Royal Netherlands
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North Sea Wind Climatology
Part 2: ERA-Interim and Harmonie model data

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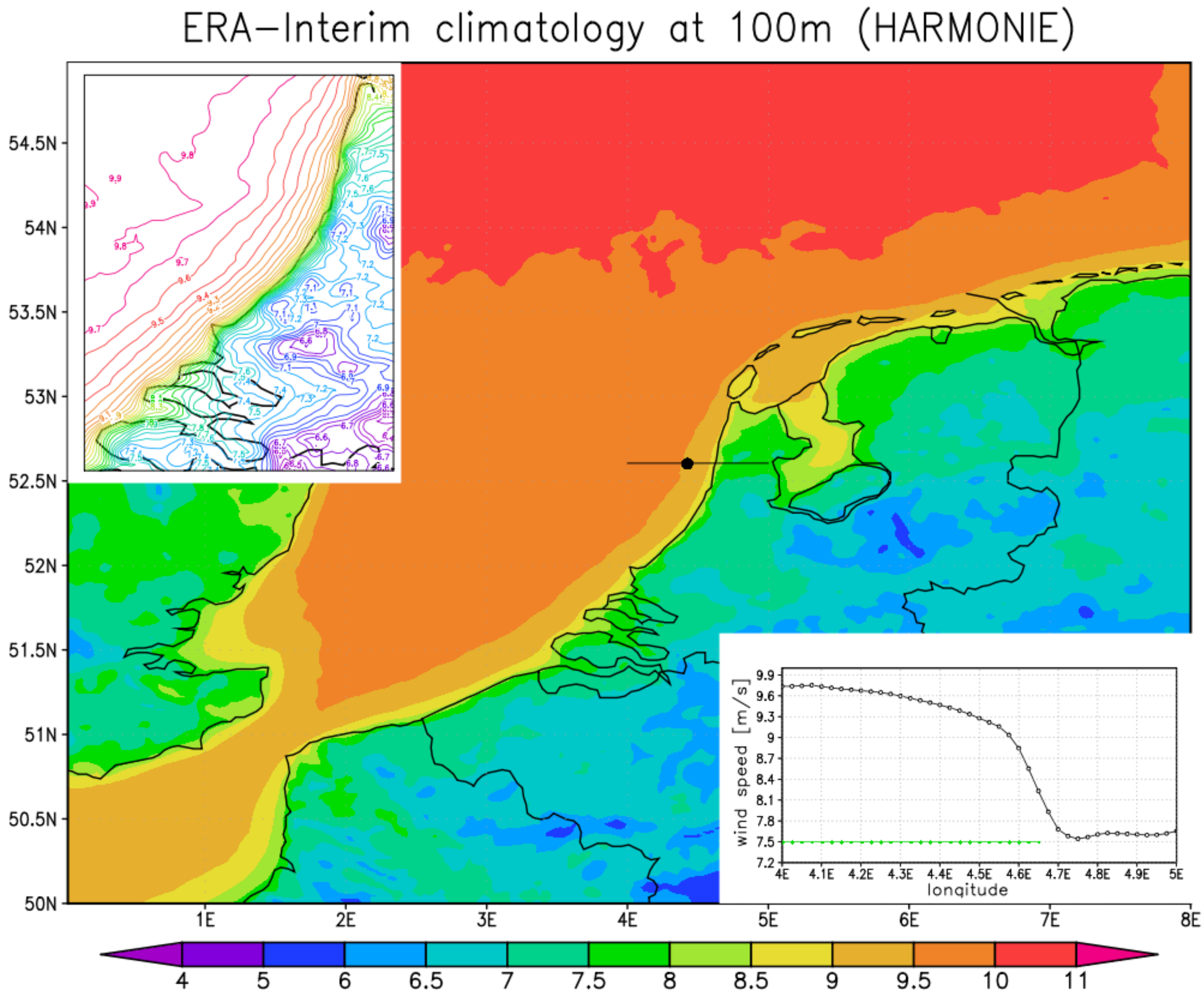
June 2014



North Sea Wind Climatology based on ERA-interim and Harmonie model data

Executive Summary

The national government needs high quality offshore wind climatology at and around hub height to be able to determine a realistic wind power potential for the North Sea and to be able to assess whether the yields predicted by wind energy companies are reliable. One "reference" wind atlas makes procedures more transparent for all stages in the process of establishing Dutch offshore wind energy: allocation of areas, tendering procedure, allocation of wind energy producer and monitoring of the wind energy yields. It will also save time and money as individual wind energy companies would not have to make their own wind climatologies. It is however essential that the quality of this "reference" wind atlas is scientifically sound and that it has the confidence of the wind energy sector and the banks (so they would be willing to lend the required funds).

Wind energy developers determine wind climatology at the site where they want to build the wind turbine or wind farm (target site) by transforming long series of near surface wind measurements at a nearby reference site, if available, to hub height at the target site. The transformation requires simultaneous measurements at both sites, but the measurement campaigns at the target site are relatively short. This is called the Measure Correlate Predict (MCP) method. The main problem with using measurements as reference data is that they are predominantly done at levels below hub height. To bridge the height difference between the reference and target measurements, assumptions have to be made on the atmospheric stability and the associated vertical wind profile. The temperature profiles required for deriving the actual atmospheric stability are only measured at a few wind masts and for a limited period.

Also wind atlases are used for siting purposes. Part 1 of this report gives an overview of the wind atlases that are currently used in the wind energy sector and explains what their limitations are. In this report (part 2) we present an approach similar to the MCP method and use the 34-year ERA-Interim reanalysis (a homogeneous model data set) on a horizontal grid of about 80 km as a starting point. The advantage of using weather model winds as reference data as opposed to measurements is that these data are available at different heights around hub height. Furthermore, the wind profile in the model adapts from hour to hour to incorporate the effect of varying stability in a dynamical way. Model data provide a complete and uniform space and time coverage, which can not be said of the observation network. Another advantage of using the analysis made by weather models is that it is based on many measurements at all heights in the atmosphere. For example, satellite-observed sea surface temperature is used as input for the model, providing additional information on stability, which determines the wind profile.

We overcome the drawback of the rather coarse ERA-Interim grid-spacing of 80 km by comparing the Weibull-distribution of the analysis wind speed of the last few years of the ERA-Interim period to that of the analysis of the operational weather forecasting model of Harmonie which has a finer grid-spacing of 2.5 km. This is similar to the correlate stage of the MCP method. Using the relationship between the Weibull-distributions, a grid-box-wise transformation can be applied to the ERA-Interim set. This improves the spatial representation of the ERA-Interim data, especially in coastal areas because Harmonie has a significantly better representation of the land-sea mask than ERA-Interim. On a 2.5 by 2.5 km grid and at

40, 60, 80, 100, 120, 140, 160, 180 en 200 m, we provide 34 year long time series of wind speed, as well as climatological information, e.g., the wind speed frequency distribution via the Weibull parameters, annual and decadal wind statistics (including the probability of extremes).

Validating the model-based time series of wind speed and the climatological information against observations (e.g. satellite or weather masts) is beyond the scope of this project and it is our most important recommendation that a verification is performed. Comparing them to other wind atlases seems superfluous: that there will be differences is to be expected, it is also clear why these differences will arise but until a comparison with high quality hub height measurements can be made, no strong conclusions can be drawn concerning which climatology comes closest to the truth. The offshore wind energy sector can play an important role here by making such measurements available for research.

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Introduction

It is the Dutch government’s target to realise 14% renewable energy in 2020 and 16% in 2023 (Energieakkoord voor duurzame groei SER 2013). To achieve this, the government intends to significantly increase wind energy production on land (to 6000 MW nominal capacity in 2020 which implies an increase of about 650 MW every year[1] and at sea to 4450 MW in 2023 which implies 3450 MW more than already planned). This is ambitious, especially for offshore wind energy production where this can only be accomplished in an economically viable way if production costs are reduced by 40% (conform the 2011 Green Deal Offshore Wind Energy between government and the Dutch Wind Energy Association NWEA representing the wind energy sector). In order to assess the wind power that will actually be produced if and when these nominal capacity targets are met, the government requires high quality wind climatology at or around hub height, especially at sea.

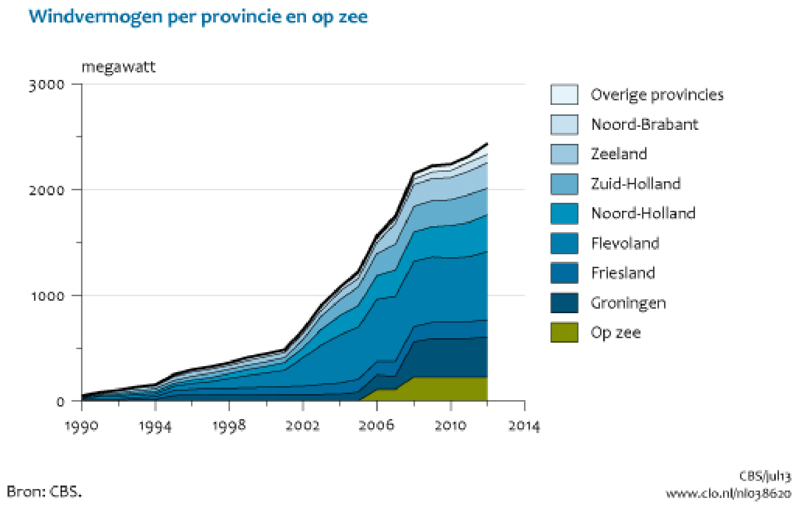

Figure 1.1 Dutch nominal capacity wind power 1990-2012 per region (blue) and offshore (green) (source: CBS)

There are two parts to this KNMI report on North Sea wind climatology. Part 1 gives an overview of the existing wind atlases and describes how they are made and what their limitations are and part 2 presents a wind climatology in which the best available stability estimates are incorporated in the wind profile at every grid box and point in time and the long-term variability of the wind climate is included.

The large number of tools, methods and models used in the wind energy sector can be confusing. To help the reader distinguish between them, Appendix 3 provides a useful overview.

[1] Document "Windparken op land" on site http://www.rijksoverheid.nl/onderwerpen/duurzame-energie/windenergie/windenergie-op-land (31-3-2014)

1 *Wind atlas including the long term variability based on ERA-Interim and Harmonie weather forecasting model*

The wind atlas that is presented in this report is based on the 34-year (1979-2012) ERA-Interim reanalysis (a homogeneous model data set) on a grid of about 80 km. This period is long enough to capture the natural long-term variability of the current wind climate. The weather forecasting model Harmonie[2] which gives information on a 2.5 km grid is used to enhance the spatial representation of the wind atlas. This is especially beneficial in the coastal zone.

1.1 *Quality of ERA-Interim and Harmonie*

The reanalysis (ERA-Interim) and weather forecasting model (Harmonie) that were used to make the North Sea wind climatology presented in this report are the best of their kind. Harmonie is not used in the "traditional" way which is to forecast the wind hours or days ahead in the future, but in the same way the ERA-Interim dataset was made, and that is as a re-analysis model to make a wind climatology of the past. Weather forecasting models get changed all the time (new model versions) to improve the forecast, but in order to create a wind climatology of the past, we have to make sure we work with one model version. Otherwise the changes or variations in the wind climate we find, may not be real (natural), but artificial (the result of changes in the model). So, after deciding which model version to use, we run this version of the weather forecasting model for a long period in the past (re-analyses). For every point in time we create the best fit between the available measurements (e.g. from weather stations, radar, satellites and at sea also from wind masts and buoys) and the model forecast made a few hours earlier and valid for the same point in time as the measurements. In the fitting process the model rejects measurements that break the laws of physics upon which the model is based which gives a result with higher quality than can be produced using only measurements, some of which contain errors. If we do this for a long period we get a 3D wind climatology based on measurements and model physics.

Era-Interim is the re-analyses version of the weather forecasting model ECMWF. Era-Interim and ECMWF are global models and because they cover the whole globe, they calculate on a relatively course resolution. To enhance this resolution, regional models which cover a smaller area (such as Harmonie) are nested within these global models.

ERA-interim and ECMWF are extensively validated and well-documented. Harmonie has also been tested thoroughly before it became KNMI's operational weather forecasting model in March 2013[3]. Appendix 4 gives a summary of some of the work that has been done to validate the Harmonie wind at 10 m height in historical storm situations with high sea levels.

[2] **H**irlam **A**ladin **R**egional **M**esoscale **O**perational **N**WP **I**n **E**urope

[3] The operational Harmonie version is 36h1.4 (https://hirlam.org/trac/wiki/Harmonie_36h1/ValidationTests#Observationverification), but new versions have already been tested: version 37 (http://hirlam.org/index.php/component/docman/cat_view/77-hirlam-official-publications/78-hirlam-newsletters/279-hirlam-newsletter-no-59?Itemid=70) and since February 2014 version 38. As Harmonie is a new model, comparison with other models (ECMWF and HIRLAM) requires a substantial effort and when completed, the results will become available via https://hirlam.org/portal/oprint/WebgraF/ObsVer/KNMI/index.html?choice_ind=Surface .

1.2 *Method*

The wind climatology presented here was essentially made in three steps:

a) First we perform two Weibull fits of the 2007 wind speeds for all grid boxes in the horizontal grid (2.5 by 2.5 km) and all levels relevant for offshore wind energy (40 up to 200 m in 20 m steps): one for ERA-Interim and one for Harmonie.
b) For every grid point, the differences between the fits are then used to transform the whole ERA-Interim data set.
c) From the transformed ERA-Interim data set, wind speed time series of the whole 34 year period are extracted and climatological statistics derived, e.g. the wind speed frequency distribution via the Weibull parameters, wind roses and annual and decadal wind statistics (including the probability of extremes).

1.2.1 Weibull fit

Wind speed distributions are commonly described with the two-parameter Weibull function:

$$F = 1 - \exp -(\frac{U}{a})^k \tag{1}$$

In which *F* is the cumulative probability density function, *U* is the wind speed, *a* is the scale parameter (which is a measure for the wind speed average) and *k* the shape parameter (which is a measure of the variation in the wind speed; a small value of *k* indicates a skewed distribution with a longer tail towards high wind speeds than towards low wind speeds).

Wind speed distributions are commonly shown on a so-called Weibull plot, in which log(u) is shown against log(–log(1-F(u))), which results in a straight line if the distribution follows a Weibull function. In figure 1.1 a Weibull function is fitted to the ERA-Interim wind speeds of 2010 of a sea grid point. It shows that the wind speed is well described by a Weibull function, as the distribution (red line) is well described by a straight line.

Figure 1.2 shows a cross section at 52.5ºN of the Weibull scale parameters at 100m height of Harmonie (black) and ERA-Interim (green) for 2007. Note that the Harmonie domain is smaller than the ECMWF domain described in appendix 2: from 0ºE to 8ºE (ECMWF from 12ºW to 12ºE). Figure 1.2 shows that even at 100m height, Harmonie can distinguish the effect of Lake IJssel (5.25-5.55ºE) where ERA-Interim does not. Over open sea where ERA-Interim and ECMWF compared well (figure A2.2), there is a significant difference between ERA-Interim and Harmonie (about 6% at a height of 100 m; figure 1.2). Baas (2014) also found a comparable difference between ERA-Interim and Harmonie over open sea at 10 m (figure 1.3) and concluded that this was due to a better sea roughness representation in Harmonie[4] (ERA-Interim and ECMWF apply a similar sea roughness parameterisation).

[4] Harmonie uses the ECUME drag relation whereas ERA-interim applies Charnock (Baas, 2014).

For the comparison of the Weibull distributions of ERA-Interim and Harmonie the year 2007 was chosen because it is the only full year to date with Harmonie-reanalyses.

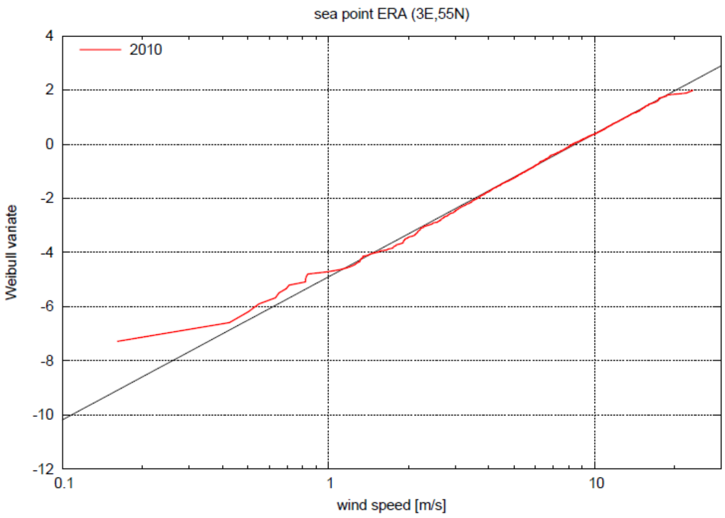

Figure 1.1 ERA-Interim wind speed distribution for 2010 (red line) and Weibull fit (black line) for a sea grid-point. The distributions are presented as a Weibull plot[5].

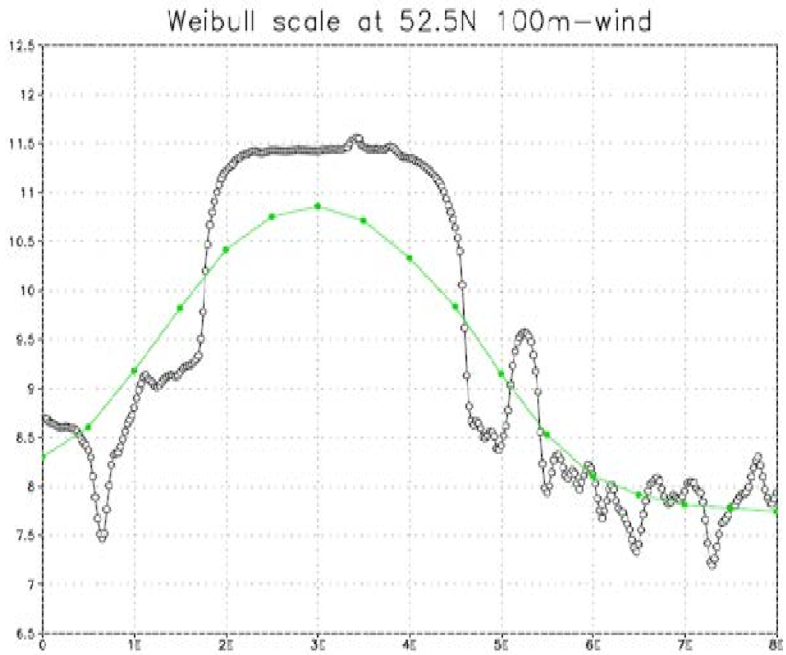

Figure 1.2 Cross section at 52.5°N of the Weibull scale parameters at 100m of Harmonie (black) and ERA-Interim (green) for 2007. Dip in wind speed around 0.5°E is a result of Thetford Forest Park in Norfolk, English coast around 1.7°E, Dutch coast around 4.5 °E, Lake IJssel 5.25-5.55°E.

[5] On the x-axis the wind speed and on the y-axis ln(-ln[1-F(U)]) where [1-F(U)] is the probability that the wind speed exceeds wind speed U. The Weibull function is represented by the straight line k(ln U) – k ln a where k is the shape parameter and a the scale parameter. When U is equal to the scale parameter a the value on the y-axis becomes zero (= k ln a - k ln a). The scale parmeter is therefore not the average, but the wind speed with a 37% probability of being exceeded (ln (-ln[1-0.63] = 0 as ln[1-0.63] = 1). The slope of the line is the shape parameter k.

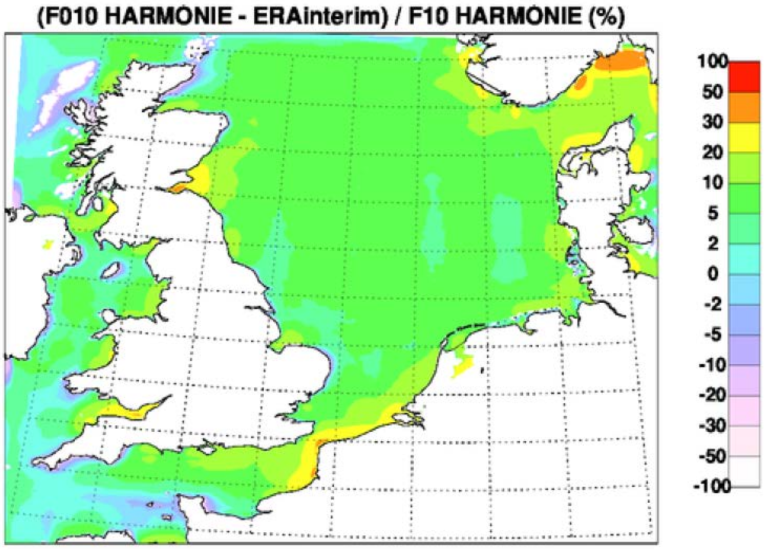

Figure 1.3 Relative difference (in %) in 10 m wind speed between Harmonie and ERA-Interim for all data in the 16 historical storm data set (Source: Baas, 2014).

1.2.2 Transformation of ERA-Interim set

In order to transform the ERA-Interim wind speeds to speeds that the operational forecasting model would have produced, we look for a transformed wind speed $\tilde{U}$ which has the Weibull parameters of the operational (Harmonie) distribution:

$$\tilde{F}_e = F_o \tag{2}$$

$$\tilde{U}_e = U_o \tag{3}$$

$$1 - \exp -(\frac{U_e}{a_e})^{k_e} = 1 - \exp -(\frac{\tilde{U}_e}{a_o})^{k_o} \tag{4}$$

$$(\frac{U_e}{a_e})^{k_e} = (\frac{\tilde{U}_e}{a_o})^{k_o} \tag{5}$$

$$\tilde{U}_e = a_o(\frac{U_e}{a_e})^{k_e/k_o} \tag{6}$$

In which the subscript *e* refers to the ERA-Interim set, and *o* to the operational (Harmonie) set. The transformation of the ERA-Interim wind speeds into the speeds that would have been produced by Harmonie is obtained by assuming that the latter is the Harmonie wind speed with the same probability of occurrence as the given ERA_interim wind speed. The cumulative probabilities of the Weibull distributions of the two models are made the same by equation 4. The left hand side of equation 4 is the cumulative probability of the ERA_Interim wind speed U_e and the right hand side that of the Harmonie wind speed U_o, expressed as $\tilde{U}_e$ (which is U_e transformed: see substitution equations 2 and 3 in which the cumulative probability and wind speed of Harmonie are renamed as the transformed ERA_interim probability and speed). Formula 6 for transforming the ERA_interim wind speed (on the right hand side) into a Harmonie equivalent wind speed follows via equation 5 from equation 4.

Equation (6) thus shows the transformation that has to be applied to all ERA-Interim wind speeds to reproduce the Weibull characteristics of the operational Harmonie model. This transformation is applied to all time steps of the 34-year ERA-Interim dataset, all grid points (0.1° grid) and all requested levels (40, 60, 80, 100, 120, 140, 160, 180 en 200 m).

As an illustration, figure 1.4 shows the transformation formula (formula 6) used to transform a ERA-Interim distribution ("original wind speed" in the figure) with a_e=8 and k_e=2 into a distribution of the operational model with a_o=10 and k_o=3. The higher value of a in the operational model indicates a higher average wind speed and the higher value of k, a shorter tail of the distribution towards higher wind speeds. Figure 1.4 shows that only for wind speeds of 16 m/s, the original and transformed wind speeds are the same. For wind speeds lower than 16 m/s the original ERA-Interim wind is decreased to get the transformed wind speed and for wind speeds higher than 16 m/s the original wind is increased to get the transformed wind speed.

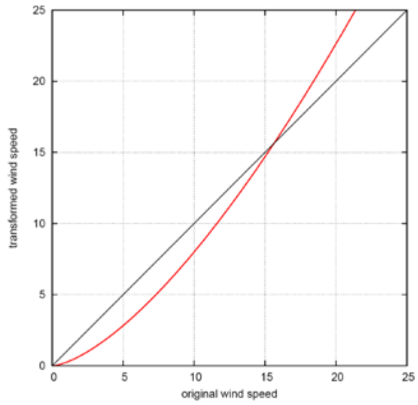

Figure 1.4 Example of a transformation formula for a_e=8,k_e=2 to a_o=10,k_o=3. The black line shows the y=x line.

1.3 *Results*

1.3.1 Average wind speed

Figure 1.5 shows the average wind speed at 100 m height over the period 1979-2012, obtained by transforming the ERA-interim wind speeds into those that could have been generated by Harmonie. The figure consists of a main panel showing a map of the North Sea area where each colour represents a range of average wind speeds that is 0.5 m/s wide (for wind speeds between 6 and 10 m/s; for example the yellow area on Lake Ijssel represents 8.5-9.0 m/s) or 1 m/s wide (for wind speeds above 10 m/s and below 6 m/s). The two smaller panels give exactly the same information, only presented in a different way. The upper left panel shows the 0.1 m/s contours (lines of equal average wind speed with steps of 0.1 m/s between them) and the lower right panel a cross-section of the wind speeds found along the black line on the main panel (the black dot indicates the position of the OWEZ wind mast). In the lower right panel, the blue on the x-axis refers to sea, the green to land. The main panel shows that for the cross section along the black line, the average wind speed decreases from orange (9.5-10 m/s) at open sea to green (7.5-8 m/s) on land and that the value at OWEZ is light orange (9-9.5

m/s). The lower right panel gives the same information in a different way: for the cross section along the black line, the average wind speed decreases from 9.7 m/s to 7.5 m/s and the value at OWEZ is 9.4 m/s. In the upper right panel the black dot shows the position of OWEZ and, as one would expect, the 9.4 m/s contour touches it. Although the information in the small panels looks more detailed, it is not better than in the main panel: it is exactly the same information, only presented in a different way.

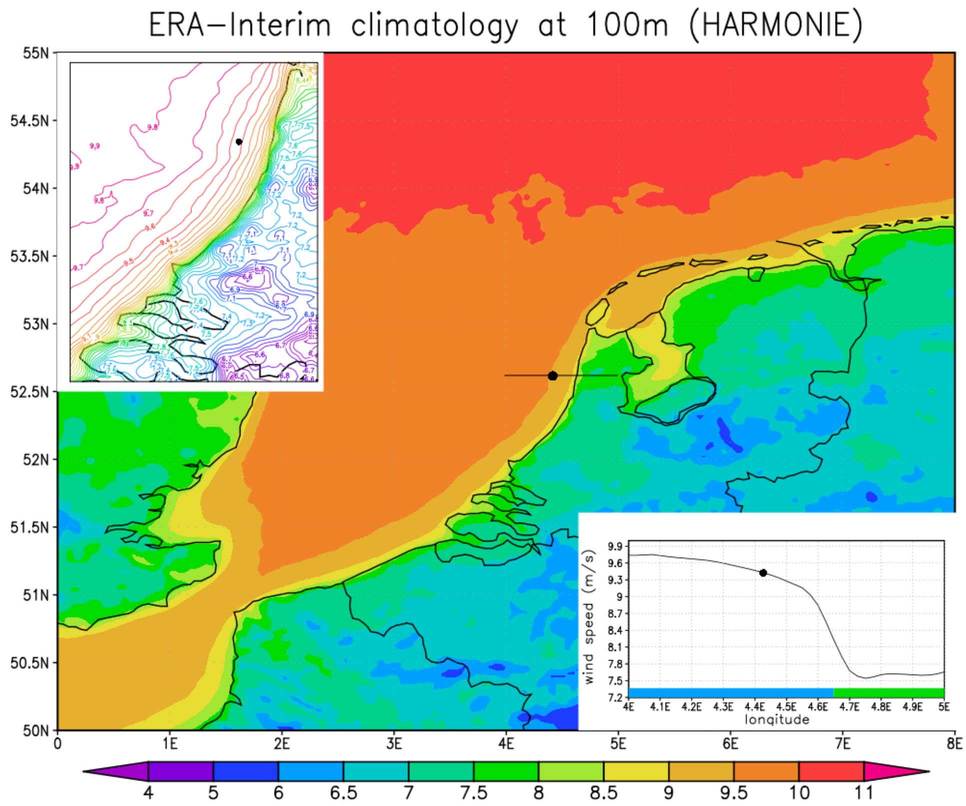

Figure 1.5 ERA-Interim climatological average wind speed at 100m over the period 1979-2012, transformed to represent the Harmonie climatology. The upper left panel shows the 0.1 m/s contours and the lower right panel a cross-section at the location indicated on the main panel (the black dot indicates the position of the OWEZ wind mast). Blue refers to sea, green to land.

1.3.2 Weibull parameters

Figure 1.6 shows the Weibull scale parameter (a) which is related to the average wind speed and figure 1.7 the Weibull shape parameter (k), which is a measure of the variation in the wind speed where a small value of *k* indicates a skewed distribution of the frequency of occurrence of the various wind speeds with a longer tail towards high wind speeds than towards low wind speeds (see also explanation in paragraph 1.2.1). A large value of k means that the distribution of the wind speeds around the most common wind speed is more symmetrical. In figure 1.6 and 1.7, the top panel is based on ERA-Interim and the lower panel on Harmonie.

With a higher resolution, Harmonie obviously gives far more detailed information than ERA-Interim. Figure 1.6 shows that the general pattern of the 2007 Weibull scale parameter of Harmonie compares well to that of ERA-Interim. The differences are largest in coastal areas and over higher and complexer land surfaces as was to be expected. Note that Harmonie produces higher wind speeds over open water. This is a result of a better sea roughness representation in Harmonie (appendix 4).

Also the general pattern of the 2007 Weibull shape parameter of ERA-Interim and Harmonie compare well (figure 1.7). There are however large local differences, especially in areas where ERA-Interim has water grid boxes and Harmonie land (or vice versa) and the coastline is oriented along the wind directions associated with storm winds (west to southwest). Very noticeable is the large difference between the Harmonie and ERA-Interim shape parameter in the south-eastern half of Norfolk. Harmonie gives a much larger shape parameter indicating that the distribution of the wind speed is less skewed (tail towards higher wind speeds less long, distribution more like a normal distribution). This is because high wind speeds which are mainly from the west to southwest get slowed down more over land in Harmonie than in ERA-Interim, where this area is largely sea. There is also a significant difference in the shape parameters of ERA-Interim and Harmonie in the English Channel where high wind speeds from the west to southwest are enhanced by the Venturi effect. ERA-Interim cannot reproduce these high wind speeds because in ERA-Interim much of the sea off the south coast of England is considered to be land (which means that the wind gets slowed down too much). Harmonie with a far better representation of the coast line does reproduce these high wind speeds and gives a lower shape parameter (more skewed wind speed distribution with a long tail towards high wind speeds).

Figure 1.8 shows the Weibull scale parameter and figure 1.9 the Weibull shape parameter based on the ERA-Interim reanalyses from 1979-2012 (whereas the scale parameter in figure 1.6 and the shape parameter in figure 1.7 are only based on one year: 2007), but then "downscaled" with Harmonie. Figure 1.9 shows e.g. that the shape parameter (k) at sea is lower than on land: the frequency distribution of the wind speed at sea is more skewed and has a longer tail towards higher wind speeds. On land the frequency distribution of the wind speed is more like a normal distribution because the very high wind speeds that occur at sea, but then rarely, do not occur at all inland.

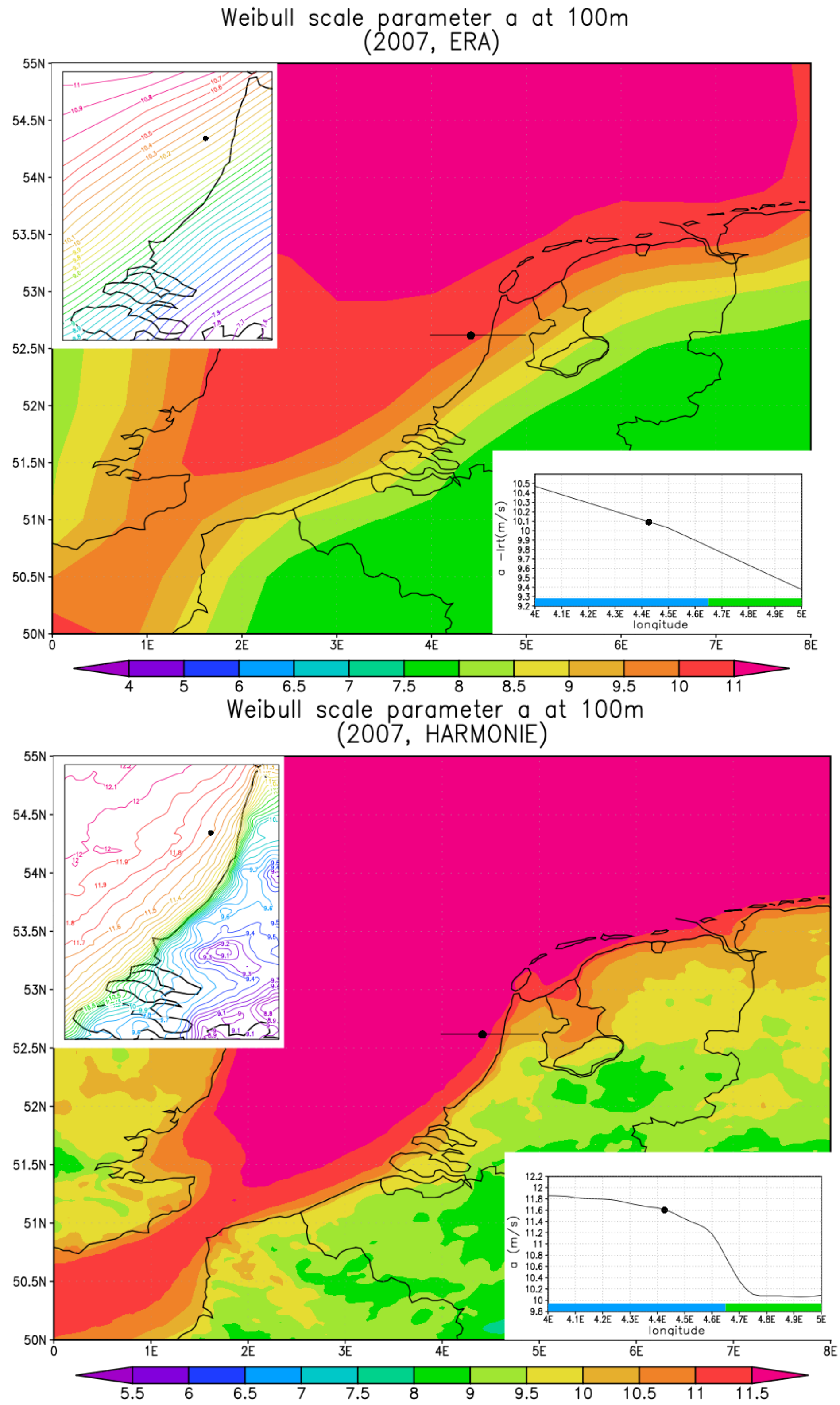

Figure 1.6 Weibull scale parameter a *of the wind speed at 100m for 2007 based on ERA-Interim (upper figure) and Harmonie (lower figure). The upper left panel in each figure shows the 0.1 m/s contours and the lower right panel in each figure a cross-section at 100 m at the location indicated on the main panel (the black dot indicates the position of the OWEZ wind mast. Blue refers to sea, green to land.*

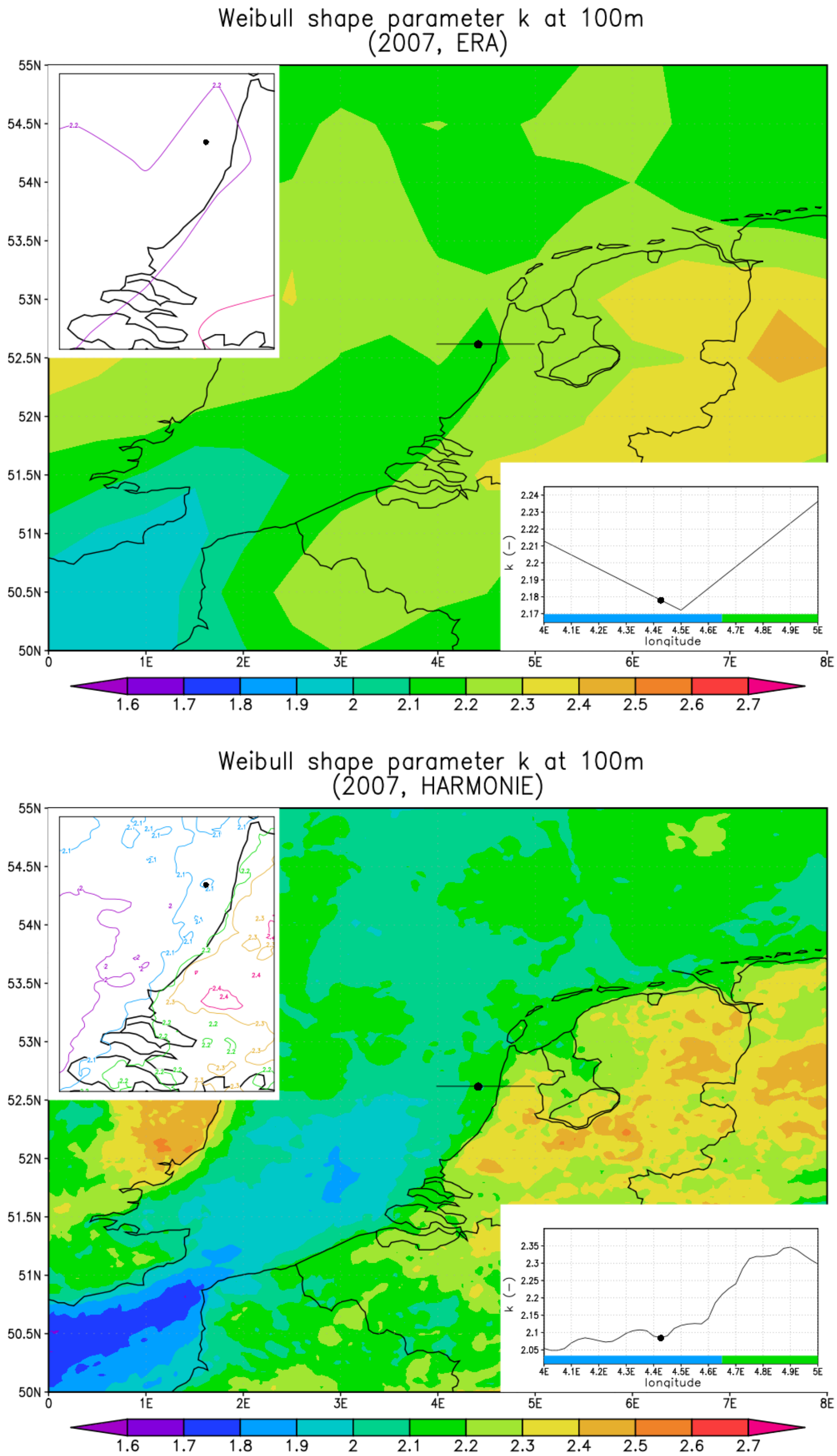

Figure 1.7 Weibull shape parameter k of the wind speed at 100m for 2007 based on ERA-Interim (upper figure) and Harmonie (lower figure). The upper left panel in each figure shows the 0.1 contours and the lower right panel in each figure a cross-section at 100 m at the location indicated on the main panel (the black dot indicates the position of the OWEZ wind mast). Blue refers to sea, green to land.

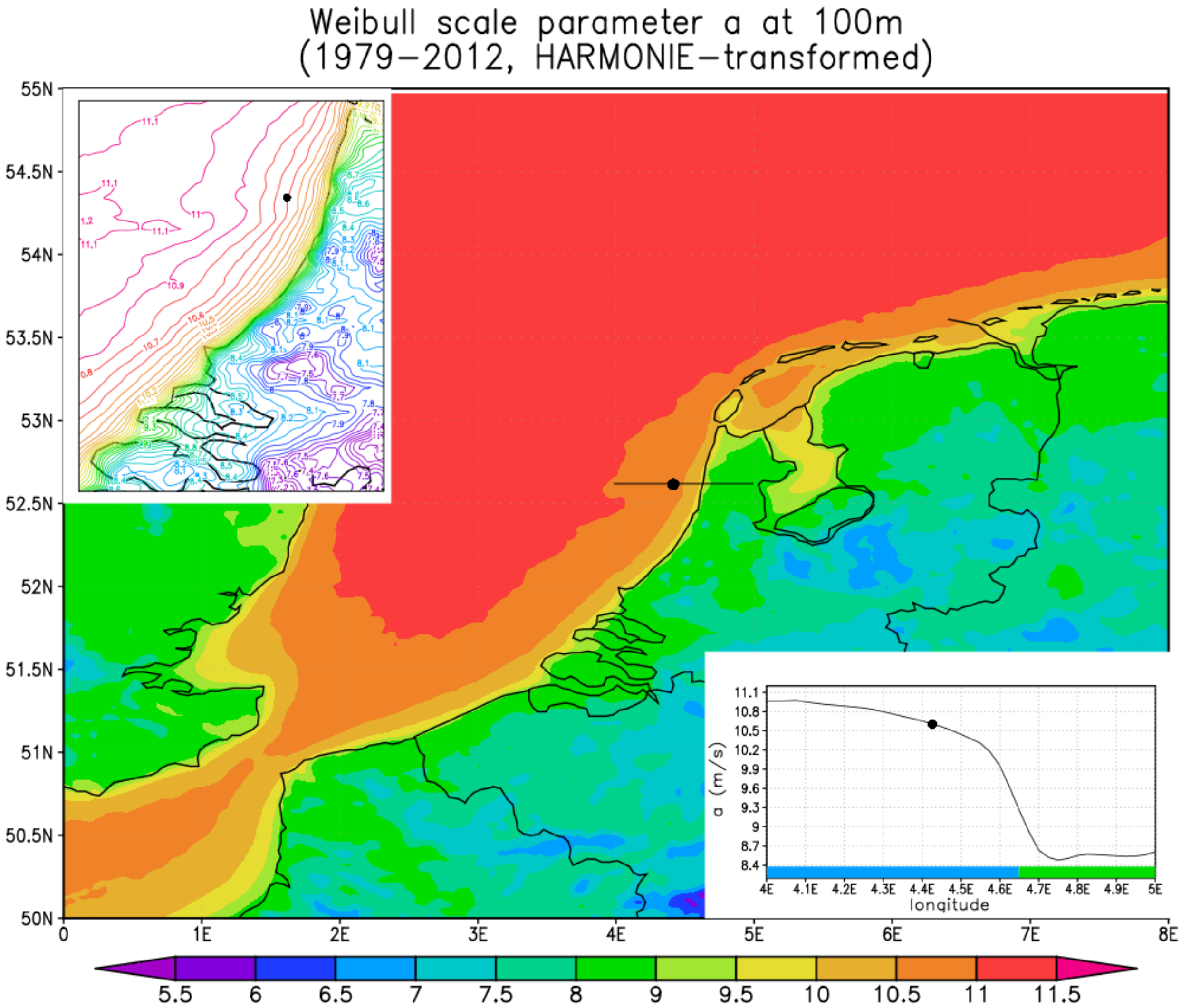

Figure 1.8 Weibull scale parameter a *of the wind speed at 100m over the period 1979-2012, transformed to represent the Harmonie climatology. The upper left panel shows the 0.1 m/s contours and the lower right panel a cross-section at the location indicated on the main panel (the black dot indicates the position of the OWEZ wind mast). Blue refers to sea, green to land.*

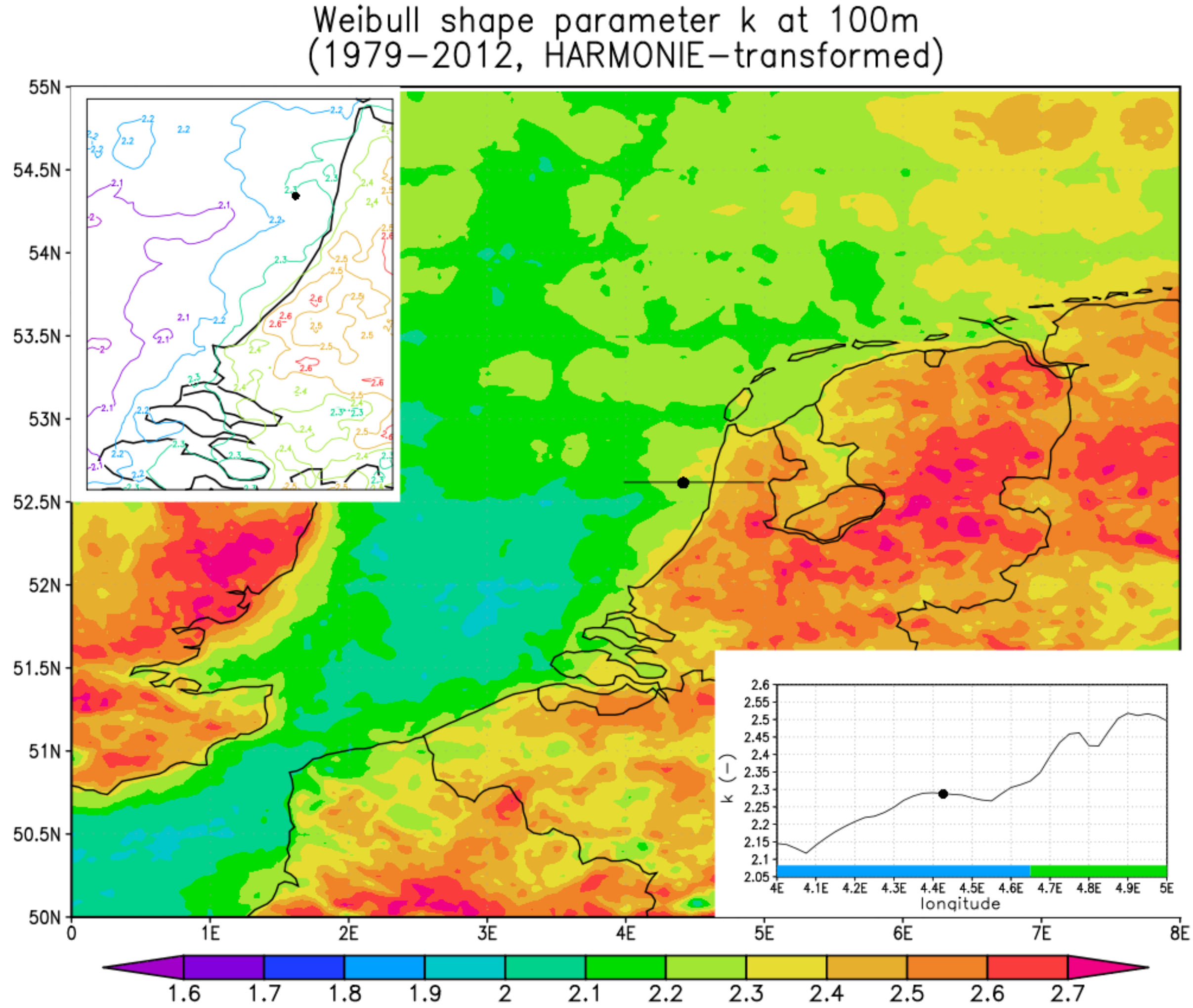

Figure 1.9 Weibull shape parameter k *of the wind speed at 100m over the period 1979-2012, transformed to represent the Harmonie climatology. The upper left panel shows the 0.1 contours and the lower right panel a cross-section at the location indicated on the main panel (the black dot indicates the position of the OWEZ wind mast). Blue refers to sea, green to land.*

1.3.3 Minimum and maximum 11 year moving annual average

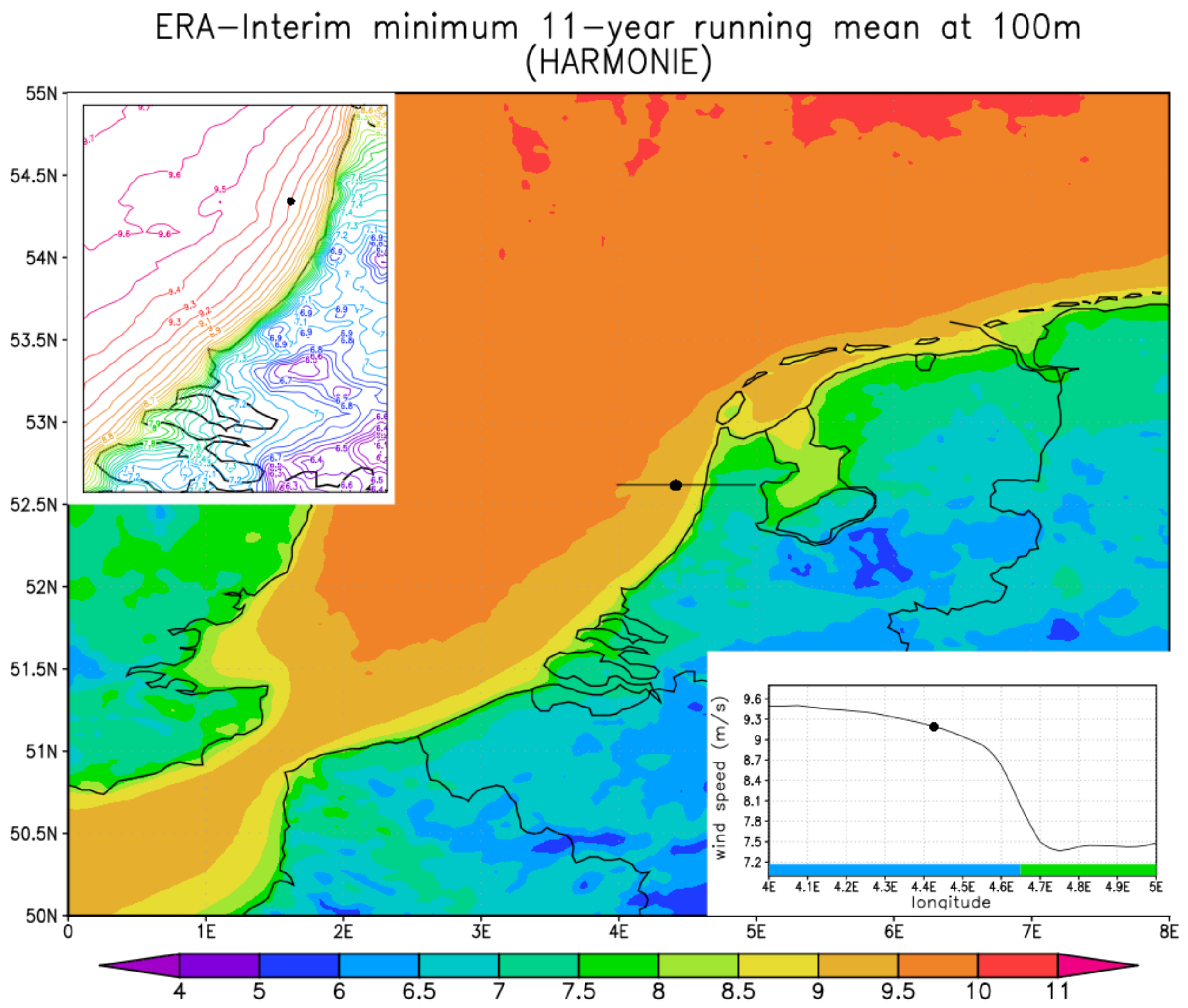

Figure 1.10 Minimum of the 11-year running mean annual average wind speed at 100m over the period 1979-2012, transformed to represent the Harmonie climatology. The upper left panel shows the 0.1 m/s contours and the lower right panel a cross-section at the location indicated on the main panel (the black dot indicates the position of the OWEZ wind mast). Blue refers to sea, green to land.

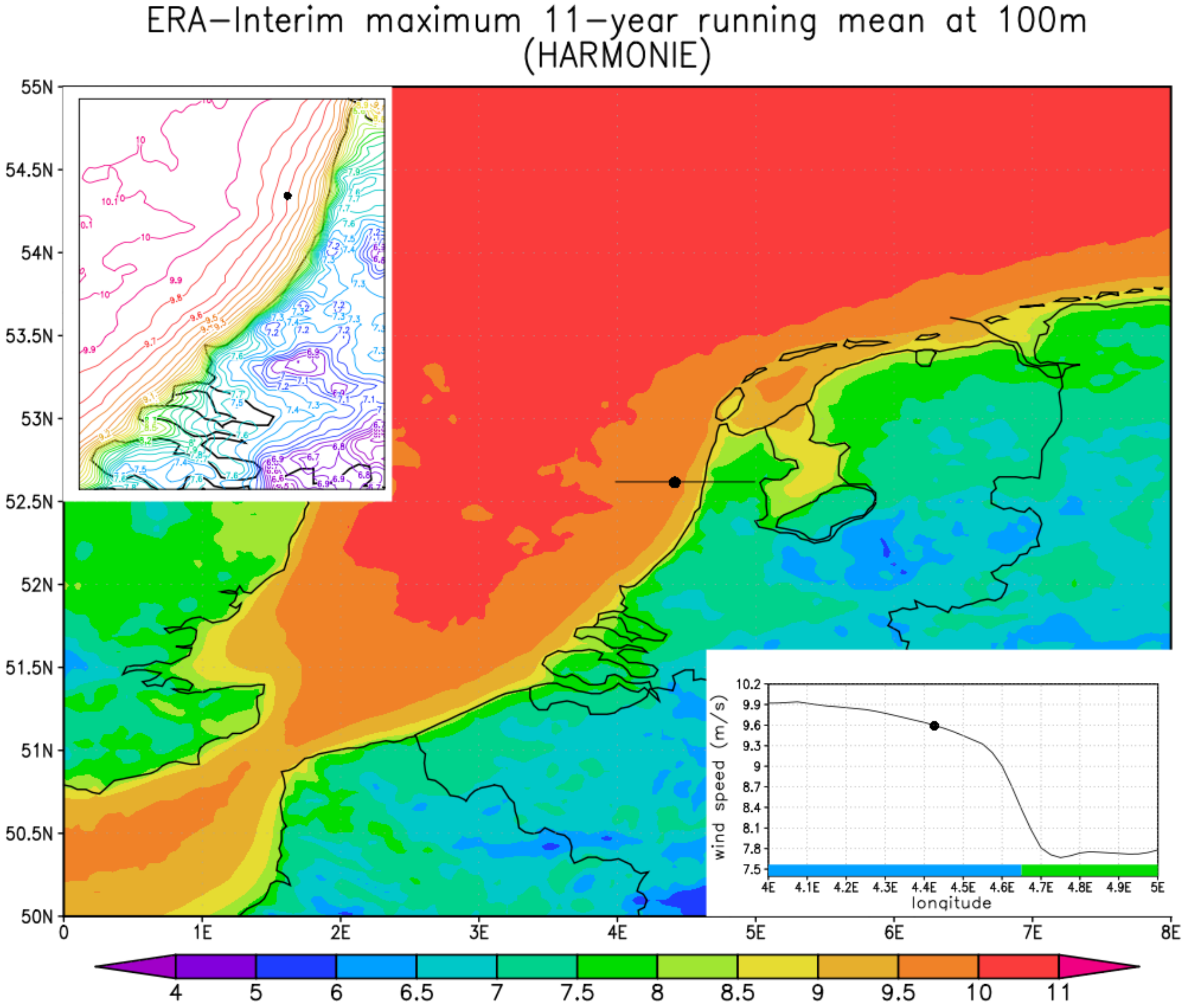

Figure 1.11 Maximum of the 11-year running mean annual average wind speed at 100m over the period 1979-2012, transformed to represent the Harmonie climatology. The upper left panel shows the 0.1 m/s contours and the lower right panel a cross-section at the location indicated on the main panel (the black dot indicates the position of the OWEZ wind mast). Blue refers to sea, green to land.

So according to figure 1.10 and 1.11 the 11 year running mean wind speed at OWEZ has not been higher than 9.6 m/s and not lower than 9.3 m/s in the period from 1979 until 2012. Unfortunately this model climatology can not be verified with the wind measurements at the OWEZ-site, because these measurements are not available for a period that is long enough: the wind at OWEZ was measured only in the period from July 2005 until December 2010[6] (at 21, 70 and 116 m height).

[6] http://www.noordzeewind.nl/kennis/rapporten-data/

1.3.4 10 and 90%-percentile 11-year moving annual average

Banks often use a conservative estimate of the 10 year moving average wind speed (e.g. the 10% percentile) to decide how much money they are willing to invest in a wind park. This kind of information can be derived from the ERA-Interim/ Harmonie climatology as well. In this paragraph we present the 10%-percentile and the 90%-percentile of the 11-year[7] moving average of the average wind speed at 100 m height for 1979-2012.

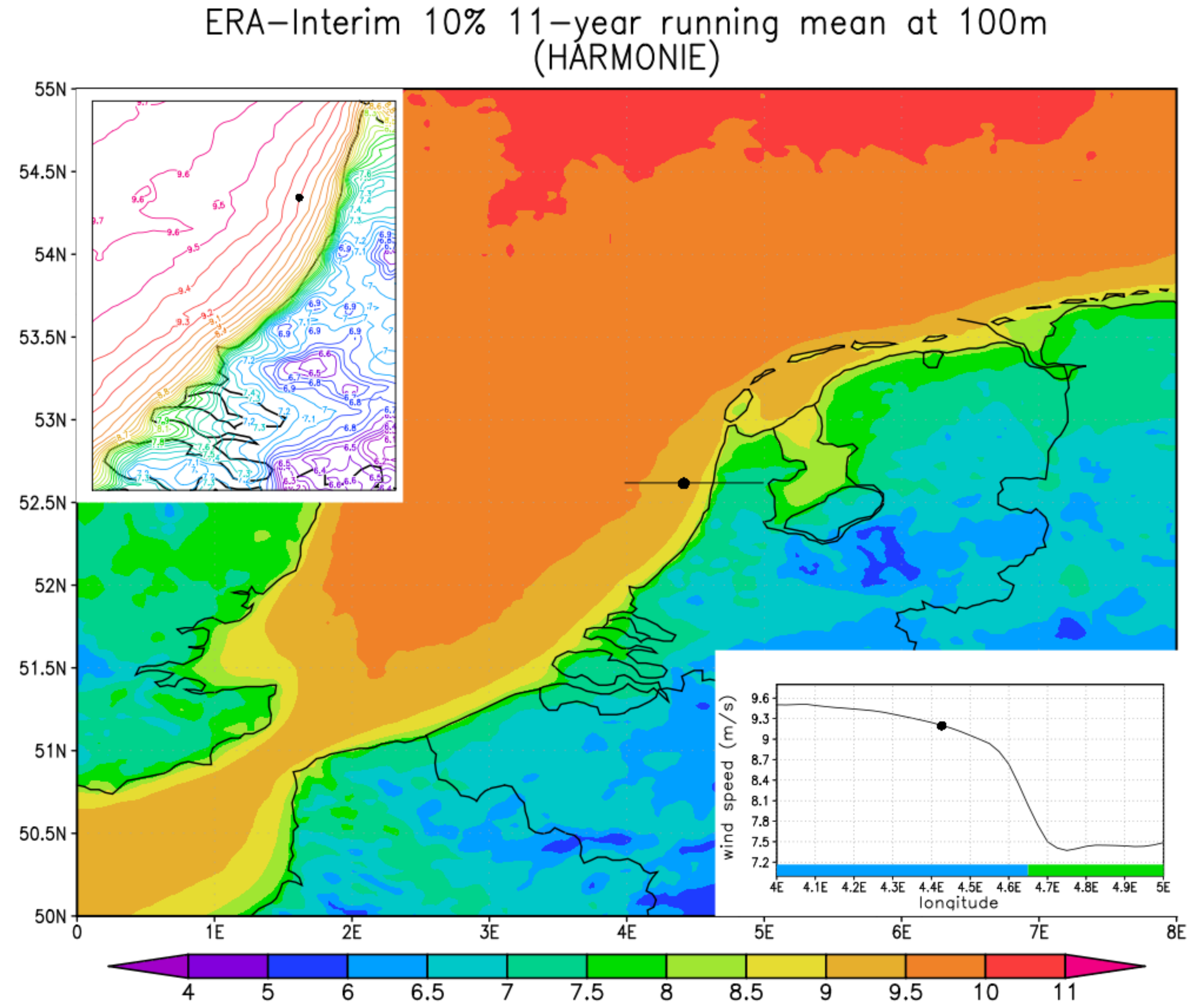

Figure 1.12 10%-percentile of the 11-year moving average annual wind speed at 100m over the period 1979-2012, transformed to represent the Harmonie climatology. The upper left panel shows the 0.1 m/s contours and the lower right panel a cross-section at the location indicated on the main panel (the black dot indicates the position of the OWEZ wind mast). Blue refers to sea, green to land.

[7] 11 years instead of 10 years because then a full year is the middle year of the period.

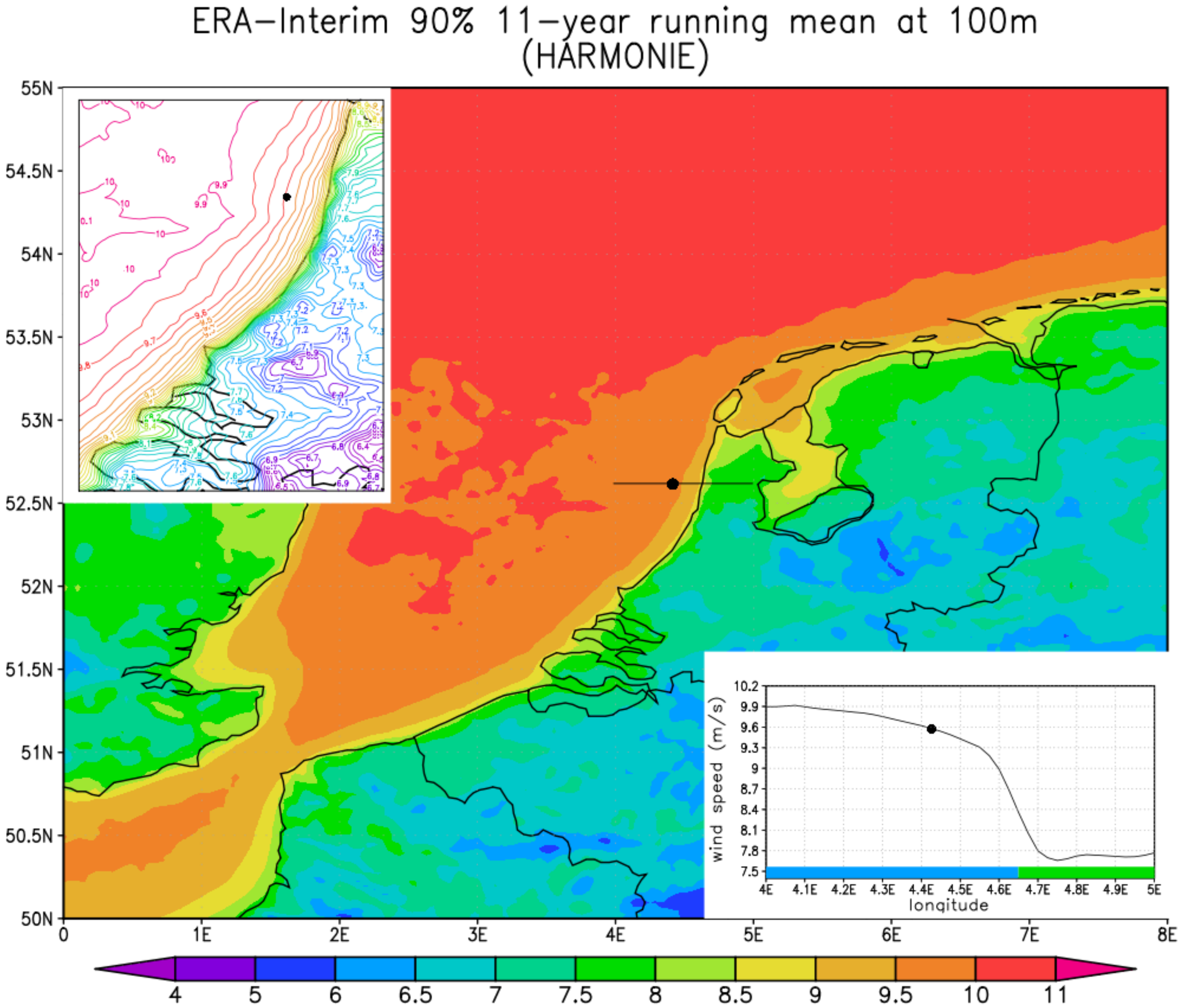

Figure 1.13 90%-percentile of the 11-year moving average annual wind speed at 100m over the period 1979-2012, transformed to represent the Harmonie climatology. The upper left panel shows the 0.1 m/s contours and the lower right panel a cross-section at the location indicated on the main panel (the black dot indicates the position of the OWEZ wind mast). Blue refers to sea, green to land.

1.3.5 Return values

Figures 1.14, 1.15 and 1.16 show the wind speed at 100 m which according to the ERA-Interim/ Harmonie climatology occurs only once in 10, once in 50 and once in 100 years. Obviously the 100-year return value (once in 100 year wind speed) is a lot higher than the 10-year return value (once in 10 year wind speed). Therefore the legend bar underneath the figures is adapted (the legend in figure 1.16 begins and ends at higher wind speeds and each colour represents a range of average wind speeds that is 3 instead of 2 m/s wide.

The return values are calculated by fitting a Gumbel function to the annual extremes of the squared wind speed. This fitted distribution is then extrapolated to return periods of 50 and 100 years, respectively. The squared wind speed is used in order to improve the convergence to the Gumbel function.

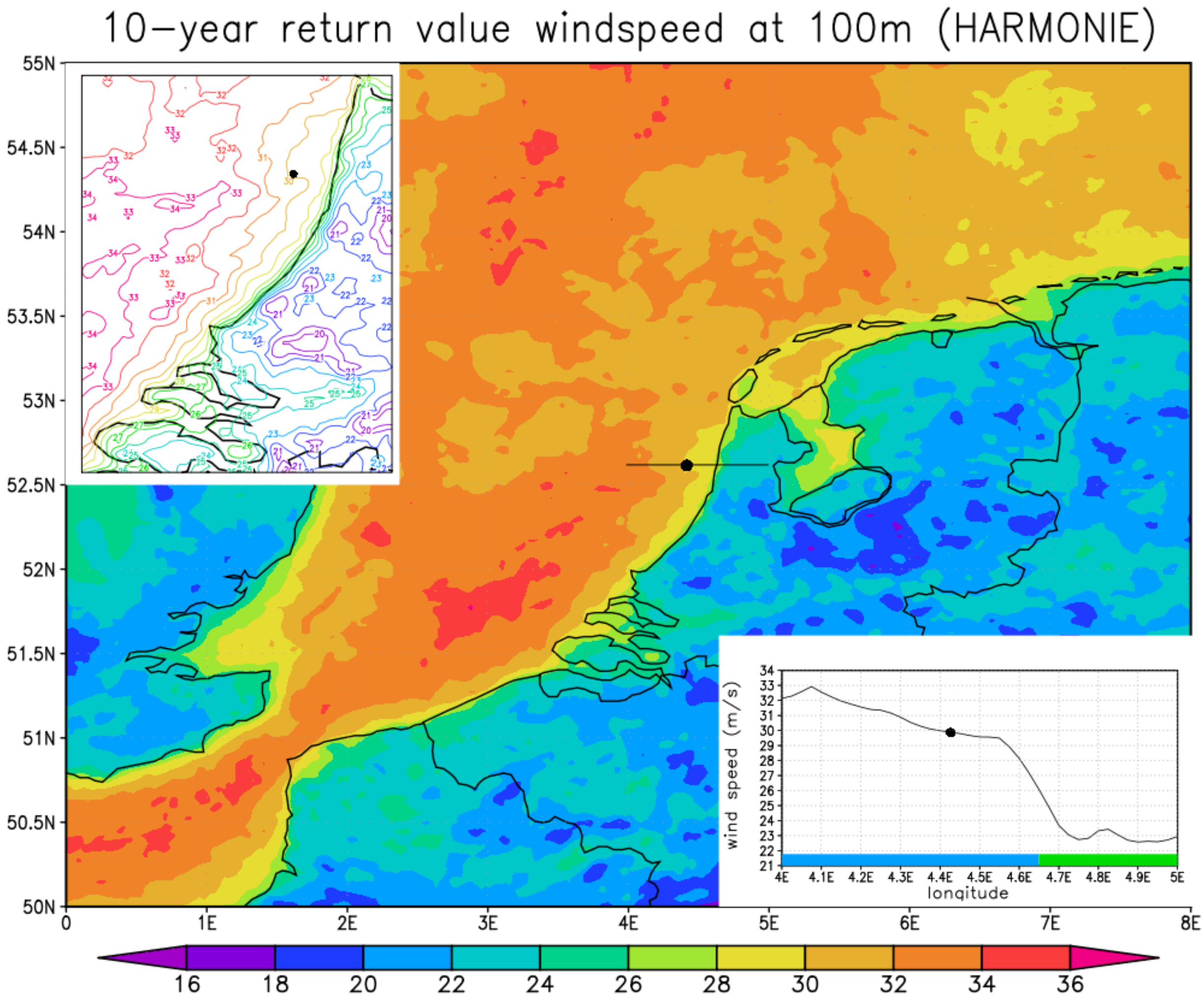

Figure 1.14 10-year return value of the wind speed at 100m based on the period 1979-2012, transformed to represent the Harmonie climatology. The upper left panel shows the 0.1 m/s contours and the lower right panel a cross-section at the location indicated on the main panel (the black dot indicates the position of the OWEZ wind mast). Blue refers to sea, green to land.

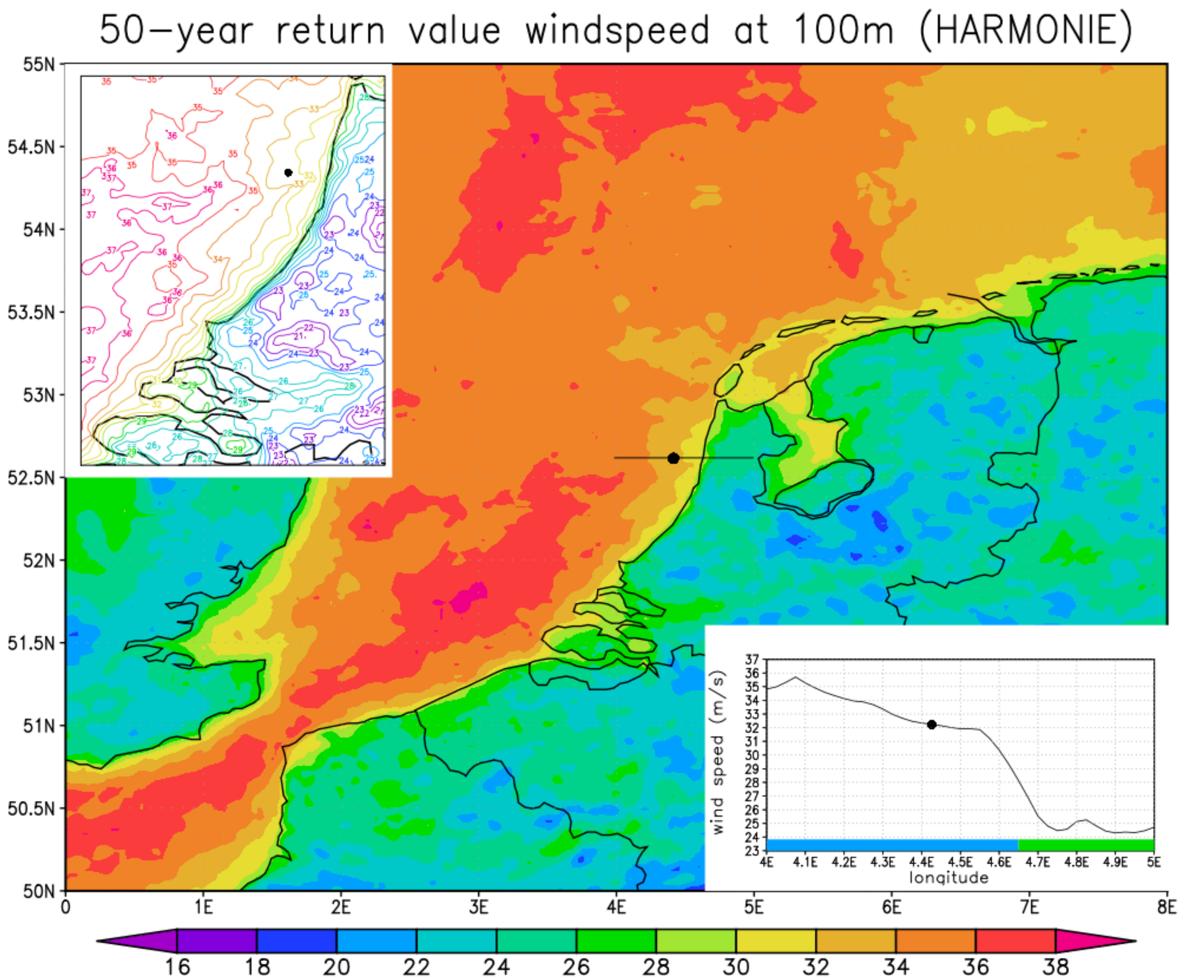

Figure 1.15 50-year return value of the wind speed at 100m based on the period 1979-2012, transformed to represent the Harmonie climatology. The upper left panel shows the 0.1 m/s contours and the lower right panel a cross-section at the location indicated on the main panel (the black dot indicates the position of the OWEZ wind mast). Blue refers to sea, green to land.

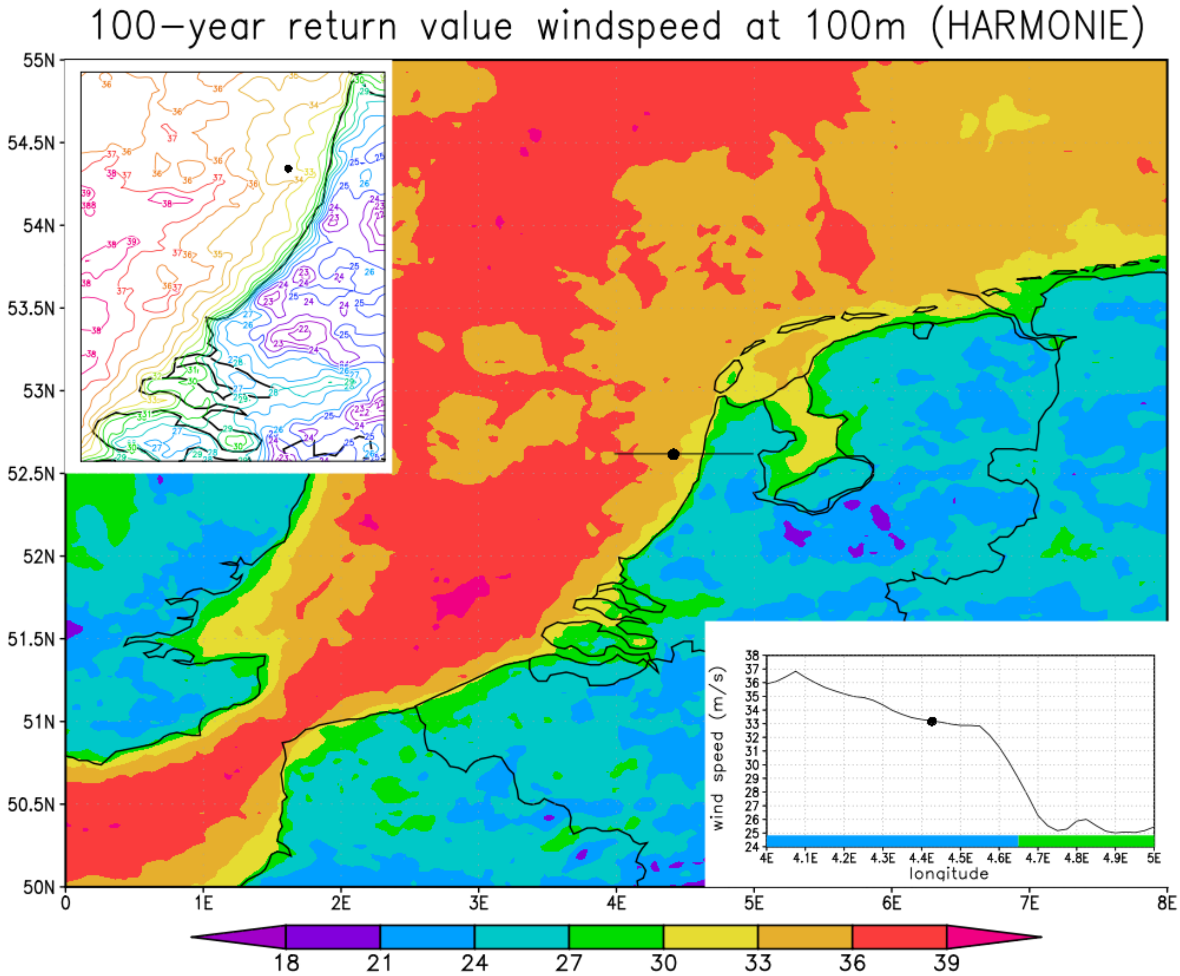

Figure 1.16 100-year return value of the wind speed at 100m based on the period 1979-2012, transformed to represent the Harmonie climatology. The upper left panel shows the 0.1 m/s contours and the lower right panel a cross-section at the location indicated on the main panel (the black dot indicates the position of the OWEZ wind mast). Blue refers to sea, green to land.

1.3.6 Wind roses

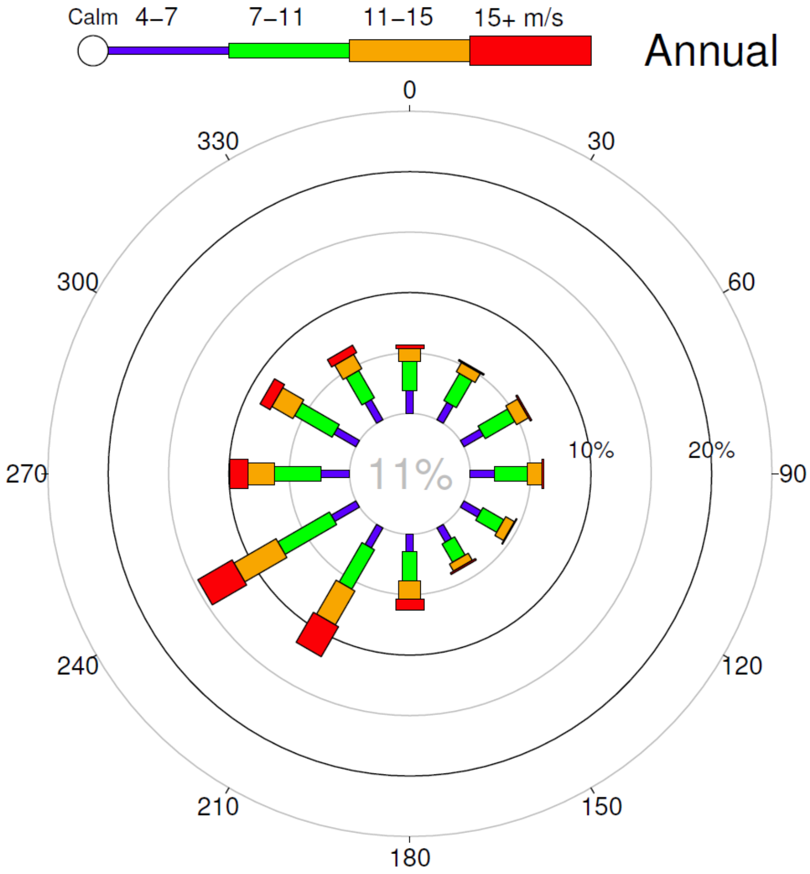

Figure 1.17 Wind rose of the wind direction and speed distributions for OWEZ-location (4.42E 52.6055N) at 100 m based on the period 1979-2012, transformed to represent the Harmonie climatology.

Figure 1.17 shows a wind speed distribution at 100 m for wind direction "bins" of 30 degrees. According to the ERA-Interim/Harmonie climatology the wind at OWEZ is calm in 11% of the time (inner circle) and blows from the southwest (wind direction between 225-255 degrees) almost 15% of the time. As the legend in the figure shows, the colours refer to the strength of the wind: southwesterly winds exceeding 15 m/s occur only 3% of the time.

Recommendations

Comparison of the ERA-Interim-Harmonie climatology with measurements:

- Obviously, the main recommendation for future work is to verify the ERA-Interim-Harmonie climatology by comparing it to high quality measurements:
  - The number of sites with publicly available measurements is limited. Most useful are the high quality measurements from the OWEZ mast, the FINO mast and the ECN IJmuiden site. Baas (2013, 2014) used the wind measurements of the OWEZ and FINO mast to validate Harmonie, but the focus of his work was on high wind speeds. Publicly available wind measurements have been made on numerous oil and gas rigs on the North Sea but many of these measurements exhibit overspeeding around the rig and are generally too low in quality for wind energy purposes (Berge, 2009). Validating the ERA-Interim-Harmonie climatology with these publicly available measurements should be the first priority for future work.
  - Meanwhile KNMI would like to invite the wind energy developers to share their non-public siting-related wind measurements. KNMI has no commercial interest, only a scientific interest, in the non-public measurements made by the wind energy sector and could create a safe archive where these measurements could be used for research beneficial to the whole sector while keeping the underlying measurements anonymous.
  - Also the suitability of other measurement sources for validation of the ERA-Interim-Harmonie climatology should be explored: e.g. AMDAR (Aircraft Meteorological Data Relay); the SPARTA project[8] and the LIDAR measurements of the NORSEWInD project.

- A tall meteorological measurement mast offshore, comparable to the CABAUW wind mast on land, would be very useful, and not only for wind energy purposes. The offshore mast should be equipped with wind sensors and remote sensing instruments (e.g. LIDARS) to measure not only wind at different levels and up to large heights, but also temperature and heat flux so that it is possible to determine accurately the atmospheric stability. Provided that this mast is built in an area where no wind farms are planned or expected and that this mast is maintained for a long enough period (at least 50 years), it would produce very valuable information on long-term variability and off-shore atmospheric stability climatology. It could serve as a reference data set for the Measure-Correlate-Predict method of assessing wind energy production at potential sites and could be used to improve weather forecasting and climate models. More directly the measurements could be assimilated into the operational weather forecasting models to improve the short range wind forecasts necessary for a good functioning electrical grid with a large part of the supply coming from wind parks. A mast like this will be very expensive to build and maintain and should be seen as an international effort for the benefit of all the countries around the North Sea.

[8] http://www.thecrownestate.co.uk/news-media/news/2014/sparta-project-to-drive-offshore-wind-cost-reduction/

Test the method used to transform from ERA-Interim to Harmonie:

- Compare the winds of ERA-Interim transformed with Harmonie with those of Harmonie for a year that was not used for the transformation
- Does a wind direction dependant transformation give significantly different results near the coast?

Once the ERA-Interim - Harmonie wind climatology is validated against high quality measurements and the transformation method has been sufficiently tested and secured in a scientific publication, the climatology can receive the KNMI seal of approval and be used as a "reference" wind atlas for all stages in the process of establishing Dutch offshore wind energy: allocation of areas, tendering procedure, allocation of wind energy producer and monitoring of the wind energy yields. Then other climatological information can also be derived from this "reference" atlas e.g. monthly and seasonal wind climatologies and the duration of relatively calm or windy periods.

Improve spatial resolution:

- The North Sea wind climatology based on Harmonie has limited value for the area up to 2.5 km from the coast because Harmonie grid boxes in this area contain both land and sea. In these grid boxes the land and sea roughness lengths are averaged and the modelled wind speed is underestimated offshore (average roughness too high) and overestimated for land areas (average roughness too low). This does not pose much of a problem as wind farms are not allowed within territorial waters (up to 22 km from the coast) and even if government policy changes and wind farms are allowed closer to the shore, they will probably not be allowed within 2.5 km of the coast. However, it might be useful to downscale the wind climatology in the coastal zone and around wind farms in a later stage using a downscaling technique such as DALES (Dutch Large Eddy Simulation).
- It is possible to use satellite winds to improve the horizontal resolution of the measurement network used to validate the wind climatology. Satellites provide measurements with a good horizontal coverage offshore but the temporal resolution is relatively poor (4 times a day at best). This means sampling biases have to be corrected for by collocation procedures. The same goes for local biases caused by quality control procedures. This has not been done yet for any of the wind atlases of the NORSEWInD project so it is strongly recommended that it be done if these measurements are to be used in the validation.

Improve lifting method:

- In the NORSEWInD project first attempts have been made to lift satellite wind products to 100 m using the surface heat flux and vertical profiles of temperature (which determine stability) and the height of the planetary boundary layer (PBL) from the atmospheric model WRF. Measurements from wind masts and LIDARs are used to improve the understanding of the vertical profiles of wind speed and vertical wind shear and have resulted in modifications of the extrapolation formula and stability function described in part 1 of the report. One of our recommendations would be to use alternative models (ECMWF or HARMONIE instead of WRF) to provide the required stability information (temperature and heat flux) and PBL height because they are more commonly used, monitored, extensively validated and changes in the model are better documented. Furthermore, the PBL height and sea surface temperature are poorly modelled by WRF.

- By combining model information with measured vertical wind profiles a better wind climatology at hub-height (and therefore better estimates of wind energy production) should be achieved. Weather forecasting models have problems representing wind profiles in stable conditions resulting in wind speeds that are too low at the heights relevant for producing wind energy, so combining the model stability information with measured vertical wind profiles should improve the wind climatology presented in this study. The model underestimation of the wind speed at hub-height is certainly important in coastal areas in the spring when warmer air from the land moves over the then cold sea water which results in very stable atmospheric conditions. How large this, and other, stability effects are still needs to be quantified and how often they occur too.

<u>Long-term variability and trends:</u>

- We recommend updating the North Sea geostrophic wind speed time series of figure 3.1 to monitor the wind climatology for signs of change which global warming may bring. Currently, both climate models and observations give no clear evidence that this is the case. The long-term records of 10m wind speeds above land show a decreasing trend which correlates well with increasing roughness caused to some extent by urbanisation (Wever, 2012).
- Several satellite-based wind products should be combined so that the period covered is long enough to include most of the long-term natural variability of the current wind climate. These satellite winds could be used along with ERA-Interim reanalyses such that the sampling biases and biases as a result of the quality control procedure may be accounted for.

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Appendix 1: Project Plan

Noordzee windklimatologie op hoogte t.b.v. sturing energiebeleid van IenM

Profijtbeginselproject (deelopdracht structuurvisie wind op zee) voor DGRW

Projectgroep:
Ine Wijnant (projectleider/rapportage), Henk van den Brink en Andrew Stepek (windklimatologie kaarten), Gerrit Burgers (assistent projectleider), Gertie Geertsema (advies)
Opdrachtgevers:
Nathalie de Koning en Frank Stevens van Abbe
Budget en doorlooptijd:
32.000 euro en half jaar
Plan van aanpak (wat willen we doen en waarom zo):

Gebruik modellen i.p.v. waarnemingen:

Er zijn weinig waarnemingen op hoogte op de Noordzee. Daarom willen we voor het bepalen van de windklimatologie op 120 m hoogte gebruik maken van weermodellen. Het voordeel van deze modellen is dat ze een 100% dekking van het gebied geven en bovendien een fysisch onderbouwd beeld geven van de verticale opbouw van de atmosfeer (stabiliteit). Een nadeel is dat de oppervlakteruwheid niet afhankelijk is van de windrichting, maar een gemiddelde is over de kleinste gebiedsgrootte ("gridbox") van het model. Boven zee is dit nadeel echter alleen significant op afstanden van de kust die kleiner zijn dan de kleinste roosterpuntsafstand ("horizontale resolutie") van het model.

Lange reeksen en hoge resolutie:

Bakker[*] heeft een studie gedaan naar de wind op de Noordzee en heeft op basis van drukmetingen een geostrofische windreeks van 140 jaar gecreëerd. Deze reeks laat zien dat een periode van ruim 40 jaar nodig is om de volledige jaar op jaar variatie van de (geostrofische) windsnelheid van de hele periode (140 jaar) te bemonsteren. Het enige model waarmee we een dataset van dichtbij 40 jaar windinformatie kunnen genereren is ERA-Interim (34 jaar). Nadeel van ERA-Interim is echter de vrij lage horizontale resolutie (80 km). Daarom zijn we van plan om ook de operationele ECMWF uitvoer (resolutie 16 km) van de afgelopen 2 jaar te gebruiken om de uiteindelijke kaarten te maken (langer dan 2 jaar kan niet, omdat er dan te grote wijzigingen zijn in het model). Door een statistische relatie te leggen tussen de operationele ECMWF winduitvoer en die van ERA-Interim, kunnen we klimatologische kaarten leveren met een resolutie van 16 km.

Beperkt geldig voor de territoriale wateren:

Met een horizontale modelresolutie van 16 km blijven de kaarten beperkt geldig voor het gebied tot 16 km uit de kust omdat het model daar de oppervlakteruwheid van de zee middelt met die van het land. Aangezien windparken op dit moment gerealiseerd worden buiten de territoriale wateren (meer dan 22 km uit de kust), is dat geen probleem (alle modelpunten hebben daar uitsluitend de zeeruwheid). Mocht het beleid op dit punt wijzigen, wordt dat wel een punt van aandacht.

Inhoud kaarten:

Naast kaarten met de klimatologisch gemiddelde windsnelheid, stellen wij voor ook de twee Weibullparameters (vormparameter, k en schaalparameter, λ uit onderstaande formule voor de frequentieverdeling van de windsnelheid, x) voor elk model gridpunt op de Noordzee te berekenen. M.b.v. een standaard windturbine power curve is op basis van deze gegevens de windenergie opbrengst uit te rekenen.

$$F(x; \lambda, k) = 1 - e^{-(x/\lambda)^k}$$ ·(Weibull verdeling)

Naast de gemiddelde windsnelheid en de Weibullparameters, is het belangrijk om per roosterpunt op de Noordzee informatie te geven over de variabiliteit van de wind, bijvoorbeeld het maximum en het minimum van het 10 jaar lopend gemiddelde. Aangezien de financiering van windparken vaak gebeurt op basis van een conservatieve raming van de 10 jaar gemiddelde windsnelheid en verdeling, is het interessant om de laagste 10 jaar gemiddelde windsnelheid met een kans van optreden van bijvoorbeeld 10% te geven.
Op verzoek van DGRW leveren we ook de eens in de 50 en eens in de 100 jaar extremen, een windroos met windrichtingverdeling, een kaart met windsnelheden die gestandaardiseerd zijn op de standaard luchtdichtheid en (indien tijd en budget het toelaat) een beperkte vergelijking met OWA-NEEZ.

De operationele ECMWF run geeft een standaarduitvoer op 100m, en op sigma levels (percentages van de luchtdruk op gemiddelde zeeniveau). Wij leveren de gegevens aan op sigmalevels overeenkomend met 40, 60, 80, 100, 120, 140, 160, 180 en 200 m.

Rapportage:

Rapportage is in het Engels. In het rapport zal naast een inleiding over bestaande windkaarten op hoogte (met hun nut en beperkingen), een uitgebreide beschrijving gegeven worden van de methode waarop de kaarten in dit project gemaakt zijn en hoe ze gebruikt dienen te worden. Verder zullen aanbevelingen gedaan worden voor verificatie en verbetering van de kaarten (bijvoorbeeld met gegevens van de OWEZ meetmast, scatterometer data die gebruikt is in het NorseWind project of hindcast HARMONIE modeluitvoer op 2.5 km resolutie).

[*] Bakker AMR and Van den Hurk BJJM (2011) Estimation of persistence and trends in geostrophic wind speed for the assessment of wind supply in Northwest Europe, Clim. Dyn.(accepted). DOI 10.1007/s00382-011-1248-1

Appendix 2: ERA-Interim/ECMWF wind atlas

Harmonie on a 2.5 km grid was not available at the start of this project. Therefore we initially transformed the ERA-Interim dataset with the operational ECMWF weather forecast model on a 16 by 16 km grid.

Figure A2.1 illustrates the difference in spatial resolution of the operational forecasting model ECMWF (on a 0.1 degree grid) and ERA-Interim (on a 0.5 degree grid). Note that, although the resolution differs, the patterns on the North Sea are similar. The differences are largest over land and in the coastal areas.

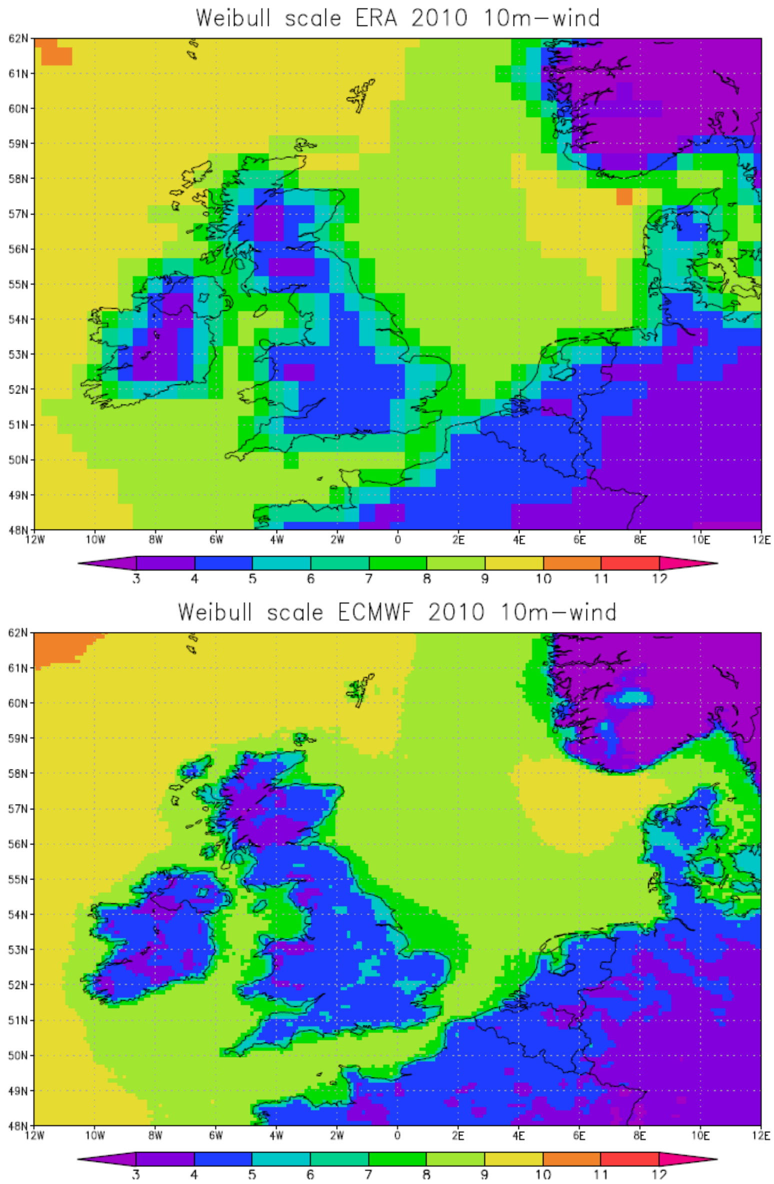

Figure A2.1 Weibull scale parameter for 2010 (at 10 m height) based on ERA-Interim on a 80 km grid (top panel) and the operational forecasting model ECMWF on a 16 km grid (bottom panel). Note that the patterns are similar on the North Sea and improvements are significant in coastal areas.

This is illustrated in more detail in Figure A2.2, which shows a cross section of the Weibull scale parameters at 52.5ºN for 2010 (black), 2011 (red) and 2012 (green) based on the operational ECMWF analysis. Also shown is the 2010 scale parameter based on the ERA-Interim data. Figure 4.3 illustrates the following. First, over open sea the ERA-Interim climatology is similar to the operational climatology. Second, the climatological wind speed in 2010 is considerable lower than in 2011 and 2012. Third, ECMWF distinguishes Lake IJssel (5.25-5.55ºE) where ERA-Interim does not.

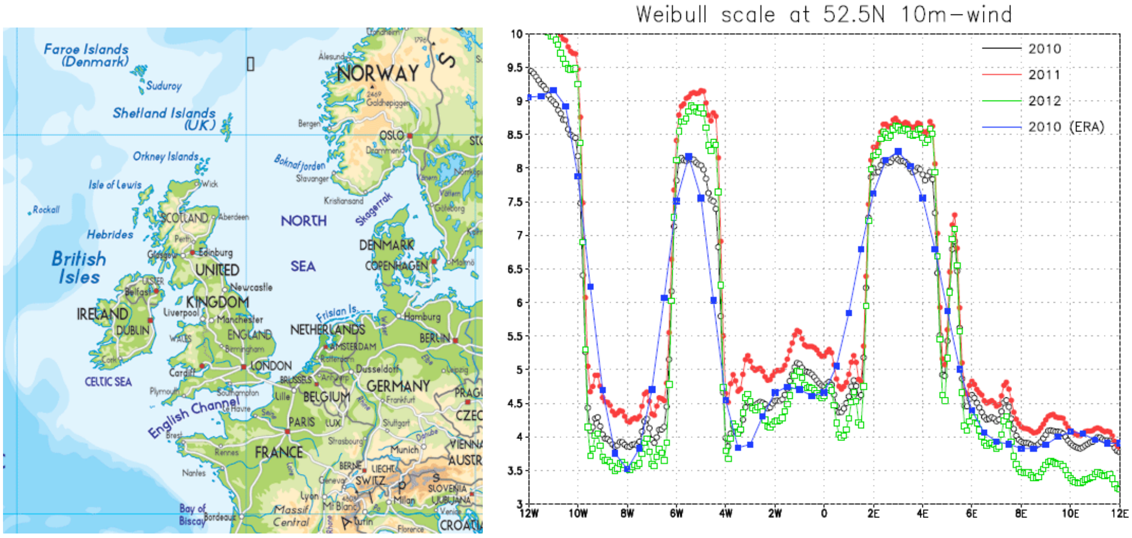

Figure A2.2 Cross section of the Weibull scale parameters at 52.5ºN of ECMWF for 2010 (black), 2011 (red) and 2012 (green) and of ERA-Interim for 2010 (blue). From left to right the peaks represent: the Atlantic, the Celtic Sea, the North Sea and Lake IJssel.

For the comparison of the Weibull distributions the most recent years of the operational ECMWF forecast model are chosen, as they are assumed to have the best quality[9]. Three years (2010-2012) were intercompared (2013 was left out because the number of vertical levels was changed halfway the year from 91 to 137 vertical levels). Figure A2.3 shows the Weibull scale parameters for 2010-2012, both for the operational and ERA-Interim datasets. It illustrates, again, that 2010 was a year with low wind speeds. More importantly, it shows that the ERA-Interim and operational models behave similarly: they were both low in 2010. The small mutual differences between ERA-Interim and the operational model can partly be attributed to sampling effects, and partly to changes in the operational model. We decided to intercompare ERA-Interim and the operational model based on two years: 2011 and 2012. We have the following reasons for this: First, these years are the most recent years without significant changes in the EMCWF operational model; second: selecting two years instead of one year gives more robust results; third, 2010 was an exceptional year, which might be of negative influence on the derived statistical relation.

[9] It is not possible to use the high resolution ECMWF operational model for the whole period because the model is continually improved and we want to limit the number of versions that we use.

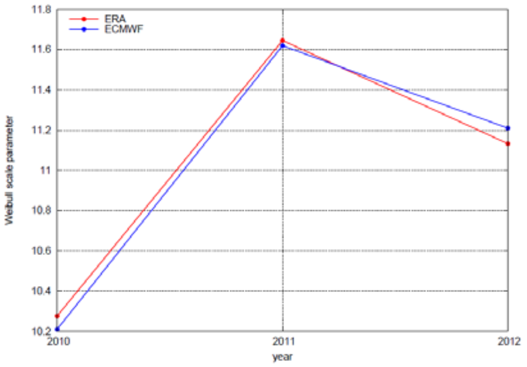

Figure A2.3 ERA-Interim and ECMWF Weibull scale parameter for 2010-2012 for the (3°E, 55°N) grid point.

The climatology based on ERA-Interim and ECMWF is summarised in this appendix:

Average wind speed:

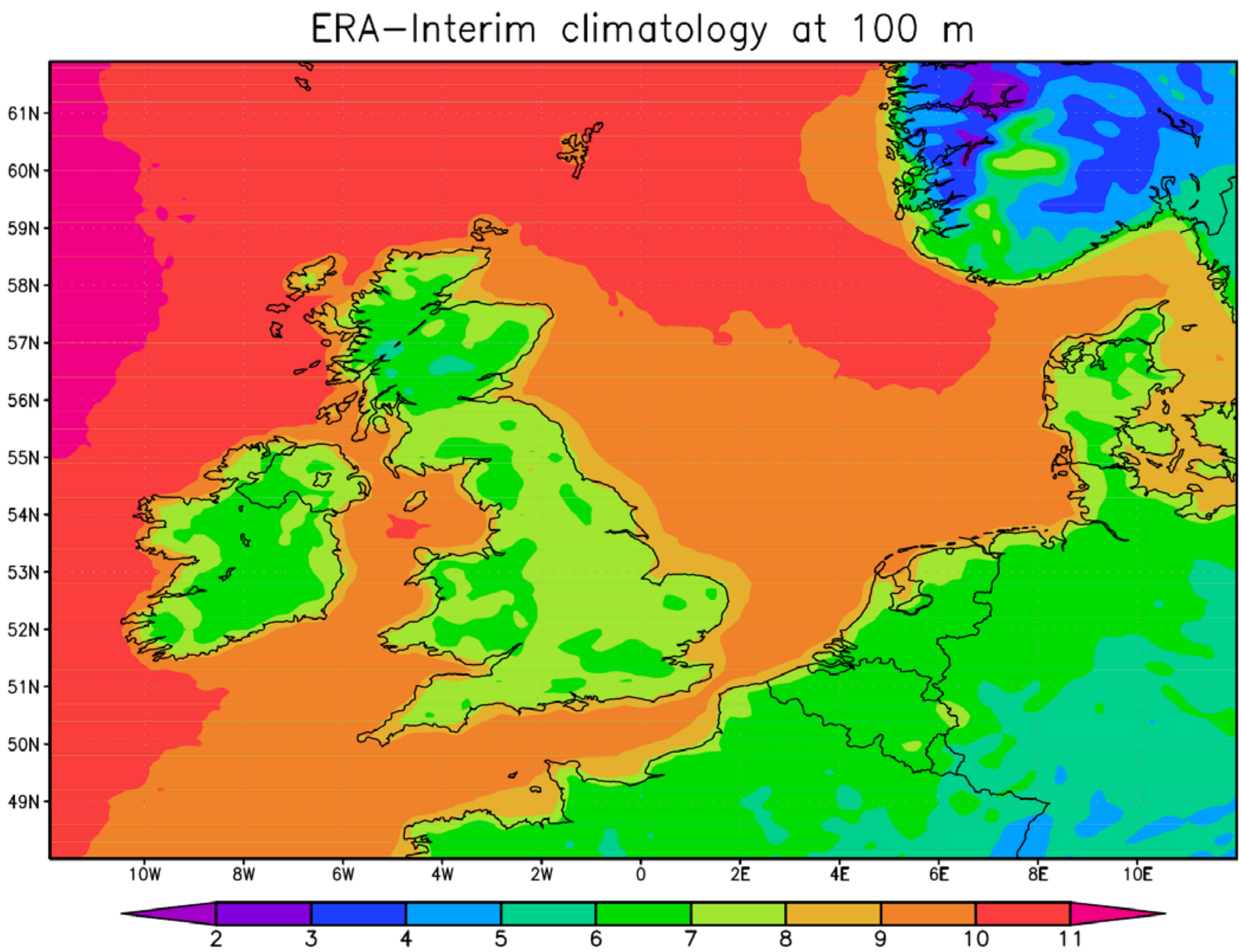

Figure A2.4 Climatological wind speed over the ERA-Interim period of the wind speed at 100m, transformed to represent the 2011-2012 ECMWF operational climatology.

Weibull parameters:

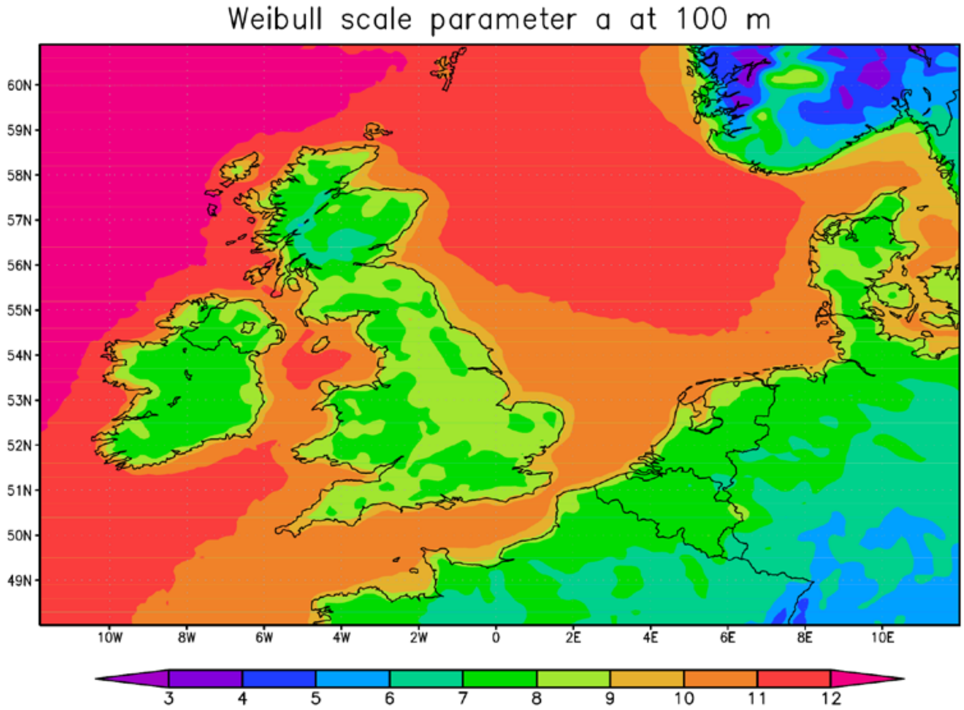

Figure A2.5 Weibull scale parameter a *of the wind speed at 100m over the period 1979-2012, transformed to represent the ECMWF operational climatology.*

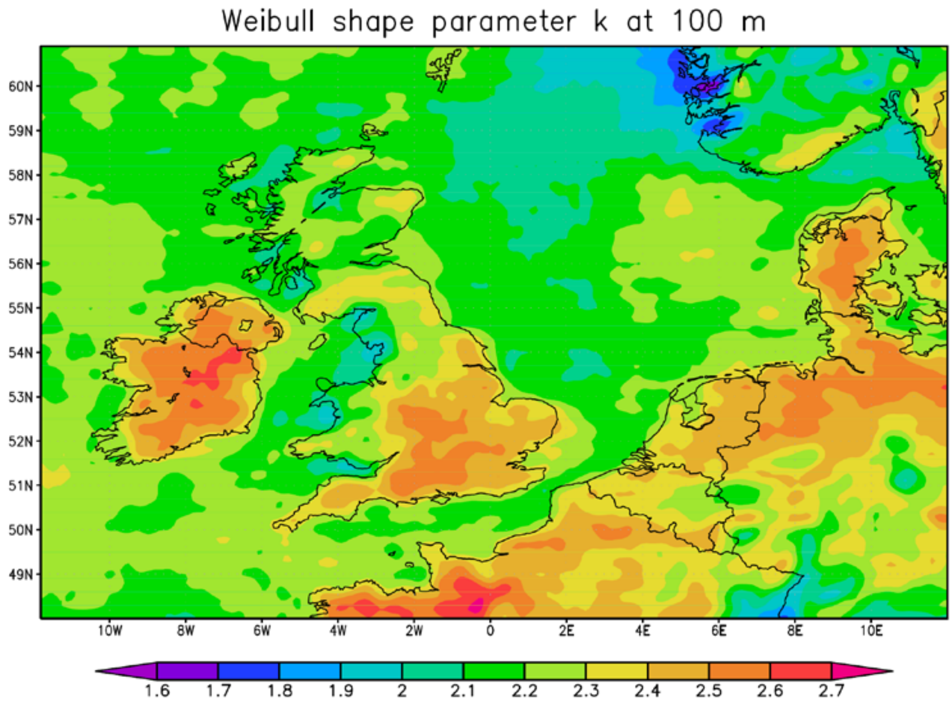

Figure A2.6 Weibull shape parameter k *of the wind speed at 100m over the period 1979-2012, transformed to represent the ECMWF operational climatology.*

Minimum and maximum 11-year moving average:

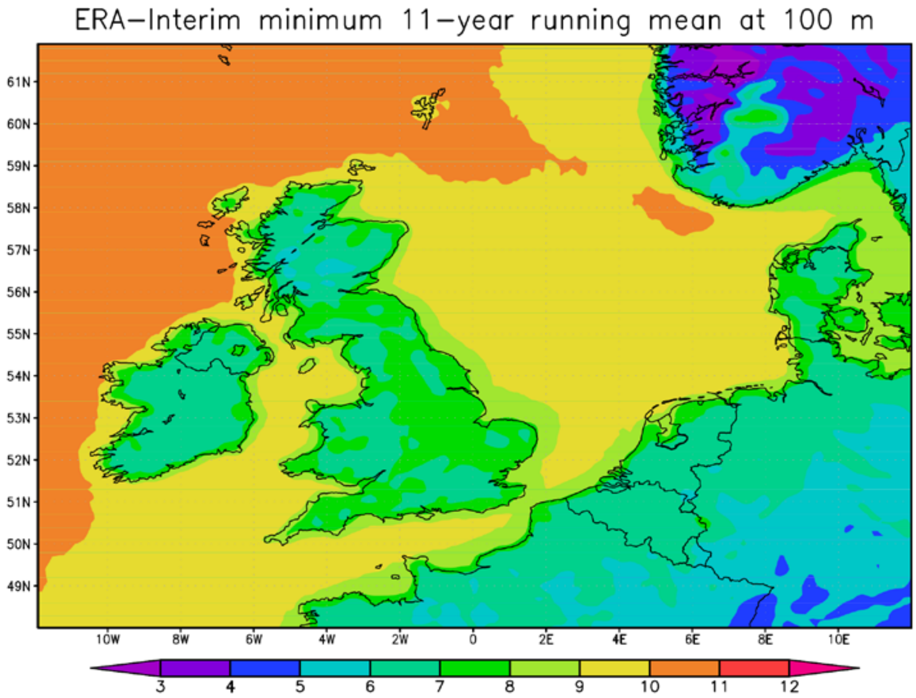

Figure A2.7 Minimum of the 11-year running mean annual average wind speed at 100m over the period 1979-2012, transformed to represent the ECMWF operational climatology.

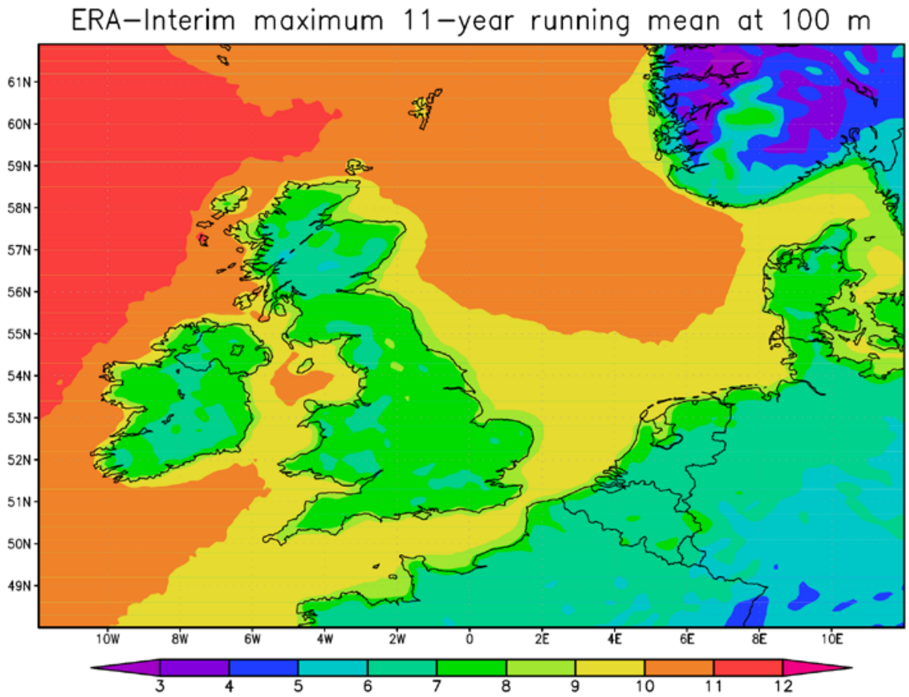

Figure A2.8 Maximum of the 11-year running mean annual average wind speed at 100m over the period 1979-2012, transformed to represent the ECMWF operational climatology.

10%-percentile 11-year annual wind speed:

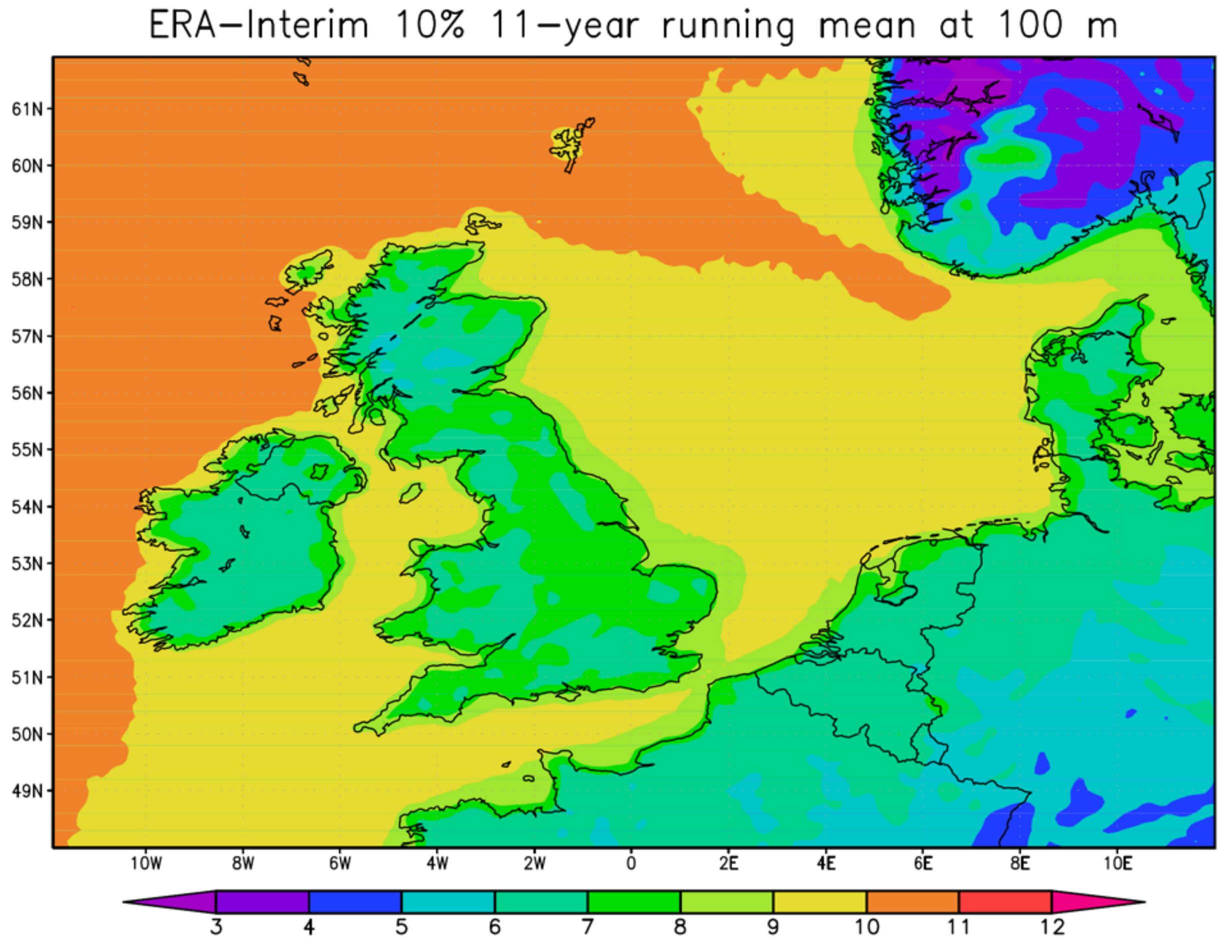

Figure A2.9 10%-percentile of the 11-year moving average annual wind speed at 100m over the period 1979-2012, transformed to represent the ECMWF operational climatology.

Return values:

The return values are calculated by fitting a Gumbel function to the annual extremes of the squared wind speed. This fitted distribution is then extrapolated to return periods of 50 and 100 years, respectively. The squared wind speed is used in order to improve the convergence to the Gumbel function.

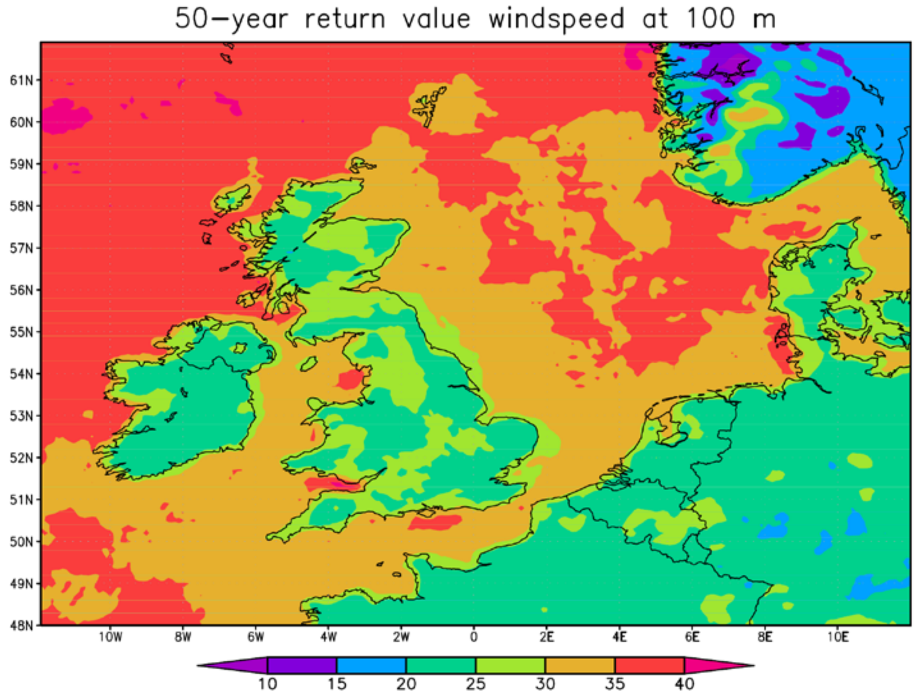

Figure A2.10 50-year Return value of the 6-hourly[10] wind speed at 100m based on the period 1979-2012, transformed to represent the ECMWF operational climatology.

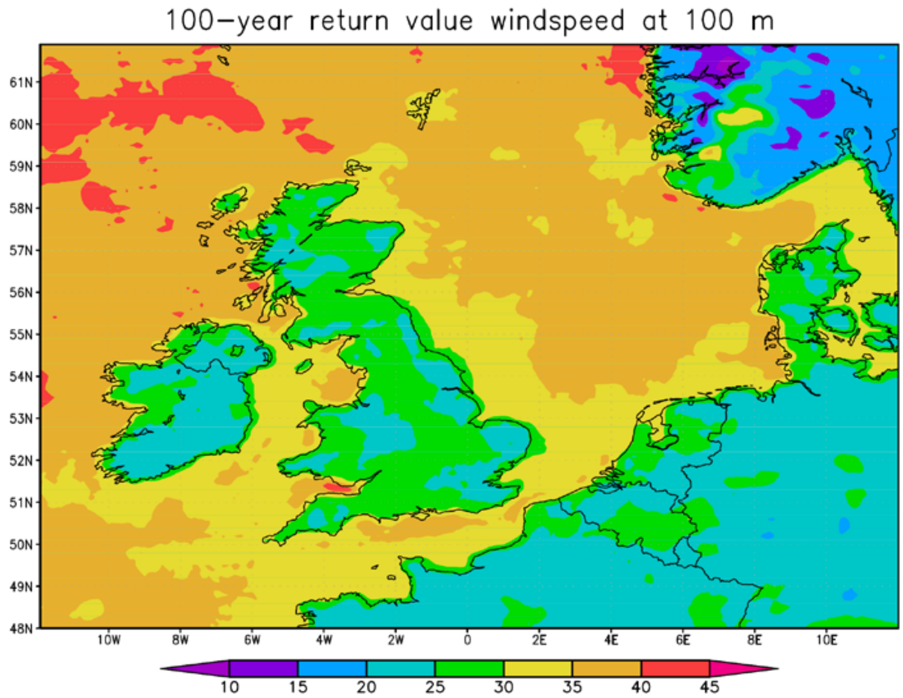

Figure A2.11 100-year Return value of the 6-hourly wind speed at 100m based on the period 1979-2012, transformed to represent the ECMWF operational climatology.

[10] Era-interim gives model values every 6 hours.

Wind roses

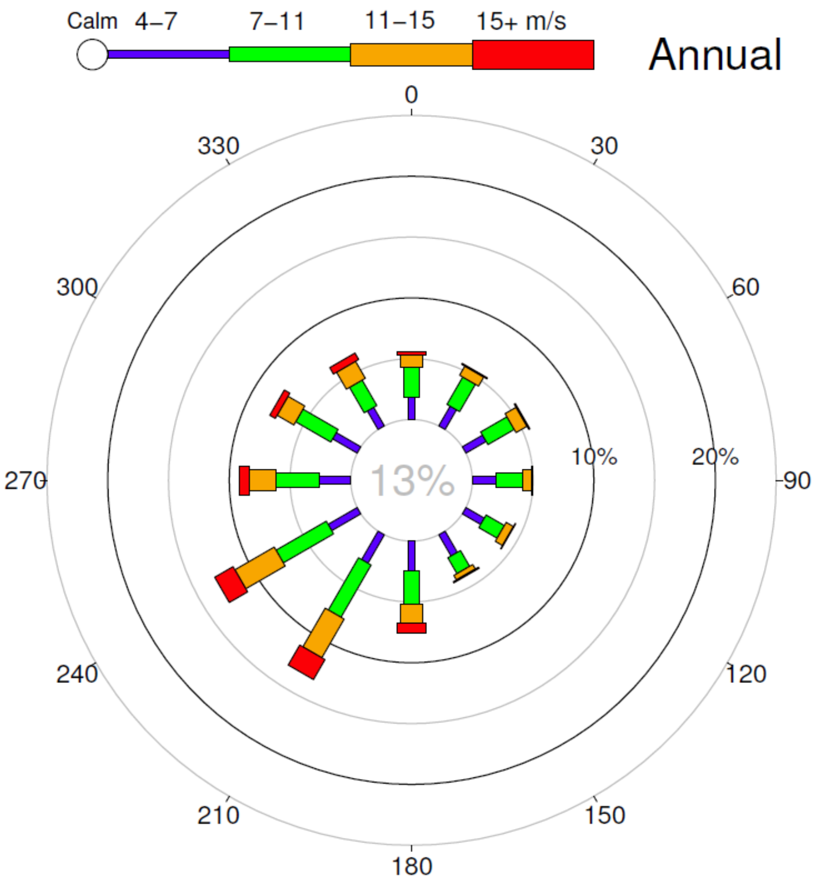

Figure A2.12 Wind rose of the wind direction distribution for (3E,55N) at 100 m.

Appendix 3: Methods and models in wind energy and weather forecasting

Many tools are used in wind energy which can all be referred to as “models”. The following descriptions are designed to make clear what the different tools are used for and hopefully avoid confusion.

Windex

Windex-CBS is used to monitor the energy production of existing wind turbines and parks in the Netherlands and on the North Sea. It is a monthly statistic based on the wind energy produced by many wind turbines and is used as a benchmark to check for problems at specific wind energy installations.

Measure – Correlate – Predict (MCP)

MCP is used in the pre-installation phase of a project to estimate the wind climatology at the site of a wind energy installation that has yet to be built (“target site”). In the wind energy sector it is standard practise to measure the wind at the target site for one year and compare these measurements to those made simultaneously at a reference site that has been measuring for at least ten years. KNMI has shown that at least 40 years are required to capture the full range of decade average wind speeds and that the estimated wind climatology will be significantly incorrect when only ten years are used. The comparison of the target site to the reference site is then used to estimate the wind that would have been measured had the target site been measuring for those ten years. The wind estimated by this method can be used to estimate the wind energy production of a single wind turbine if it were to be installed at the target site. In the UK, this method is compulsory and it costs millions of pounds sterling for each offshore measurement campaign. In the Netherlands, less costly methods are not excluded.

Weather forecasting models

These models can be used both estimating the wind available to both existing and planned wind energy installations. For existing wind energy installations the forecast of the wind hours or days in the future is used to forecast e.g. low wind periods for maintenance but also the price of energy or what other types of electrical power stations have to produce to match the supply to the demand. For planned wind energy installations the wind climatology can be calculated from many years of the analysis (as opposed to the forecast) of a weather forecasting model. The analysis is useless for forecasting the wind because it describes the weather at the point in time that the model was originally run. It contains a 3D description of the wind at a given point in time which becomes a very useful 3D wind climatology (a “reanalysis”) when many such analyses are combined. Each analysis is based on measurements from very many locations and is the best fit to these measurements that can be made with the model that still satisfies the laws of physics contained in the model. One benefit is that measurements that can not possibly be correct are automatically rejected by the model. The reanalysis (ERA-interim) and weather forecasting model (Harmonie) used to make the North Sea wind climatology presented in this report are the best of their kind. A different sort of model can be used to estimate the wind climatology at some point in the distant future. These are referred to as climate models and they are used to estimate the effect of global warming; *not* wind climatology for the wind energy sector.

Wake Model

The input for the wake model is a wind forecast from a weather forecasting model for an existing wind energy installation or a wind climatology for a proposed site, estimated using the MCP method or a reanalysis of a weather forecasting model. The output is the wind energy produced by a wind park (as opposed to a single wind turbine) including an estimate of the losses caused by turbines lowering the wind speed experienced by turbines further downwind. Wake modelling is one of ECN's areas of expertise, whereas KNMI is the expert when it comes to weather forecasting models and wind climatology.

Wind turbine specific power curve

The power curve is the relationship between the hub height wind speed and the electrical energy production of the wind turbine and is provided by the wind turbine manufacturer. Once the wind climatology has been estimated, an estimate of the wind energy production can be made by using the power curve to transform wind speeds into energy. The wind climatology should then be in the form of a wind speed frequency distribution (which shows which percentage of the time a given wind speed occurs). Once the hub height wind speed distribution, the power curve and wake losses are known, wind energy production can be estimated.

Appendix 4: Harmonie 10 m wind verification for 16 historical storm situations

Baas (2013) investigated the general wind climatology of Harmonie. For 16 historical storm periods (table A4.1), PDF's of the modelled and measured 10 m wind speeds[11] were compared (figure A4.1) and the differences were in general small (only the occurrence of extreme wind speeds is slightly too high in the model).

Nr.	Max. wind date	Max. U_p (m/s)	Hindcast start date	Hindcast end date
1	1953 02 01	25.7	1953 01 26	1953 02 04
2	1979 02 14	24.7	1979 02 10	1979 02 17
3	1983 02 01	24.1	1983 01 27	1983 02 04
4	1983 11 27	24.6	1983 11 23	1983 11 29
5	1984 01 14	26.3	1984 01 10	1984 01 19
6	1989 02 14	19.3	1989 02 10	1989 02 17
7	1990 01 25	27.0	1990 01 21	1990 02 03
8	1990 02 26	24.9	1990 02 22	1990 03 02
9	1990 12 12	20.4	1990 12 07	1990 12 14
10	1993 11 14	22.5	1993 11 10	1993 11 16
11	1994 01 28	19.4	1994 01 24	1994 01 30
12	1996 02 19	14.5*	1996 02 15	1996 02 22
13	2000 05 28	22.7	2000 05 24	2000 05 30
14	2002 10 27	25.7	2002 10 23	2002 10 29
15	2006 11 01	22.1	2006 10 28	2006 11 03
16	2007 01 18	23.5	2007 01 10	2007 01 20
17	2007 11 09	18.7	2007 11 05	2007 11 11

Table A4.1:Overview of simulated storms: date of main storm event, maximum potential wind speed and start date and end date of Harmonie hindcast. The storm of 1953 was not analysed as there are no ERA-Interim data available for this storm. (Source: Baas, 2013)

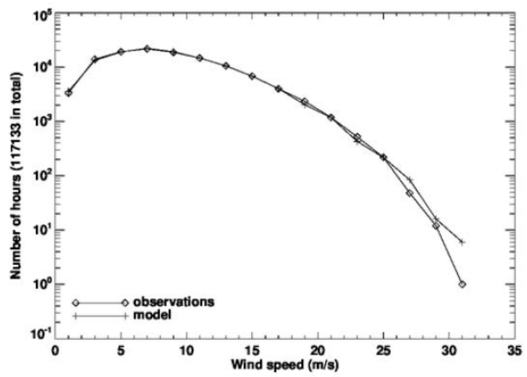

Figure A4.1 Distribution of modelled and observed 10 m wind speed (m/s) for all 16 historical storms and all stations in bins of 2 m/s. Only at wind speeds above 25 m/s the there are more hours with high wind speeds in the model (+) than in the observations (◊) (Source: Baas, 2013).

[11] Summarised over all storm periods and all stations, 117133 hours of data are included in the comparison which is the equivalent of 13 years.

Figure A4.2 shows that for 10 m wind speeds rms-errors are on average about 1.5 m/s and that Harmonie has a positive bias of about 0.5 m/s over sea. This does not necessarily mean that the Harmonie wind speeds are 0.5 m/s too high. The measured wind speeds may be too low since the wind sensors are for the most part mounted on oil and gas rigs that are known to affect the wind flow. The largest errors occur for stations in heterogeneous terrain such as coastal stations (not specifically shown: the left panel of figure A4.2 shows all land and coastal stations).

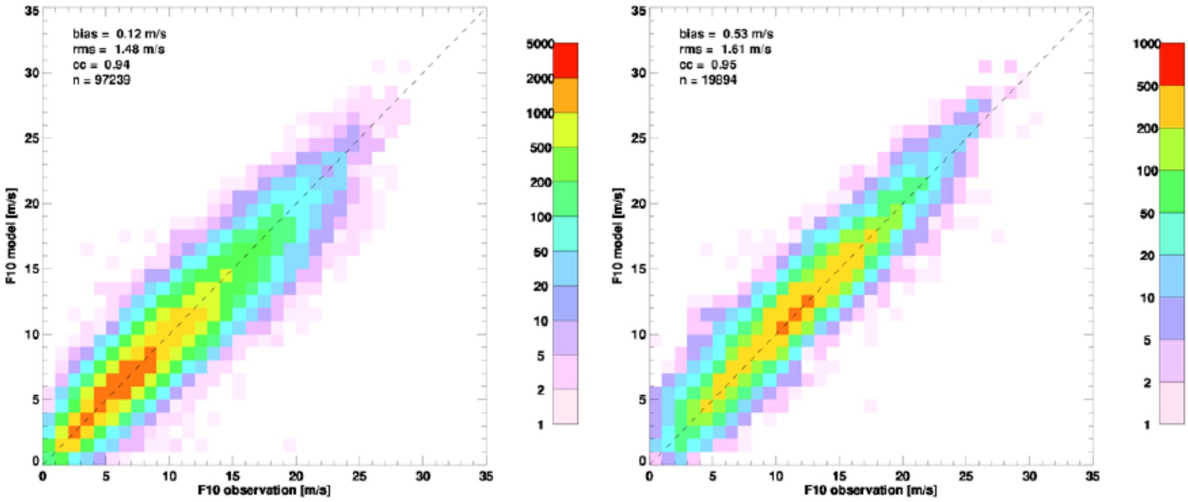

Figure A4.2 Density scatter plots of modelled versus observed 10 m wind speeds (m/s) for coast/land (left) and open water stations (right). Colours indicate the number of occurrences for each bin (Source: Baas, 2013).

The wind speeds of Harmonie look more realistic than those of ERA-Interim, especially nearer land as Harmonie has a much better representation of the land-sea mask (Baas, 2014). Figure A4.3 shows that 10 m wind speeds in Harmonie are systematically higher than in ERA-Interim. The difference varies from 0.5-1.0 m/s far from the coast to 3-4 m/s in coastal areas and over Lake IJssel. For high wind speeds, differences are larger (1-2 m/s far from the coast and 4-6 m/s in coastal areas). So although the benefit of Harmonie is largest in coastal areas and over Lake IJssel, it is still noticeable far from the coast, especially for higher wind speeds.

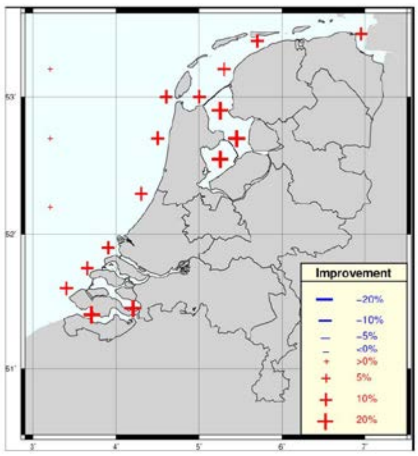

Figure A4.3 Improvement of the 10 m wind speed by using Harmonie instead of ERA-Interim (Source: Baas, 2014)

Two of the measurement sites are selected to illustrate the comparison between model and measurements: one in open sea (K13) and another nearer the coast (Lichteiland Goeree). Figure A4.4 shows the results of the comparison, again for the 16 historical storm periods mentioned earlier. ERA-Interim clearly underestimates wind speeds near the coast (right, bottom) and high wind speeds at the open sea location (right, top). Harmonie performs significantly better (left).

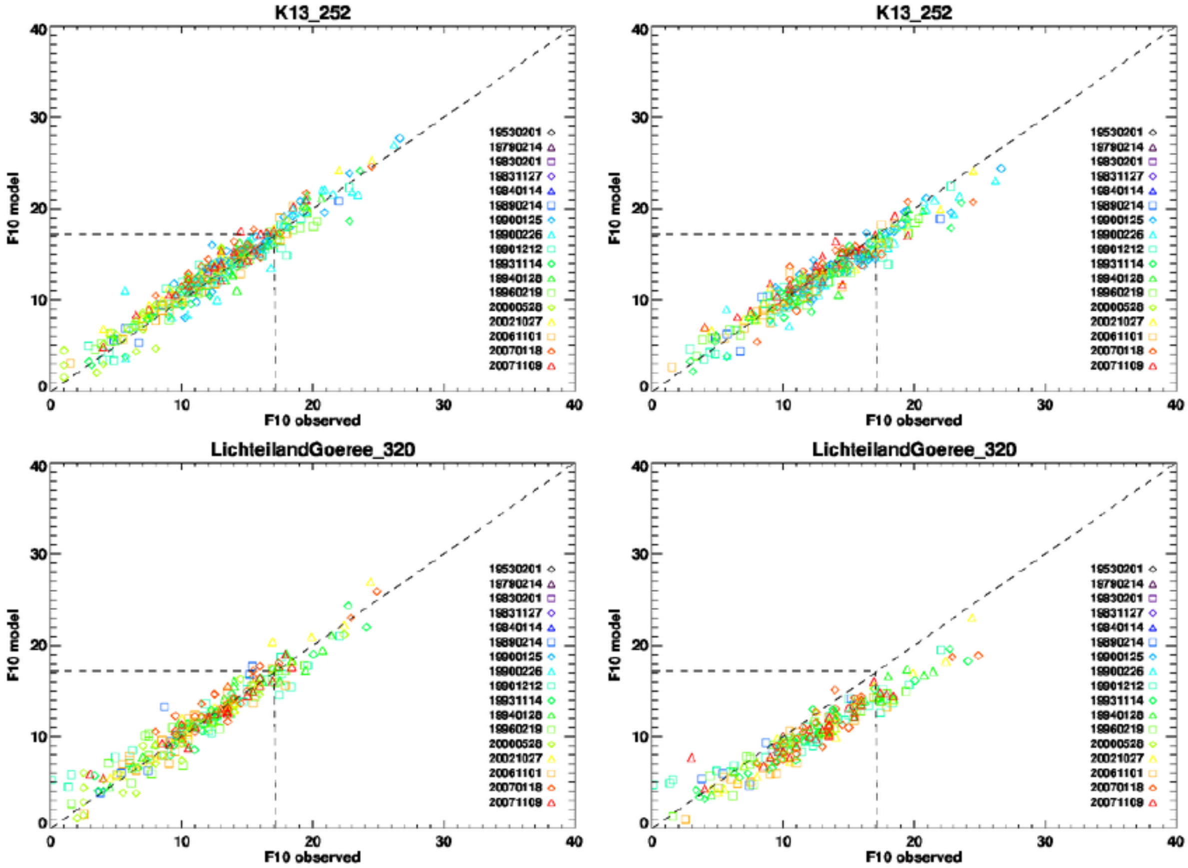

Figure A4.4 Scatter plots of modelled versus observed 10 m wind speed for Harmonie (left) and ERA-Interim (right) for K13 (top) en Lichteiland Goeree (bottom). The dashed lines represent the 1:1 line and 17 m/s (the low end of 8 bft).(Source: Baas, 2014)

Baas (2014) also showed how HARMONIE represents the impact of stability on the near-surface wind over Lake IJssel and demonstrated that the benefits of Harmonie are not limited to its more detailed land-sea mask. No ERA-Interim results will be shown here because where Lake IJssel should be the model has land due to its large gridbox size. Figure A4.5 shows the average evolution of the wind speed over a west-east cross-section over Lake IJssel for westerly winds (wind direction between 225° and 315°) for three stability classes. The location of the cross-section is indicated in the left panel of the figure. Wind speeds are normalised with the wind speed at the RWS (Rijkswaterstaat, a part of the Dutch civil service) measuring station FL2. The black crosses indicate the modeled water fraction. At the location of the cross-section, Lake IJssel is eight grid points wide.

In stable conditions the wind speed increases faster to an equilibrium value than in unstable conditions. Consequently, in stable conditions the wind speed is more constant over Lake IJssel than during unstable conditions, where a strong east-west gradient is observed and the wind reaches higher speeds. For each stability class, the red asterisks indicate the observed ratio between the RWS measuring stations FL26 and FL2. The measurement height of the RWS stations is 10 m. The impact of stability on the near-surface wind is clearly present in Harmonie, but in neutral and especially stable conditions it is too weak.

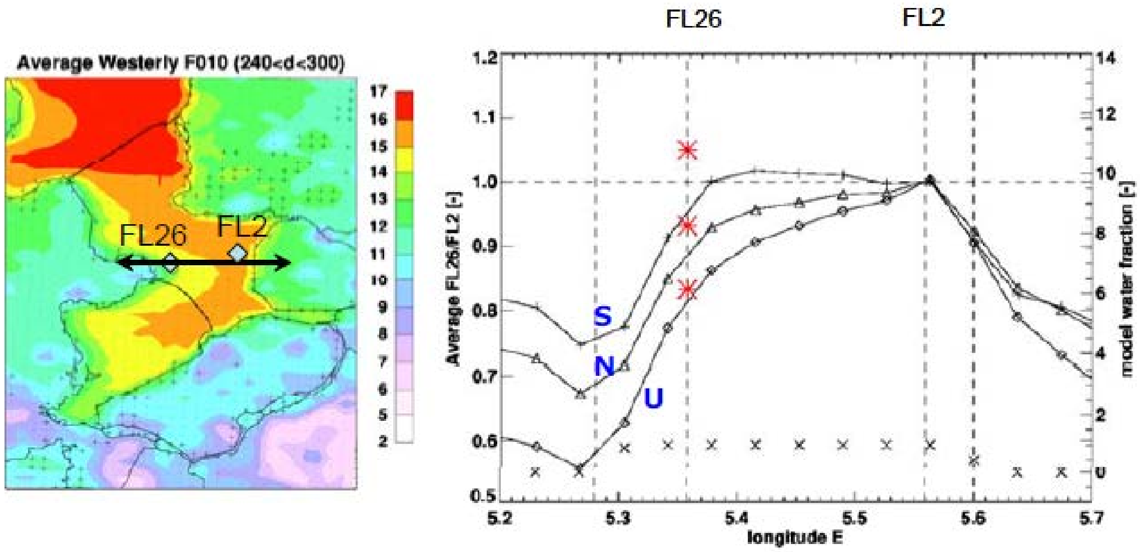

Figure A4.5 Cross-section over Lake Ijssel of 10 m wind for three stability classes (right panel) for westerly winds, Diamonds indicate the unstable cases, triangles the neutral case and plusses the stable cases. The asterisks indicate the observed wind speed ratio for three different stability classes; the crosses indicate the modelled water fraxion (right axis) The left panel indicates the averaged wind field (in m/s) over all Harmonie storm hindcast runs for westerly winds. The location of the cross-section is indicated (Source: Baas, 2014).

To illustrate how stable and unstable conditions are modeled differently, we discuss the two-dimensional cross-sections of the thermodynamic state of the boundary layer with the help of two cases. For both cases the wind comes from the west. Figure A4.6 shows the vertical cross-section for potential temperature (colours, in Kelvin) and wind speed (lines) for the lowest 500 m of the atmosphere. The location of the cross section is the same as in figure A4.5. The location of the shorelines is indicated by vertical dashed lines.

In the stable case, the water temperature is about 4 K lower than the air temperature. Consequently, as the air flows over the water the air temperature starts to drop. With the fetch over the water becoming larger, the vertical potential temperature gradient increases and this layer becomes more stable. Due to the low roughness over water the wind speed increases rapidly as soon as the air starts flowing over the water. However, the stably stratified air prevents the downward mixing from layers above this where the wind speed is higher. Hence, the wind speed soon stops increasing after less than 10 km from the western shore of the lake (cf. figure A4.5). The impact of the land-water transition on the wind speed decreases rapidly with height. Above about 200 m the impact is small.

In the unstable case, the water temperature is about 5 K higher than the air temperature. So, as the air flows over the water the air temperature increases, resulting in intense vertical mixing which very quickly wipes out the vertical temperature gradient and forms a horizontal gradient caused by the warmer water. In this case, the near-surface wind speed keeps increasing until the flow hits the eastern shoreline of the lake (cf. figure A4.5). Initially, the wind speed increases rapidly because of the reduced surface roughness. The increase is continued, albeit at a lower rate, by the downward mixing of high-momentum air towards the surface. In this unstable case the wind speed at higher levels (above 500 m, not shown in the figure) decreases significantly. Compared to the stable case, the impact of the change of surface has a much stronger effect throughout the whole boundary layer.

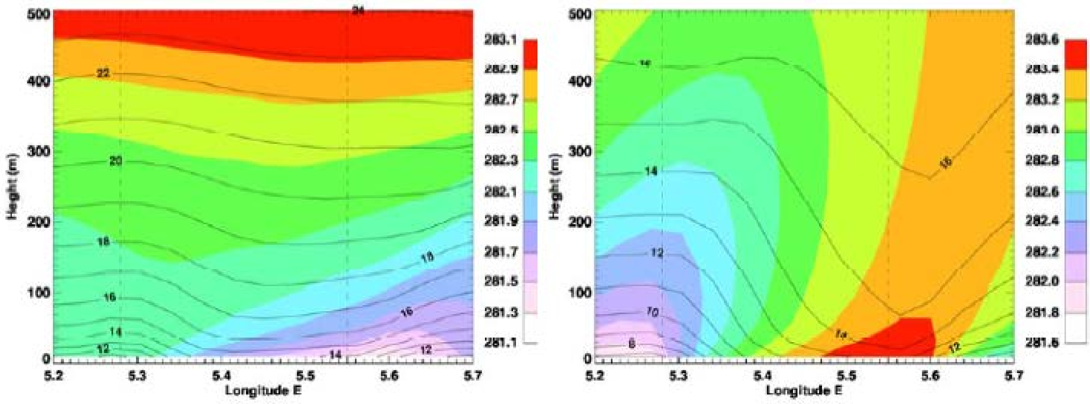

Figure A4.6 Example of a stable (16 Feb 1996, 14UTC) (left panel) and an unstable (24 Oct 2002, 1 UTC) (right panel) case. The colours indicate the potential temperature (in K), the solid black lines indicate the wind speed (in m/s).The vertical dashed lines indicate the western and eastern shorelines of Lake IJssel. (Source: Baas, 2014)

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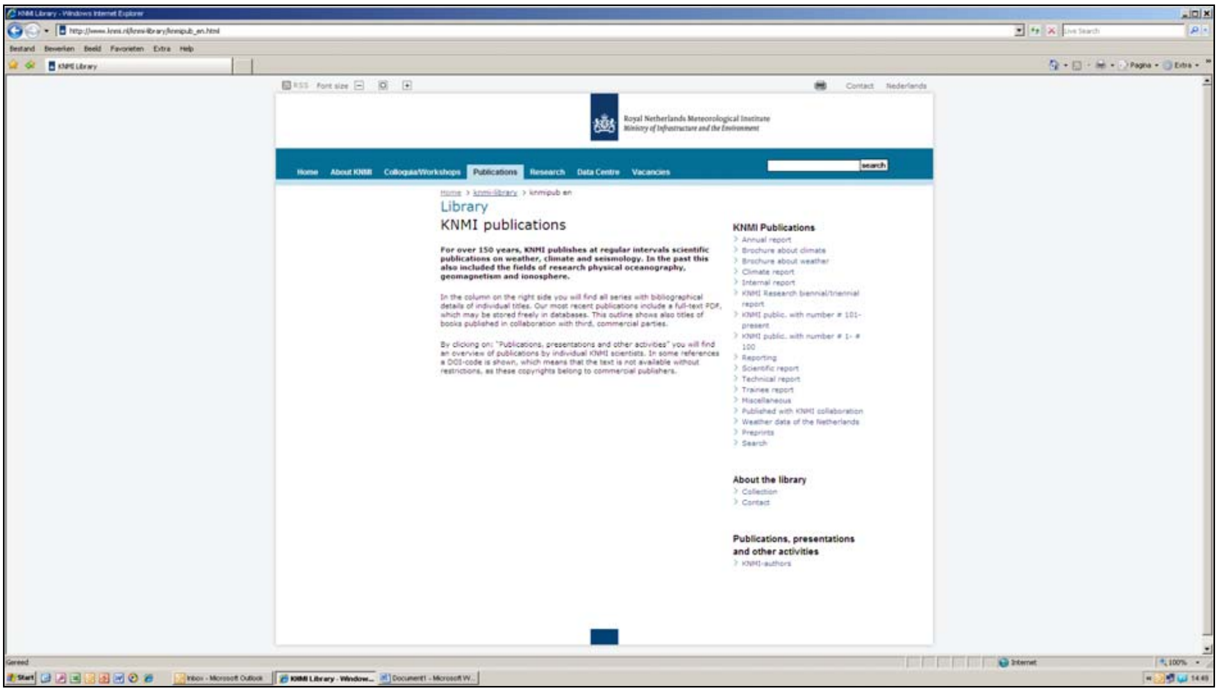

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