Offshore Wind Atlas of the Dutch Part of the North Sea

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This paper has been presented at the EWEA 2011,
Brussels, Belgium, 14-17 March 2011

ECN-M--11-031 MARCH 2011

OFFSHORE WIND ATLAS OF THE DUTCH PART OF THE NORTH SEA

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Summary A wind atlas of the Dutch part of the North Sea was made by using a numerical wind atlas method fed with six years of data from the numerical weather prediction model HiRLAM. This atlas contains distributions of mean wind speed, Weibull parameters and reference wind speed in the Netherlands' Exclusive Economic Zone at 40, 90 and 140 meter above mean sea level. This atlas was made by employing a sea surface roughness which, apart from wind speed, depends on wave steepness. By using such a sea surface roughness, the accuracy of wind speed distributions is improved with 1% to 2% over distributions calculated with a sea surface roughness that depends on wind speed alone.

1 Introduction

The Offshore Wind Atlas of the Netherlands' Exclusive Economic Zone (OWA-NEEZ) was first published in 2005 [1]. Since then more data have become available and the opportunity to employ variable sea surface roughness has appeared [2]. This resulted in the second version of the OWA-NEEZ containing distributions of mean wind speed, Weibull parameters and reference wind speed at 40, 90 and 140 meter above mean sea level.

Like the first version, the second OWA-NEEZ is based on time series of meteorological variables originating from the numerical weather prediction model HiRLAM. A total of six years of data have been processed. Again, measurements of wind speed and direction were only used for validation, unlike other wind maps which are based on measurements [3]. Unlike in the first version, where sea surface roughness depends on wind speed alone (Charnock relation), in the second version sea surface roughness is a function of wave steepness too (Hsu equation).

This paper presents the second version of the Offshore Wind Atlas of the Netherlands' Exclusive Economic Zone. First, the method by which the OWA-NEEZ was made is explained (section 2). Next, validation of mean wind speed is treated (sections 3), and content of the second version of the OWA-NEEZ and comparisons to other wind maps are addressed (section 4). Finally, the conclusions are presented (section 5).

2 Method

2.1 Numerical wind atlas method

2.1.1 Model chain

A long-term time series of atmospheric data is constructed by combining consecutive short-term time series of HiRLAM data over the period 2003 - 2009, retaining the first six hours of data

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only. These data are subsequently translated to the location and height of interest. The model chain is shown in figure 1.

The translation to location and height of interest consists of two steps: a vertical interpolation between model levels and a horizontal interpolation between grid points. For vertical interpolation of wind speed and potential temperature the Holtslag profiles (under very stable conditions) or the Businger-Dyer profiles (all other conditions) are used in combination with the Monin-Obukhov length [4, 5]. Wind speed and potential temperature in the four grid points forming the corners of the cell that contains the location of interest, are linearly interpolated to the location of interest.

The resulting long-term time series includes wind speed, wind direction, stability length, temperature, pressure and turbulence intensity. The time series of wind speed and wind direction subsequently is reduced into a sectorwise distribution of wind speed, and, finally, into a sectorwise scale parameter A and shape parameter k of the Weibull distribution.

2.1.2 Sea-surface roughness

In the first version of the OWA-NEEZ sea surface roughness was assumed to depend on wind speed only: sea surface roughness z_0 was determined by using Charnock's relation [6], where the Charnock parameter α_{ch} is constant:

$$z_0 = \alpha_{ch} \frac{u_*^2}{g} \ .$$

The other variables in this equation are friction velocity u_* and acceleration of gravity g.

In the second version it is recognized that sea surface roughness depends on waves too. To this end the equation of Hsu is employed [7]. In this equation the Charnock parameter depends on wave steepness H/L, where H is wave height and L is wave length:

$$z_0 \propto \frac{H}{L} \frac{u_*^2}{g} \ .$$

Assuming that the southern part of the North Sea is shallow and using the general wave equation, which relates sea depth and wave length to the phase velocity of the waves, wave length is expressed in terms of wave period T and sea depth d. As a result, Hsu's equation for shallow water is:

$$z_0 = \frac{H}{T\sqrt{gd}} \frac{u_*^2}{g} \ .$$

The required quantities H, T and d are derived from measured values originating from Dutch Ministry of Infrastructure and Environment and Netherlands Hydrologic Service [8, 9].

Unfortunately, these data are unknown for the whole NEEZ. As shown in figure 2, wave data are available in a select group of locations whereas sea depth is available in a limited area. To overcome the problem of missing data, data are interpolated by using inverse distance weighting [10]. If $z(x_i)$ is the value of quantity z in the observation point x_i, the value $z(x_0)$ of quantity z in the point of interest x_0 is:

$$z(x_0) = \sum_{i=1}^{N} w_i \, z(x_i) \quad \text{with} \quad w_i = \frac{1/d_i^p}{\sum_{i=1}^{N} 1/d_i^p} \ .$$

Here the weight w_i of an observation depends on the distance d_i between the observation point and the point of interest, and the power p.

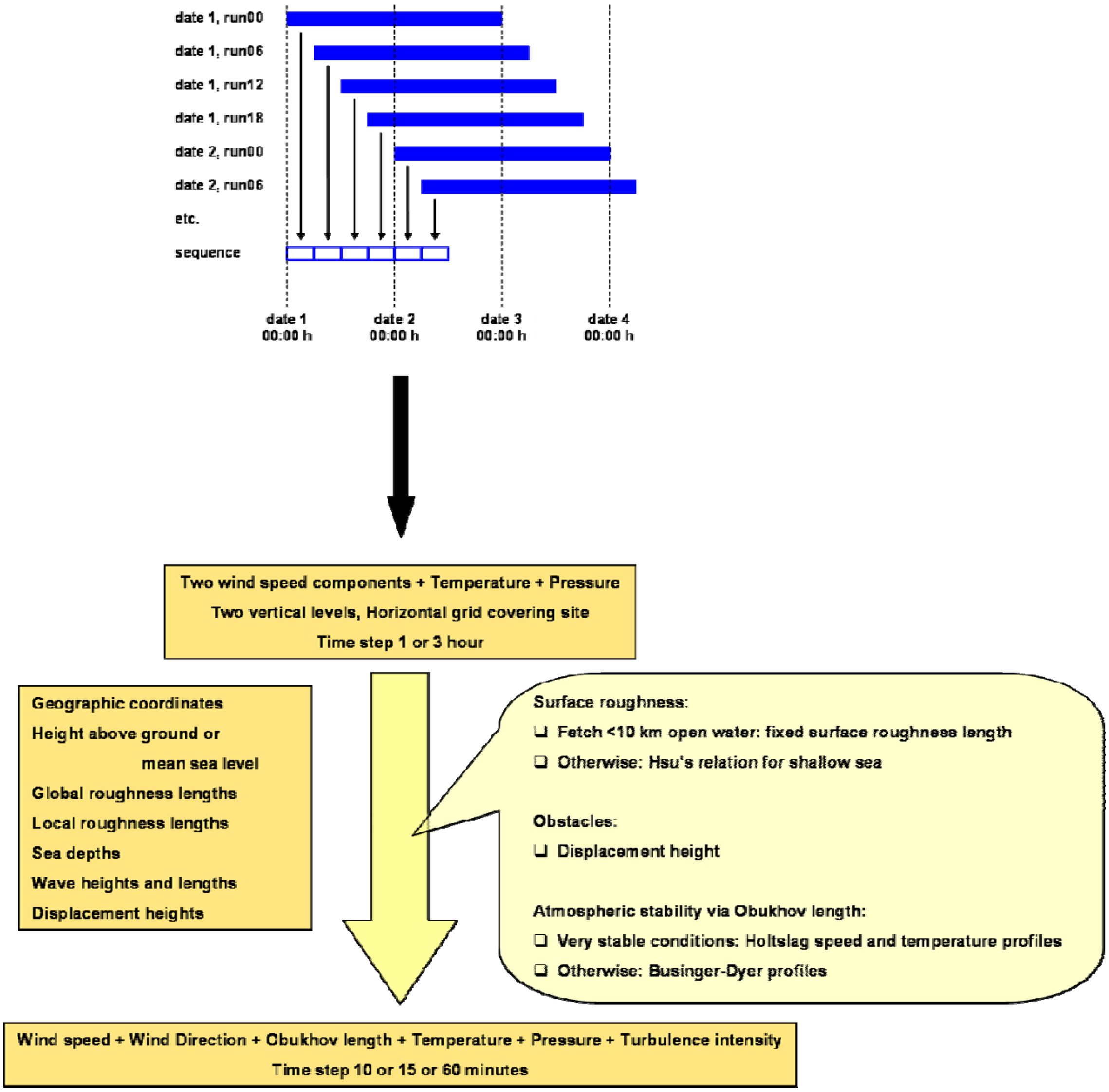

Figure 1 Construction of a long-term time series of wind data and vertical interpolation of these data

2.2 Reference wind speed

Reference wind speed is defined by the standard IEC1400-1ed2 as the extreme 10-minute average wind speed at turbine hub height with a recurrence period of 50 years. Following the Gumbel-Bergström method, in the second version of the OWA-NEEZ the reference wind speed is estimated from the scale parameter A and shape parameter k of the Weibull distribution [11]. These two parameters are obtained by fitting the Weibull distribution to a calculated wind speed time series.

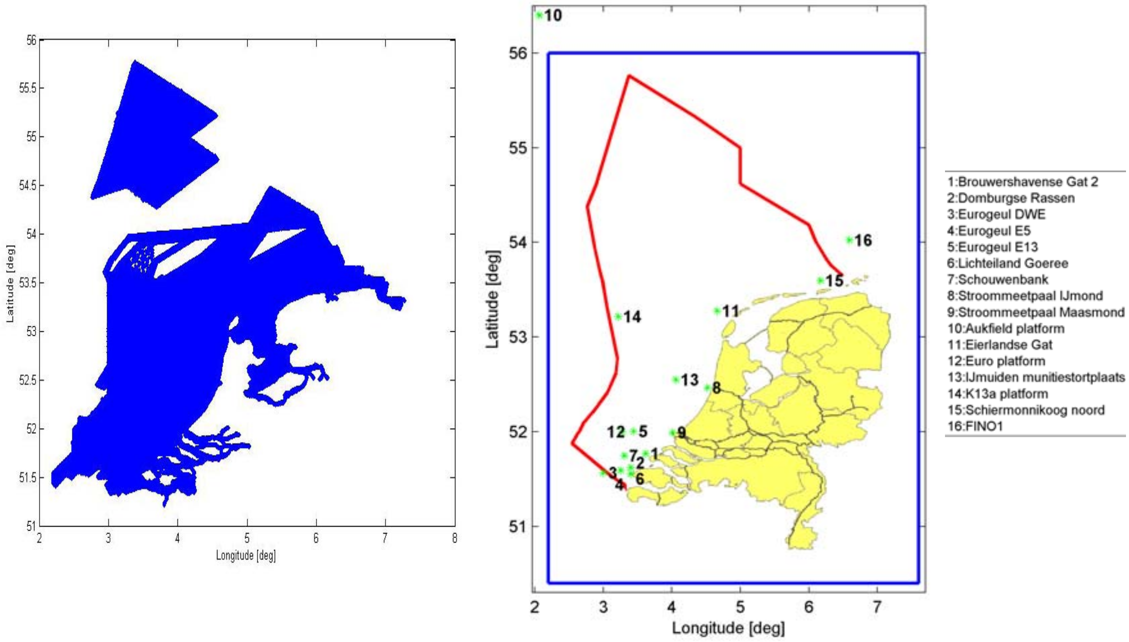

Figure 2 Locations where sea depth (left) and wave data (right) are known. In order to estimate sea surface roughness these data are interpolated to the location of interest by inverse distance weighting

3 Validation of the method

3.1 Outline

The numerical wind atlas method described in section 2.1 was validated by using wind speeds and wind directions measured at various heights in eleven locations (figure 3). Two onshore locations were selected: the meteo mast in Cabauw and a meteo mast in the ECN Wind turbine Test site Wieringermeer (EWTW). Since the OWA-NEEZ is focused on the North Sea, nine offshore locations were selected: the meteo mast at the Offshore Wind farm Egmond aan Zee (OWEZ), the meteo mast FINO-1 and the meteo stations Europlatform, K13-α, Meetpost Noordwijk, IJmuiden, Lichteiland Goeree, Vlakte van de Raan and Oosterschelde. As can be seen in figure 3, most of the offshore locations are in the south west corner of the NEEZ, near the Dutch coast. Exceptions are station K13-*α* in the west part of the NEEZ, and FINO-1 in the north east but outside the NEEZ.

3.2 Discussion

In the following three subjects are discussed: regression between measured and calculated wind speed time series, map error, and comparison of Weibull distributions.

A linear regression was applied between the measured and calculated wind speed time series. Only wind speeds above 4 m/s were taken into account. For the locations with multiple measurement heights (Cabauw, EWTW, OWEZ and FINO-1) a height was found where underestimation of wind speed turns into overestimation. This height is called turn-over-point. Going from west to east, it was found that the turn-over-point rapidly decreases. Note however that this observation is based on only four locations in a rather large area – the correctness of this observation should be checked by adding additional locations for which measurements are available at multiple heights.

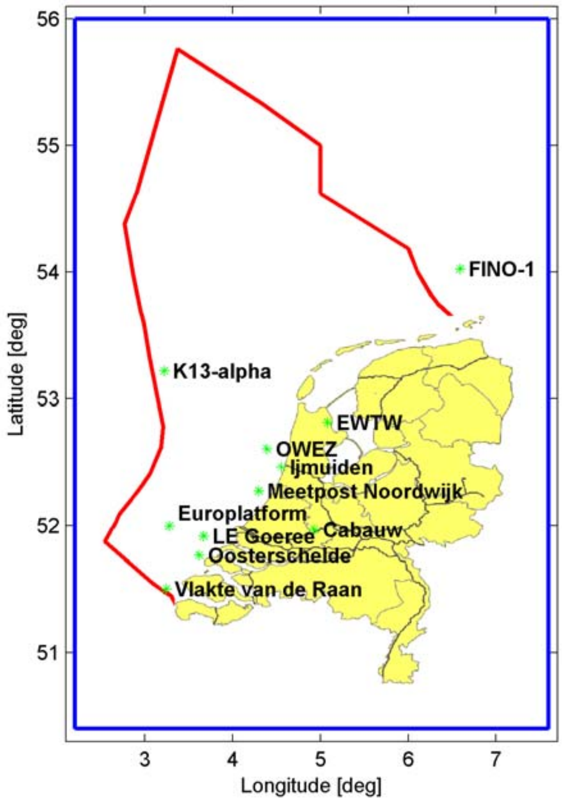

Figure 3 Locations used in the validation

Map error is the difference between calculated and measured wind speed as averaged over the locations that are considered. In order to determine map error, the locations were subdivided into two groups. The first group consists of the meteo stations where "measured" and calculated potential wind speed was compared. (Potential wind speed is a hypothetical wind speed which is valid for a standard height and a standard value of the surface roughness.) The second group consists of the locations for which multiple heights could be analyzed.

For the first group of locations it was found that the mean of the map error is –0.08 m/s. (A negative value of the mean map error indicates that, on average, the map gives a lower value of the mean wind speed than the measurements.) The standard deviations of the map error were in the range of 0.42 to 0.44 m/s. It was noted that the map error is very sensitive: adding or removing one location to or from the sample has a large influence on the map error.

For the second group of locations, three height ranges were made: low, medium and high. For the low height range (between 10 m and 50 m), a mean map error of 0.36 m/s was found with a standard deviation of 0.39 m/s. The results of the medium height range (between 50 m and 100 m) are –0.07 m/s for the mean map error and 0.26 m/s for the standard deviation. Note that this height range contains the turn-over-point which results in a small mean map error. For the high height range, with heights between 100 m and 200 m, the mean map error is –0.25 m/s and the standard deviation is 0.33 m/s. These results are in agreement with the results of the analysis of the mean wind speed in regression plots. Note that in this analysis a constant value of the Charnock parameter was used because only for one location in this group it was possible to use a variable Charnock parameter.

Regarding the Weibull distributions it was found that for the scale parameter it does not matter whether a constant or variable Charnock parameter is employed because values have the same order of magnitude. On the other hand, it was found that the shape parameter calculated with a constant Charnock parameter is usually lower than the shape parameter found from the measurements. Using a variable value of the Charnock parameter gives the better estimate of the shape parameter which is higher than was found with a constant value but closer to the value found from the measurements. It appears that using Hsu's equation mainly influences the shape parameter of the Weibull distribution.

3.3 Evaluation

By inspecting wind measurements at several locations it is found that, compared to the first version of the OWA-NEEZ, adding wave data results in a slight improvement in the estimate of the wind speed distribution. For each location a two-parameter Weibull distribution is determined and a comparison is made between the various shape and scale parameters. It is found that generally the scale parameter is overestimated by both versions of the OWA-NEEZ. The cause might be found in the data used to make the OWA-NEEZ. The shape parameter is well predicted when wave data is employed.

4 Offshore wind atlas of the Dutch part of the North Sea

4.1 The second version of the OWA-NEEZ

The second version of the Offshore Wind Atlas of the Netherlands' Exclusive Economic Zone contains maps for the heights of 40 m, 90 m and 140 m spatial distributions of mean wind speed, Weibull scale parameter, Weibull shape parameter, and reference wind speed. There are maps for all wind directions as well as per sector of 30 deg. In addition, the OWA-NEEZ contains maps of the mean wind speed per year, and per month. Data for a height of 90 m are shown in figures 4 and 5.

4.2 Comparison to other wind maps

The mean wind speed of the second version of the OWA-NEEZ is compared to mean wind speeds from other wind maps. There are several wind maps freely available, the three addressed in this study are: the European Wind Atlas made by Risø National Laboratory [12, 13], the wind map of the Netherlands made by SenterNovem [14], and the first version of the OWA-NEEZ made by ECN [1]. Preferably, this comparison is done for equal height and resolution. As will be shown, this is not possible so that the comparison is made to one map only.

The European Wind Atlas made by Risø was published in 1989 and created by using the wind atlas method WaSP. It is divided into two parts. The first part is an onshore wind atlas indicating the wind speed for five different types of land use [12], and for that reason cannot be used in the comparison. The second part is an offshore wind atlas indicating the wind speed at five different heights [13]. There are, however, two reasons why the offshore wind map can not be used for the comparison. The first reason is that the resolution of the average wind speed ranges from 1 m/s for low heights to 1.5 m/s for high heights. Because of this, almost the whole NEEZ is covered with the same color making the comparison already impossible. The second reason is that the spatial resolution is quite large, the map comprises the whole continent of Europe and is therefore not on the same scale as the new OWA-NEEZ. A comparison with the European Wind Atlas is therefore not possible.

The wind map of the Netherlands made by SenterNovem was published in 1995 and was created by using WaSP too [14]. There are two reasons why this map can not be used for the comparison. First, the map covers the Netherlands excluding the NEEZ. Secondly, the spatial resolution of this map is very high with 200 x 200 m^2 whereas the spatial resolution of the OWA-NEEZ is only 22 x 22 km^2.

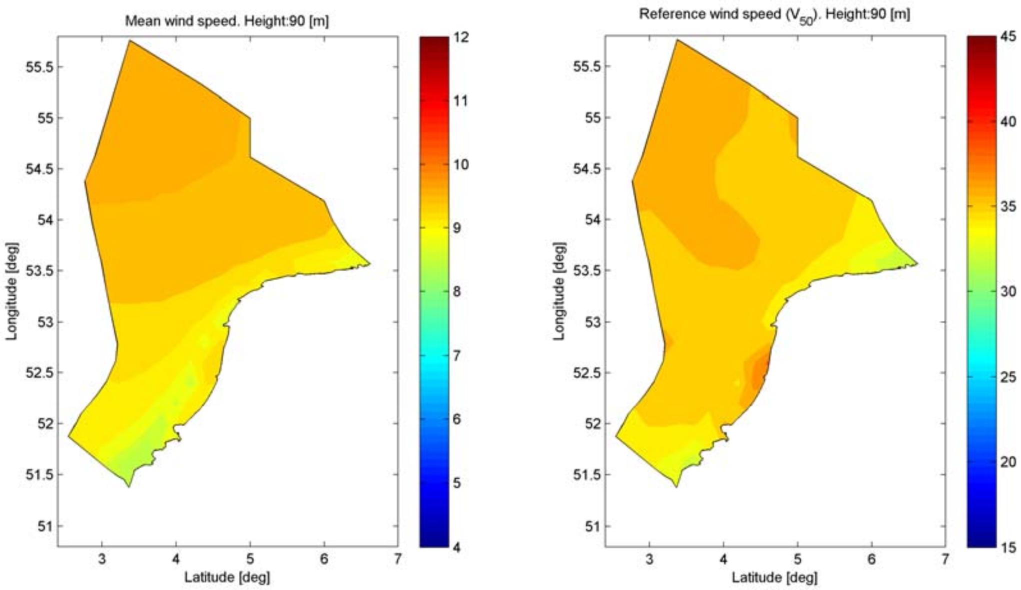

Figure 4 Mean wind speed (left) and reference wind speed (right) at a height of 90 meter in the Netherlands' Exclusive Economic Zone

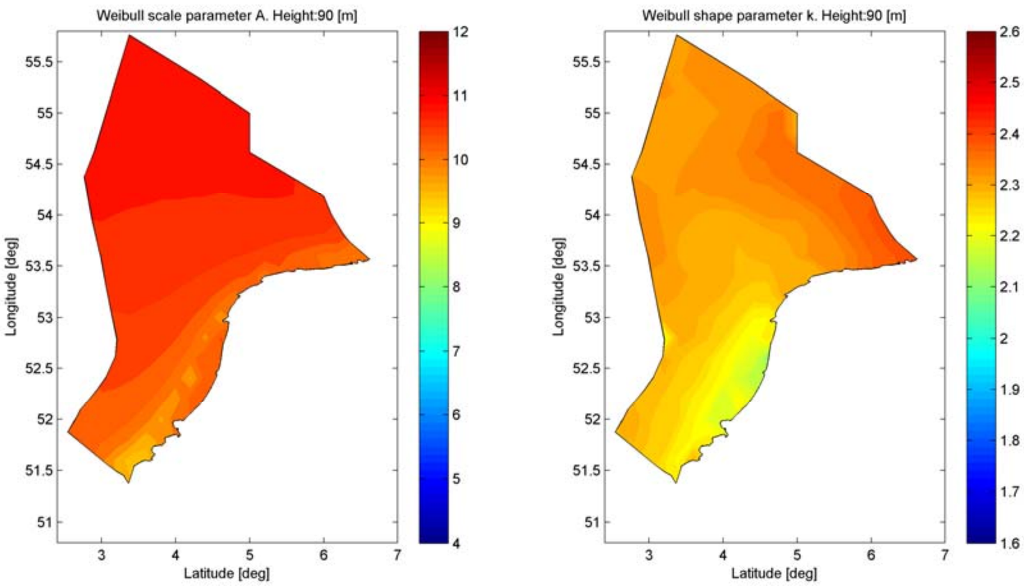

Figure 5 Weibull scale parameter (left) and Weibull shape parameter (right) at a height of 90 meter in the Netherlands' Exclusive Economic Zone

The third wind map is the first version of the OWA-NEEZ [1]. Four public maps have been made for the heights of 60 m, 90 m, 120 m and 150 m. Note that only for a height of 90 m a map is available from the second version of the OWA-NEEZ. The spatial resolution of this map is in the same order as was used to make the second version of the OWA-NEEZ. Resolution of the mean wind speed is 0.2 m/s. The period considered comprises the years 1997 until 2002. In the following the mean wind speeds of the first and the second versions of the OWA-NEEZ are compared for the same height of 90 m. Figure 6 shows the mean wind speed at 90 m according to the first version of the OWA.

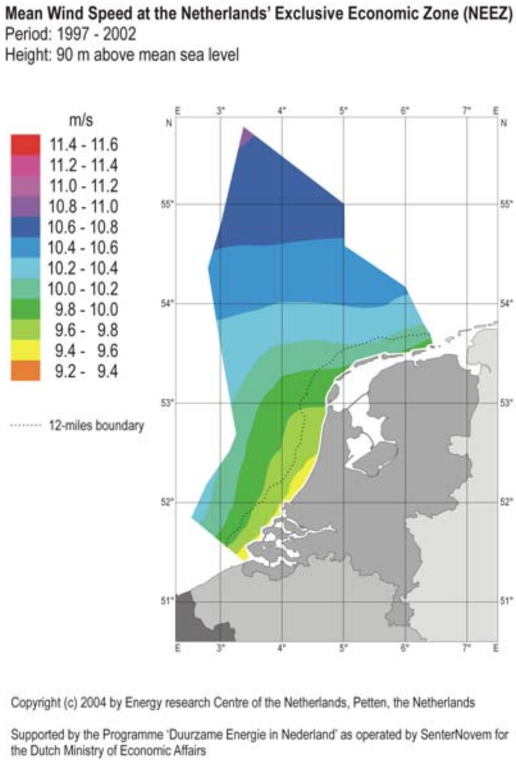

Figure 6 Mean wind speed at a height of 90 m in in the Netherlands' Exclusive Economic Zone according to the first version of the OWA-NEEZ.

Although the color schemes in the plots are different, it can still be seen that there are significant differences in mean wind speed. In the north part of the NEEZ, according to the first version the wind speed is between 10.6 and 10.8 m/s. The same area in the second version gives a wind speed between 9.8 and 10.0 m/s. This is a difference of 0.8 m/s which is rather large. Such a difference in mean wind speed can be found throughout the whole map, but near the coast, the difference increases to 1 m/s. Note that this does not indicate that either of these maps are wrong. It simply indicates that there is a large difference when two different periods are being compared.

The following notes have to be made. First of all, in summer, the average wind speed generally is lower than in winter. Including an extra summer in a certain period already decreases the average wind speed considerably. Secondly, it is very well possible that in the periods considered for both maps a different amount of storms passed by. Thirdly, the average wind speed may indeed be decreasing. This however does not directly indicate that the wind climate is changing. To determine the wind climate, a period of 30 years should be considered. Currently, it is not possible to determine this on basis of the HiRLAM data because there is not yet enough data for that.

For the first version of the OWA-NEEZ the map error has been calculated. It was found that the mean map error is –0.17 m/s with a standard deviation of 0.20 m/s. Because the validation for the first version of the map was done using potential wind speeds, it should be compared to the map error of the second version as found for potential wind speeds. For the second version of the OWA-NEEZ, the mean map error is –0.08 m/s with standard deviation of 0.42 m/s. When these values are compared, it can be seen that the mean map error of the first version and the second version of the OWA-NEEZ corresponds well. The standard deviation of the map error for the second version however is twice as large as for the first version. This is mainly due to the location IJmuiden which was not present in the first version.

5 Conclusion

The second version of the Offshore Wind Atlas of the Netherlands' Exclusive Economic Zone was made by employing a sea surface roughness which, apart from the wind speed, depends on wave height, wave period, and sea depth. By using such a variable sea surface roughness, the accuracy of wind speed distributions is improved with 1% to 2% over distributions calculated with a sea surface roughness that depends on wind speed alone.

Acknowledgements

Netherlands Hydrologic Service of the Royal Netherlands Navy supplied sea depths in the Dutch part of the North Sea.

Rijkswaterstaat supplied wave heights and wave periods in select stations in the Dutch part of the North Sea.

Bundesministerium für Umwelt BMU and Projektträger Jülich PTJ supplied data from the FINO-1 meteo mast in the German part of the North Sea.

Royal Dutch Meteorological Institute KNMI provided data from the meteo stations Europlatform, K13-α, Meetpost Noordwijk, IJmuiden, Lichteiland Goeree, Vlakte van de Raan and Oosterschelde.

Data from the meteo mast in Cabauw originates from the CESAR-database (Cabauw Experimental Site for Atmospheric Research).

Energy research Centre of the Netherlands ECN provided data from a meteo mast in the ECN Wind turbine Test station Wieringermeer (EWTW) and the meteo mast in the Offshore Wind farm Egmond aan Zee (OWEZ).

References

1. Brand AJ, Hegberg T. Offshore Wind Atlas - Wind resource in the Dutch part of the North Sea. ECN, Report ECN-CX--04-136, 2005
2. Donkers JAJ. Update Offshore Wind Atlas - Implementing a variable sea surface roughness. ECN, Report ECN-M--10-103, 2010
3. Landberg L et al. Wind resource estimation - An overview. *Wind Energy* 2003; 6:261-271
4 Holtslag AAM. Estimates of diabatic wind speed profiles from near surface weather observations. *Boundary-Layer Meteorology* 1984; 29:225-250
5. Businger JA et al. Flux profile relationships in the atmospheric surface layer. *Journal of the Atmospheric Sciences* 1971; 28:181-189.
6. Charnock M. *Quarterly Journal of the Royal Meteorological Society* 1955; 81:639-640.
7. Hsu SA. A dynamic roughness equation and its application to wind stress determination at the air-sea interface. *Journal of Physical Oceanography* 1973; 4:116-120
8. Historische waterdata. Rijkswaterstaat, Ministerie van Infrastructuur en Milieu. Online: www.rijkswaterstaat.nl/water/scheepvaartberichten_waterdata/historische_waterdata, accessed 7 March 2011
9. Dieptemeten. Dienst der Hydrografie, Koninklijke Marine. Online: www.defensie.nl/marine/hydrografie/geodesie_en_getijden/dieptemeten, accessed 7 March 2011
10. Li J, Heap AD. A review of spatial interpolation methods for environmental scientists. Geoscience Australia, 2008
11. Bergström H. Distribution of extreme wind speed. Wind Energy Report WE92:2, 1992
12. Troen I, Petersen EL. European Wind Atlas. Risø National Laboratory. 1989
13. Petersen EL. Wind resources of Europe (the offshore and coastal resources). In: Proceedings of the conference "The potential of wind farms", Herning. 1992
14. Windkaart van Nederland op 100 meter hoogte. SenterNovem. 2005

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Atlas

Offshore Wind Atlas of the Dutch part of the North Sea was first published in 2005. Since then more data have become available and the opportunity to employ variable sea surface roughness has appeared.

Like the first version, the second atlas is based on time series of meteorological variables originating from the HiRLAM. A total of six years of data have been processed. Unlike in the first version, where sea surface roughness depends on wind speed alone (Charnock relation), in the second version sea surface roughness is a function of wave steepness too (Hsu equation).

The second version of the Offshore Wind Atlas of the Dutch part of the North Sea contains distributions of mean wind speed, Weibull parameters and reference wind speed at 40, 90 and 140 meter above mean sea level.

Product

Wind resource assessment for developers or designers is performed in three steps.

First step – Rough and rapid.
Estimates of mean wind speed from pre-calculated tables.

Second step – More detail.
Pre-calculated distributions in select locations. A distribution includes wind speed, wind direction, turbulence intensity, and stability class.

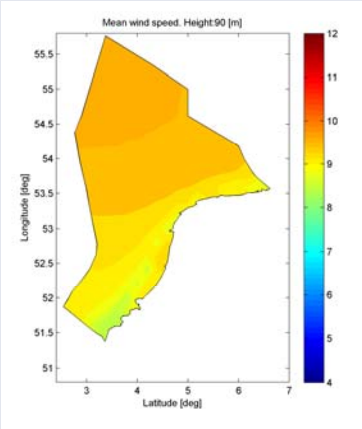
Third step – Site specific.
Time series and distributions. Parameters include wind speed, wind direction, turbulence intensity and stability length.

Experience includes:

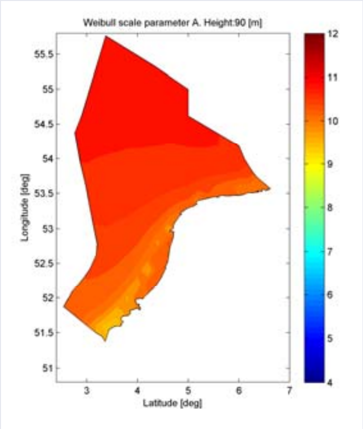
Maps and spreadsheets with mean wind speeds and distributions of wind related parameters in the Netherlands and in the Dutch part of the North Sea.

Time series and distributions of wind speed and other data in the southern part of the North Sea, the Netherlands, and most of Belgium.

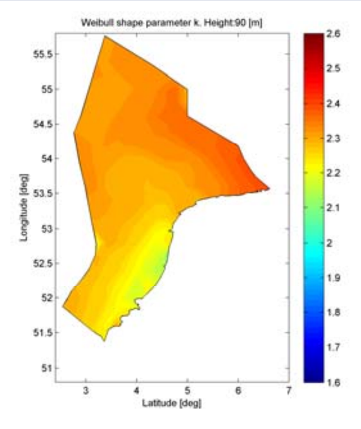
Mean Wind Speed



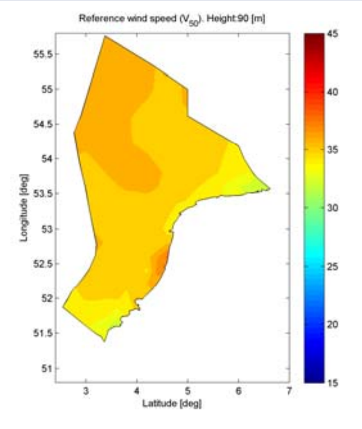
Weibull Scale Parameter



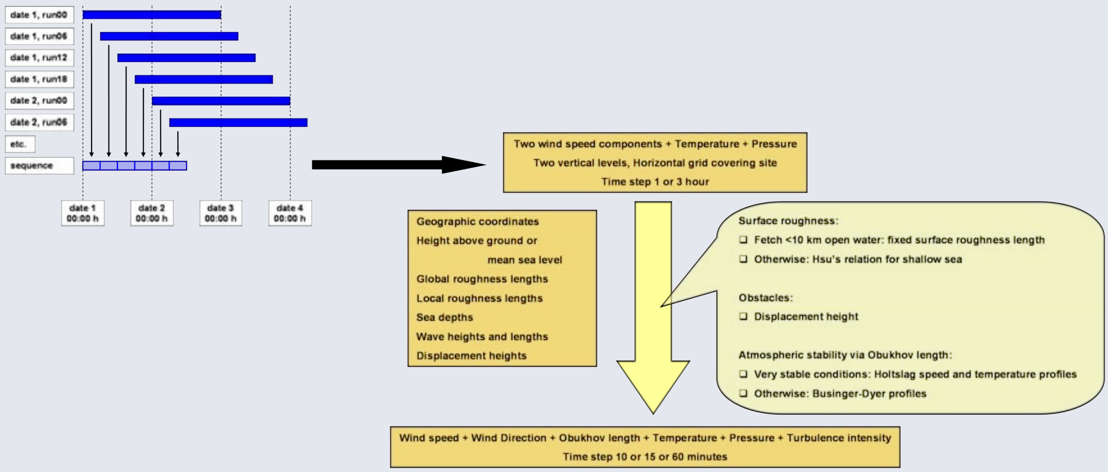
Weibull Shape Parameter



Reference Wind Speed



Model Chain



References

Brand A.J., Hegberg T., 2005. ECN, Report ECN-CX--04-136

Businger J.A. et al., 1971. J. Atmos Sci. 28, 181-189

Donkers J.A.J., 2010. ECN, Report ECN-M--10-103

Holtslag A.A.M., 1984. Boundary-Layer Meteorol. 29, 225-250

Hsu S.A., 1973. Journal of Physical Oceanography 4, 116–120

Landberg L. et al., 2003. Wind Energy 6, 261-271