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### Introduction

In 2016 a study was published by Garrad Hassan and Partners Ltd (DNV GL) on the inter-annual variability (IAV<sup>1</sup>) of wind in UK offshore waters [1]. The main conclusion of this study, which was commissioned by The Crown Estate (TCE), is that the current industrial standard for the IAV is too conservative for UK offshore waters: a range of 4.0-5.5% is suggested to be more appropriate than the 6% standard currently used.

The 6% standard stems from a study in 1997 by Garrad Hassan and is based on long-term measurement campaigns at onshore meteorological stations. In the 2016 study the values for the IAV were derived from a 20 year (1996-2015) MERRA-2 reanalysis<sup>2</sup> [2]. Based on annual means (defined by calendar year) of gridded wind speed data at 50 m height, the IAV-values in the UK Exclusive Economic Zone (see Fig.1) vary from 3-4% for the North Sea and the English Channel to 4-5% for the Irish Sea. This is much lower than the industrial standard of 6%. DNV GL “adjusted” the IAV-values to 4-5.5% in order to account for the fact that they depend on the definition of the year and the length of the period considered. Using different year definitions than the calendar year, can give rise to IAV-values that are up to 0,9% different. This shows how sensitive the 20 year period is to choices that should not affect the IAV-value. Comparing the 20-year MERRA reanalysis to a MERRA reanalysis of 36 years (1980-2015) shows that the IAV is generally higher based on 36 years (up to 1% in Scottish waters). Earlier studies into the IAV [3,4] have also shown that it is important to include the whole spectrum of windy and calm years that are part of the wind climate. This means that the IAV should be based on at least 30 years of measurements or model data (or an intelligent selection of years).

The IAV-values of the 2016 study based on 20 years of MERRA-2 reanalysis data were validated against 24 datasets of wind measurements from offshore lidars and wind masts (including KNMI stations Euro Platform and K13), production data from 24 wind farms and measurements from coastal onshore and offshore UK meteorological stations. At K13 MERRA-2 gave a higher IAV than the measurements and at Euro Platform the MERRA-2 value was smaller than the measurements: the differences were less than 0.5%. At the measurement sites in the southern North Sea part of the UK Exclusive Economic Zone, the IAV-values of MERRA-2 are mostly higher than the measured values. The difference ranges from -0.3 to + 1.7% and the largest differences are for short measurement campaigns (4-6 years) from non UK Met. Office stations. At Met. Office stations the MERRA-2 IAV is on average 0.4% higher than the measured IAV.

The aim of this study is to assess the IAV of the wind speed in the Dutch Economic Exclusive Zone (DEEZ) of the North Sea (see Fig.1) at heights relevant for wind energy

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<sup>1</sup> Standard deviation of the annual mean wind speed, expressed as a percentage of the mean wind [%]

<sup>2</sup> A reanalysis is a multi-year, global, gridded representation of the atmospheric state, using weather models and data-assimilation techniques. The weather model makes a best fit of the available measurements constrained by the laws of physics. The grid-spacing in MERRA-2 is about 50 km (<http://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-16-0758.1>)

(near hub height). As in the report of DNGV GL, the IAV of the wind speed is based on calendar years and defined as the ratio of the standard deviation of the annual mean wind speed and the mean long term wind speed:

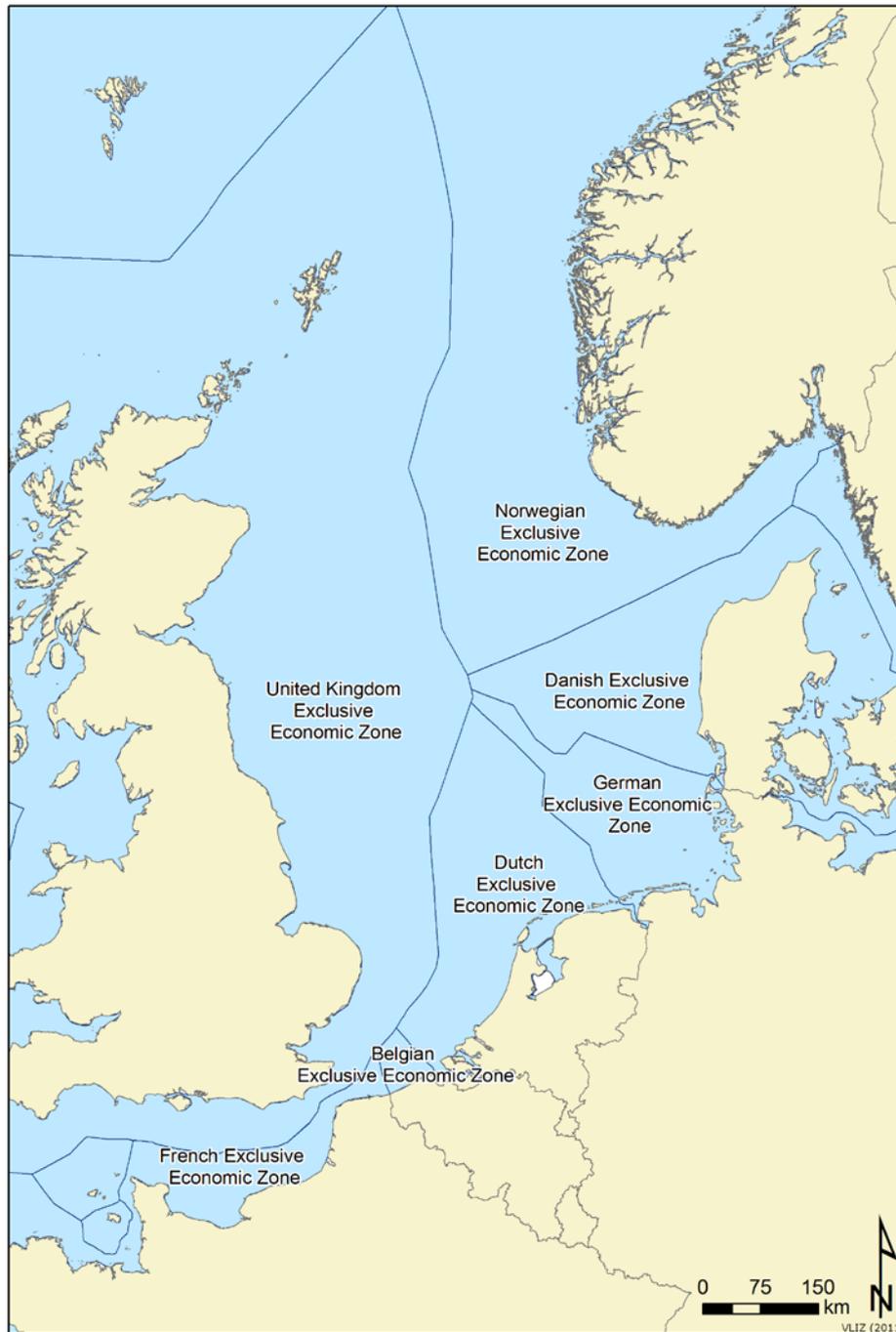
$$IAV = \frac{\sigma_a}{\bar{u}_a} \quad (1)$$

where  $\sigma_a$  is the standard deviation of the annual mean wind speed and  $\bar{u}_a$  is the mean long term wind speed. The IAV is determined for a number of locations near or in the DEEZ (see Fig. 2 and Table 1 for an overview of the locations and their coordinates).

## Method

The IAV values in this study are calculated with the hourly wind speed information in the KNW wind atlas [5]. The KNW-atlas is based on the ERA-Interim reanalysis dataset [6] 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 forecasting model HARMONIE [7] with a horizontal grid spacing of 2.5 km. The wind speeds were then adjusted with a single wind shear correction factor [8] throughout the whole KNW-atlas area. The correction factor increased the change of wind speed with height between 20 and 200 m height by 15% of the original value. The 15% factor was derived by comparing the HARMONIE wind speed to the measurements at the tall wind mast at Cabauw. The result is a high resolution dataset of 35 years containing hourly information for 8 different heights (10, 20, 40, 60, 80, 100, 150 and 200 m).

For this study the KNW wind speeds at 40, 60, 100 and 200 m are used because 40 and 60 m are closest to the 50 m used in the study of DNV GL, and 100 and 200 m because they are respectively close to the hub and tip height of modern wind turbines. 35 annual mean wind speeds are calculated for each location at these 4 heights. These annual mean wind speeds are then used to calculate the standard deviation of the annual mean wind speed and subsequently the IAV of the wind speed using formula (1). The values for IAV are shown in table 2. For each location, the 35 annual means are also used to estimate the probability density function or frequency distribution of the annual means using a kernel density estimation approach [9], for which a Gaussian kernel is adopted with a bandwidth that is given by Scott [10]. These results are shown in figure 4.



*Fig 1: Map of the North Sea showing the different economic exclusive zones, including the Dutch Exclusive Economic Zone (DEEZ), Source: [ww.marineregions.org/eezsearch.php](http://ww.marineregions.org/eezsearch.php)*

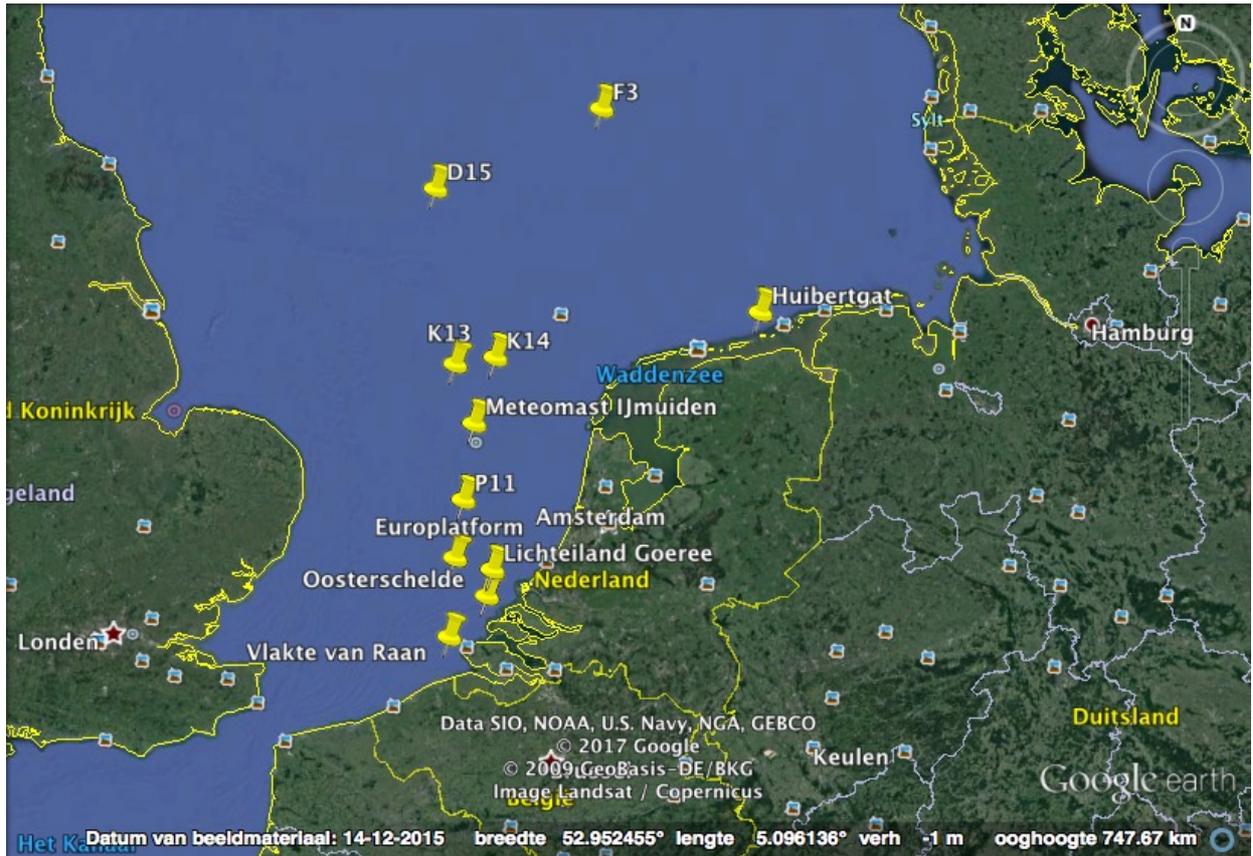


Fig 2: Google Earth map (© 2015 Google Inc.) with the locations in or near the DEEZ where the IAV is assessed using wind information in the KNW-atlas.

Station name	Latitude (°N)	Longitude (°E)
Meteomast IJmuiden	52.84	3.45
K14	53.27	3.62
K13	53.21	3.24
D15	54.31	2.93
P11	52.37	3.36
F3	54.60	4.72
Huibertgat	53.58	6.40
Oosterschelde	51.67	3.60
Vlakte van de Raan	51.50	3.23
Lichteiland Goeree	51.92	3.68
Europlatform	51.99	3.28

TABLE 1: DEEZ offshore location identifiers and coordinates

## Results

In table 2 we see that the far offshore locations (Meteomast Ijmuiden, K14, K13, D15, P11, F3) have a smaller IAV at 40 m height than at 200 m. This can be explained by the effect of roughness on the wind speed profile. At both low and high wind speeds the roughness of the sea has more effect on the wind speeds at lower levels: speeding up low winds (calm, smooth sea) and slowing down high winds (rough sea). This does not apply to the near shore locations because the roughness of land and the resulting internal boundary layer strongly affects the wind speed profile for many wind directions. The daily cycle of atmospheric stability above land makes it even more difficult to explain the results for near coast locations. Note that the calculated IAVs in table 2 are between 3.5 and 4% for the stations on the North Sea north of P11 (MMIJ, K14, K13, D15, F3, Huibertgat) and between 4 and 4.5% for the stations south of P11 (P11, Oosterschelde, Vlakte van de Raan, Lichteiland Goeree and Europlatform). The greater variation in annual mean wind speed is probably due to the strong influence of land on the wind speeds for more wind directions than is the case for the more northerly locations.

The values in IAV in table 2 compare well to the values found by DNV GL for the UK Exclusive Economic Zone of the North Sea using 36 years (1980-2015) of MERRA-2 data ([1]; their figure 4-12). The IAV's based on 36 years have not been validated directly by DNV GL (only the IAV's based on 20 years). In the DNV GL study it was found that the IAV based on 20 years was underestimated at Euro Platform by MERRA-2 and overestimated at K13. Both differences were however less than 0,5%. The KNW atlas IAV at Euro Platform (measurement height of 29 m) was 4.18% at 40 m height and the measured IAV 4.2%. K13 measures at 74 m height and the 60 m KNW atlas IAV was 3.75% and the measured value 3.5%. For these 2 locations the KNW atlas comes a little closer to the measured IAV than MERRA-2 and the accuracy of the KNW atlas IAV seems to be at least as good as that of MERRA-2. So, it can safely be concluded that the British industrial standard of 6% is also too high for the Dutch Exclusive Economic Zone where IAV ranges between 3.5 and 4.5%.

<i>Station Name</i>	<i>IAV 40 m %</i>	<i>IAV 60 m %</i>	<i>IAV 100 m %</i>	<i>IAV 200 m %</i>
Meteomast Ijmuiden	3.90	3.85	3.83	3.99
K14	3.82	3.79	3.75	3.92
K13	3.79	3.75	3.72	3.91
D15	3.68	3.68	3.70	3.88
P11	4.04	3.99	3.99	4.12
F3	3.55	3.55	3.56	3.73
Huibertgat	3.78	3.74	3.71	3.79
Oosterschelde	4.48	4.41	4.32	4.31
Vlakte van de Raan	4.29	4.25	4.24	4.3
Lichteiland Goeree	4.36	4.31	4.27	4.35
Europlatform	4.18	4.14	4.14	4.26

TABLE 2: IAV values for offshore locations based on the KNW atlas

Figure 3 shows the annual mean wind speed of the KNW atlas for 1979 until 2013 of the location K13 at 4 different heights: 40 m (upper left panel), 60 m (upper right panel), 100 m (lower left panel) and 200m (lower right panel). There are periods where the annual mean wind speeds vary a lot in successive years (e.g. during the windy late 80's and early 90's from 1986-1992), but there are also periods where successive annual means are more constant, "clustered" around a given speed. This shows again the need to base IAV on data for periods much longer than these clusters (much longer than 10 years). It also shows that even if based on a long enough period, there will be clusters of up to 10 years where the IAV underestimates or overestimates the year-to-year variability of the annual mean wind speed. Just how large the under- and overestimates can be, is shown in figure 4 where running averages of IAV (KNW atlas 100 m height at the K13 location) are shown for periods of 5, 10 and 20 years. The range of IAV values decreases dramatically with increasing the length of the period. The 10 year IAV values show fluctuations with time that are twice as large as the spatial variation of the 35 year IAV in table 2 and are in that respect significant. 10 years is a period that is often used in wind resource assessment for wind energy projects. More than 20 years are required to make the IAV fluctuations smaller than the spatial variations shown in table 2. In figure 5 the 5, 10 and 20 year running averages of IAV at 100 m height are shown for the location of Oosterschelde which has the highest IAV in table 2 (based on 35 years). In the late '80s and early 90's the IAV values based on 5 year periods are about 6%, which implies that although the British standard is generally conservative, it is a realistic estimate for limited areas of the DEEZ when considering short periods such as 5 years.

Figure 3 also shows the 10 year running mean where a decreasing trend from the windy early 90's to 2010 is obvious, which is consistent with the decrease in the geostrophic wind for this period found in [3]. So far, there is no clear evidence that this is a persistent decreasing trend: the windy early 90's and the calmer years around 2010 are exceptional periods but are part of the natural variability of the current wind climate. Similar periods have happened before and according to the latest climate scenario's they will happen again. Measurements at different heights at the Cabauw site from 2001-2016 and at 74 m height at K13 (figure 6) confirm that 2010 was an extremely calm year and that the years after 2010 have been a lot windier (with the exception of 2016). A recent study into the effect of climate change on wind power yields in Europe [11] suggests that the 10 m wind speed on the southern North Sea will decrease by less than 2% by 2050 and that the European 2050 fleet mean yield, as a whole, will not change by more than 5%, even under the most extreme RCP 8.5 scenario (8.5 W/m<sup>2</sup> radiative forcing in the year 2100).

Figure 7 shows the probability density function (pdf) of the annual mean wind speed of K13, again for the same 4 heights as in figure 3. At all heights the annual mean wind speed is fairly normally distributed and both the mean wind speed and the standard deviation of the mean wind speed increase with height. The reason why the standard deviation of the wind speed is lower nearer the sea surface than at greater heights is that extremely high wind speeds near the sea surface decrease more as a result of increasing sea roughness than wind speeds at higher levels. So mean wind speeds and standard deviation of the mean wind speed increase with height, but the increase with height of the ratio of the two (the IAV) is much smaller and ranges from a value of 3.79 at a height of 40 m to a value of 3.91 % at a height of 200 m.

KNW: K13

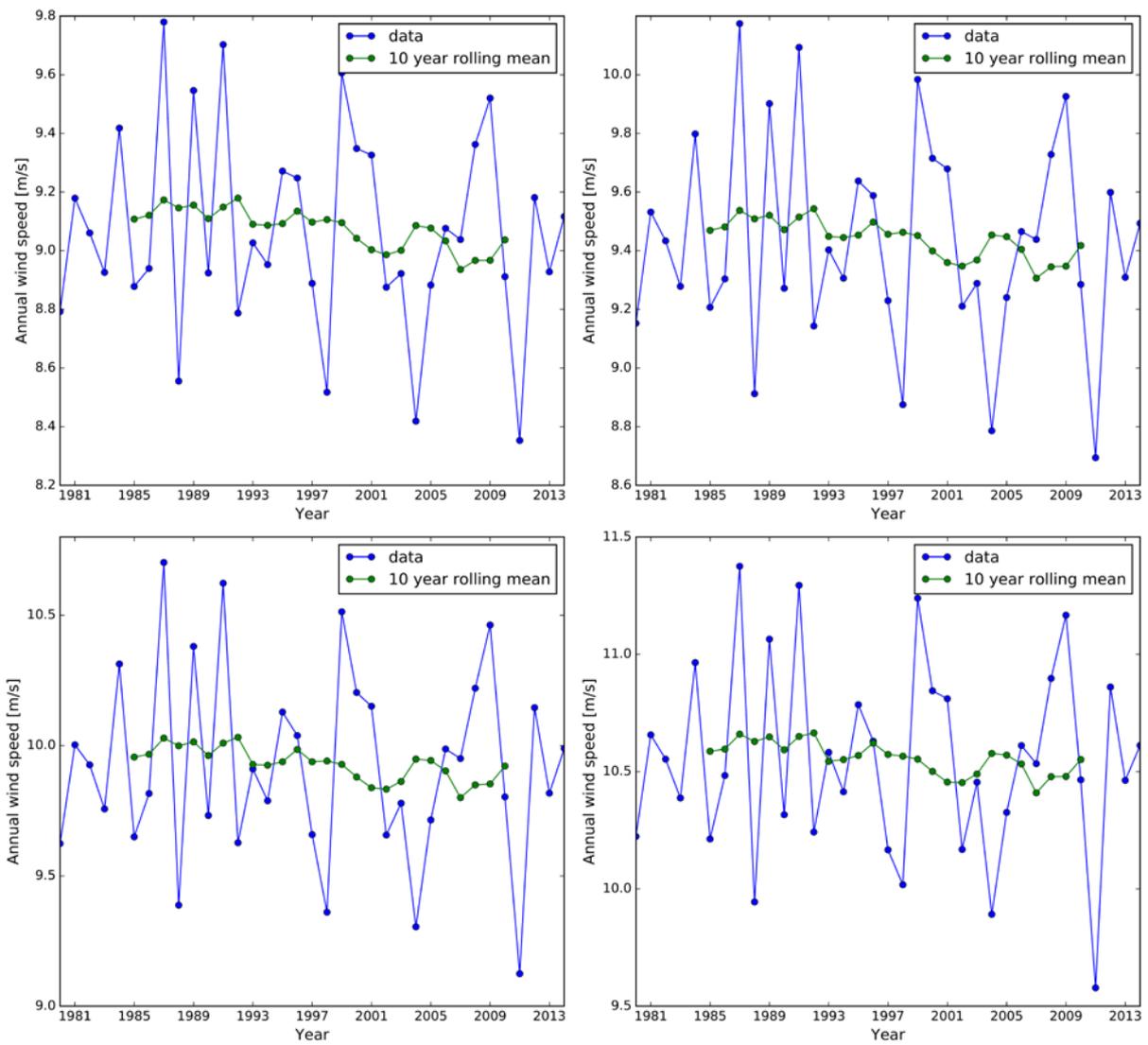


Fig. 3: KNW atlas time series of the annual mean wind speed at the location of K13 in blue and 10 year running mean in green at 40 m height (upper left panel), 60 m (upper right panel), 100 m (lower left panel), and 200 m (lower right panel).

KNW rolling IAV (100 m): K13

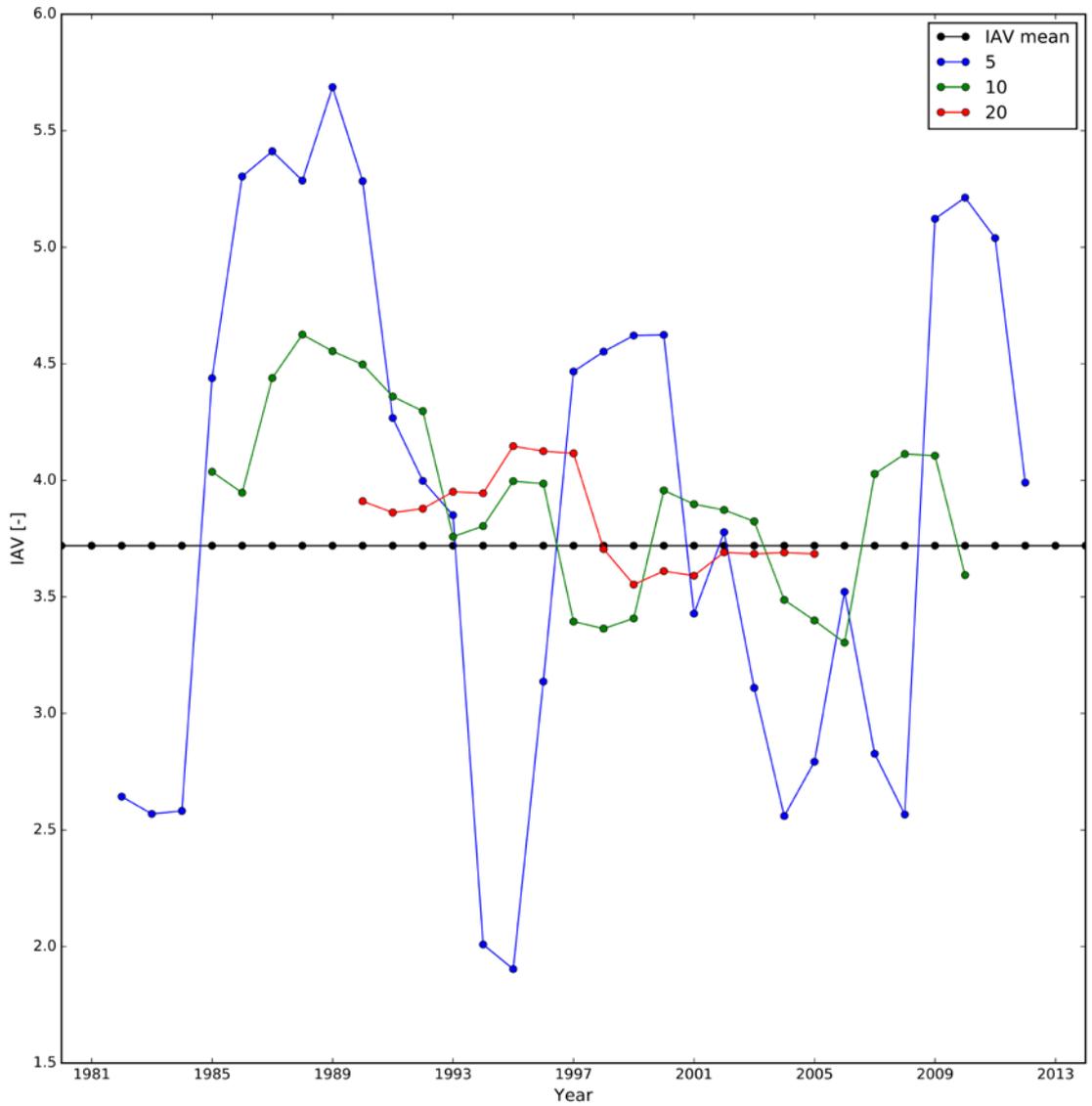


Fig. 4: running means of IAV for periods of 5 (blue), 10 (green) and 20 (red) years at location K13 at 100 m height, calculated with wind speeds from the KNW-atlas. The IAV based on 35 years (IAV mean) is 3.72.

KNW rolling IAV (100 m): Oosterschelde

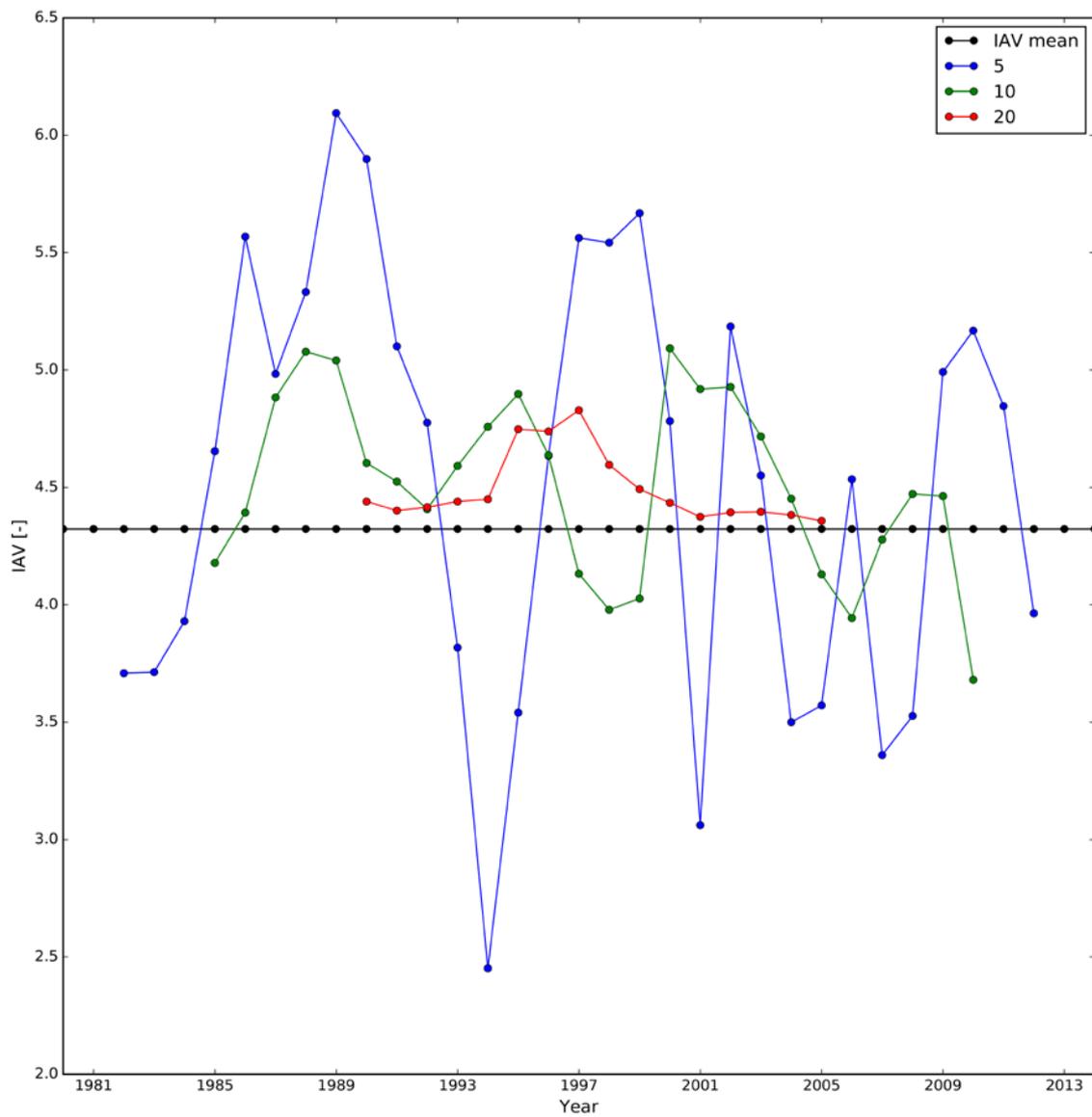


Fig. 5: running means of IAV for periods of 5 (blue), 10 (green) and 20 (red) years at location Oosterschelde at 100 m height, calculated with wind speeds from the KNW-atlas. The IAV based on 35 years (IAV mean) is 4.32.

CABCLIM 2001-2016  
Yearly averaged wind speed

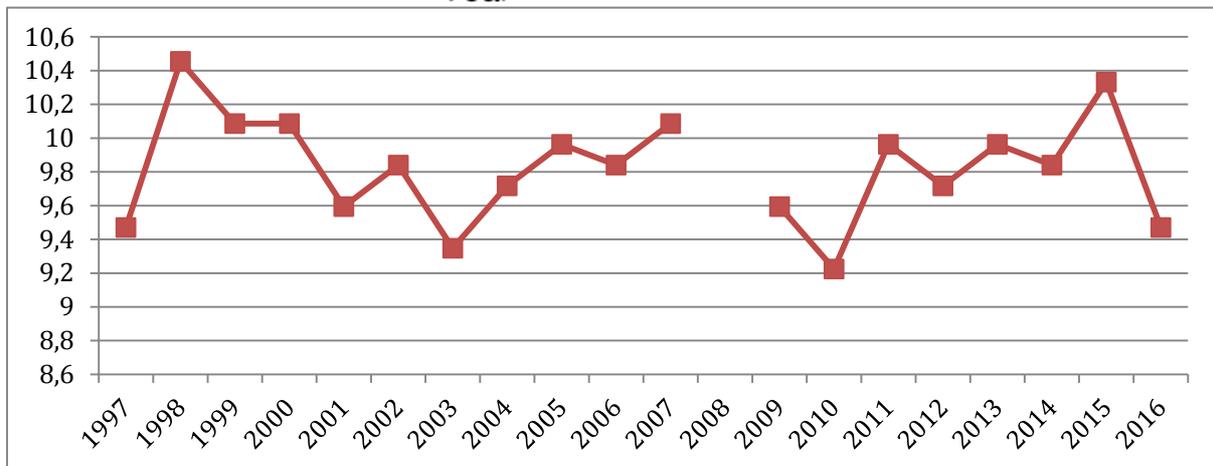
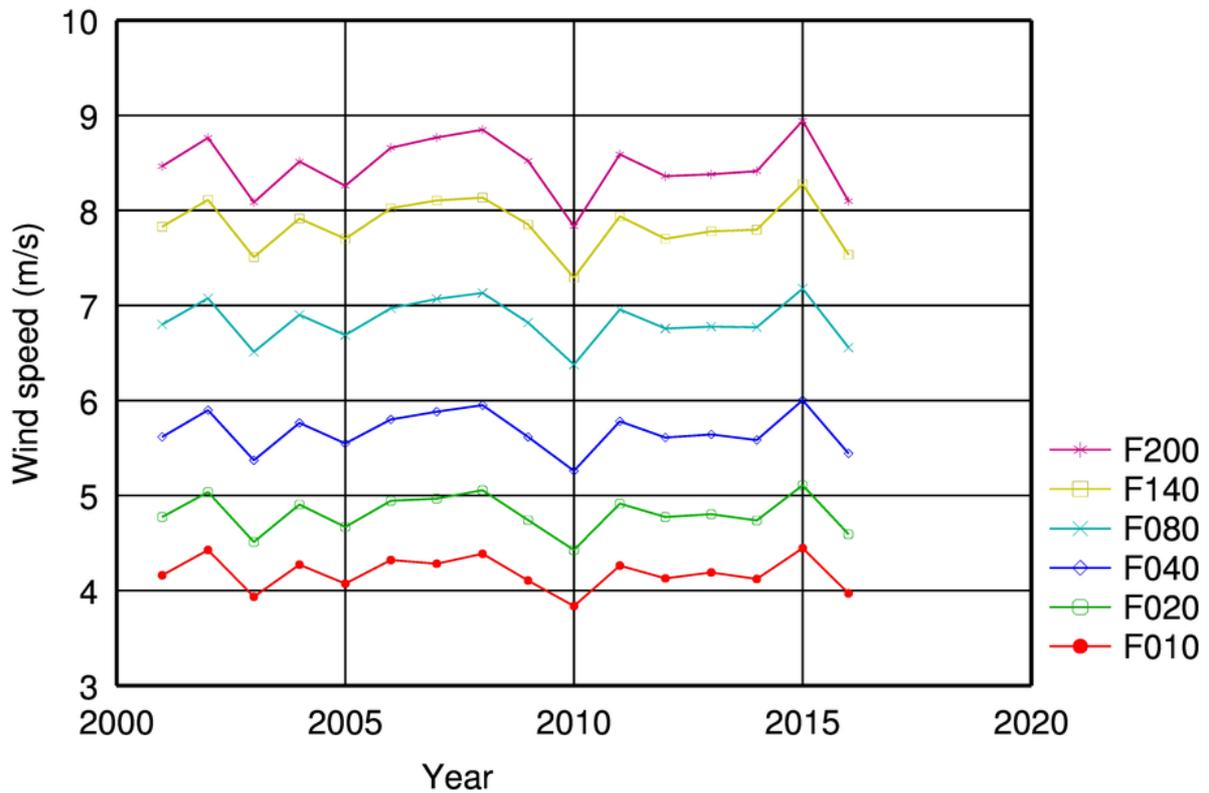


Fig. 6: Top panel: measured annual mean wind speed at Cabauw from 2001 to 2016 at 10m (red), 20m (green), 40m (blue), 80m (light blue), 140 m (olive green) and 200 m height (pink). Panel below: measured annual mean wind speed at K13 at 29m from 1997 to 2016, again with the lowest value in 2010.

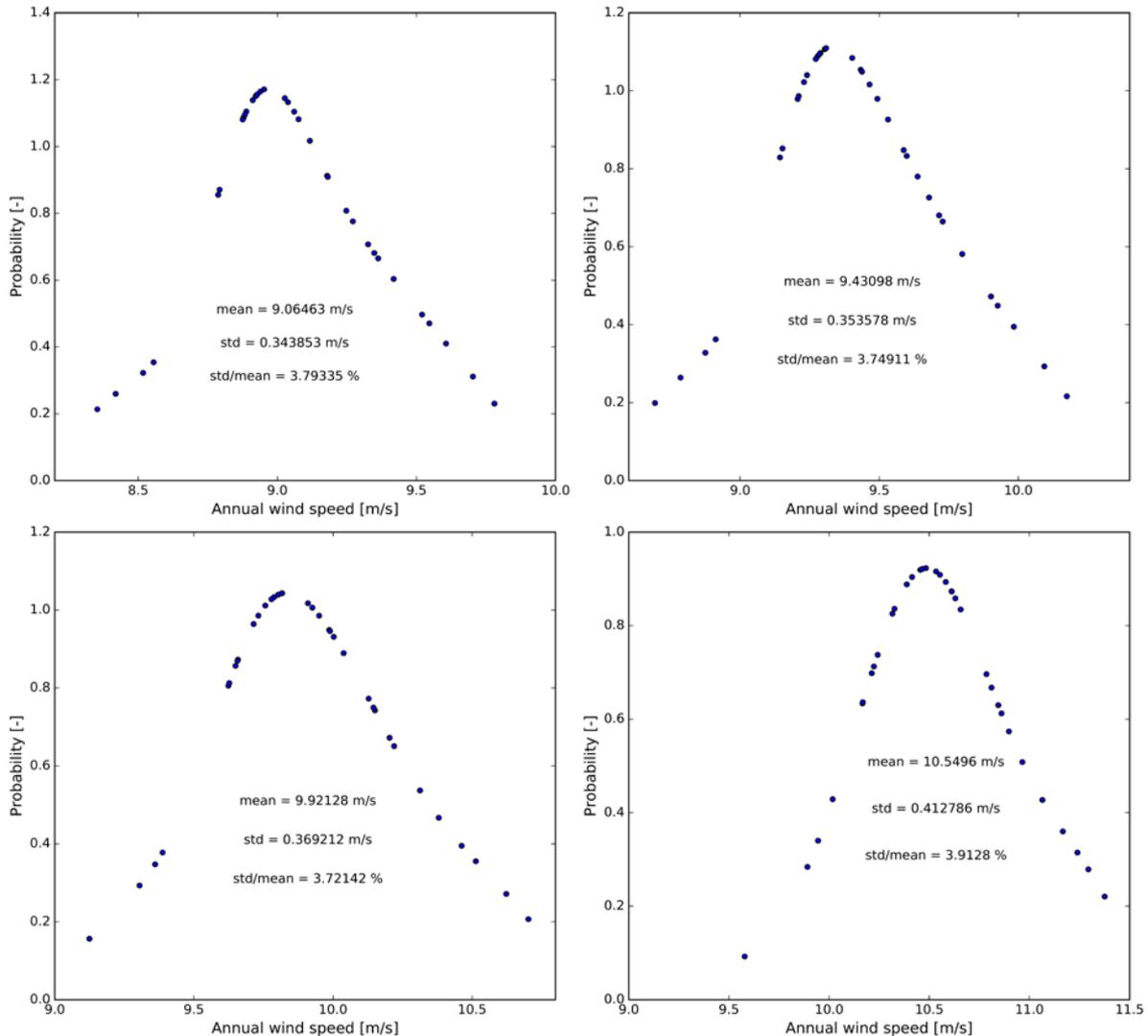


Fig. 7: probability density function for the annual mean wind speed at 40 m (upper left panel), 60 m (upper right panel), 100 m (lower left panel), 200 m (lower right panel).

## Conclusion

The aim of this study was to quantify the IAV of the wind speed at a number of locations within the Dutch Exclusive Economic Zone. Therefore, for each year and for each location, wind speeds from the KNW-atlas are extracted and used to calculate the annual mean wind speeds, which are subsequently used to calculate the IAV at each location.

In agreement with the results obtained by DNV GL we find that for the DEEZ the inter-annual variability is (much) lower than the British industrial standard of 6 %. It appears that the annual means are approximately normally distributed, with typical values for the IAV that range between 3.5 and 4% for sites in the northern part of the DEEZ and between 4 and 4.5% in the southern part of the DEEZ. An analysis at K13 shows that more than 20 years are required to make the IAV fluctuations at 100 m height smaller than the spatial variations on the North Sea.

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