Directorate-General for Spatial Development and Water Affairs (DGRW) of the Dutch Ministry of Infrastructure and the Environment (IenM) for funding the KNW-atlas and its validation. More specifically we would like to thank Henk Merkus from DGRW for being so enthusiastic and helpful.

Content

Introduction

The KNMI North Sea Wind (KNW) atlas is based on 35 years (1979-2013) of ERA-Interim reanalyses[1] (80 by 80 km grid) and mesoscale atmospheric model HARMONIE (2.5 by 2.5 km grid, version CY37h1.1). The 6 hourly ERA-Interim reanalyses are used to initialise HARMONIE throughout its domain, so at the start of each forecast the HARMONIE values are the same as the ERA-Interim values. The resulting wind climatology consists of the + 1 hour up to and including the + 6 hour wind forecast of HARMONIE. The ERA-Interim climatology is as it were "down-scaled" to the HARMONIE 2.5 by 2.5 km grid in the course of each 6 hour forecast. This results in a three dimensional grid with a horizontal domain of 500 by 500 grid points and 60 levels along the vertical axis. For the vertical validation of the KNW atlas with publicly available wind mast measurements only part of this domain was selected and analysed (figure 0.1).

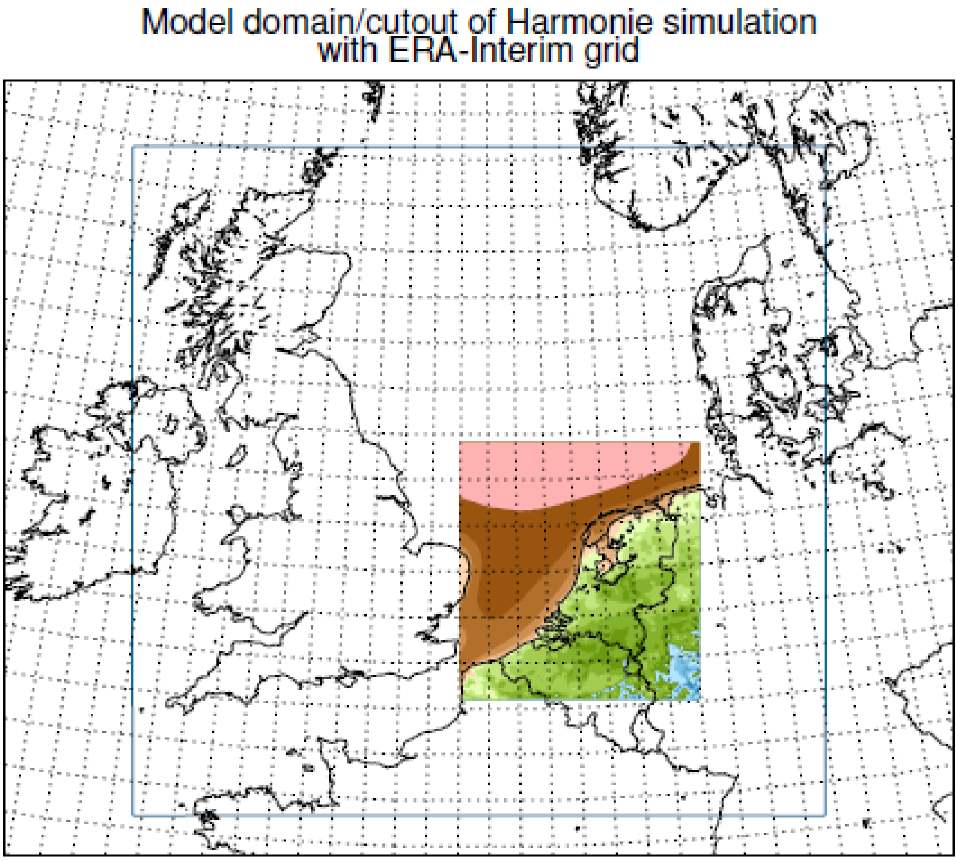


Figure 0.1
Domain of HARMONIE (blue) The coloured subdomain is stored and used for analyses. The grid lines indicate the ERA-Interim 0.75° by 0.75° grid cells (about 80 km by 80 km).

[1] A reanalyses is the representation of the atmospheric state that corresponds best with all available measurements in a way that is consistent with the laws of physics.

CHAPTER 1 Atmospheric models and scatterometer winds

1.1 Atmospheric models

1.1.1 ERA-Interim

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

The KNW-atlas is based on 35-years (1979-2013) of ERA-Interim reanalyses. This period is long enough to capture the natural long-term variability on the scale of decades of the current wind climate. The high resolution mesoscale model HARMONIE is used to enhance the spatial representation of the wind atlas which is especially beneficial in the coastal zone**.**

1.1.2 HARMONIE

HARMONIE (HIRLAM ALADIN Research on Mesoscale Operational NWP In Euromed), also known by the name AROME, is the numerical weather prediction model that KNMI uses operationally since 2012. It is extensively tested and continually improved by the HIRLAM-ALADIN consortium (figure 1.1). HARMONIE is a non-hydrostatic limited-area model which runs on a very high resolution grid (spacing of 2.5 km). For more details on HARMONIE /AROME, see Seity et al. (2011) and www.hirlam.org. Here, we use the CY37h1.1 version of HARMONIE that was released on 13 June 2012. More information on the HARMONIE model set-up can be found in Geertsema et al. (2014).

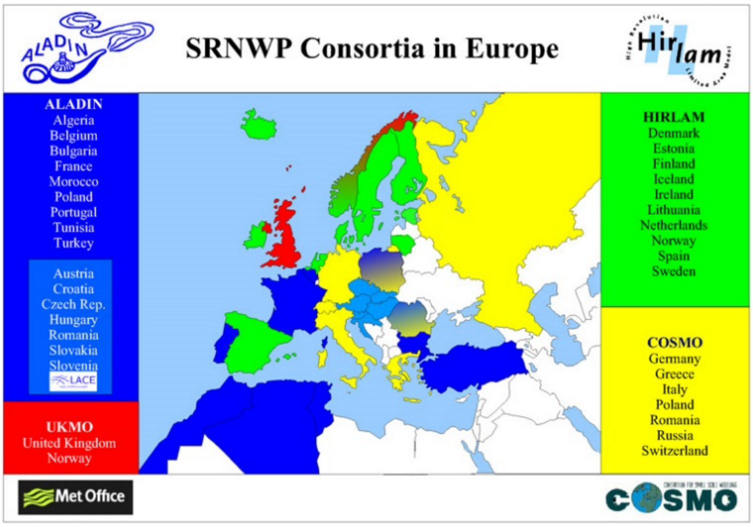


Figure 1.1 Participating countries in HIRLAM (green) and ALADIN (blue) consortium. (source: http://www.eumetnet.eu)

The HARMONIE data used are the forecasts for hours 1 up to and including 6. Every six hours ERA-interim provides a new initial state.

HARMONIE produces momentary values of wind speed for each grid box with a volume in the planetary boundary layer of 2.5 by 2.5 km and tens of meters deep. These values are volume averages of the wind speed in the grid box. Compared to anemometer measurements which average over much smaller volumes, the model values fluctuate less rapidly. Averaging the anemometer measurements over longer time periods provides wind speeds that fluctuate less rapidly too. To discover which averaging time provides the best agreement with the model's spatially averaged values, several averaging periods were applied to the 100 m height wind speed measurements of the FINO1 mast (corrected for mast effects). Figure 1.2 shows the result of this analysis. The blue values are based on hourly samples of running averages of the measurements and the red are based on all the available running averages. Sampling implies that yearly maxima are sometimes missed (so the blue line is lower than the red line). The KNW value should be compared to the blue values because the KNW values are also based on hourly samples (of the 60 momentary wind speeds per hour that HARMONIE generates). The KNW value can best be compared to the blue values based on 40-60 minute averages of the measured wind speed.

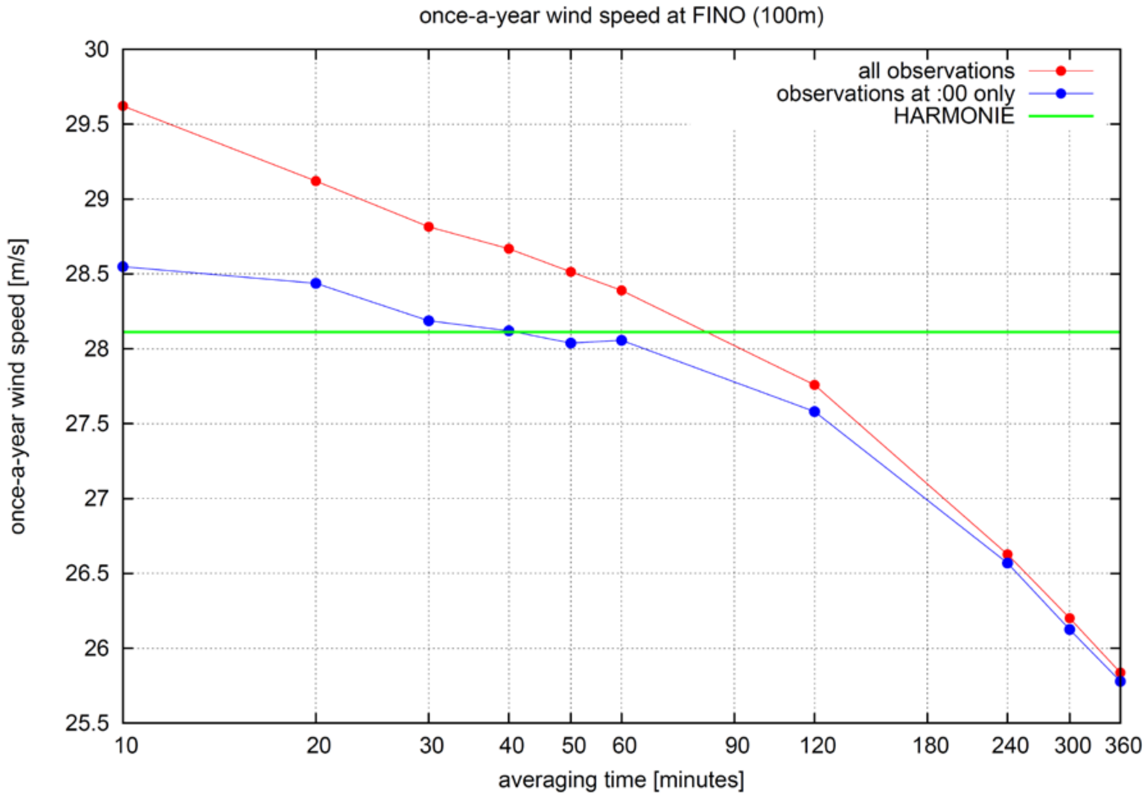


Figure 1.2: Comparison at FINO1 of the once a year return values of wind speed at 100 m from the KNW atlas (green) and from the measurements averaged over various lengths of time (blue and red).

For the comparison with measurements (which are 10 minute averages), it is assumed that the momentary model value should be compared to an hour of measurements (half an hour before to half an hour after the moment of the model value. All 6 measurements in the hour (every 10 minutes, all representing 10 min averages) are compared to this momentary HARMONIE value (figure 1.3). This may seem strange since we have shown that the HARMONIE values should be compared to hourly average anemometer measurements. However, the validation results are long term aggregates of the (HARMONIE – measurement) differences and are exactly the same as if the six 10 minute average measurements were first aggregated to hourly averages and then compared to the HARMONIE value.

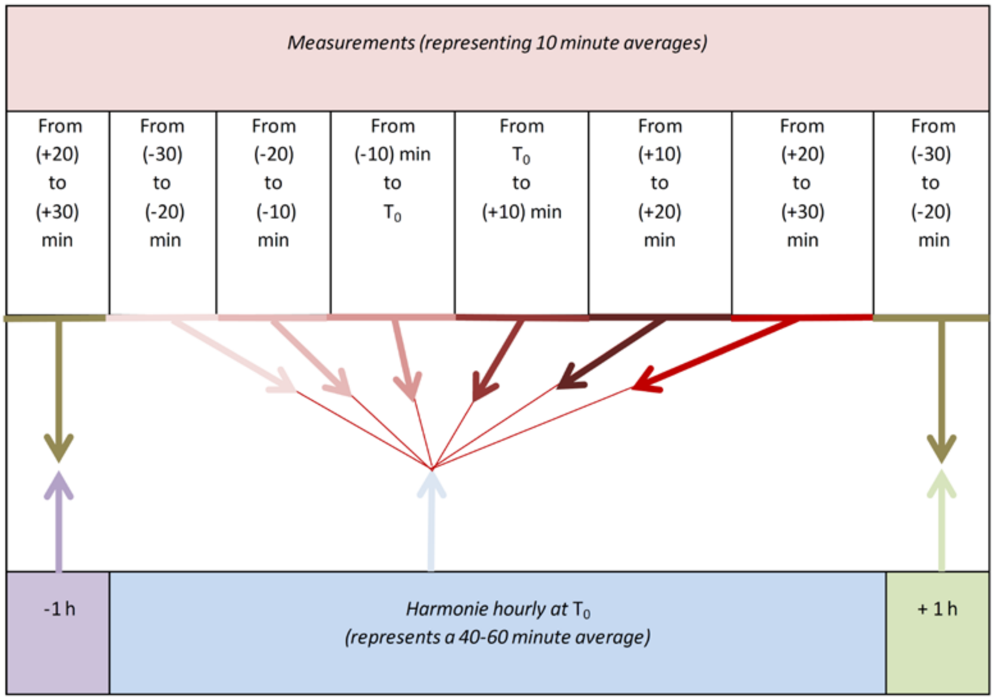


Figure 1.3 Validation scheme: for every 10 minute time step, the measurements (that represent 10 minute averages) are compared to one HARMONIE value (which represents a 40-60 minute average) i.e. the one at T_0 . So for every hour 6 different measurements (here reddish arrows) are compared to the same HARMONIE value (here blue).

1.1.3 Wind shear corrected HARMONIE

Most state-of-the-art operational weather forecasting and climate models have problems with the representation of wind profiles in stable conditions because they overestimate the vertical mixing, i.e., they underestimate the increase of wind speed with height (Wijnant et al., 2014). This is also the case for HARMONIE and more so for ERA-Interim. In a study comparing the wind speeds of HARMONIE initialised with ERA-Interim to mast measurements on the Dutch mainland for a 10-year period (2004-2013), Geertsema (2014) concluded that the model underestimates the vertical wind shear by a factor of about 15% which implies that the wind at a 100 m height is underestimated by about 5%. Fortunately, this small underestimation can be easily corrected (see Appendix A1). At all heights the HARMONIE wind speeds, corrected for the underestimation of the vertical wind shear, differ from the measured values at Cabauw by less than 0.1 m/s on average (figure 1.4). For four other tall masts at coastal sites the correction improved the validation results. At 100m height the underestimation of the wind speed was reduced by 0.3-0.4 m/s, leaving a difference of 0.1 m/s or less for three of the four masts. These validation results imply that the shear corrected HARMONIE wind speeds describe the 10 year average wind speed at nearly all locations on the mainland with an accuracy comparable to direct measurements.

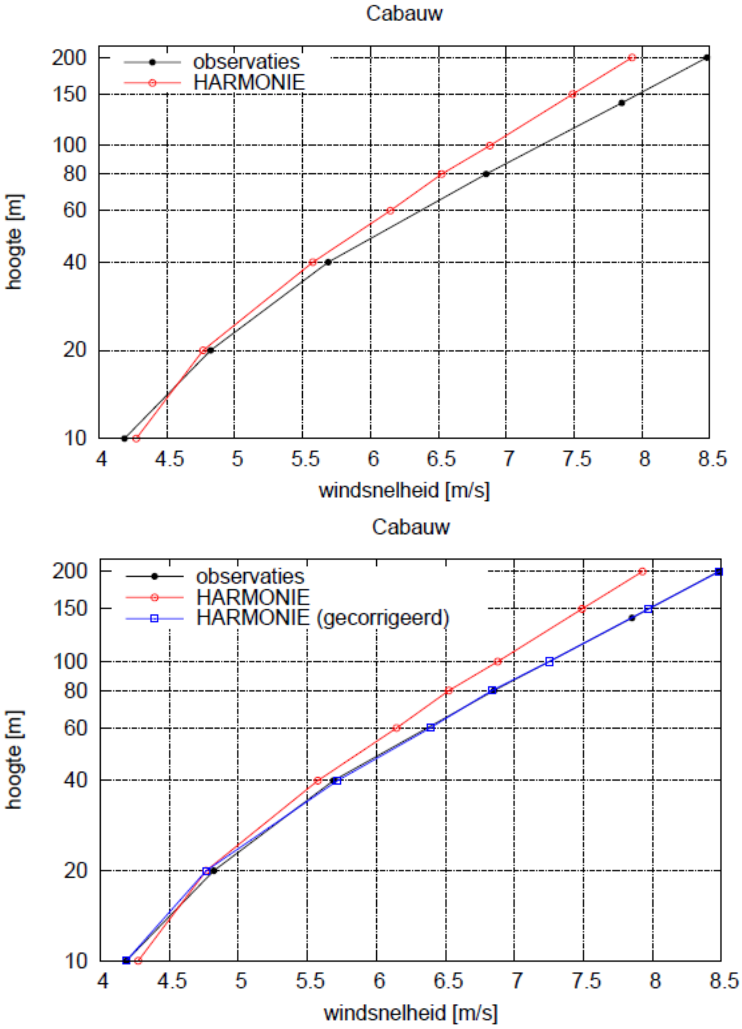


Figure 1.4 Average vertical wind profile Cabauw 2004-2013: observed (black), HARMONIE (red) and HARMONIE corrected (blue) (source: Geertsema, 2014).

Geertsema (2014) concludes that a shear correction should be generally applied to HARMONIE profiles for mainland locations and Stepek et al (2015) found that this shear correction also improves validation results at wind masts on the North Sea (OWEZ, FINO, MMIJ).

The KNW dataset validated against the scatterometer 10 m wind products has not been wind shear corrected because at this height the correction is very small.

1.2 Scatterometer winds

In this study the HARMONIE 10 m height winds of the KNW-atlas are compared to scatterometer winds which are derived from satellite measurements of sea surface roughness. The scatterometer measurements used are the available 10 years (1999-2009) from the SeaWinds scatterometer (on board the US polar orbiting QuikSCAT satellite) and one year from the ASCAT scatterometer (on board the polar orbiting European Metop-A satellite). Scatterometer winds are used operationally and have undergone extensive calibration and validation against measurements made on buoys and model winds using advanced methods. Moreover, they are routinely monitored for quality assurance[2].

Satellite observations are available twice a day for a given location and therefore do not represent the average of the full diurnal cycle. When deriving wind climatology from satellite observations, sampling biases have to be accounted for, but for the validation in this report sampling errors are not relevant because only collocated (synchronized) data are compared. This means that KNW-atlas data from periods when scatterometer data are not available, are not included in the validation. There are however a few problems with the validation dataset that are relevant here. Some scatterometer data are biased due to imperfections in quality control (QC) procedures. For example, QuikSCAT wind measurements affected by rain clouds are excluded and these rain-flagged data are biased towards higher wind speeds. Some ASCAT wind measurements are also biased. For example, those from the offshore anchor areas of the port of Rotterdam are too high because the ships enhance the backscatter of radiation which the instrument measures. Furthermore, the QC identifies this during periods with low winds and excludes these measurements and fails to do so during periods of high winds.

1.3 Effective horizontal resolution

There is a difference between horizontal grid spacing and effective resolution, the latter being a measure of the spatial scales that the model can resolve, i.e. how fine the structures are that the model equations are able to describe. As a rule of thumb, the effective resolution of numerical weather prediction models is about 7-10 times the model grid spacing (Shamarock, 2006). A grid spacing of 80 km, such as in ERA-Interim, implies an effective horizontal resolution of 550-800 km. HARMONIE (with a grid spacing of 2.5 km) has an effective horizontal resolution of about 15-25 km. ECMWF-OPER (used in chapter 3) has a grid spacing of 16 km and an effective horizontal resolution of 110-160 km. In this study we use the QuikSCAT 25-km product (25 km spacing between neighbouring observations) which has an effective resolution of about 50 km. For ASCAT we use the 12.5 km coastal product which has an effective resolution of about 25 km . The effective resolution of the KNW-atlas is probably about 250 km, i.e. halfway between the effective resolution of HARMONIE and ERA-Interim, but this has not been quantified scientifically. On average, the effective resolution of the model wind fields used to make the KNW atlas is therefore coarser than that of both QuikSCAT and ASCAT.

[2] www.knmi.nl/scatterometer/ascat_osi_co_prod/ascat_app.cgi and
http://research.metoffice.gov.uk/research/interproj/nwpsaf/scatter_report/nwp.html

CHAPTER 2 Comparing KNW-atlas and QuikSCAT

2.1 QuikSCAT SeaWinds

For the validation of the KNW-atlas we used the climatology based on measurements made by the SeaWinds scatterometer (QSCAT) from the National Aeronautics and Space Administration (NASA) satellite QuikSCAT. This satellite provided twice daily (06 and 18 UTC) near global coverage for more than 10 years (July 1999-November 2009). The QuikSCAT measurements are available on a 25 km grid, with an effective resolution of about 50 km.

QuikSCAT measurements are sensitive to rain: measurements in rainy areas are identified (flagged) by Quality Control (QC) and have not been used in the validation. This means that the validation dataset may not entirely reflect the true wind climatology but the aim here is to compare the KNW winds to measured winds and the validation dataset is suitable for this purpose. When, for example, the QuikSCAT data set excludes winds in convective regions, the mean wind will be slightly underestimated because convection often causes strong downbursts. Similarly, wind speed measurements around 15 m/s are often rejected because thick rain clouds make it difficult to obtain a good measurement and these occur relatively often at such wind speeds.

Figure 2.1 shows the number of QuikSCAT data per 0.2 by 0.2 degrees grid box (which corresponds to the QuikSCAT sampling size) on the North Sea for the 10 year period used for the analyses presented in section 2.2.2. Note that the area over the North Sea is larger than in figure 0.1.

The QuikSCAT winds are calibrated against 10m equivalent neutral wind speeds[3] from buoy measurements. Therefore biases compared to buoy measurements are on average less than 0.1 m/s . The standard deviation of the difference between buoy and scatterometer component winds (U and V) is 0.5-0.7 m/s. For wind climatology the bias is however much more important than the standard deviation. It should be noted that about half of the buoys used for calibration are found in the tropics and that there are none in the North Sea. In Karagali et al (2012) QuikSCAT ocean wind speed and direction were compared to observations from three offshore wind masts on the North Sea: HornsRev M2, Fino1 and Greater Gabbard (locations are shown in figure 2.2). Mean biases (mast observations minus satellite) are close to zero for wind speed and -2.7° for wind direction with a standard deviation of 1.2 m/s and 15° respectively. One would not expect the standard deviation of the mast measurements to be higher than that of the buoy measurements. The reason is that the buoy measurements have been adapted to the scatterometer grid box size, whereas the mast measurements have not.

[3] A 10m equivalent neutral wind speed is the wind speed at 10 m height derived from the buoy winds nearer the sea surface assuming neutral stability and a logarithmic wind profile.

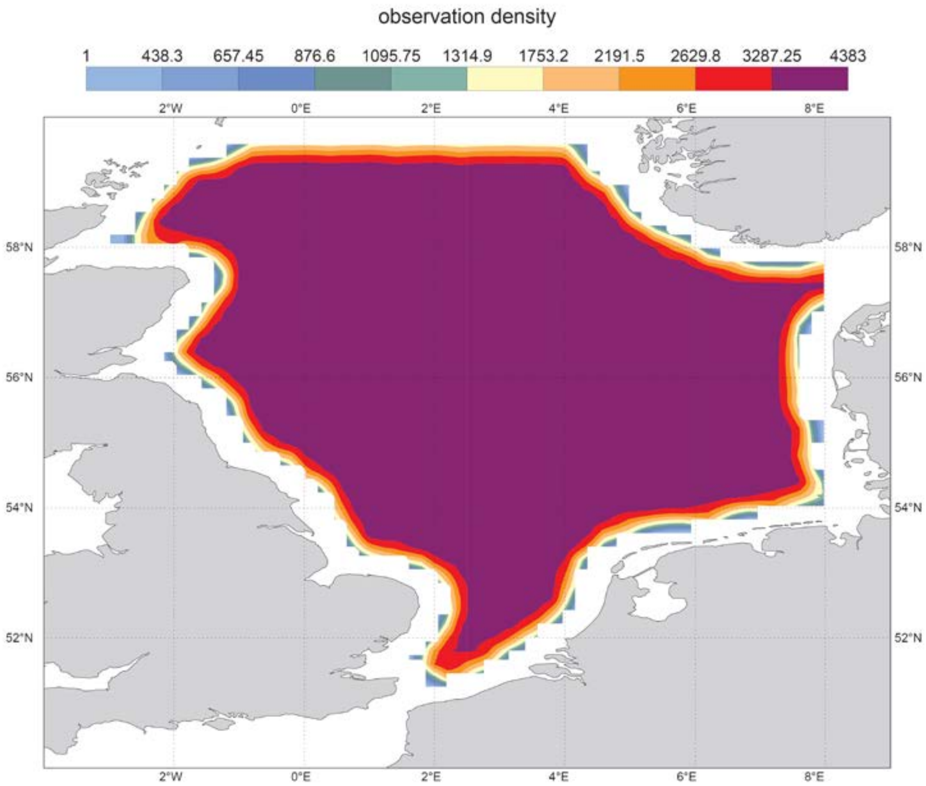


Figure 2.1: Observation density: number of QuikSCAT data per grid box of 0.2 by 0.2 degrees for the 10 year period used in the analysis presented in section 2.2.2.

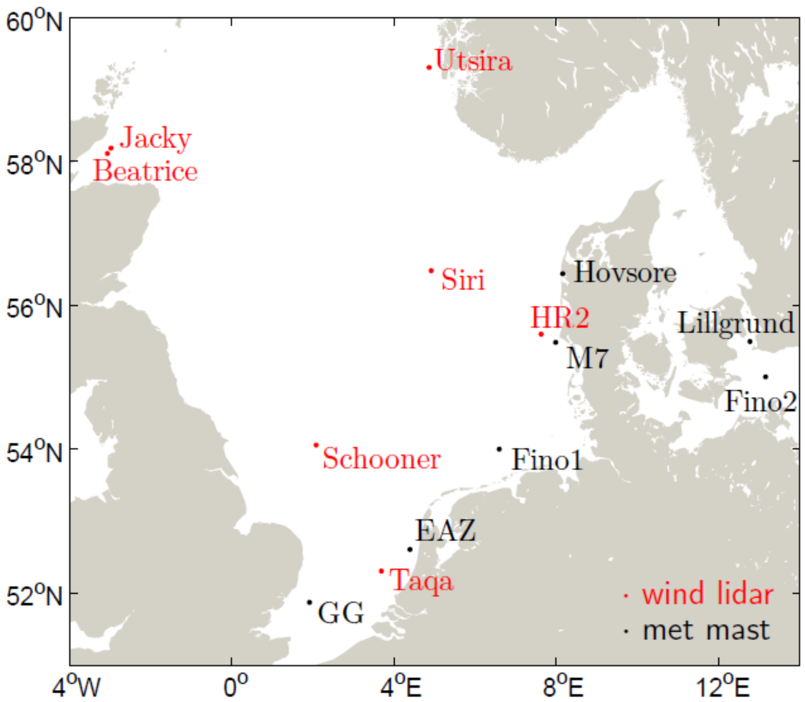


Figure 2.2: The NORSEWInD network of meteorological and LIDAR stations in the North and Baltic Sea: HR2 = Hors Rev M2, M7 = Horns Rev M7, GG = Greater Gabbard and EAZ = Egmond aan Zee (source: Peña, 2012)

2.2 Comparing KNW and QuikSCAT

The KNW 10 m wind data (HARMONIE short-term forecasts based on ERA-Interim) from locations which correspond to the collocated QuikSCAT- ERA-Interim dataset[4] are selected for the comparison of 10 m wind climatologies described in section 2.2.2 (an additional requirement is set for the wind shear analyses in section 2.2.1). The QuikSCAT satellite crosses the North Sea at about 6 and 18 UTC which coincides with the 6 hour HARMONIE forecasts based on the ERA-Interim analyses at 00 and 12 UTC. It is no surprise that the forecast with a 6 hour lead time most often coincides with the time that the satellite passes over the North Sea, but it is worth noting that the KNW-atlas winds from an hour earlier and an hour later (respectively the 5 hour and 1 hour forecasts) also often coincide with the satellite times[5].

2.2.1 How well does KNW reconstruct small scale wind structures at 10 m height?

Figure 2.3 shows a typical example of the rather smooth ERA-Interim 10m wind fields and the more detailed wind fields of the KNW atlas (in this case based on the 6 hour forecast of HARMONIE) and QuikSCAT. However, the KNW atlas does not only consist of 6 hour forecasts. Every 6 hours ERA-Interim provides an new initial state (which is often referred to as a " cold start") and the KNW atlas consists of 6 forecasts (one for each of the 6 hours: +1h to +6h) based on these initial states. All data assimilation (fitting the model to the available measurements) is done within ERA-Interim and HARMONIE is mainly used as a downscaling tool. Figure 2.4 shows that the + 1h HARMONIE forecast of the wind field ("FC + 1" in the figure) is relatively smooth and similar to ERA-Interim (over the North Sea).With increasing forecast length ("FC+2", "FC+4" and "FC+6" in the figure) HARMONIE produces more small scale features and higher wind speeds. How realistic are these small scale features? To answer this question quantitatively, we compared the horizontal wind shear produced by KNW to the wind shear observed by QuikSCAT. Wind shear is the wind speed difference between two successive grid boxes (here going from west to east) divided by the distance between the grid boxes.

As can be seen from figure 2.5, the horizontal wind shear produced by KNW increases with forecast lead time (the x-axis of the graph). It is similar to ERA-Interim for a lead time of 1 hour and becomes comparable to that of QuikSCAT for lead times of 5 hours. The comparison is however not entirely fair as KNW and QuikSCAT do not have the same effective resolution (respectively 15 and 50 km) and this probably explains why the 6 hour lead time displays a higher wind shear than the scatterometer. As one would expect, the wind shear of ERA-Interim and QuikSCAT does not differ much for different HARMONIE forecast lead times. ERA-Interim has such a coarse effective horizontal resolution that it cannot reproduce small scale structures realistically, shown quantitatively by a horizontal wind shear value much lower than QuikSCAT's. For the wind shear analyses only 28% of the whole collocated dataset was used because only the times when at least 500 QuikSCAT grid box measurements were made on the North Sea were considered suitable. This subset is a mixture of fairly smooth wind fields

[4] QuikSCAT and ERA-Interim data have been collocated which means that only ERA-Interim data are selected at times of QuikSCAT observations over the North Sea (when the satellite crosses part of the North Sea) that have not been rejected by the quality control procedure. Collocation also involves interpolating the ERA-Interim values to the QuikSCAT grid.
[5] Total number of QuikSCAT-model collocations over the North Sea for the 1999-2009 period for various HARMONIE forecast (FC) lead times: FC + 1h: 1024902; FC + 2h: 233784; FC + 3h: 2234; FC + 4h: 732534; FC + 5h: 1102206 ;FC + 6h: 1252528

where small scale structures are not yet well developed (31% of the data consists of forecast lead times of 1 hour) and more developed wind fields (69% of the data consists of forecasts with lead times of 4, 5 or 6 hours). When the forecast lead times are 2 or 3 hours ("FC +2h" and "FC+3h" in the footnote) QuikSCAT only samples small parts of the North Sea[6].

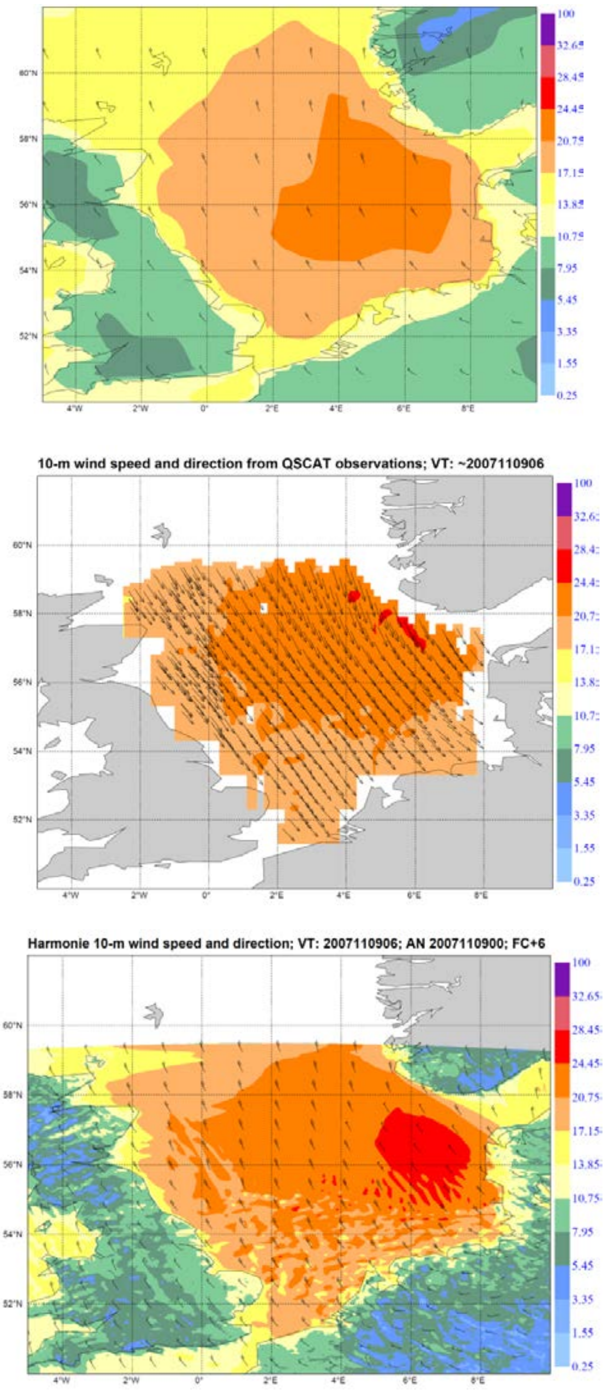


Figure 2.3: ERA-Interim 20071109 00 FC + 6 (top panel), QuikSCAT (middle panel) and KNW (bottom panel) 10-m wind fields valid for 9-11-2007 06 UTC. This storm became famous because it was the first time that the Maeslantkering sea flood defence had to be closed.

[6] See previous footnote, but now for cases with a pre-defined number of at least 500 QuikSCAT data points over the North Sea: FC +1h: 380150; FC +2h: 503; FC +3h: 0; FC + 4h: 187116; FC +5h: 453143; FC+6h: 214087

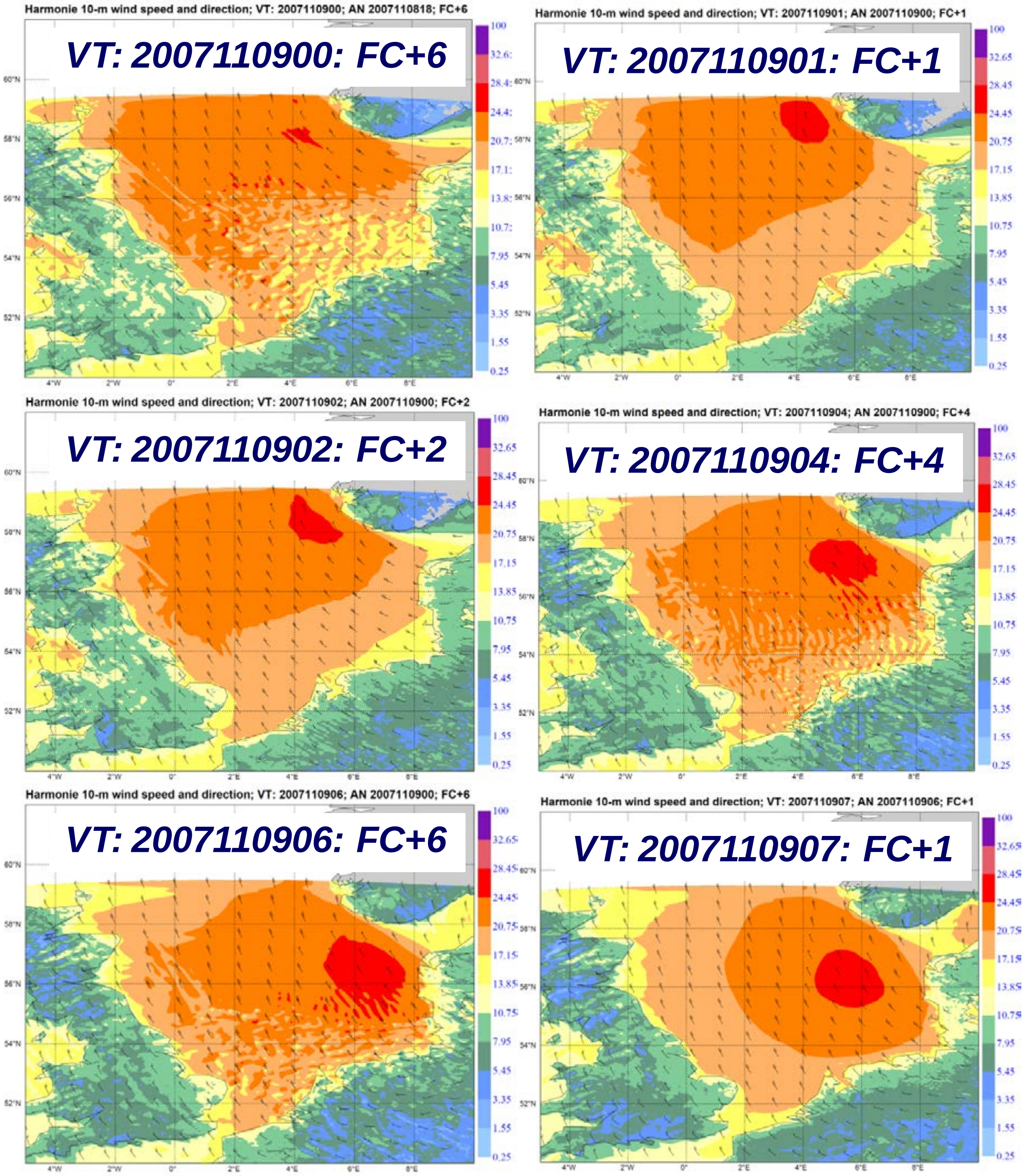


Figure 2.4: KNW model wind fields for 9-11-2007 at 10 m height derived from 6 hourly ERA-Interim fields and + 1h to + 6h HARMONIE "forecasts".

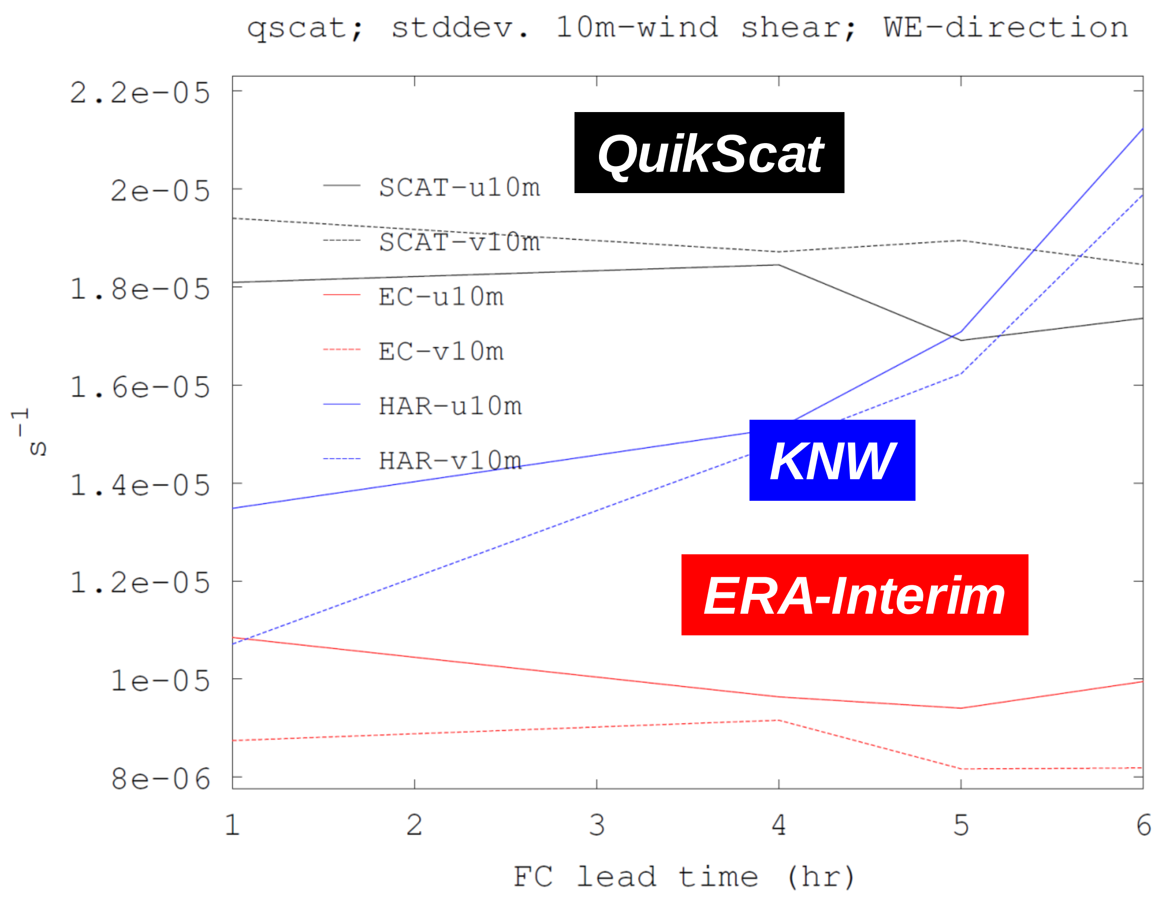


Figure 2.5: Comparison of the standard deviation of the horizontal shear of 10 m zonal (u, solid) and meridional (v, dashed) wind components (a measure of how detailed the wind fields are) derived from ERA-Interim (red), QuikSCAT (black) and KNW (blue) as function of the forecast lead time. Data are included at times and locations where data from all three sources are available.

From Fig. 2.5 it is clear that HARMONIE needs at least and possibly more than 6 hours to fully develop its small scale structures since the KNW shear values show no sign of levelling off at the maximum lead time shown. Moreover, the effective horizontal resolution of (fully developed) HARMONIE is 3 times better than that of QuikSCAT so the KNW wind fields are expected to achieve higher shear values. The HARMONIE wind fields display much the same level of detail as the QuikSCAT measurements for forecast lead times of 4-6 hours. One could argue that (on hindsight) it would probably have been better to use forecasts with lead times of at least 2-7 hours instead of the 1-6 used for the KNW–atlas[7] as more spatial detail is present in the wind forecasts with longer lead times. This is what the diurnal analysis of the validation against tall North Sea mast measurements (see for example figure 2.5a from the vertical validation report; Stepek et al, 2015) suggested as well (although applying the vertical wind shear correction to HARMONIE improved the results so that even the 1 hour forecast lead time wind speeds were on average only about 4% lower than the measurements at heights around 100 m).

[7] HARMONIE forecasts with a lead time of 7 hours have been archived, but were not used for the KNW-atlas. That is why they are not analysed in figure 2.5. HARMONIE forecasts with a lead time of 8 hours or more have not been archived.

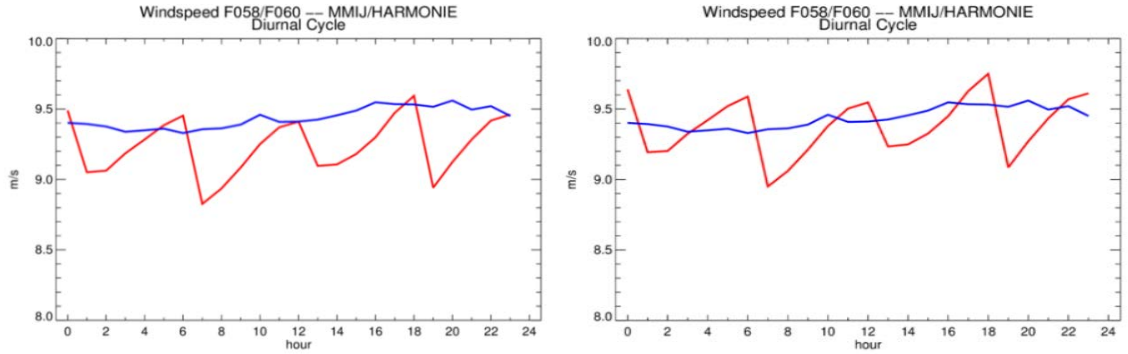


Figure 2.5a Diurnal analysis of the 60 m wind speed at the location of MMIJ (tall mast on the North Sea). Measurements (blue) and + 1 to +6 hour forecast HARMONIE (red); left panel without shear correction and right with shear correction

2.2.2 How do KNW and QuikSCAT 10 m climatology compare?

In this section the collocated[8] datasets of ERA-Interim, QuikSCAT (1999-2009) and the KNW atlas are compared at 10 m height. Because of the collocation procedure the only KNW data used in the comparison are the ones coinciding with QuikSCAT observations (mostly at 6 and 18 UTC). This subset of the KNW atlas contains significantly more HARMONIE forecasts with lead times of 4-6 hours (71%) than of 1-3 hours (29%) and therefore reproduces small scale wind features more realistically than in the complete KNW atlas where the forecast lead times are evenly represented.[9] The subset also contains slightly higher wind speeds than the complete KNW dataset for 1999-2009.

In figure 2.6 the 10 m wind speed biases (average of the model minus scatterometer measurement differences) of KNW and ERA-interim are shown. While KNW overestimates the wind speed for most of the North Sea, ERA-Interim underestimates. At least part of this overestimation is due to the high proportion of longer forecast lead times in the collocated dataset, so the complete KNW dataset may well agree better with the scatterometer wind speed measurements if the satellite passed the North Sea more often than twice a day. The wind speeds in the area around 54°N on the western side of the North Sea is overestimated by both ERA-Interim and KNW. This is the only area where the bias of the models has the same sign so this local effect may be related to a shared shortcoming of the models. Both models are known to overestimate the vertical mixing in the boundary layer when the layer is stably stratified, which results in 10 m wind speeds which are too high. This is the case on warm days in Spring when the prevailing southwesterly winds are warmed over the wide expanse of southern England before flowing out over the relatively cold sea water. For the largest part of the North Sea, ERA-interim differs from QuikSCAT less than KNW does, but in most coastal regions the opposite is true and ERA-interim severely underestimates the QuikSCAT measurements by about 1 m/s. KNW overestimates the wind speed at 10 m height (by less than 0.5 m/s for most of the North Sea) , but in the most southern part (including the areas Borssele and Hollandse Kust that have been allocated for wind energy) the KNW wind speeds are on average a little too low (0.1-0.3 m/s). The verification of WRF (another high resolution weather forecasting model; see Appendix A2) looks the same as the KNW verification, although the difference between WRF and QuikSCAT is even larger (more than 0.5 m/s) for most of the North Sea. KNW seems to quite severely underestimate the wind

[8] The collocation procedure is described in section 2.3.1. The threshold of at least 500 QuikSCAT data points applied for the horizontal wind shear analyses is not applied for the wind climatology comparison in this section which means more data points are analysed.
[9] Total FC +1h and +2h: 5026261 (29%), total FC +3h and +4h: 2929778 (17%)) and total FC +5h and +6h: 9420842 (54%)

speed along the northern edge of the HARMONIE domain but this is a 10 grid box wide erroneous edge effect. The other 3 edges of the HARMONIE domain were not included in the comparison and the northern edge should have been excluded too.

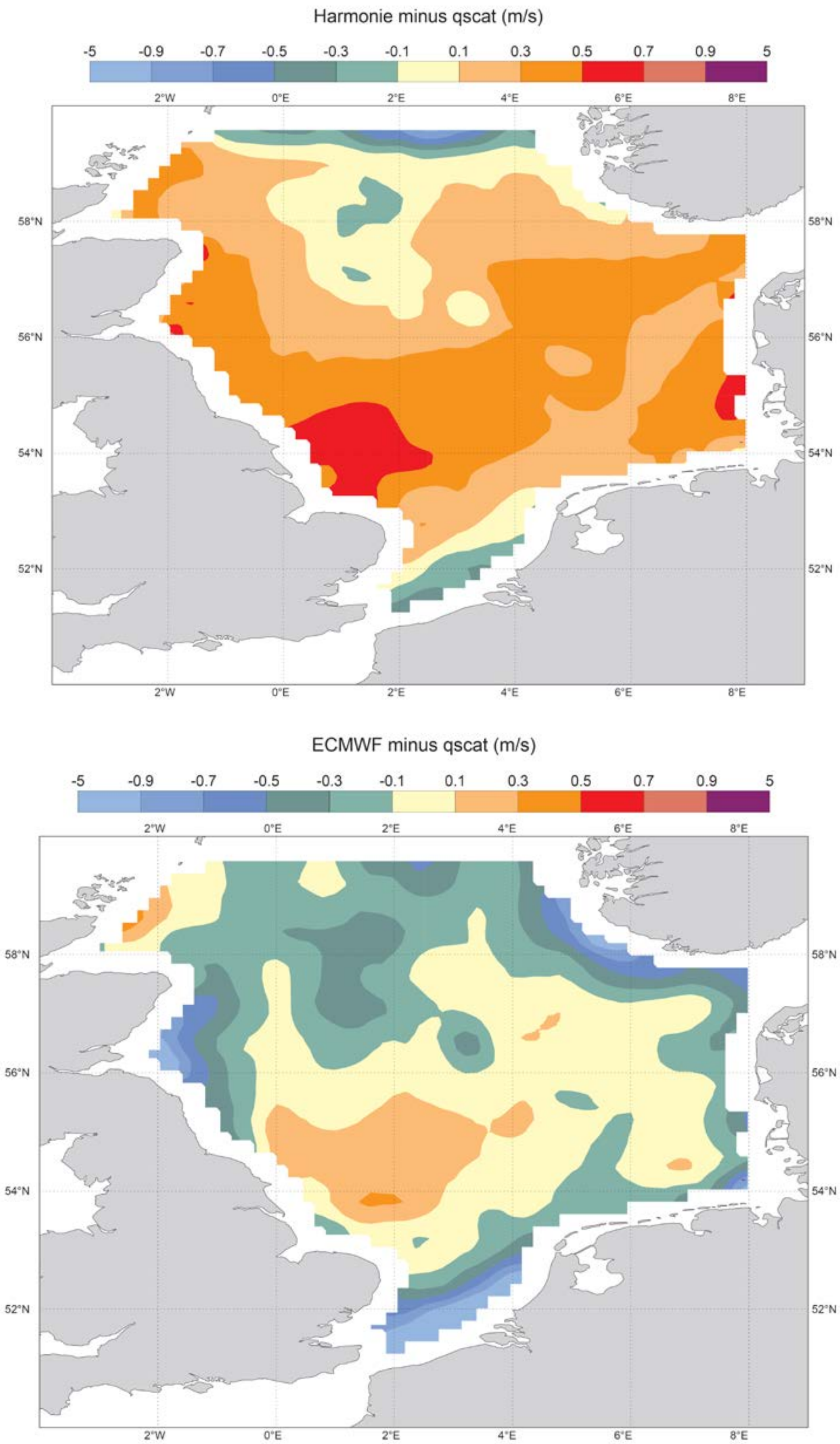


Figure 2.6: Average 10 m wind speed difference (bias) between KNW and QuikSCAT (top panel) and between ERA-Interim and QuikSCAT (lower panel).

Figure 2.7 shows the wind speed standard deviation, which quantifies how far the wind speeds deviate from the average. The wind speed standard deviations of the collocated ERA-Interim dataset are smaller and the standard deviations of the QuikSCAT and KNW datasets more comparable. This might be due to the fact that the effective horizontal resolution of ERA-Interim (about 600 km) is much coarser than that of QuikSCAT (50 km) and the KNW-atlas (unknown, but probably about 250 km). The largest spread of values is found in the collocated KNW dataset. However, part of this spread is synthetic, due to the discontinuity of the wind field every 6 hours (the "cold start"). Also the KNW collocated dataset generally overestimates wind speeds (figure 2.7) which automatically introduces a larger deviation between wind speeds during calm periods and the average of the complete dataset. The relatively low standard deviations along the east coast of England and in the German Bight are probably related to relatively low average wind speeds there (see figure A2.3 in appendix A2 and figure 3.2) where the prevailing southwesterly wind is still adapting after moving from rough land to smooth sea. The scatterometer values show this expected pattern less clearly in the southern North Sea.

A relatively large proportion of the energy produced by North Sea offshore wind turbines is generated when the 10 m wind speed is 10 m/s or more[10]. This 10 m/s is actually the peak production wind speed because higher wind speeds occur less often and lower wind speeds generate less wind power. Moreover, above the rated wind speed of the wind turbine (typically 15 m/s at hub height) the energy output no longer increases with increasing wind speed. More than half of the energy is generated by wind speeds in the range between the average wind speed (8-9 m/s at 10 m) and the rated wind speed (typically 13 m/s at 10 m). Therefore we analysed the collocated dataset to quantify how often QuikSCAT, KNW and ERA-Interim produce wind speeds above 10 m/s and compared the results. Figure 2.8 shows that in the KNW dataset 25-30% of the wind speeds in English coastal waters are above 10 m/s, along the Dutch west coast about 30% and further offshore 30-35%. The QuikSCAT percentages are about 5% lower in English coastal waters, 3-4% lower further offshore and very slightly lower along the Dutch west coast. Again, at least part of this difference can be explained by the high proportion of forecasts with longer lead times and slightly higher KNW wind speeds in the collocated dataset. A validation of the complete KNW dataset would be better. Just west of the Netherlands and Belgium there is a local maximum of 30% on both the KNW and QuikSCAT maps. This is the expected pattern when the wind direction is southwest and this direction dominates the dataset at higher wind speeds. The lower occurrence of high KNW winds along the northern edge of the HARMONIE domain is not what one would expect and this is a consequence of the erroneous edge effect mentioned earlier. The ERA-interim values further offshore agree with QuikSCAT, but in coastal areas the ERA-Interim values are 5% lower. This might be due to the coarser resolution of ERA-Interim (mixing of "land" fractions increases the average surface roughness in the grid box near the coast and reduces the wind speed.

[10] Assuming neutral stability, a logarithmic wind profile with 10 m/s at 10 m height means that at 100 m height (typical hub height of offshore wind turbines) the wind speed is 12 m/s.

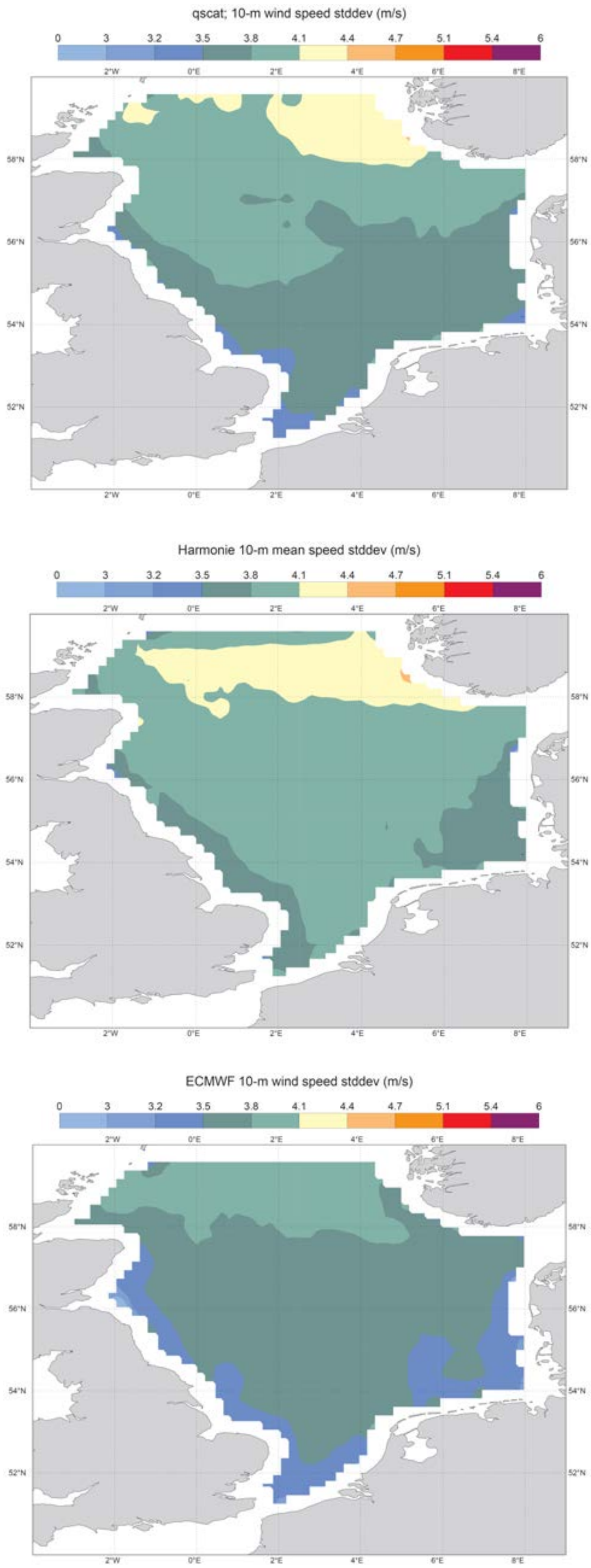


Figure 2.7: Wind speed standard deviations of QuikSCAT (top panel), KNW atlas (middle panel) and ERA-Interim (lowest panel) from the collocated dataset.

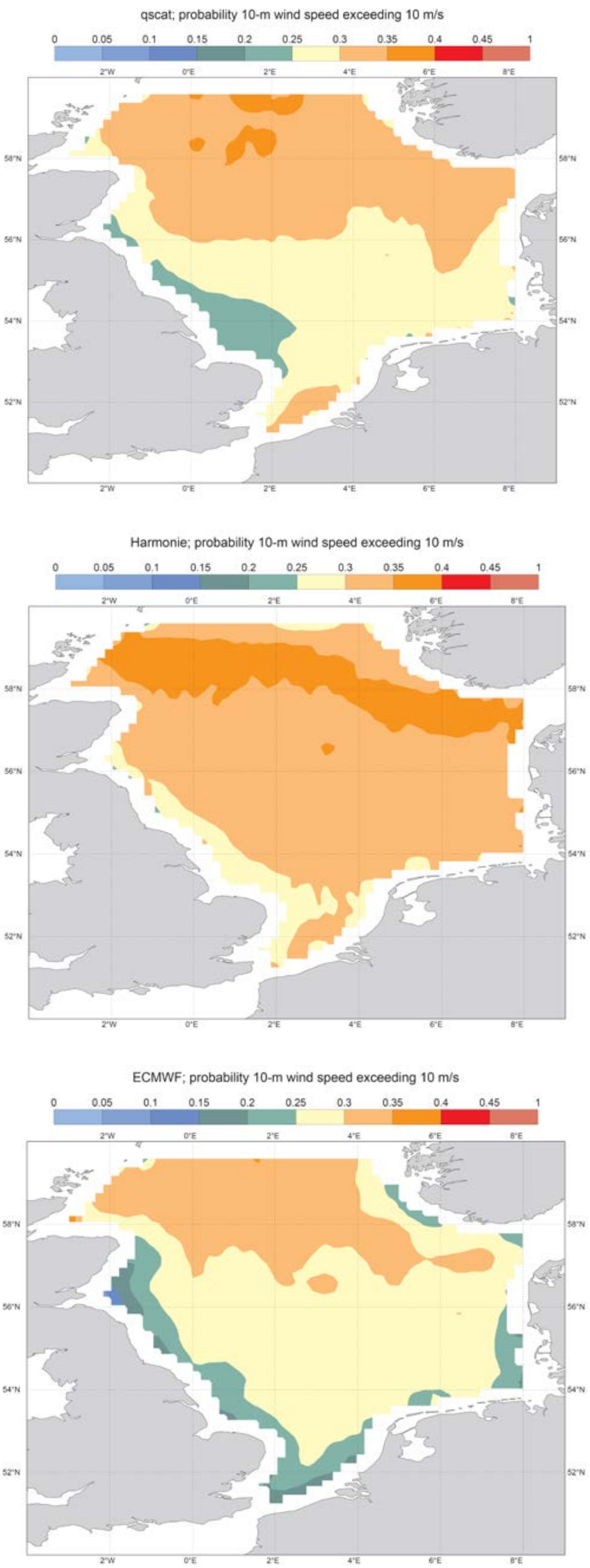


Figure 2.8: Fraction of data with 10 m wind speed above 10 m/s from QuikSCAT (top panel), KNW atlas (middle panel) and ERA-Interim (lowest panel) in the collocated dataset.

Finally, the wind speed frequency distributions of the collocated dataset were compared. Figure 2.9 shows that there is a fairly good match between the wind speed frequency distributions of the KNW and QuikSCAT 10 m wind speeds (black and blue). The peak of ERA-Interim (red) is clearly larger. Focussing on the wind speeds most important for wind energy production, we see KNW overestimating the occurrence of wind speeds between 10 and 17 m/s and performing correctly for higher speeds. The KNW occurrences for high wind speeds shown in figure 2.9 are probably higher than the complete KNW dataset would show because the collocation procedure produced a subset biased towards the longer forecast lead times. Also, the erroneous edge effect causes lower KNW wind speeds along the northern edge of the domain and this is the area where the highest wind speeds normally occur. For the once in ten year wind speeds is figure 2.9 of little use because such speeds lie at the extreme right hand side of the graph where there are very few or no occurrences. However, in Appendix A4 there is a comparison between KNW values and KNMI's own anemometer measurements which shows KNW overestimating the once in ten year 10 m wind speed by 0-8% at sea stations located west of the Netherlands. ERA-Interim performs correctly between 10 and 14 m/s and underestimates the occurrence of higher speeds. This explains why we in figure 2.8 saw that ERA-Interim was in better agreement with QuikSCAT over most of the North Sea than KNW was. The frequency of occurrence of wind speeds between 10 and 14 m/s is much larger than those above 16 m/s so the lower wind speed range dominates the frequency of occurrence of wind speeds above 10 m/s. The behavior of the ERA-Interim wind speeds can be explained by its course resolution. Wind fields with high wind speed tend to have a smaller horizontal extent than wind fields with lower wind speeds. This means that ERA-Interim averages the high wind speeds over too large an area so the resulting wind speed is lower than the wind speeds KNW and QuikSCAT (with their higher resolution) produce.

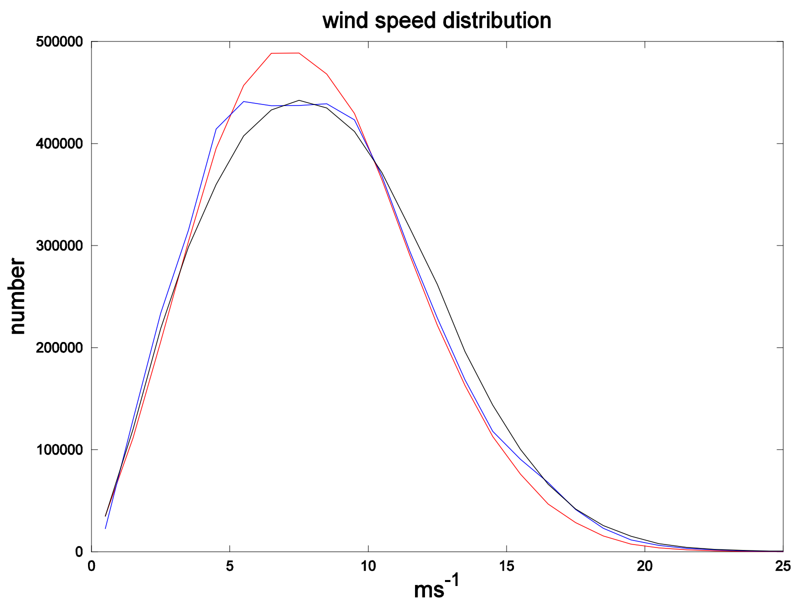


Figure 2.9: Wind speed frequency distribution of all data on the North Sea per collocated dataset: QuikSCAT (blue), KNW atlas (black) and ERA-Interim (red).

CHAPTER 3 Comparing KNW-atlas and ASCAT

3.1 ASCAT level-2 12.5-km coastal product

Since November 2009 KNMI produces the ASCAT (Advanced Scatterometer) coastal product[11] as part of the EUMETSAT OSI-SAF (Ocean and Sea-Ice Satellite Application Facility). This product consists of measurements of 10 m equivalent neutral[12] wind speed and direction within a wind vector cell (WVC) of size 12.5 km. The effective horizontal resolution is 25 km. The measurements are available for 2007-present, but this study only includes 2013. One of the advantages of ASCAT compared to QuikSCAT is the different radar frequency used which makes ASCAT measurements virtually free of rain contamination. The product that is used for the comparison with the KNW-atlas, the so-called ASCAT coastal product (figure 3.1), is based on enhanced processing of the beam footprints to enable the wind as close as 15 km from the coast to be calculated. For the default ASCAT 12.5 km product, i.e., without the enhanced processing, WVC's closer than 35 km from the coast are flagged due to land contamination (just like in QuikSCAT). 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.

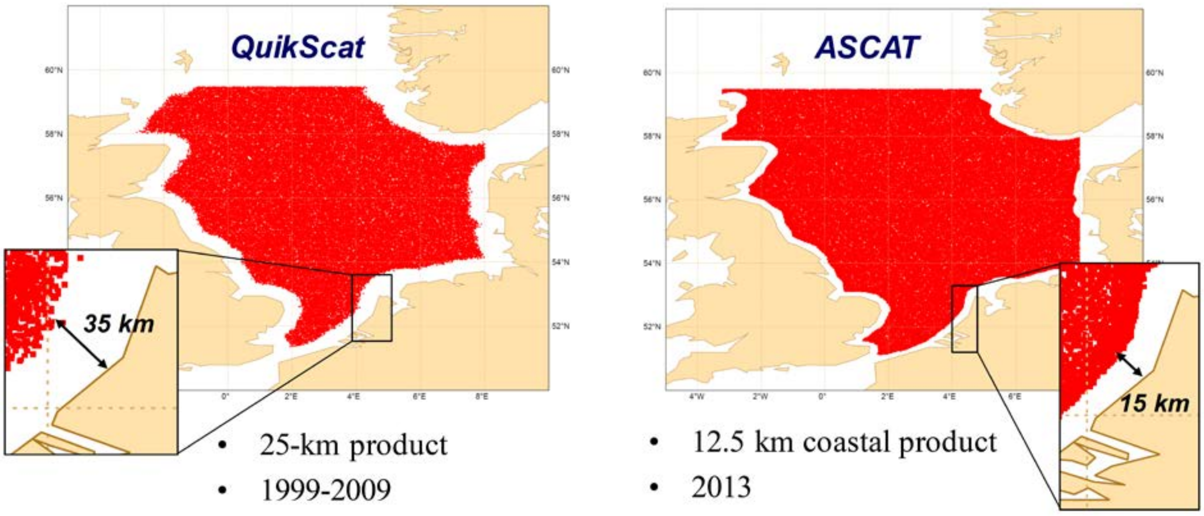


Figure 3.1: The ASCAT level-2 12.5-km coastal product (right panel) makes wind measurements nearer to the coast than QuickSCAT (respectively 15 and 35 km) which is shown in the left panel. In this study an existing dataset of collocated ASCAT and ECMWF winds (the 2013 operational version of the ECMWF model with 16-km grid size, but used at 80 km grid size in the collocated dataset) with only one year of data from 2013 is used which is much shorter than the 10 year collocated dataset of QuickSCAT and ERA-Interim (1999-2009).

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

[12] 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.

In the ASCAT coastal product significant outliers, not always detected by QC, are found near the main harbours such as Rotterdam where large numbers of ships (sometimes about 100) often wait at the anchor areas and contaminate the back scattered ocean signal read by the instrument. QC screens some of the ship-reflection contaminated measurements at low winds, but less so at high wind speeds (when there is little contrast between contaminated and good signals). The imperfect QC passes unrealistically high winds at anchor areas along the Dutch and Belgian coast as can be seen in figure 3.2 (based on a different ASCAT coastal product, the "L3", but showing the same problem that the level 2 12.5 km product suffers from). Improving QC is work in progress at KNMI. The contamination due to reflections from oil platforms are smaller than in QuikSCAT (see figure A2.2 in Appendix A2).

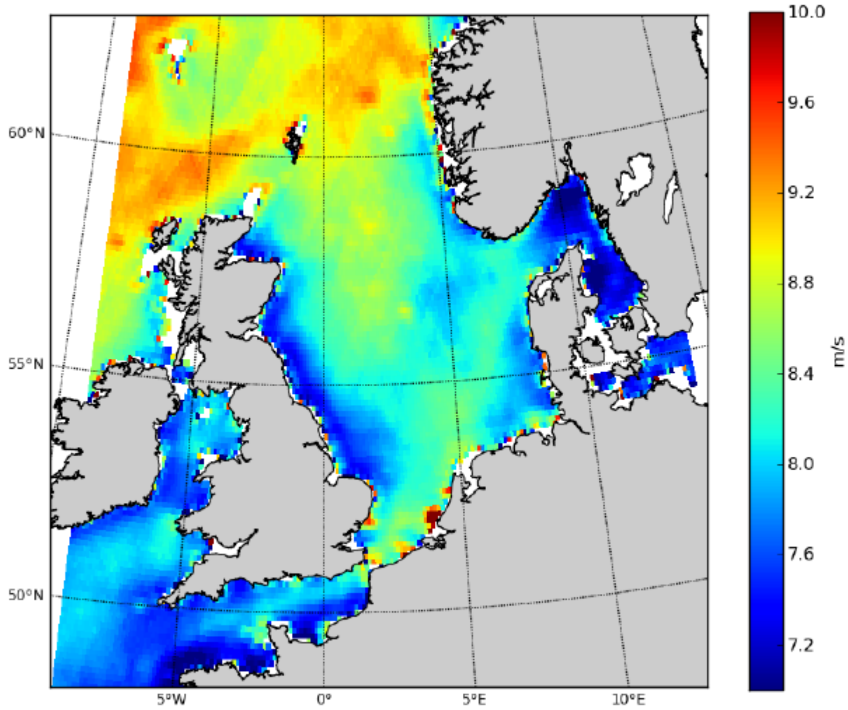


Figure 3.2: ASCAT coastal wind atlas (2007-2008) based on the L3 coastal product of KNMI OSI-SAF (source: poster Living Planet Symposium Edinburgh (2013); http://orbit.dtu.dk/ws/files/59448583/Wind_atlas_of_the_Northern_European_Seas.pdf)

All ASCAT winds are calibrated against 10m equivalent neutral wind speeds[13] from buoy measurements (none of which were made on the North Sea however). The wind speed bias is less than -0.23 m/s in coastal areas (up to 50 km from the coast) and -0.29 m/s elsewhere (ASCAT underestimates the wind speed). The standard deviation (sd) is less than 1.6 m/s for both the u and the v-component of the wind (Verhoef, 2010). ASCAT coastal products are also compared in near real time to ECMWF model winds for quality assurance purposes. KNMI is currently working to improve the ASCAT coastal product for wind speeds below 5 m/s and above 35 m/s.

[13] A 10m equivalent neutral wind speed is the wind speed at 10 m height derived from the buoy wind speeds measured at lower heights assuming neutral stability and a logarithmic wind profile.

Figure 3.3 shows the number of ASCAT measurements per grid box of 0.2 by 0.2 degrees selected for the 2013 collocated dataset used in the analyses presented in section 3.2.2. The observation density is mostly higher near the coast because additional processing of the instrument signal is required for these areas.

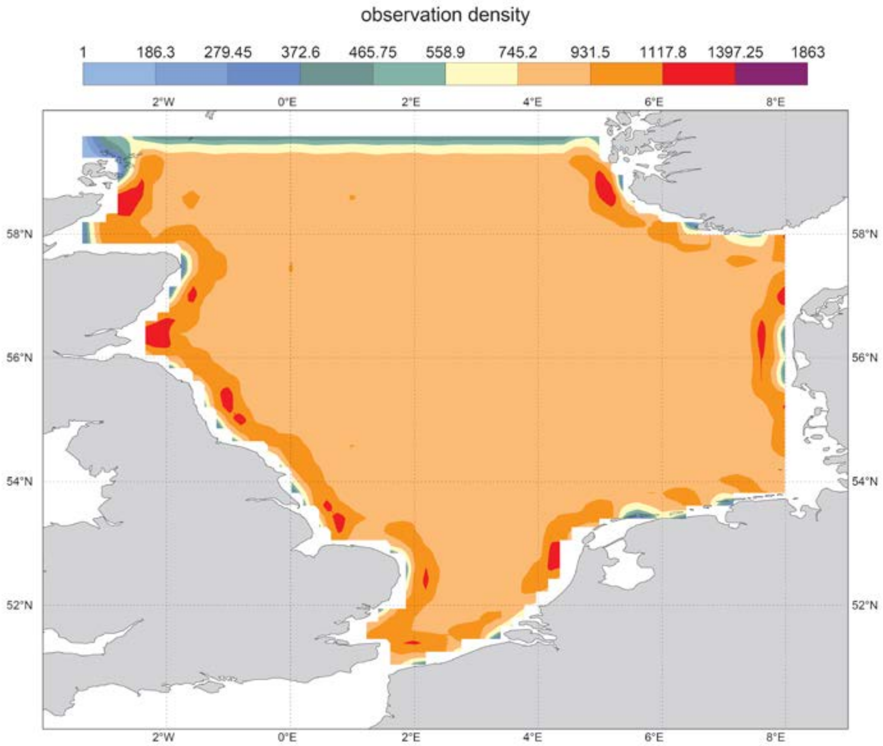


Figure 3.3: Observation density: number of ASCAT measurements per grid box of 0.2 by 0.2 degrees selected for the 2013 collocated dataset used in the analyses presented in section 3.2.2.

3.2 Comparing KNW and ASCAT

The ASCAT coastal product had previously been collocated[14] on a 80 km grid with the 2013 data from the ECMWF operational model, further denoted as ECMWF-OPER[15]. Ideally we would want to collocate all available ASCAT measurements (2007-present) with ECMWF-OPER on a finer grid (as close as possible to 12.5 km), but that was not feasible within this project. Note that ERA-Interim was used for the collocation with QuikSCAT. In order to be able to compare the 10 m wind climatologies described in section 3.2.2, the KNW data were selected that are valid at the same time and location as the data in the existing collocated ASCAT and ECMWF-OPER dataset. An additional requirement is set for the wind shear analyses in section 3.2.1. The ASCAT satellite crosses the North Sea at 9:30 and 21:30 UTC which coincides with the 3 and 4 hour HARMONIE forecast lead times, initiated from the 6 and 18 UTC analyses of ERA-Interim. As one would expect, the 3 hour forecast is therefore well represented in the collocated dataset. However the forecasts with shorter lead times

[14] Only ECMWF-OPER data are selected at times when there are ASCAT observations on the North Sea (when the satellite crosses part of the North Sea) that are not rejected (quality control).

[15] The ECMWF operational model when used for weather forecasting (its primary use) has a much smaller grid spacing than 80 km.

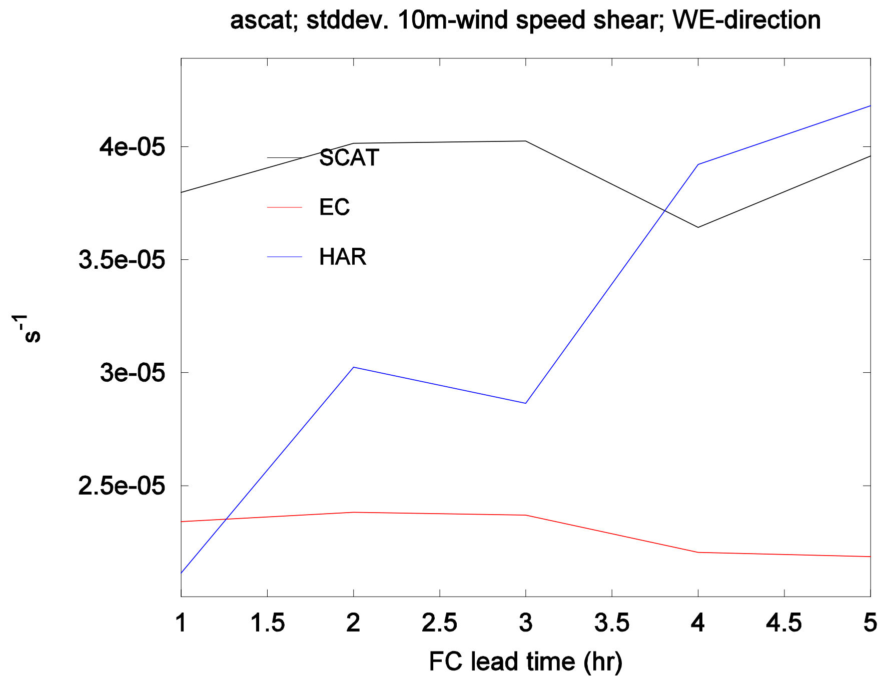
dominate the collocated dataset so one would expect that the full KNW dataset for 2013 would describe small scale features of the wind fields better than the collocated dataset.[16]. The same analyses were performed on this collocated dataset (including ASCAT measurements) as on the collocated dataset of section 2.1 (with QuikSCAT measurements).

3.2.1 How well does KNW reconstruct small scale wind structures at 10 m height?

The horizontal wind shear of the three data sources in the collocated dataset were calculated in the same way as described in section 2.2.1 including an additional requirement for the number of near simultaneous scatterometer measurements used. The left graph of figure 3.4 shows that the 1 hour HARMONIE forecasts of the KNW atlas (the "HAR" blue line) have the same level of detail as the ECMWF-OPER 10 m wind speeds. The wind fields become more detailed as the forecast lead time lengthens until the 4 hour and 5 hour forecasts become as detailed as the scatterometer measurements. There are no 6 hour forecast lead times on the graphs because the few ASCAT measurements made at these times did not meet the additional coverage requirement. Because the effective horizontal resolution of the ASCAT measurements is twice that of the QuikSCAT measurements, one would expect that forecast times of more than 4 hours (when HARMONIE wind speeds are as detailed as QuikSCAT; figure 2.5) would be needed before HARMONIE reached the same level of detail as the ASCAT measurements. This discrepancy may be due to the ASCAT dataset being relatively small (only 1 year compared to the 10 years of QuikSCAT). The right graph shows that the level of detail in the wind direction (represented by the direction of the horizontal wind velocity vector shear divided by the distance between adjacent grid boxes) increases slowly with longer forecast lead time and even after 5 hours is only about halfway between the level of ASCAT and ECMWF-OPER. These results (like those of the comparison with QuikSCAT) imply that the use of longer HARMONIE forecast lead times (4-9 hours for wind speed and more than 5 hours for wind direction) could improve the representation of small scale structures in the wind fields of the KNW atlas. It is however important to bear in mind that the collocated dataset contains only a subset of the KNW atlas dataset for year 2013. This subset consists of more 1-3 hour HARMONIE forecasts than 4 and 5 hour forecasts and therefore reproduces small scale wind features less realistically than the full dataset which contains the same number irrespective of forecast lead time. [17]

[16] Number of KNW wind data selected for the collocated dataset per forecast lead time (FC + 1h: 78591; FC + 2h: 249986; FC + 3h: 502975; FC + 4h: 194029; FC + 5h: 311671 ;FC + 6h: 6867). Total FC +1h to +3 h: 831552 (62%); total FC +4h to +6 h: 512567 (38%).

[17] Number of KNW wind data selected for the collocated dataset with the additional coverage requirement per forecast lead time (FC + 1h: 69465; FC + 2h: 245385; FC + 3h: 491105; FC + 4h: 166034; FC + 5h: 304911 ;FC + 6h: 0). Total FC +1h to +3h: 805955 (63%); total FC +4h and +5h: 470945 (37%).



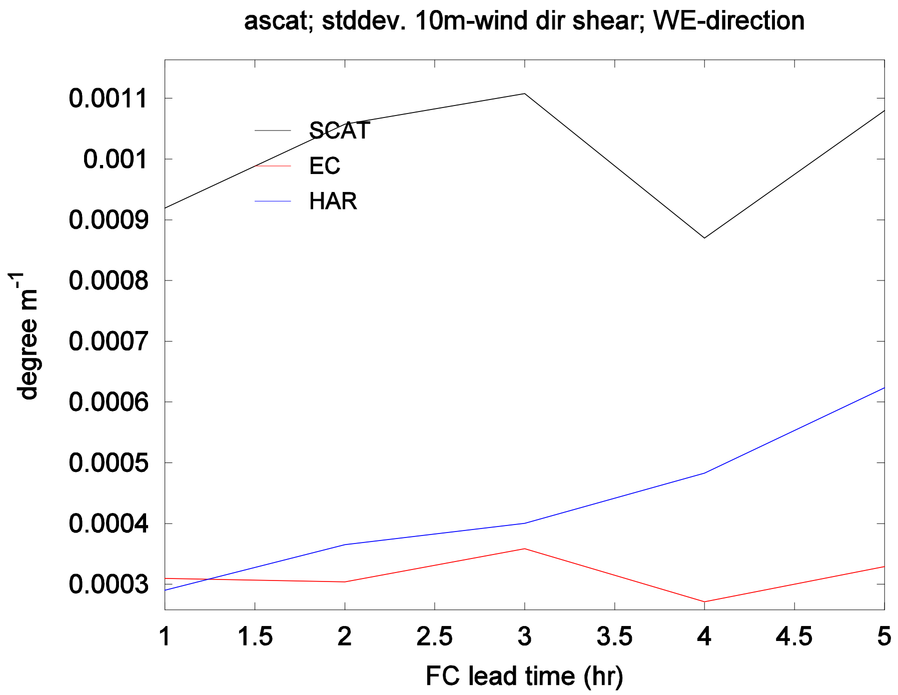


Figure 3.4: Standard deviation of the 10 m wind speed differences (top) and the resulting directions of the horizontal wind velocity vector differences(bottom) between adjacent grid values per meter grid box separation for the three data sources of the collocated dataset: scatterometer measurements (black), ECMWF-OPER model winds (red) and the KNW atlas winds (blue). These set out against increasing forecast lead times of the HARMONIE forecasts which form the KNW atlas.

3.2.2 How do KNW and ASCAT 10 m wind speed climatology compare?

In this section the 10 m wind speed of the collocated datasets of ECMWF-OPER (80 km grid spacing), ASCAT (2013) and the KNW atlas are compared to each other. As a result of the collocation procedure the only KNW data used in the comparison are those coinciding in space and time with ASCAT observations. This subset of the KNW atlas consists of more 1-3 hour HARMONIE forecasts than 4-6 hour forecasts and therefore, compared to the full dataset it

(1) reproduces small scale wind features less realistically
(2) has slightly lower wind speeds
(3) has lower extreme wind speeds (often a small part of the wind field which is spatially averaged over a large grid box).

In figure 3.5 the wind speed biases (average differences) of both KNW and ECMWF-OPER are shown compared to the ASCAT measurements. For most of the North Sea, KNW overestimates the wind speed at 10 m height (by about 0.5 m/s) , but along the Dutch coast (including the areas Borssele and Hollandse Kust that have been allocated for wind energy) the KNW wind speeds are on average about 0.4 m/s too low. Taking the bias of the ASCAT measurements into account reduces the overestimate from 0.5 to 0.2 m/s and increases the underestimate from 0.4 to 0.6 m/s. Since the subset of the KNW dataset used for the comparison has slightly lower wind speeds than the full KNW dataset, the full KNW dataset probably agrees better with the ASCAT measurements in coastal areas whereas it probably overestimates the 10 m wind speed further offshore by a bit more than 0.2 m/s. As explained in section 3.1, the ASCAT measurements off the coast near Rotterdam area are too high and should be excluded from the analyses: this possibly explains part of KNW's underestimation of the wind speed along the Dutch coast. Efforts to take this into account but the wind speed difference contours around Rotterdam in the upper graph of figure 3.5 extend northwestwards to halfway between the Netherlands and England. Hasager (2012) compared WRF (another weather forecasting model with a fine grid) to ASCAT, but for a different period (June 2007-November 2008) and found that WRF also overestimates the 10 m wind speed for the largest part of the North Sea (Appendix A3) and by a similar amount (more than 0.5 m/s). While KNW overestimates the wind speed for most of the North Sea, there is very good agreement between ECMWF-OPER and ASCAT. Here again the coastal areas are the exception to that and along the Dutch coast ECMWF-OPER underestimates the wind speed more than KNW does. Taking the bias of the ASCAT measurements into account means that ECMWF-OPER underestimates the 10 m wind speed over the whole of the North Sea and quite severely along the Dutch coast. Just as in the comparison with QuikSCAT, the maximum bias of the model-based data can be found off the east coast of England around 54°N and in German Bight. ECMWF seems to have the same shortcoming as the other models.

Figure 3.6 shows the standard deviation of the 10 m wind speed which quantifies the deviation of the individual values from the mean of those values. Just as in the comparison with QuikSCAT, the largest spread of values is found in the collocated KNW dataset (due to the discontinuities in the dataset every 6 hours and the fact that KNW overestimates the wind speed more than ECMWF-OPER). The standard deviation of the ECMWF-OPER wind speed is the smallest and the standard deviations of ASCAT and KNW are more comparable. Again this is probably due to the fact that the effective horizontal resolution of the ECMWF operational model (110-160 km) is much coarser than that of ASCAT (25 km).The resolution of ECMWF-OPER is made courser than that of the ECMWF operational model because the original 16 km grid has been thinned out on a 80 km grid. In this dataset the KNW wind speeds probably have an effective horizontal resolution of about 300 km but this has not been quantified. The standard deviation is comparable to that of ASCAT because the synthetic jumps in the wind speed (due to the 6 hourly "cold start" initialisations of HARMONIE) probably cause the standard deviation to be larger than one would expect given its fairly course resolution.

Figure 3.7 shows the fraction of the ASCAT, KNW and ECMWF-OPER data with 10 m wind speeds above 10 m/s. For KNW 25-30% of the wind speeds in Dutch coastal waters are above 10 m/s and further offshore 30-35%. These results are not very different from the 10 year period presented in figure 2.8. Compared to ASCAT, KNW overestimates (by 3% or less) how often wind speeds of more than 10 m/s occur, except near the Dutch west coast where it slightly underestimates. ECMWF-OPER and ASCAT are in better agreement, except in coastal areas, where ECMWF-OPER suggests a lower precentage of wind speeds above 10 m/s (also lower than KNW near the Dutch west coast). These comments take into account the fact that ASCAT overestimates the wind speed in the Rotterdam area. The subset of KNW data selected by the times ASCAT passes overhead probably reduces the fraction of wind speeds above 10 m/s compared to the full KNW dataset for 2013. The negative bias of the ASCAT measurements probably means that the fraction above 10 m/s is probably higher than the ASCAT graph shows and that KNW probably verifies better.

Finally the wind speed frequency distributions of the three data sources of the collocated dataset are compared in figure 3.8. There is a very good match between the wind speed frequency distributions of the KNW and ASCAT datasets (respectively the black and blue lines) for wind speeds above 12 m/s and ECMWF-OPER underestimates the occurrence of these wind speeds. For the range 5-11 m/s the opposite is true. Below 5 m/s the ASCAT curve has a different shape from that of the modeled winds and this range of ASCAT winds is currently being investigated at KNMI. So, KNW's apparent underestimation of the occurrence of 5-11 m/s wind speeds may be caused by an excess of scatterometer wind speeds in this range that should be in the < 5 m/s range under investigation. The slight overestimation by KNW of the occurrence of wind speeds > 10 m/s seen in figure 3.7 for most of the North Sea (excluding coastal areas) can also be seen in figure 3.8 (KNW slightly overestimates the occurrence of the small 10-12 m/s range). The underestimation near the Dutch west coast cannot be seen in figure 3.8 because this area is but a small fraction of the North Sea. One would expect to see an underestimation of the more extreme wind speeds by KNW because the subset is biased towards shorter HARMONIE forecast lead times which are more similar to the ERA-Interim wind fields (course horizontal resolution which averages out the extremes) than the longer lead times. There is no sign of this in figure 3.8, so the ASCAT occurrences may be too high. This could be explained by the erroneous very high wind speeds found at the anchor areas. In terms of surface area they are insignificant compared to the whole of the North Sea but that may not be the case for the small subset of extreme wind speeds. Accounting for the (suspected) problems of ASCAT with both low wind speeds and high, the comparison with KNW becomes more like that of KNW and QuikSCAT (figure 2.9), where KNW overestimated the extremes and was similar to QuikSCAT for the mid-range of wind speeds around the peak of the curve. If KNW overestimates the occurrence of 10 m wind speeds in the range 11-17 m/s (figure 2.9) this has little effect on the wind energy production above the rated wind speed (typically 13 m/s at 10 m) of the North Sea offshore wind turbines because power output no longer increases with increasing wind speed above rated wind speed. Taking the negative bias of the ASCAT wind speed measurements probably lowers the overestimate of the KNW winds in this range. The KNW wind speed frequency distribution may verify well at all wind speeds once the various biases of both the ASCAT measurements and the KNW subset have been taken into consideration. For the once in ten year wind speeds is figure 3.8 of little use because such speeds lie at the extreme right hand side of the graph where there are very few or no occurrences. However, in appendix A4 there is a comparison between KNW values and KNMI's own anemometer measurements.

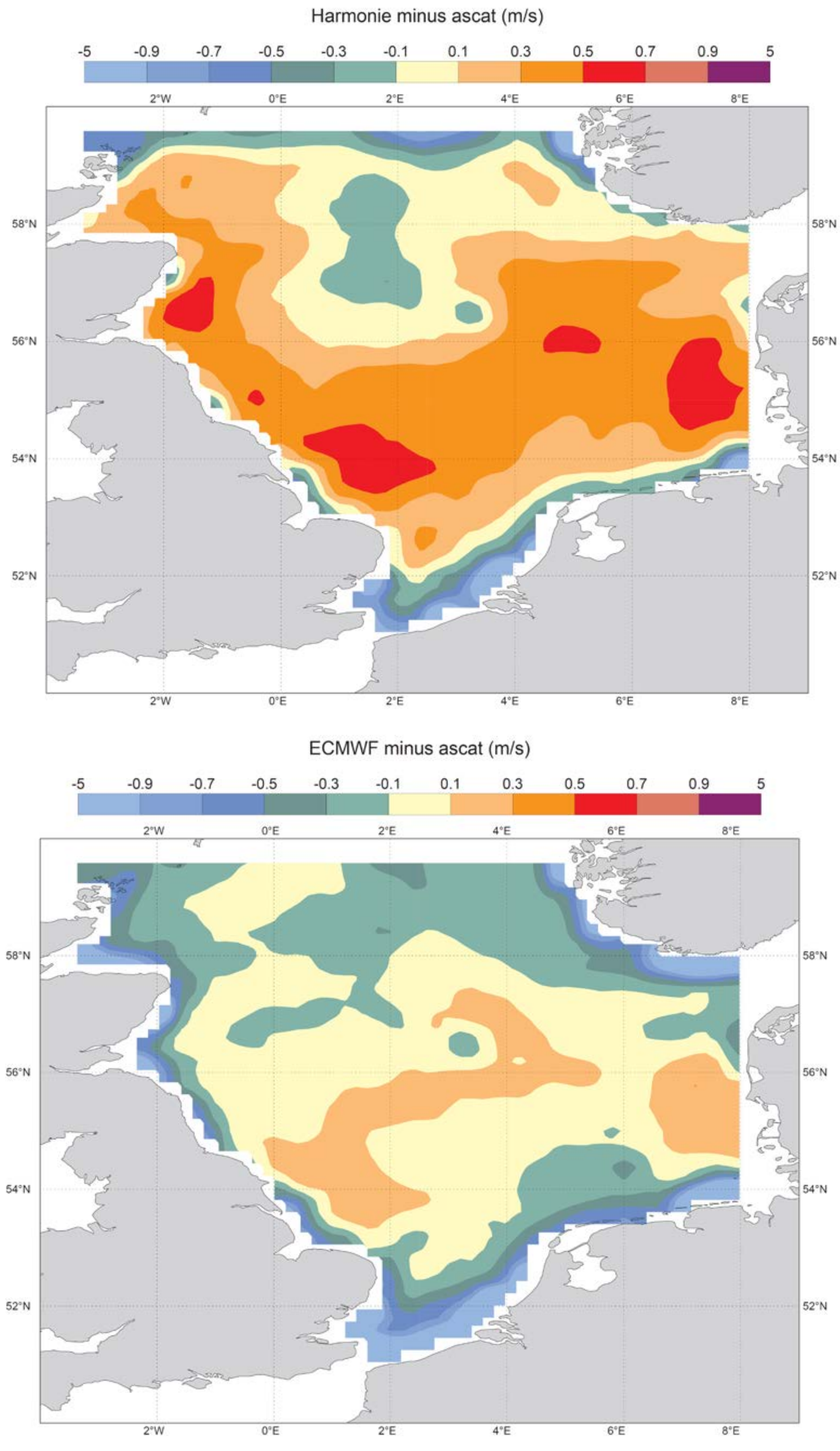


Figure 3.5: Average 10 m wind speed difference (bias) between KNW and ASCAT (top panel) and between ECMWF-OPER and ASCAT and (lower panel).

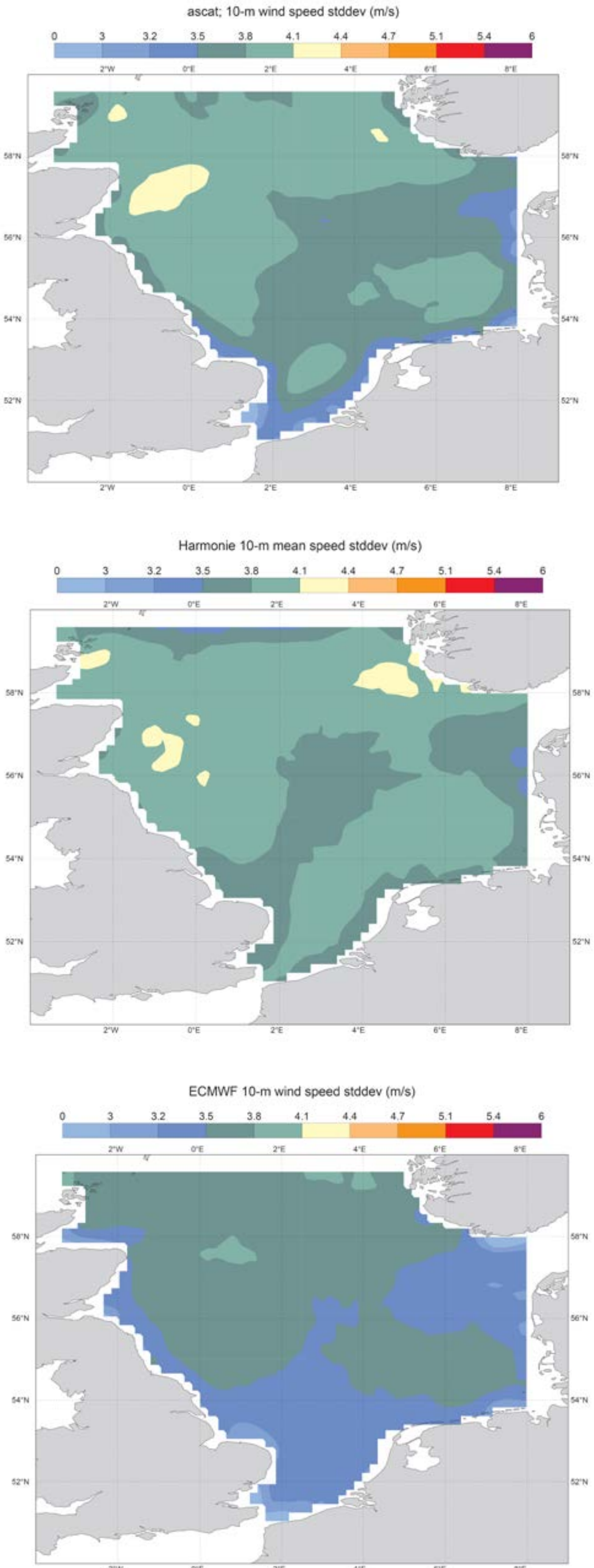


Figure 3.6: The standard deviation of the 10 m wind speeds of the ASCAT (top panel), KNW atlas (middle panel) and ECMWF-OPER (lowest panel) collocated wind data.

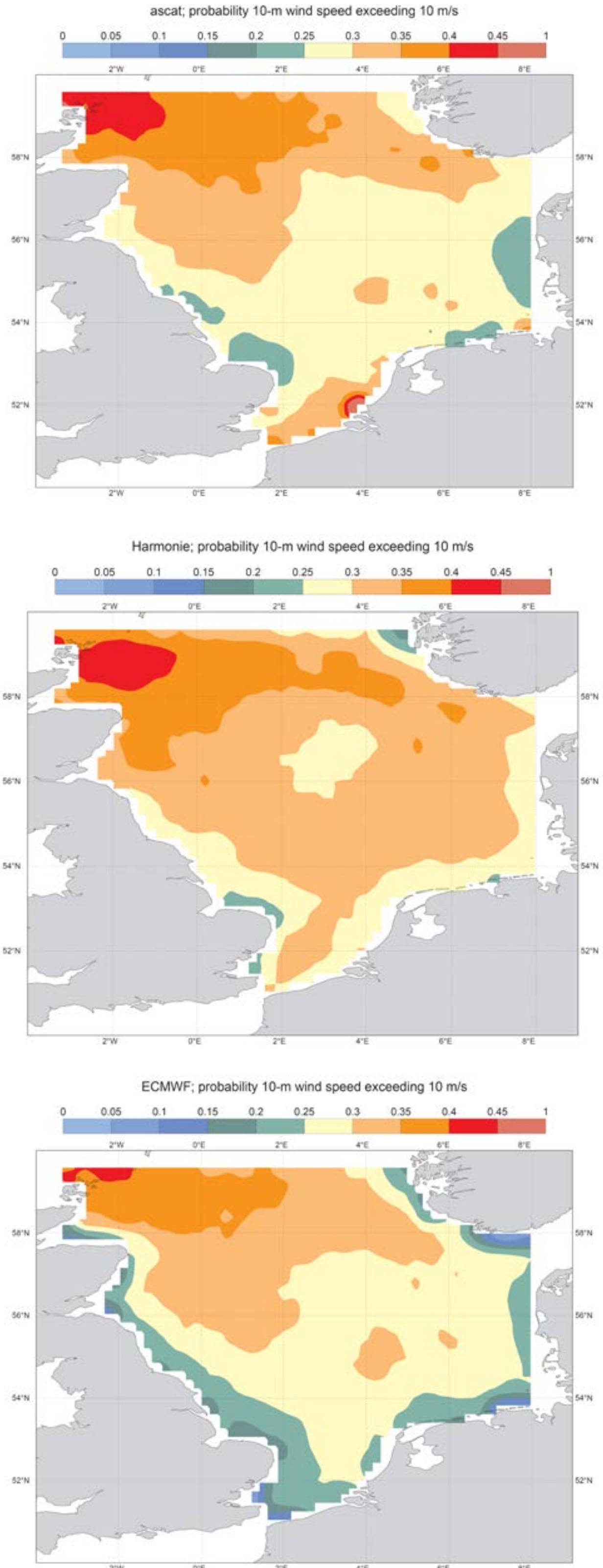


Figure 3.7: Percentage of the collocated dataset with the ASCAT (top panel), KNW atlas (middle panel) and ECMWF-OPER (lowest panel) 10 m wind speeds above 10 m/s.

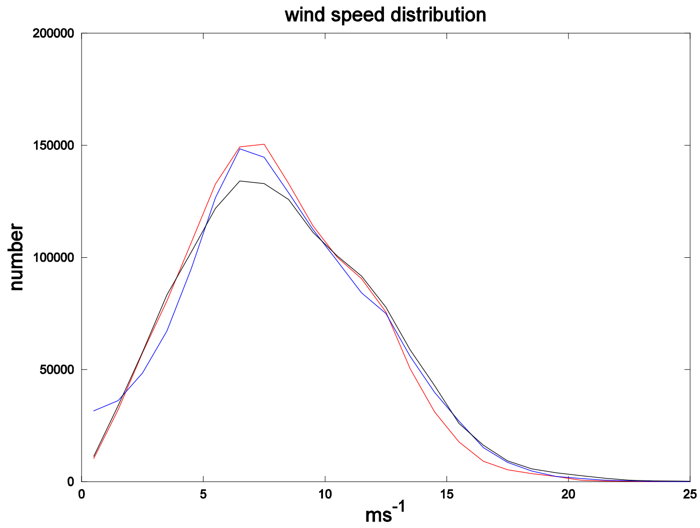


Figure 3.8: Frequency distribution of ASCAT (blue), KNW atlas (black) and ECMWF-OPER (red) 10 m wind speeds from the 2013 collocated dataset.

CHAPTER 4 Horizontal and vertical validation compared

The horizontal verification shows that the KNW atlas wind speed at 10 m above mean sea level is overestimated compared to QuikSCAT and ASCAT measurements for most of the North Sea. The overestimate is 0.3-0.4 m/s for more than half of the North Sea (see the upper panels of figures 2.6 and 3.5 and take into account the negative bias of ASCAT and the effect of the collocation on the KNW dataset) and this area differs little between QuikSCAT and ASCAT. Stepek (2015) showed that the KNW atlas wind speeds at heights above 10 m were on average almost identical (bias 0.2 m/s or less) to those of three tall offshore measurement masts (MMIJ, OWEZ[18] and FINO1). At first sight the horizontal and vertical verification results seem contradictory. However, if we look more closely at the horizontal verification using both scatterometer instruments at the MMIJ location we see that this is not the case. The bias (KNW – scatterometer) there is <0.2 m/s which agrees with the vertical validation results above 10 m. The same cannot be said at the FINO1 location: there the KNW atlas overestimates the QuikSCAT[19] 10 m wind speed by slightly less than 0.3 m/s which differs from the vertical validation results above 10 m (see figure 4.1). Compared to ASCAT (corrected for its negative bias) the overestimate is slightly more than 0.0 m/s but more weight should be given to the QuikSCAT validation because it covers 10 years to ASCAT's 1 year.

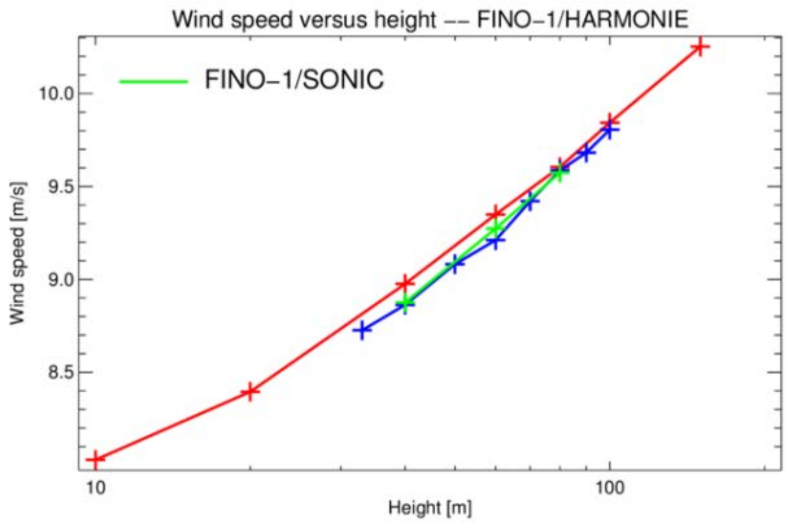


Figure 4.1: Validation at FINO 1 in undisturbed period (20040101-20081231) using measurements with DEWI UAM-corrections (source: Westerhellweg, 2012) and shear-corrected HARMONIE. Anemometer measurements (blue) and sonic measurements (green) and HARMONIE (red). Source: Vertical validation report (Stepek et al, 2015)

That KNW wind speeds at 10 m overestimate the true wind speed for most of the North Sea does not necessarily imply that the same is true for KNW wind speeds above 10 m. The vertical verification at FINO1 demonstrates this because the overestimation at 10 m is slightly less than 0.3 m/s (horizontal validation) and at wind turbine hub height (around 100 m) the vertical validation shows no overestimation. More locations with measurements at heights around 100 m in these areas are

[18] The scatterometer measurements do not come close enough to the shore to cover the OWEZ location.

[19] In the comparison with QuikSCAT, a collocated subset of the complete KNW dataset was used which is biased towards longer HARMONIE forecast lead times. This means that the overestimate is in part due to KNW 10 m wind speeds that are on average slightly higher than those of the whole dataset. The opposite is true for the subset collocated with the ASCAT measurements.

required to resolve this issue. However, there are no publicly available wind speed measurements in this area. The offshore wind energy sector does have access to such measurements so we would invite them to verify the KNW atlas with these measurements and publish the results or share their measurements with KNMI.

We can also compare the probability of exceeding 10 m/s at 10 m height of the horizontal verification (figures 2.8 and 3.7) to the wind speed frequency distributions of the vertical validation (see figures 3.2a and 5.4 in vertical validation report (Stepek et al, 2015) at locations FINO1 and MMIJ:

- FINO1: the vertical validation shows that KNW slightly overestimates the frequency of occurrence of 100 m wind speeds in the 8-19 m/s range. The horizontal verification similarly shows that the KNW probability of exceeding 10 m/s at 10 m height (in percent) is 3% higher than the QuikSCAT percentages and slightly higher than the ASCAT percentages.
- MMIJ: the vertical validation shows no consistent under or overestimation for any range of wind speeds when compared to the measurements. Similarly, the horizontal verification shows that the KNW probability of exceeding 10 m/s at 10 m height is at most 1% higher than the scatterometer (both QuikSCAT and ASCAT) percentages.

On the basis of this evidence, there is no reason to doubt that what the horizontal validation at 10 m height tells us about the KNW probabilities of exceeding 10 m/s can be applied in a general sense to the exceedance probabilities at heights closer to wind turbine hub height. This means that KNW is likely to overestimate the probability of exceeding 12 m/s at 100 m (equivalent to 10 m/s at 10 m) for sea areas far from the coast. KNW probably models the stronger wind speeds along the Dutch west coast at a 100 m height correctly because it also does that at 10 m height. Once again, more measurements at heights above 10 m are required to substantiate this tenuous statement and we invite the offshore wind energy branch to use their privately owned measurements to do this or share those measurements with KNMI.

The comparison of the values of the once in 10 year 10 m wind speeds (Appendix A4) of KNW and KNMI anemometer measurements showed KNW overestimating by 0-8% at offshore station locations west of the Netherlands. In the vertical validation report (Stepek et al, 2015) the only tall mast in that same area with enough undisturbed measurements to make an extreme analysis reliable was MMIJ. KNW overestimated the once in 10 year wind speed at 90 m height by a bit less than 3% although this difference was statistically insignificant. These results help substantiate the hypothesis that validation of KNW values of strong winds at 10 m does tell us something, in a qualitative sense, about how KNW would validate at higher heights.

CHAPTER 5 Conclusions and recommendations

- The KNW atlas 10 m wind speeds are on average 0.3-0.4 m/s too high for most of the North Sea. For the southern part (including the wind energy areas Borssele and Hollandse Kust) the KNW atlas underestimates the 10 m wind speed by 0.1-0.3 m/s and probably slightly more. The comparison with both scatterometers supports the first conclusion. The second is based on the comparison with the QuikSCAT measurements (as there is only one year of ASCAT measurements and in that area the ASCAT measurements may be contaminated by the influence of the anchor areas). Comparison with the results of the vertical validation against tall measurement masts indicates that it cannot be assumed that the overestimation found at 10 m height means that KNW also overestimates the wind speed at wind turbine hub height.

  Recommendations:
    - The offshore wind energy sector has hub height measurements of the wind in the areas where the scatterometer measurements show that KNW overestimates the 10 m wind speed. We recommend that the sector uses these privately owned measurements to extend the vertical validation of the KNW atlas to these areas or shares the measurements with KNMI.

- The probability of 10 m wind speeds of > 10 m/s occurring along the Dutch west coast is correctly modelled by the KNW atlas and more than half the wind energy produced by wind turbines on the North Sea is generated at these wind speeds. The atlas overestimates the probability by less than 5% in English coastal waters and 3% or less further offshore. These conclusions are based on comparison to both QuikSCAT and ASCAT scatterometer measurements. The comparison of the wind speed distributions (averaged over the whole North Sea) support these conclusions. Figure 2.9 shows that KNW overestimates the range 10-16 m/s compared to QuikSCAT but the KNW wind speeds in the collocated subset are probably lower than in the full 1999-2009 KNW dataset. Figure 3.8 shows the KNW atlas overestimating the occurrence of 10 m wind speeds above 12 m/s compared to ASCAT but the comparison improves when the shortcomings of both the ASCAT measurements and the collocated KNW subset are taken into account . Comparison with the vertical validation results indicates that the conclusions for the 10 m wind speed may also be valid in general terms at wind turbine hub height.

  Recommendations:
    - The tenuous conclusion that the same pattern found at 10 m height can be assumed for wind turbine hub height is based on measurements from only two tall measurement masts. We recommend that the offshore wind energy sector extends the vertical validation to other parts of the North Sea with its privately owned hub height wind measurements or shares them with KNMI.

- KNW does not make use of HARMONIE at its full potential because the development of small-scale spatial structures, starting from smooth ERA-Interim fields, is still ongoing 6 hours into the forecast and KNW is based on the first 6 hours of the forecasts.

  Recommendations:
    - Compare wind statistics from collocated QuikSCAT (and/or ASCAT) and KNW data with a single forecast lead time of 6 hours to obtain a subset of KNW winds of uniform quality.

- Evaluate HARMONIE forecasts with lead times longer than 6 hours to find out how long HARMONIE needs to fully develop small-scale structures.
- The KNW representation of the diurnal cycle and small-scale spatial structures of the wind can be improved using the existing dataset because the HARMONIE 7 hour forecasts have also been archived. These should replace the 1 hour forecasts in the KNW dataset, e.g. the 00UTC + 7 hour forcecast replaces the 06UTC + 1 hour.
- Create a new KNW dataset based on a continuous series of HARMONIE forecasts to avoid the problems caused by the ERA-Interim based cold starts every 6 hours. HARMONIE would then have to assimilate the 6 hourly ERA-Interim analyses into its forecast with a lead time of 6 hours. Although more costly, the benefits are clear: no severe discontinuities in the series every 6 hours and HARMONIE is used at its full potential. Three years of continuous HARMONIE data is available from the Reforecasting project that could be used to quantify the potential benefits.

- The intercomparison of datasets with different effective resolutions is not trivial and to do it properly, the higher resolution datasets should be averaged to obtain effective horizontal resolutions comparable to the dataset with the lowest resolution.

  Recommendations:
  - Average HARMONIE wind data over the scatterometer footprint before the intercomparison.
  - Collocate with ASCAT measurements from the period 2007-present (instead of only 2013) and with the operational version of the ECMWF weather forecasting model (grid spacing 16 km) instead of ECMWF-OPER (on a 80 km grid).
  - Use a triple collocation technique that takes into account the various effective horizontal resolutions of the different HARMONIE forecast lead times.

  Other recommendations:
  - Distinguish between wind blowing from land to sea and wind blowing from sea to land to find out why KNW underestimates 10 m wind speeds along the Dutch west coast. Is this related to the differing atmospheric stability of these wind direction sectors? Does wind direction make no difference, in which case, the course ERA-Interim grid may be "contaminated" by coastal land. Compare stress-equivalent wind speeds instead of 10 m wind speeds because this is what the scatterometer actually measures. The conversion to 10 m wind speeds assumes uniform atmospheric stability and air density which actually change in time and space.
  - Improve the validation of the diurnal cycle of KNW 10 m winds, by using a period at the end of 2013 with 4 scatterometers in orbit, passing over the North Sea at different times of day. : ASCAT-A passes over the North Sea at 9:30 and 21:30 UTC, ASCAT-B at 10:15 and 22:15, the Indian OceanSat-2 scatterometer at 00:00 and 12:00 and the Chinese Haiyang-2 scatterometer at 06:00 and 18:00 UTC.

Literature

- Geertsema G T and van den Brink HW (2014) Windkaart van Nederland op 100 m hoogte. KNMI Technical Report TR351 (in Dutch)

- Stepek A, Savenije M, van den Brink HW and Wijnant IL (2015) Validation of KNW atlas with publicly available mast observations (Phase 3 of KNW project). KNMI Technical Report TR352

- Verhoef A and Stoffelen A (2013) Validation of ASCAT coastal winds, version 1.5. SAF/OSI/CDOP/KNMI/TEC/RP/176, EUMETSAT

- Wijnant IL, van den Brink HW and Stepek A (2014) North Sea Wind Climatology. Part 1: a review of existing wind atlases. KNMI Technical Report TR342

Appendix A1 Shear Correction

The formula Geertsema (2014) used to correct for the underestimation of the wind shear is formula 1 (in which FF_{20} is the wind speed at 20 m height, FF_h is the wind speed at height h and $FF_{h,c}$ the corrected wind speed at height h)[20]. The corrected HARMONIE wind speed profile (blue) reproduces the observed profile (black) remarkably well.

$$FF_{h,c} = FF_{20} + \frac{FF_h - FF_{20}}{0.85} \qquad (1)$$

In order to determine whether shear correction formula 1 could be applied in a more general way (not only for Cabauw) two tests were performed: one to find out if the correction would be independent of the wind direction at Cabauw (which would imply independence of terrain/surface roughness) and another to find out if the correction would also work for the Wieringermeer wind mast.

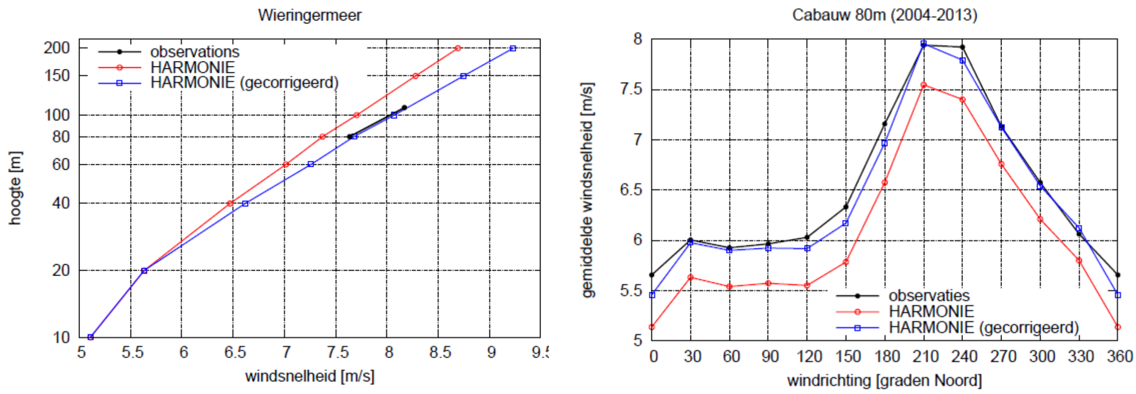


Figure A1.1 Average vertical wind profile Wieringermeer (left) and Cabauw per wind direction (right) for 2004-2013: observed (black), HARMONIE (red) and HARMONIE corrected (blue) (source: Geertsema, 2014).

Figure A1.1 shows that shear-correction formula 1 also works for the Wieringermeer wind mast (left). It also shows that the improvement of HARMONIE is almost independent of wind direction (terrain) and that measurements and HARMONIE with shear-correction are in good agreement (right). The latter implies that (at least at Cabauw) shear-correction of HARMONIE wind profiles suffices. The roughness map that HARMONIE uses, is adequate.

For the KNW-atlas the shear correction was applied to all levels (including the ones below 20 m) but the KNW dataset validated against the scatterometer 10 m wind products has not been shear corrected because the corrections at 10 m are very small.

[20] In a small number of cases applying this shear correction would result in negative values for the wind speed. In those cases the shear correction was not applied. This has no effect on the wind statistics.

Appendix A2 QuikSCAT

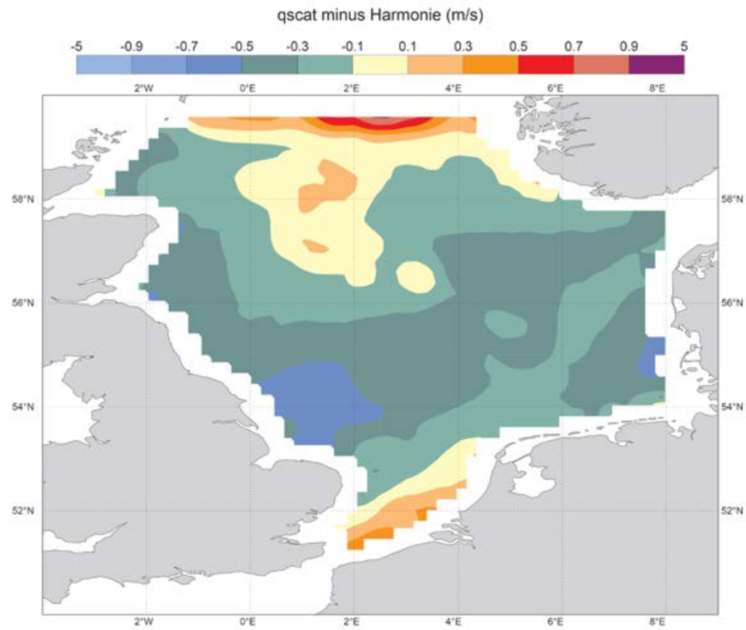


Figure A2.1: Average difference (mean bias) between QuikSCAT and KNW

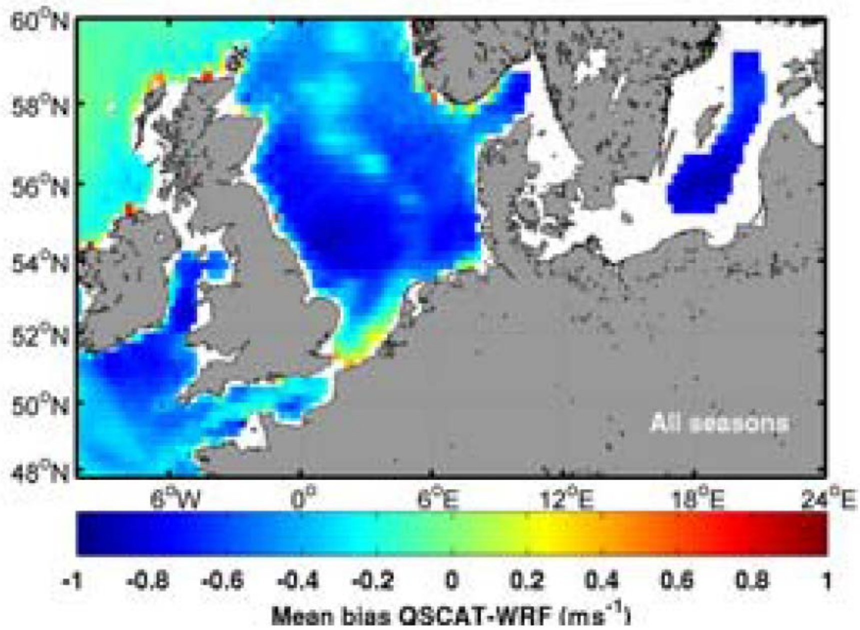


Figure A2.2 Comparison QuikSCAT and WRF: for most of the North Sea WRF gives higher wind speeds than QuikSCAT (bias mean wind speed QuikSCAT – WRF is negative), except offshore from the Netherlands where the bias is positive. Note the light blue spots in the North sea bias of WRF minus QSCAT. These are due to the oil platforms and ships that contribute radar backscatter by corner reflections. At low winds these are noted and removed by Quality Control procedures; this enhances the mean QuikScat winds. Errors due to QC still need to be removed from the satellite wind maps as do sampling errors (source: Hasager, 2012).

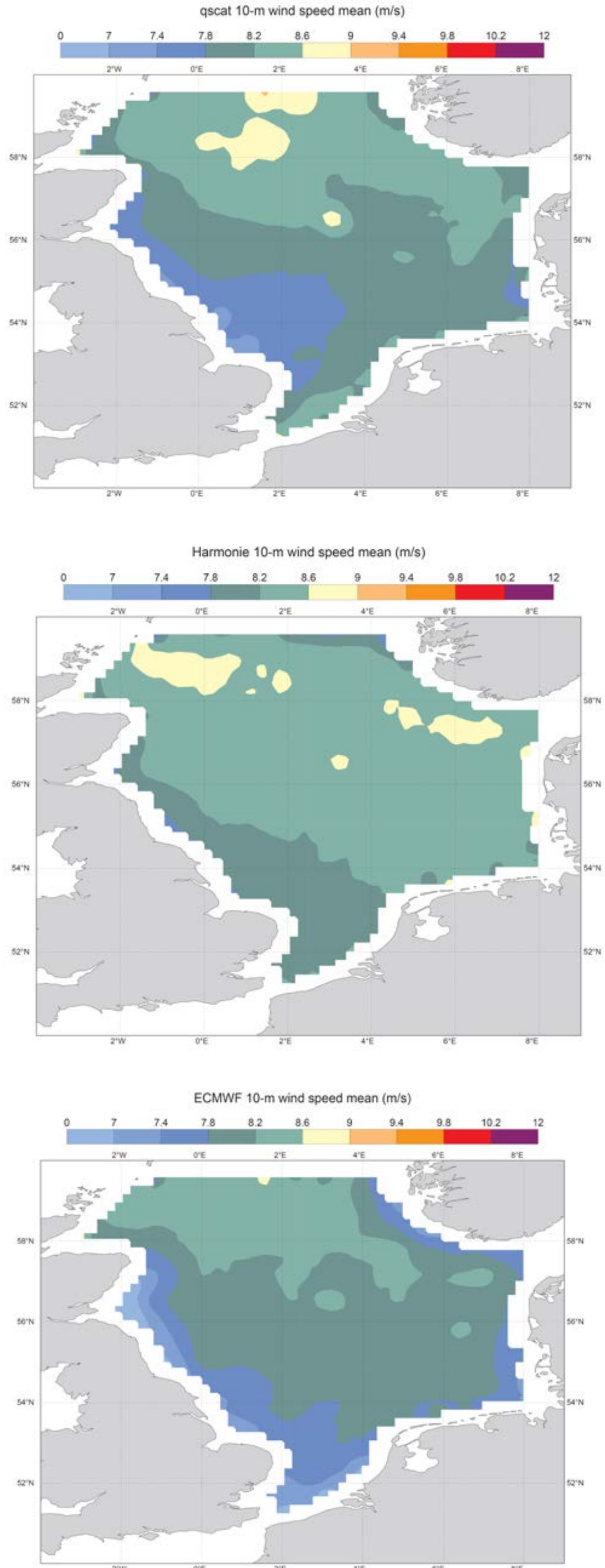


Figure A2.3: Comparison between the 10 m wind speed of the collocated datasets of QuikSCAT (top panel), KNW atlas (middle panel) and ERA-Interim (lowest panel).

Appendix A3 ASCAT

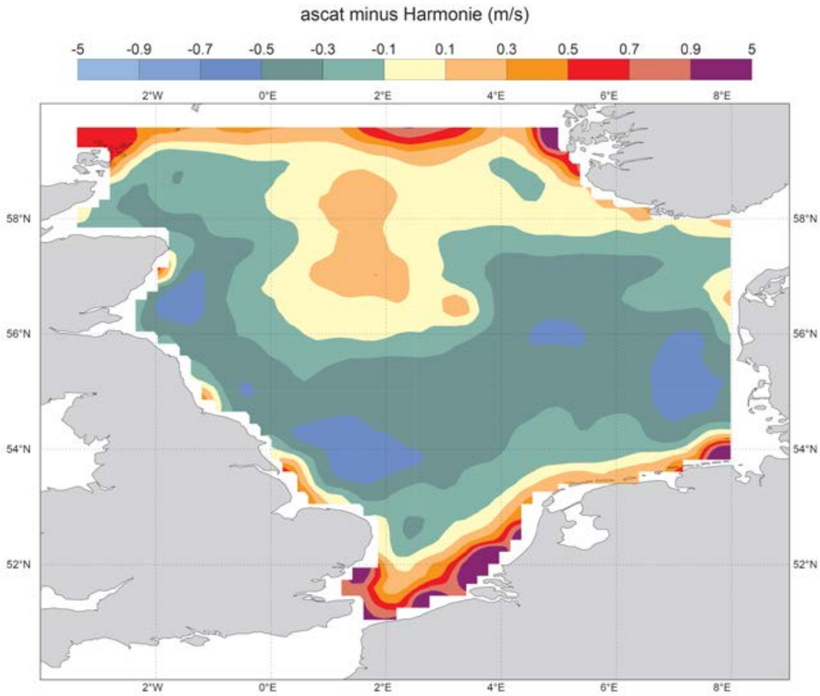


Figure A3.1: Average10 m wind speed difference (mean bias) between ASCAT and KNW

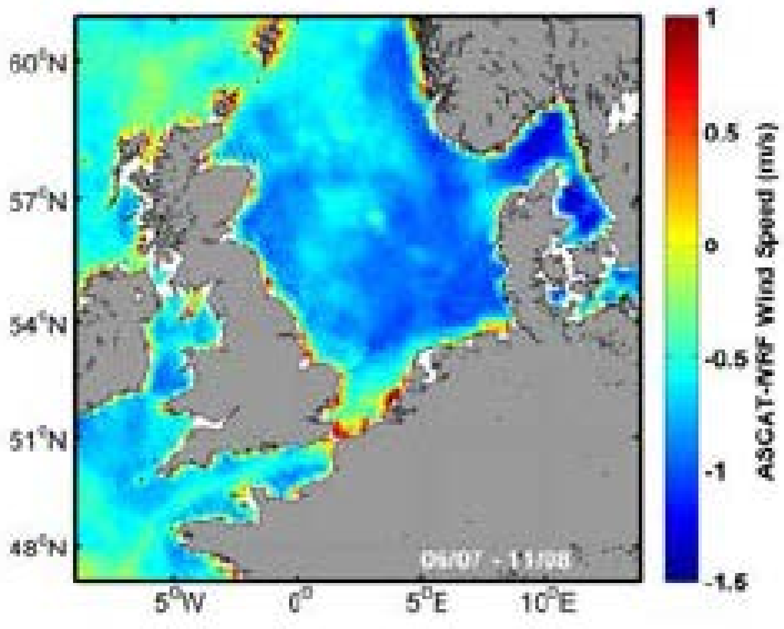


Figure A3.2 Comparison ASCAT and WRF: for most of the North Sea WRF gives higher wind speeds than ASCAT (bias mean wind speed ASCAT – WRF is negative), except offshore from the Netherlands where the bias is positive (source: Hasager, 2012).

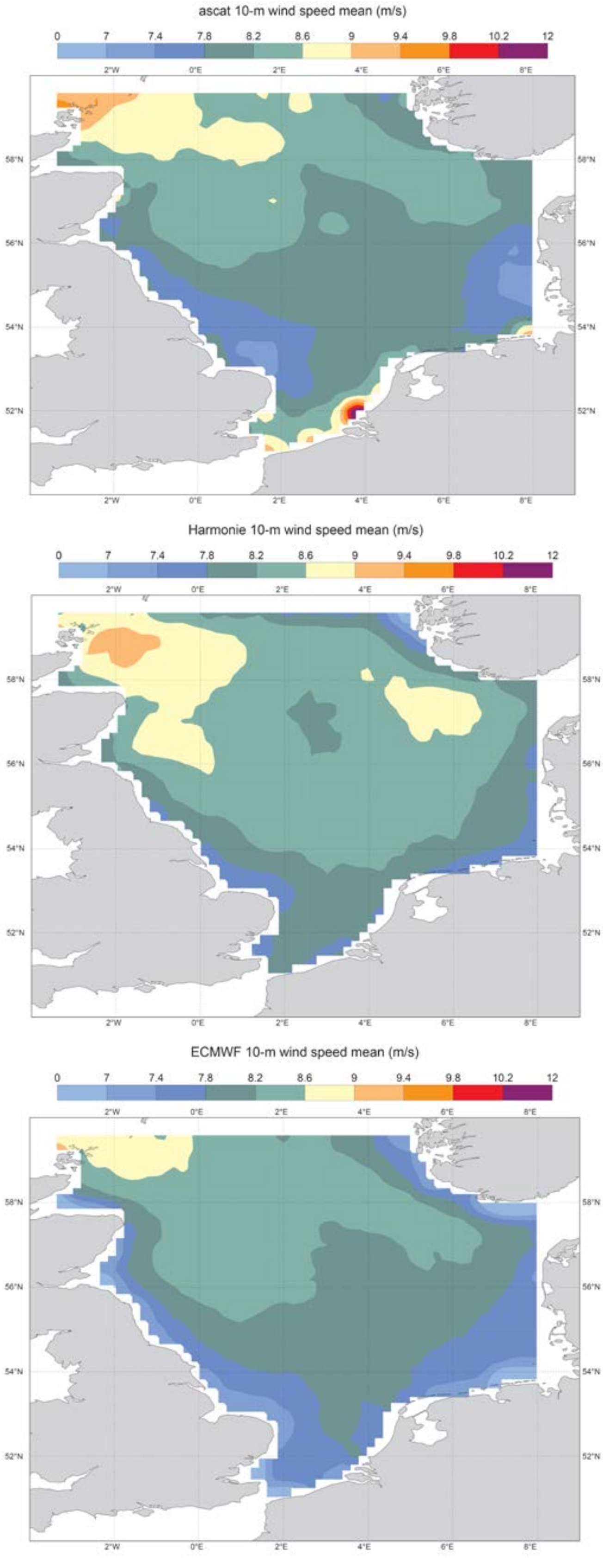


Figure A3.3: Comparison between 10 m period (2013) average wind speeds collocated datasets of ASCAT (top panel), KNW atlas (middle panel) and ECMWF-OPER (lowest panel).

Appendix A4 Once in 10 year wind speed validation

Although the KNW extreme wind speeds compare well to the measured extremes at wind turbine hub height (Stepek et al, 2015), figure A4.1 (left panel) shows that this is not the case at the standard meteorological wind measurement height of 10 m.

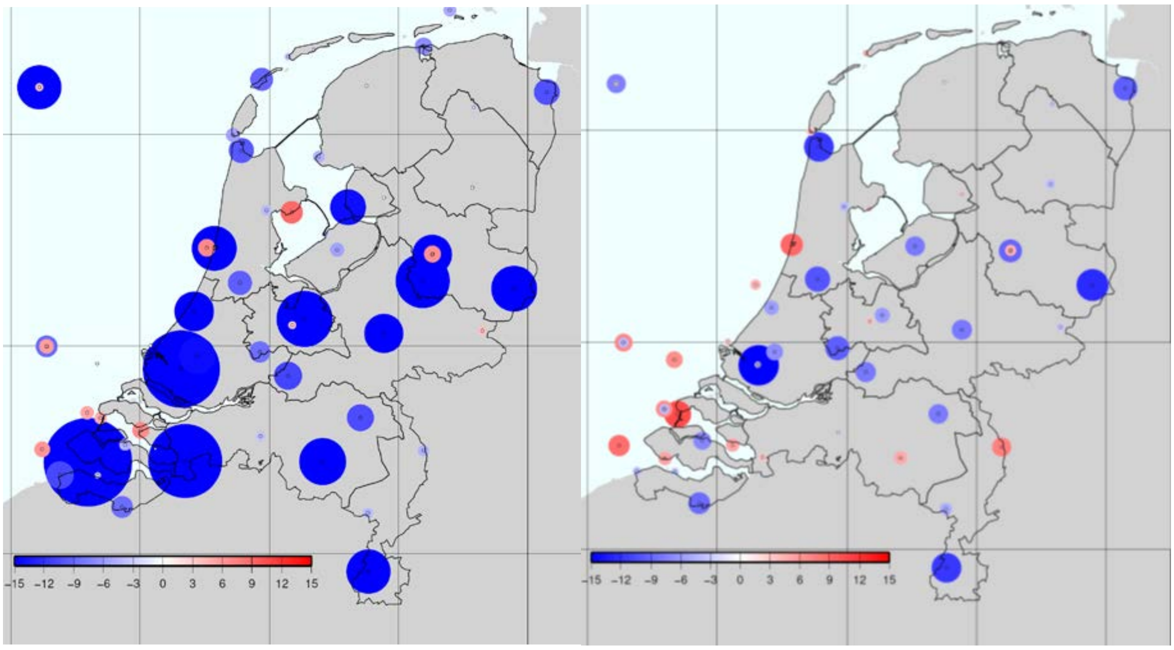


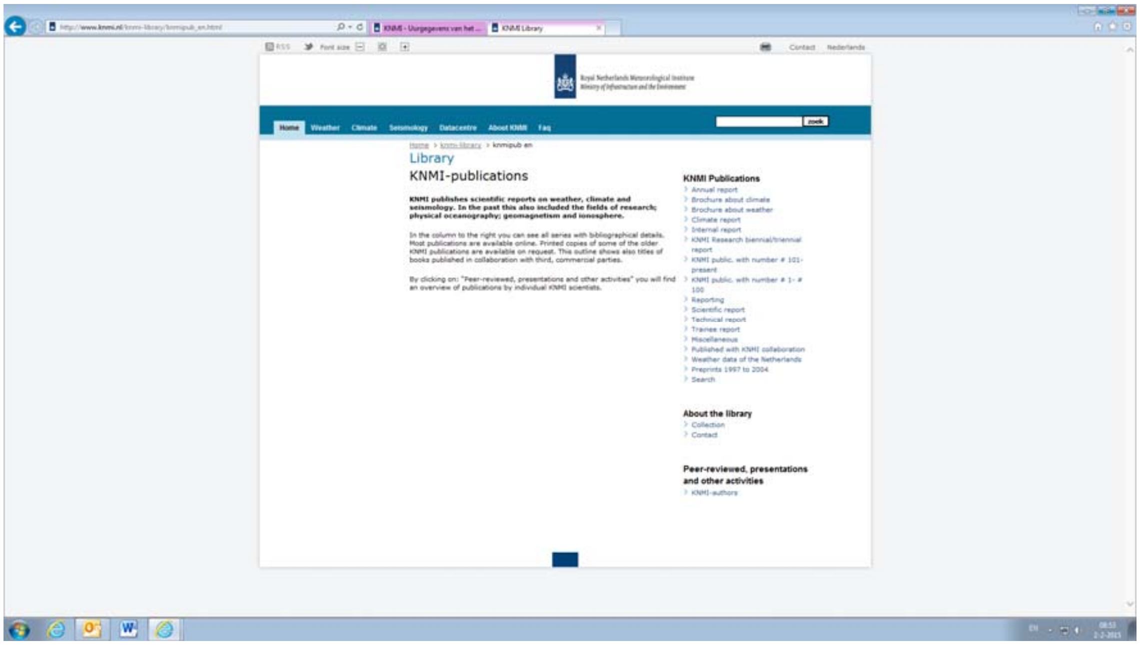
Figure A4.1 Left: Once in 10 year 10 m wind speed differences (KNW – measured) in percent of the once in 10 year measured wind speed. Right: idem but then for the potential wind speed.

These large differences are mainly due to the fact that wind measurements are mostly only representative for a small area (the wind is different a hundred meters from the measurement location) because they are sensitive to the roughness of the surrounding terrain. Potential wind[21] was developed to address this problem by adjusting the measured wind speeds so they are representative for a wider area and normalised to a standard roughness length for all wind directions. The potential wind is better suited for comparison with the HARMONIE values because the effect of roughness is averaged over the 2.5 by 2.5 km grid box of the model and is the same for all wind directions. To make the comparison with potential wind possible, the HARMONIE values had to be converted into potential winds by normalising them to the same standard roughness length (in this case 0.03 m for both sea and land stations) used to calculate the potential wind from the measurements. The resulting improvement of the comparison of the extremes can be see in the right panel of figure A4.1: the KNW values now differ from the measured values by less than 10% for most of the measurement locations.

[21] The potential wind is the measured wind speed corrected for differences between the measured local roughness (for each wind direction sector of 20°) and the standard local roughness the World Meteorological Organisation requires for wind measurements (0.03 m for land).

Focussing on the measurements made at sea we see that the differences are smaller (8% or less). Although these values are nominally for heights of 10 m, the original measurements were made at greater heights and transformed to 10 m equivalents using a logarithmic wind profile assuming neutral stability. The original measurement heights range from K13's 74 m in the north to 17 m wind masts (Oosterschelde and Vlakte van de Raan) off the coast of Zeeland in the south. All of the stations show KNW overestimating the measured value, except K13. This is probably due to the fact that one of the two anemometer locations at K13 is known to suffer from 8% overspeeding for some wind directions.

A complete list of all KNMI-publications (1854 – present) can be found on our website www.knmi.nl/knmi-library/knmipub_en.html



The most recent reports are available as a PDF on this site.